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Master Thesis

Comparison between Desktop and VR in Virtually Performing Superficial Decontamination

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Contents

Abstract

The interest of younger generations is dwindling in science fields such as nuclear and radiochemistry. The A-CINCH consortium is creating all-inclusive digital tools for nuclear and radiochemistry studies to stop the wane of interest, raise awareness, and reach a wider audience. In order to attract students, these tools also include a virtual lab with various hands-on training experiments. One of these experiments is a decontamination procedure that releases materials from superficial contamination.

In this work, a virtual decontamination method based on the A-PHADEC process is presented. The experiment will be a part of a virtual lab setup and is developed for desktop (WebGL) and VR systems. In addition, a number of lab interactions are covered, including using pipettes and tweezers. Additionally, various comparisons are made between these two systems' accessibility, development effort, interactions, and more.

The developed applications were evaluated with a user study among 15 participants divided into desktop and VR groups. The user study assessed factors of knowledge gain, presence, usability, and cybersickness. The results indicate that the VR group, besides cybersickness, performed better in all factors compared to the desktop group. In addition, an informal expert interview was conducted, and it provided insights on the benefits and drawbacks of the developed applications, along with their potential in the future. Furthermore, based on a general comparison between the desktop and VR, it was revealed that both systems have their own benefits and are promising tools for decontamination experiment training.

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1

Introduction and Motivation

1.1 Motivation

With the development of computers as a technology, education has also changed over time. They are frequently employed to support the learning of trainees and students. These devices are crucial from primary school through higher education [SUPPES, 1966]. The gadgets used range from hand-held devices like cell phones and tablets to head-mounted displays such as virtual reality (VR) headsets. Additionally, during the COVID-19 pandemic [SINGHAL, 2020], when gathering in a room for theoretical lectures was all but impossible [MOORHOUSE, 2020], these gadgets served as an invaluable teaching tool. For instance, solutions such as TeachInVR [SCHIER et al., 2022] came into existence to assist remote teaching to students from different locations.

In addition to theoretical lectures taught to the students, many courses involve practical sessions to supplement the lectures. These practical sessions aim to provide students with training and practical knowledge that help them prepare for a profession. However, multiple challenges must be solved to organize these practical sessions. For example, personnel issues like few supervisors handling many students, physical problems such as spacing issues to fit all students in the same room, and resources limitations such as missing materials. These problems can commonly occur in science related labs [KIRSCHNER and MEESTER, 1988]. To add to the problems, science fields such as nuclear and radiochemistry (NRC) also shows a decline in interest from younger audiences [SMODIŠ, 2006; WALTHER, 2016]. Therefore, a suite of digital tools can not only assist in training students but also help reach a broader audience in creating awareness and interest about fields such as NRC.

One type of digital tool that can help with training is a virtual lab. Compared to a real lab, it would be a secure environment that would not be prone to damage. While it cannot replace a physical lab, it can act as a supplement to it. This can be accomplished by simulating actual dangers, such as contamination and flames, to make the user aware of them. It may serve as a catalyst for encouraging youth to investigate NRC experiments. Additionally, it can lower the expenses related to training or learning experimentation techniques.

Even though there are several works involving training applications [Fast et al., 2004] and virtual labs [Miranda-Valenzuela and Valenzuela-Ocaña, 2020], very few or none target the NRC field, particularly those involving experiments or training procedure with the decontamination of superficially contaminated materials. Additionally, a comparison of various platforms (desktop vs VR) for NRC virtual labs is missing, especially when it comes to a desktop platform that is easily accessible to use, like WebGL. This thesis aims to investigate these gaps.

1.2 Goals

The primary objective of this work is to create a virtual environment where students can release materials from superficial contamination using the A-PHADEC based decontamination process, which is covered in more detail in the **Background** chapter. Applications will be implemented in both a desktop (WebGL) and a VR version. Additionally, the interactions required for the aforementioned applications will be realized. These interactions range from basics such as object selection and manipulation to specifics used in radiochemistry labs like handling tweezers and automatic pipettes. Moreover, making a direct general comparison between the desktop and VR platforms is another goal. A comparison of aspects such as accessibility, implementation, and interactions is to be investigated.

Additionally, applications developed within this thesis for desktop and VR are assessed for their presence, usability, and comfort. A knowledge test is also part of the assessment to comprehend the effects of knowledge gain. Finally, the evaluation is concluded through an informal expert interview to examine various use cases and the potential of the application.

The last goal is to include the created desktop application into an existing virtual lab architecture, i.e. the A-CINCH lab[1]. Multiple NRC experiment procedures already make up the virtual lab framework, so adding another would broaden the framework's potential applications. However, since the virtual lab framework is only available for desktop use, only the desktop version will be integrated.

1.3 Contributions

In the following list, the contributions made from this thesis are described.

- **A desktop and VR training application to virtually perform decontamination procedure:** the first and foremost contribution is a developed training application to learn about the decontamination process, namely the A-PHADEC decontamination method. The application can also supplement lab sessions for the decontamination procedure. Moreover, the experiment is realized for desktop and virtual reality platforms. Furthermore, the desktop variant is integrated within the A-CINCH lab - a virtual lab consisting of 8 hands-on training experiments and would be used by students in NRC study programs across 16 European universities.
- **Various interactions in desktop and VR for the virtual lab:** as part of the application mentioned above, various interactions were realized for desktop and VR. Common interactions in an NRC lab, such as mixing liquids, and building flask systems, were conceptualized and implemented. Moreover, translating different interactions from desktop to VR is also discussed. On the other hand, coding practices involved in safely managing a large project such as the A-CINCH virtual lab and the methods used to integrate the developed components into the existing framework are shortly described. Furthermore, a general discussion of the positive and negative aspects of both variants is provided.
- **Evaluation of the desktop and VR variants for the decontamination process:** another focal part of this work is the outcome of the user experience in using the virtual lab through different mediums (desktop

[1] https://www.cinch-project.eu/

and VR). A user study was performed with 15 participants with background knowledge in NRC. The factors analyzed through the study include *Knowledge Gain*, *Cybersickness*, *Presence*, and *Usability*. Furthermore, an informal expert interview was also conducted to get a general opinion on the applications from a specialist's point of view.

1.4 Structure

The structure of this thesis is organized as follows.

- **Chapter 2 - Background** deals with the necessary topics required to understand the thesis better. These topics mainly focus on NRC, especially the decontamination technique implemented in this work. Moreover, a short overview of VR and its interactions is presented as technical background.
- **Chapter 3 - Related Work** covers computer-based training tools and virtual labs, primarily focusing on their use in training and teaching. Additionally, assessments comparing virtual labs across several platforms, particularly desktop and VR, are presented.
- **Chapter 4 - Concept** deals with the various strategies investigated to realize the applications. The interactions employed are the key area of focus. Additionally, the lab setup is thoroughly described, including the lab environment and 3D models.
- **Chapter 5 - Implementation** discusses the implementation details of the applications. In addition, software development practices employed and multiple challenges encountered are discussed. Furthermore, a general comparison between the desktop and VR platforms is performed.
- **Chapter 6 - Evaluation** reviews the findings of the user study comparing the application in desktop and VR. It also summarizes an informal discussion held with a specialist in the NRC field, discussing the benefits and shortcomings of the applications.
- **Chapter 7 - Conclusion** summarizes the thesis with a general discussion. Moreover, it provides an outlook on future work, notably the application extensions.

2 Background

This chapter contains the background required to comprehend the thesis better. Firstly, the technical background involving concepts related to VR is presented. Later, the domain background-related concepts of NRC are discussed.

2.1 Virtual Reality

According to *The VR book: Human-Centered Design for Virtual Reality* (Page 9) [JERALD, 2015], the definition of VR is

"Virtual Reality is defined to be a computer-generated digital environment that can be experienced and interacted with as if that environment were real".

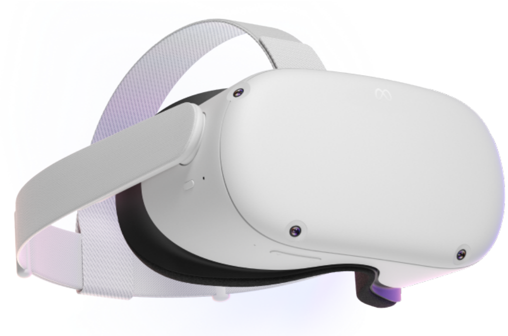


Figure 2.1: The Oculus Quest HMD from Meta[1].

[1] https://store.facebook.com/de/en/quest

In VR, the user perceives the virtual environment in 3D using the head-mounted display (HMD) (see Figure 2.1). This gives the users a feeling that the virtual world surrounds them and enables them to be immersed in it. Such technology offers a wide range of applications involving medicine, education, tourism, and entertainment [GUTTENTAG, 2010; WEXELBLAT, 2014].

In the following, different input methods, navigation, selection, and manipulation techniques in VR are discussed. Also, factors concerning VR, such as presence, cybersickness, and usability, are introduced.

2.1.1 Input Modalities

In the virtual environment, users can interact using different modes [ANTHES et al., 2016], some of which are described here.

Hand-Held

With this mode, users hold wand-like structures such as the VR controllers or the VR Stylus[2] in their hands. These devices represent the user's hand in the virtual environment, and the various buttons on them can be used to invoke several actions in the virtual world.

Wearables

These input devices exist in the form of gloves, for example, the ManusVR Gloves[3], and the users must wear them on their hands. The wearable gloves enable users to perform natural interactions in the virtual world. However, the gloves are cumbersome compared to the controllers since they must be worn, which sometimes includes a tracker to track the position. Moreover, calibration is required to adapt to different hand sizes of different users.

Hands Tracking

In this mode, the user need not wear or hold any device. Instead, they can use tracked hands with sensors attached to their HMD. However, line of

[2] https://www.logitech.com/de-de/promo/vr-ink.html
[3] https://www.manus-meta.com/products/prime-x

sight is an issue in such a mode since the tracking can be unreliable when the user removes their hands from the sensor's view.

Although different input modalities exist for VR, hand-held devices, specifically the controllers, are used in this work because of their ease of availability, comfort, and reliability compared to others.

2.1.2 Navigation Techniques

The user must navigate the virtual world to move from one place to another. The below list briefly explains different navigation techniques in virtual reality.

Walking

In this method, the user must walk in real-life to reach a destination in the virtual world. The steps from the real world are reflected in the virtual world. However, redirected walking [LANGBEHN et al., 2018] is another option when the physical space is limited or not as large as the virtual world. In this technique, the user is frequently redirected with a minimal or zero realization. It works through the gains from translation and rotation that are different to the users' actual motion. However, when users reach an obstacle in the physical space, they would have to turn away from it.

Steering

Users must steer their look or direction to navigate with this technique [CLIFTON and PALMISANO, 2020]. For example, leaning can affect the velocity and direction of the user during navigation. On the other hand, with gaze-directed steering, users can also use their gaze to change their navigation direction.

Relocation

With this technique, users can quickly relocate to any point in the virtual world of their choice without having to perform physical walking. For example, using teleportation [BOZGEYIKLI et al., 2016], the user can point using a ray or an arc at a valid virtual world point and relocate to it. Similarly, in the World in Miniature (WiM) method [DANYLUK et al., 2021], the user can point at the virtual world represented via a miniature. The miniature version can help users to navigate quickly in a large virtual world.

While walking can cause fatigue, steering can induce motion sickness due to the frequent eye or head movement. However, teleportation is better than these two techniques in avoiding fatigue and motion sickness to an extent. Hence, it is the preferred choice in this work.

2.1.3 Selection and Manipulation

Users should perform actions to interact with the virtual world objects. Different techniques exist to perform actions, such as selecting and manipulating an object. A few of them are discussed in the following.

Direct Interaction

Similar to the real world, users can interact with virtual world objects by directly holding them and manipulating them. The degrees of freedom are the same as in the real world. However, sometimes the object cannot be reached within arm's length, and such situations can be handled using the Go-Go technique [POUPYREV et al., 1996]. In this technique, the arm is extended, and the distant objects can be directly interacted with using a non-linear mapping of selection and manipulation.

Ray-Based Interaction

Interaction is performed by pointing at an object using a ray emitted from the hand-held device position in the virtual world. The first object that the ray intersects with is enabled for selection and manipulation. Ray interaction is highly suitable for interactions with distant objects that are not within reach of the user in the virtual world [SAALFELD et al., 2021].

Gesture-Based Interaction

Users can express their interactions with virtual world objects through gestures [YANG et al., 2019]. Sensors recognize gestures, and the assigned action to a gesture is invoked. For example, users can use their hands to hover over an object to perform the selection. Additionally, the movement of their hands can signal translation, and the turning of hands can indicate rotation. Furthermore, they can use gestures such as stretching both hands to scale an object.

The direct interaction with controllers, which enables the user to feel tangibility and also reflects the linear mapping of their actual motion, is used in this work.

2.1.4 Assessment Factors

Multiple factors can be used to assess a VR system. Some of them are discussed here. These factors can also be applied to other platforms, such as the desktop. However, in this case, it is explained in general relation to VR. Furthermore, all of them can be measured using question-based methods.

Presence

The concept of presence in VR can be defined as the sense of being there in the virtual environment [SANCHEZ-VIVES and SLATER, 2005]. Meaning that the user feels present in the virtual world, although their body is not in it. Multiple variables can affect presence. For example, display parameters such as framerate and field of view can increase presence. Also, feedback using auditory and haptic systems can improve presence. Furthermore, the body's engagement, such as walking, is also reported to increase presence in the virtual world [SLATER et al., 1995].

Cybersickness

Cybersickness occurs when symptoms such as headache, eye strain, sweating and more are induced through a visual simulation. It can be a serious issue and can significantly affect user experience. Factors such as lagging, flickering, and position-tracking errors contribute to cybersickness [LAVIOLA JR, 2000].

Usability

Usability is a feature that influences the acceptability of the product. It is affected by how easy and efficient it is to learn, how easy it is to remember and how often errors are committed through the system, and finally, how satisfied users are with it [NIELSEN, 1994].

2.2 Nuclear and Radiochemistry

This section contains the fundamentals of the concepts related to NRC that are necessary to understand this thesis better. Firstly, a short introduction to the field of NRC is provided. This is followed by a description of the concepts of decommissioning and decontamination. Finally, the implemented decontamination experiment and its steps are explained.

2.2.1 Fundamentals

The field of NRC deals with the concepts such as radioactivity and nuclear reactions [CHOPPIN et al., 2002; LIESER, 2008]. The study of NRC vastly discusses radioactive elements, which could be fatal as much as they are useful. Hence, their behavior and characteristics are carefully studied, and also their interaction with matter. According to the book *Nuclear and Radiochemistry* by [KÓNYA and NAGY, 2018], NRC deals with all the possible applications of radioactivity and nuclear processes in modern radiochemistry, such as nuclear medicine, nuclear energy production, nuclear power plants, nuclear waste disposal, the use of radioisotope tracers in industry, including the development of analytical methods based on the interactions of radiation with matter.

Some of the applications mentioned above that are studied in NRC bring a great variety in producing radioactive waste. However, the waste is also generated in quantities that, if not correctly managed, could have detrimental effects on the environment, substantially impact the population's health, and represent an unsustainable burden for future generations. One of such topics is the decommissioning of the nuclear facility.

Decommission

Every nuclear facility, such as a nuclear power plant (NPP), has a lifetime associated, after which it is shut down. Once a facility is retired from functioning, decommissioning activities take place to free the nuclear facility from measures for radiation protection [UNIVERSITY et al., 1994]. The decommissioning activities are performed either through a safe enclosure (entombment) of the nuclear facility (for example, the Chernobyl NPP) or directly dismantling it. Either way, the process is extremely long that could last up to a decade or more. Moreover, decommissioning activities could produce a large volume of materials that are only superficially contaminated by radioactive elements. If disposed of in their current state, they occupy a large volume in the disposal site despite their low activity. However, they could not be reused in the industry as they are since they are contaminated. Hence, this prolonged activity severely impacts both financially and environmentally, so careful consideration is required to make the process as effective and efficient as possible. One of the efficient measures is to reuse the materials from the dismantled facility. Since the materials used in a nuclear facility are high-cost and can be reused when properly released from radiation, decontaminating measures are performed.

Decontamination

Decontamination is the process of removing the contamination layers on a material's surface. The contaminated materials can be quite hazardous to the environment due to the radiation if not controlled. Moreover, when properly treated, these materials can be reused in the future, proving economical and environmentally friendly. Depending on the material and the thickness of the contaminated layer, the process is completed chemically (using acids and agents) or mechanically (scrubbing and polishing) [AGENCY et al., 1999]. Once the process is complete, residual contamination is measured by radiometric techniques to check if it is under the clearance level. The clearance levels specify values below which any materials can be released from regulatory control with negligible risk from a radiation protection point of view. At this point, materials can be released to be reused in the industry. This reuse of materials reduces both the cost and waste that would have been generated by using a relatively new material. However, decontamination processes produce secondary waste and require further energy to work. Therefore, it is paramount to develop more environmentally friendly new methods by minimizing the generation of secondary waste and reducing energy consumption.

2.2.2 A-CINCH: Virtual Lab

The A-CINCH (Augmented Cooperation in Education and Training in Nuclear and Radiochemistry)[4] is a European consortium developing an all-in-one platform for NRC learning. The aim is to increase trainees and students in the NRC field, which has recently seen wane of interest. The project aims to increase the interest among students by providing an easily accessible, all-in-one platform to learn about NRC. The project offers MOOCs (Massive Open Online Course), summer schools, and also a virtual lab. The virtual lab is a 3D environment, where users can use interactions to learn various NRC experiments. The virtual lab includes different hands-on training procedures designed and developed by various European universities. With the virtual lab, users can not only learn practices such as how to enter or exit a lab but also perform different experiments that are part of NRC course curricula. One of the experiments included in the virtual lab is a decontamination experiment, A-PHADEC [Galluccio et al., 2020], developed by the Radiochemistry Group of the Department of Energy at Politecnico di Milano (POLIMI)[5]. This thesis implements and evaluates the A-PHADEC experiment for user experience in both Desktop and VR.

2.2.3 Hands-on-Training Experiment

A NRC Hands-on-Training (HoT) is an experiment or procedure taught to students in a physical lab. These experiments are mostly part of a course curriculum at a university. Unfortunately, the HoT, although very important, is not easily accessible to the students due to various obstacles. The availability of a few supervisors, lack of space to accommodate all students, and expensive resources and materials used in the experiment all contribute to the issue. To avoid a complete lack of training, teachers use media materials such as videos and images to explain HoT procedures during lectures. However, no feedback is given when students go through these media materials. To improve this situation, a virtual lab, which includes feedback, would be helpful. Students would also have the option to access the learning based on availability. Besides, it also helps in pre-

[4] https://www.cinch-project.eu
[5] https://www.radiochimica.polimi.it

training, which the students can benefit from when experimenting in a physical lab.

In this work, the A-PHADEC decontamination process is developed and integrated into the A-CINCH virtual lab. The A-PHADEC process is based on the PHADEC process [FRANO et al., 2014], which is already implemented in the Caorso and Gundremmingen NPPs. The A-PHADEC fixes the shortcomings of the PHADEC process, mainly related to the total energy used in the process, pursuing the minimization of secondary waste. The A-PHADEC process is still under study at POLIMI to demonstrate its feasibility and effectiveness through a demonstrator plant in view of its future application in Italian NPPs [GALLUCCIO et al., 2020]. For this, professionals must be trained to learn the A-PHADEC experiment effectively.

The A-PHADEC includes four stages [GALLUCCIO et al., 2020]:

1. The contaminated layer on the material is dissolved in a suitable acid.
2. The solution containing the contamination is oxidated to precipitate appropriately.
3. Using the electrochemical precipitation, the contamination present in the solution is turned into a sludge.
4. Finally the obtained sludge is directly vitrified into a glass form.

This work considers the first two stages of dissolving (pickling) and oxidation. In the following, the details of the first two stages are explained.

1. Pickling Process

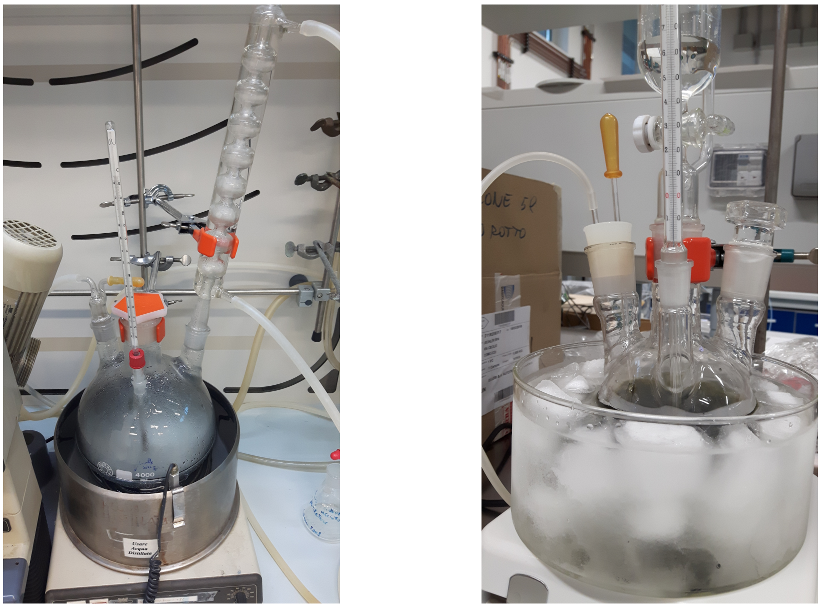
In the beginning, a scenario is created where three superficially contaminated metal scraps arrived at the lab from a decontamination activity. The sample data of these scraps are presented in a data sheet on the lab computer. The sample data on the computer represents the weight, dimensions, and contamination information. Using this data, the user has to decontaminate the metal scraps by dissolving the contaminated layer in phosphoric acid H_3PO_4. The dimensions of the contaminated material determines the acid amount that has to be used for the pickling. The dissolution is not directly performed in a regular container but a specific container as the multi-neck flask. Also, the dissolution must take place within a thermostatic bath. The following details the setup to dissolve the contamination layer within the acid.

Since the tubes are contaminated, tweezers are used to place the scraps inside the flask carefully. Afterward, the required acid amount is taken in a beaker and transferred into a multi-neck flask with scraps. After that, the flask cap is closed, and the condenser is attached to avoid evaporation. In addition, a thermometer is fitted to monitor the temperature. Finally, the multi-neck flask system is placed inside the thermostatic bath 2.2a. At this point, a suitable temperature and time are set. In most cases, the time and temperature are decided together. After waiting, the contaminants from the scraps are now dissolved into the H_3PO_4. The metal scraps would now be be under the clearance level according to the specific regulations and can be released upon analysis of gamma measurement. Moreover, the used acid (H_3PO_4) turns into a ferrous solution that is brown, and this solution needs to be treated further to limit radioactive waste.

2. Oxidation Process

The contaminated ferrous solution has to be precipitated in order to recover radioactive contamination in a small and solid fraction that could be directly vitrified into a durable glass form that could guarantee the long-term confinement of radioactive elements from the biosphere. However, the precipitation is better performed when the iron is in a Fe^{+3} (ferric) oxidation state than in a Fe^{+2} (ferrous) state. Hence, the ferrous solution from the pickling process is oxidized to convert into a ferric solution. A suitable oxidant, such as hydrogen peroxide (H_2O_2), has to be used to achieve this conversion. The oxidant is slowly diffused into the ferrous solution through a dropping funnel during the oxidation process. Similar to pickling, oxidation occurs in a thermostatic bath and requires a setup as described in the following.

Initially, the amount of oxidant required for the process is calculated. Then, a multi-neck cap is attached to the flask containing the ferrous solution. Next, a dropping funnel is connected to one of the necks to add the oxidant in drops per second. In addition, a thermometer for temperature monitoring and an automatic stirrer for mixing the oxidant with the



(a) Pickling Process Setup

(b) Oxidation Process Setup

Figure 2.2: The experiment setup required in the thermostatic bath for the first two stages of the A-PHADEC decontamination technique.

ferrous solution are attached to different necks 2.2b. Once the setup is finished, the oxidant is poured into the dropping funnel. Then, the temperature is set for the thermostatic bath. Finally, the funnel is opened, so the oxidant drips slowly inside the ferrous solution. After the waiting time, the ferrous solution is turned into a ferric solution in dark brown. The obtained ferric solution is then precipitated and vitrified in the last two steps of the A-PHADEC process.

3
Related Work

This chapter discusses an overview of using computers as a learning tool from a broader perspective. In addition, different tools used for training are described on both desktop and VR-based platforms. Besides, virtual labs are introduced, examples specifically targeting science-based, and different academic levels are presented. Finally, evaluation techniques used to assess virtual labs are briefly discussed.

3.1 Computer Based Training

With the emergence of advanced computing technology also emerged the way people used them. What was written on paper is digitized. What previously required several devices can now be completed on a single computer. This development also led to improved learning and training methods, mainly to supplement a learning program. The use of computers to improve aspects of training or learning can be termed computer-based training [BEDWELL and SALAS, 2010; CERPA et al., 1996].

Although computer-based training tools can exist on various platforms, including smartphones and tablets, a focus on desktops and VR is considered here. In the following, computer-based training applications from various domains are discussed.

3.1.1 Training Applications

In VR, training procedures can be benefitted from its immersive environments. Moreover, it offers a wide range of training simulators from surgical (see Figure 3.1) to patient rehabilitation training[LAM et al., 2006].

Figure 3.1: Surgeons using the laparoscopic surgical training simulation in VR [HUBER et al., 2017].

Multiple studies show that VR simulators can help in surgical training. For example, to reduce the time and cost of laparoscopic surgery training of apprenticeship, VR simulators were developed by GURUSAMY et al. [2009]. Additionally, they assessed to find the effectiveness of the simulator. Their evaluation shows that VR group participants performed better than video trainer-based groups. They also concluded that VR-based training can supplement apprenticeship learning. Similarly, training for orthopaedic surgery in VR showed a statistical improvement compared to before, in not just anatomical learning but also task performance by professionals [AÏM et al., 2016].

Furthermore, various industry-based training applications can also use the virtual environments [WANG and LI, 2004]. For example, AOKI et al. [2008] demonstrated a desktop VR application to give astronauts pre-flight navigation training to combat spatial disorientation. In comparison, to address inadequate training facilities in mining, systems targeting safety and awareness in mining were developed [VAN WYK and DE VILLIERS, 2009]. The system included simulation of real-life hazards in the mines. The results indicate enthusiasm in trainees in using the systems to perform training.

Training applications also exist for monitor-based platforms such as desktop and web. The web-based training applications also benefit from being accessible anywhere, although local factors such as infrastructure and language could impact their accessibility [HORTON, 2000].

Moreover, the medical domain also consists of desktop-based training systems. For example, RAMBANI et al. [2014] introduced a training system for spinal surgery on the desktop platform. The system aimed to assist junior orthopaedic trainees in performing pedicle screw fixation in the lumbar spine. They also validated the effectiveness of the system among the trainee group. The results indicated an improvement in their learning and highlighted the comfort of using the application from a training or study room.

The examples above demonstrate that training systems on multiple platforms can supplement traditional training approaches in various domains.

3.2 Virtual Labs

Physical labs can also benefit from computer-based training tools. Computer based tools, such as virtual labs, which simulate different procedures in a real lab, can offer significant advantages. The virtual labs are employed by different education levels ranging from schools to universities [GLASSEY and MAGALHÃES, 2020; LYNCH and GHERGULESCU, 2017]. Besides, they assist significantly in distance learning [STEFANOVIC et al., 2009]. Furthermore, they are also offered as commercial applications. All these details are discussed in the following.

The University of Madrid has developed a 3D laboratory [FERNÁNDEZ-AVILÉS et al., 2016] to widen the reach of laboratory practices. The lab comprises sub-labs such as chemistry, physics, electronics and topography, each offering a unique simulation for students. Similarly, LABVIRTUAL [GRANJO and RASTEIRO, 2020] offers a platform with different simulators for chemical engineering. In addition, sub-modules such as video materials and case studies are also integrated to help students improve the autonomy of their studies. Likewise, TU Dortmund developed a virtual lab [GRODOTZKI et al., 2018] for mechanical engineering students to perform laboratory simulations. Moreover, the virtual lab is to be integrated into various lectures and study programs.

Virtual learning environments are also suitable for schools. For example, a work by LYNCH and GHERGULESCU [2018] designed an atomic structure virtual lab for secondary-level students. The lab also incorporated aspects such as gamification and a feedback system. The results from this development showcase that teachers and students have responded positively to the system. In another example of a virtual learning environment for schools, ZÖLLNER [2022] developed an application in VR to supplement school children in learning about the table of nuclides in four different ways.

Education has recently faced difficulties during the COVID-19 pandemic, which signified the importance of distance learning tools such as web meeting applications, online courses, and virtual labs. A survey by USMAN et al. [2021] revealed that virtual lab media has similar effectiveness to traditional labs. The survey also indicated that the virtual lab could be used as a distance learning media option to enhance students' science process skills, especially at times like the pandemic.

Besides the previously discussed virtual labs from literature, commercial applications also offer virtual lab environments. These lab environments, such as the Labster[1] and Praxilabs[2], include many simulation modules for monitor-based systems. In addition, these two applications offer various science modules involving physics, chemistry and biology simulations. Moreover, to safely guide the user in the lab through the simulation, they comprise a step-by-step guide for simulations in the form of a task journal. In addition to these vast applications, smaller applications such as a 2D-based virtual lab[3] exist for children to learn the safety and hygiene measures in a lab. Moreover, VR-based applications such as VRChemLab[4] also exist, offering an immersive learning environment. Furthermore, a high level of realistic lab such as SuperChemVR[5] also exists with a virtual assistant to act as a guide and feedback system. These VR systems include direct interaction techniques to manipulate objects in the virtual world.

Although they are not meant to replace the traditional lab where the student can directly get practical experience with actual elements, the virtual labs are intended to strongly supplement the traditional labs and education in general to improve the teaching situation.

[1] https://www.labster.com
[2] https://praxilabs.com
[3] https://basf.kids-interactive.de
[4] https://vrchemlab.ru
[5] https://www.sbir.gov/sbirsearch/detail/1227313

3.2.1 Virtual Labs Assessment

Assessing the virtual labs developed to understand their effectiveness is necessary. Several such assessments of virtual labs are discussed here.

In work by LAI et al. [2021], a virtual lab to assemble a galvanic cell was developed for both desktop and VR. For assessment, 66 high school students were asked to perform tasks in the virtual lab and tested for knowledge gained. They evaluated using the pre-test and post-test questionnaires set and reviewed by the high school teachers. Furthermore, a physical lab test was conducted after the post-test. In both the desktop and VR groups, post-test scores were higher, indicating that virtual labs affected knowledge. In comparing desktop and VR, the desktop was superior. However, the VR group performed better in physical labs later.

Another high school study by DAVENPORT et al. [2012] demonstrated similar results where 69 students were tested for knowledge gain with a desktop-based 2D chemistry virtual lab. The lab consisted of modules focused on dilution, concentration, and balancing equations. Their results also show that knowledge gain was positive in the post-test scores.

Interestingly, the study by KLINGENBERG et al. [2020] conducted among 89 students between desktop and VR groups in learning about photosynthesis showed no differences in knowledge gain. The evaluation also assessed factors such as enjoyment, presence, and motivation, where the VR group scores were higher than the desktop group.

The work by DUNNAGAN et al. [2019] measured student performance in learning about the IR spectrometer. Their study consisted of real and VR lab labs and was evaluated using a questionnaire about Infrared Spectroscopy. According to their findings, teaching students how to operate an IR spectrometer through VR was just as effective as face-to-face teaching.

Similar to the previously mentioned related work, the assessment included in this thesis consists of a knowledge test to find the effects of the virtual lab on knowledge gain. In addition, factors such as presence and usability are also tested to gauge user experience. Besides, the evaluation also includes cybersickness measurement, which was missing from the previous studies. Furthermore, an expert interview is also conducted to get opinions on the advantages and disadvantages of the virtual lab.

4 Concept

Serious game design generally exists in education and science-based applications. Hence, the virtual lab is designed closer to a serious game. In addition, several ideas are greatly influenced by past and present video games. In this chapter, the concept designs behind the implemented features are discussed. The desktop version was already being developed on the WebGL platform prior to the commencement of this work. As a result, several features have already been developed and implemented. In order to comprehend the application as a whole, they are also discussed here.

4.1 Lab Setting

The fundamental ideas behind the virtual lab setup are covered in the following sections.

4.1.1 Environment

The virtual lab, although according to the name virtual, it should still reflect its environment close to a real-life lab. The user would also be convinced by a realistic portrayal of a lab. At the start of this work, the virtual lab's environment was already developed according to a plan designed by the experts from the A-CINCH consortium. The plan consisted of a lab comprised of 8 different rooms, of which the "Main Lab" room is the point of interest for this work (see Figure 4.1). The plan also contained dedicated workplaces for using the lab computer and fumehoods for thermostatic baths. The same floor plan is used for both desktop and VR applications.

A part of the main lab is to be developed in this work, especially the area containing fumehoods. The development should also include the placement of equipment in the workplace. However, the placement should not be based on a random choice, like a thermostatic bath in the lab computer area. Therefore, the equipment should be placed following the ideal device placement structure in a typical radiochemistry lab.

Figure 4.1: The panoramic view of the main lab containing the fumehood area.

4.1.2 3D Models

The lab environment has to be close to to reality in terms of principles and visuals. Hence, the graphical representation of the lab is a crucial factor in demonstrating the realism of the environment. Therefore, detailed models must be employed to represent their real-world equivalents accurately. On the other hand, enhancing a model's details might result in a higher poly count, which affects the application's memory and performance. The result will be lower frames per second (FPS) and lagging visuals that could create an unpleasant user experience. This can be especially true for the desktop WebGL version, which is more memory and performance conscious because it runs on a web browser.

Similarly, this can impact VR, where expensive draw calls are required for high-poly models to produce a picture twice for each eye. Therefore, utilising a model with maximal detail but a relatively modest polygon count is necessary. Unfortunately, the model becomes increasingly cartoonish as the number of polygons decreases. As a result, a balance needs to be present to avoid deviating from a realistic representation. The Figure 4.2 presents an exemplary illustration of such a balanced model.

[1] https://creativecommons.org/licenses/by-sa/1.0

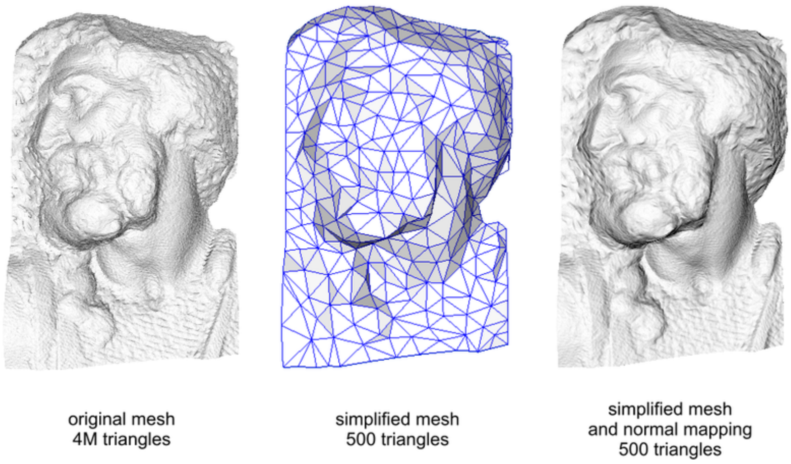


Figure 4.2: The example of a low-poly conversion in its original form.
Author: Paolo Cignoni. License: CC BY-SA 1.0[1].

The models from WALDSCHIK [2022] can be used as a result. The models in that work are constructed in a low polygon manner while also displaying sufficient detail to convey convincing visuals. Additionally, the models are created specifically for the A-CINCH virtual lab and are WebGL compatible. Furthermore, the models are created using actual measurement units, which is ideal for a VR application.

4.1.3 Lighting

The lab environment is also enhanced when appropriate lighting is provided. Additionally, lighting can affect how the colours of the materials on the model are displayed. The visual without lighting can lead to dim images. This is depicted in the Figure 4.3.

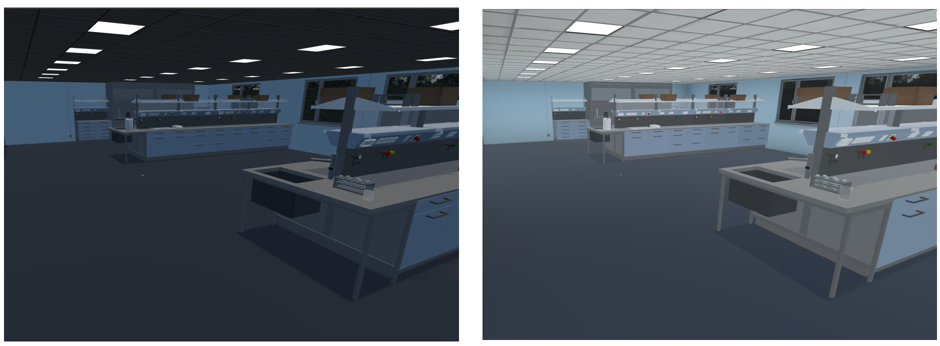


Figure 4.3: The difference in the virtual lab with and without computed lighting.

4.2 User

In the following, the information related to the user's point of view and the movement is described.

4.2.1 Point of View

The experience of a game or interactive application can be altered depending on the user's point of view and how they interact with it. For instance, a user-controlled character might convey the impression that they are controlling someone other than themselves. It is a crucial factor that needs to be determined upon in advance because so many other factors rely on it. For instance, all that is required in a first-person shooter view is a gun model in front of the camera. On the other hand, a third-person perspective requires both a character model and a gun model. In this situation, an additional model is required. The application's or game's main feature can influence how users perceive it. For instance, if the purpose of the game is to allow the player to experience the world through their eyes, a first-person perspective suffices. In any case, this viewpoint influences a lot of other game elements.

There are multiple ways in which the user perception can be set, either a third character or a first-person view. Some games, such as *Grand Theft Auto V*[2], offer a switch between the two. However, the implementation within is still based on a third person. The only change when switching to a first-person perspective is the camera's position and angle.

A serious game such as the virtual lab needs a realistic approach. Here, a first-person view is chosen, where the user feels they are controlling themself than another character. This view was already the case on the desktop from the existing A-CINCH lab architecture. The same should be been translated to VR. Despite having the same view, each variant has a different representation of them. For example, the mouse cursor on a desktop resembles the user's hands or control point. Hand models are presented in virtual reality to mimic their actual counterparts. The Figure 4.4 depicts this difference.

[2] https://en.wikipedia.org/wiki/Grand_Theft_Auto_V

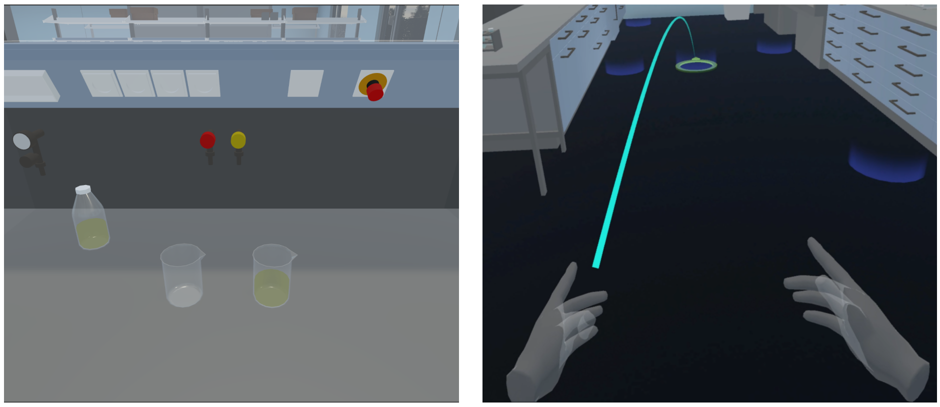


Figure 4.4: The user view difference in desktop (left) and VR (right), along with the teleport mechanism.

4.2.2 Movement

Users are required to navigate to different areas in the lab to fulfil a task. For example, consider workplaces A and B in different positions. The user might be required to measure the weight of a beaker at workplace A and then transfer the liquid to the weighed beaker at workplace B. Moreover, users should be allowed to freely move and choose a workplace to navigate within the lab. The user should also easily reach a good view of a workplace without many movement interactions. Furthermore, users should avoid passing through walls and workplaces. Therefore, appropriate collisions should be enabled.

Desktop Users can use the keyboard to move around the lab freely. The keyboard already contains arrow keys signalling the direction of the movement, which can be used. This technique is highly typical in open-world video games played on desktops. Similarly, using the mouse look to view the environment is also common. Both these features are used in this work.

VR Users have complete freedom to move and look around the lab in VR, mirroring their actual movements. However, moving constantly in real life is not ideal. There are difficulties like smaller spaces and growing fatigue from movement. As a result, another approach must be taken. Hence, standard teleportation is employed in this work. The use of teleportation enables quick travel between locations. Furthermore, while teleporting, the user's adjustable view is also available. There are still other options, like using smooth teleportation. However, compared to the standard teleportation method, it causes more cybersickness.

4.2.3 Workplace Viewpoint

While working in the lab, the user should choose a workplace to perform various experiment tasks.

Desktop The selection method can be used by users to select a workplace. However, once the workplace has been chosen, the camera view need to show a better perspective of the workplace. Because of this, the mouse look should be fixed to a predetermined position and angle to offer a steady view for workplace interaction. The predetermined viewpoint should be selected under the presumption that a particular workspace fits within the screen. In order to prevent a sudden change in camera movement, the camera view should also be smoothly interpolated to the workplace viewpoint.

VR Users have freedom in VR regarding head movement, which affects their view position and rotation. In contrast to the desktop version, locking the camera rotation in VR is not ideal for user experience. However, similar to the desktop, viewpoints can be represented in terms of teleportation destination markers in VR (see Figure 4.4). When a user uses one of these markers to teleport, the position and orientation are already predetermined. The orientation of this predetermined marker position should be forward-facing and has to be placed on the floor in the centre of the workspace. Moreover, when at the workplace, users should also be able to quickly snap their view left or right to conveniently rotate it without turning in the real world.

4.3 Basic Interactions

Interactions are required in the virtual lab to interact with different lab equipment provided. Therefore, the interactions provided to the user should not only be simple but easy to use. In the following, the different fundamental interaction concepts in the lab are described.

4.3.1 Selection

The process of selecting an object the user wants to interact with in a 3D environment is called selection. This can be accomplished in various ways for both desktop and VR.

Desktop A mouse is the existing pointing device on the desktop. It is utilised frequently when using a computer to carry out various tasks. For instance, choosing a file by clicking is one of the main actions. In the lab, choosing which equipment to interact with using a mouse is a similar option. An alternative method for choosing an object would be to use a keyboard and controller. However, using the mouse is much more intuitive to the user when selecting something. Moreover, the mouse cursor is the representation of the user control point.

VR In VR, the user also has a variety of selection options. Direct interaction and ray interaction are two of these possibilities. In direct interaction, the user makes contact with the object using the controller representation and activates the selection by pressing a button. In ray interaction, the user uses a ray emitted from the controller to point at an object, then confirms their selection by clicking a button, much like they would with a mouse. However, direct interaction is preferred in this work because it gives the user the impression that they are simulating a real-world interaction.

4.3.2 Manipulation

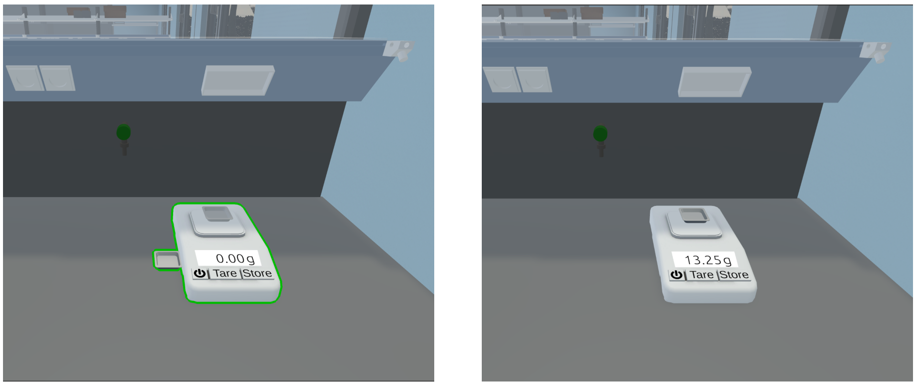
Manipulation in a 3D environment is the act of rotating, scaling, and moving, an object. Any interactive 3D application needs it to function. The manipulation strategies for both variants are described below.

Desktop In the desktop variant, the current selecting device, the mouse, can be used to manipulate the object in the virtual lab. For example, dragging an object after selecting induces translation of the object in the workplace. However, the interaction is being performed in a 3D world but perceived via 2D images on a desktop. There could be an uncertainty with the user interaction mapping with the mouse to that of the object translation. Therefore, the translation should occur on a 2D planar with X (width) and Z (depth) axes. Otherwise, manipulating along the Y (height) axis would lead to doubtful positioning of the actual user's intended position. The object manipulation on 2D planar was already realized in the existing lab architecture.

VR The user can select an object using the VR controllers and then control the object. The grabbed object should imitate the rotation and translation of the VR controller in real life.

4.3.3 Combination

Interacting with a combination of different objects is typical in a lab. For instance, transferring acid from a bottle requires both a bottle and a fluid container. In this case, two items are needed. In this work, object combination is used to realize such interactions.



(a) Combination Preview (b) Combination Confirmation

Figure 4.5: The combination system on the desktop variant.

Desktop On the desktop, the object combination was already realized by dragging an object onto another object. Consider the example above, the acid bottle is dragged onto the fluid container. Once two objects overlap, then, a combination occurs. This sort of drag interaction for performing grouping is quite common on the desktop. For instance, the drag method is used in the traditional *Solitaire* game to move a card from one deck to another. Another typical instance is moving a file on the desktop into a folder. The user also gets the impression that they can virtually move something with their hand. Besides, adding a ghost copy preview and displaying different colours such as red and green to the object outline can indicate whether a combination is appropriate or not (see Figure 4.5). More details of such feedback are given in this chapter's later parts.

VR Snapping is a typical interaction method in virtual reality that involves combining objects. Snapping is a technique where one object gets attached to another, like a magnet. This interaction primarily occurs in a puzzle or building game, where one object snaps onto another to make a combination. Snapping reduces the effort required by the user to combine objects. In this VR application, snapping is also used to combine objects when it applies. Snapping is used, for instance, when attaching a bottle cap onto a bottle. However, the acid pouring example above does not need to snap the acid bottle onto a fluid container, but instead, the user can use both the controllers to grab each object.

4.4 Virtual Lab Components

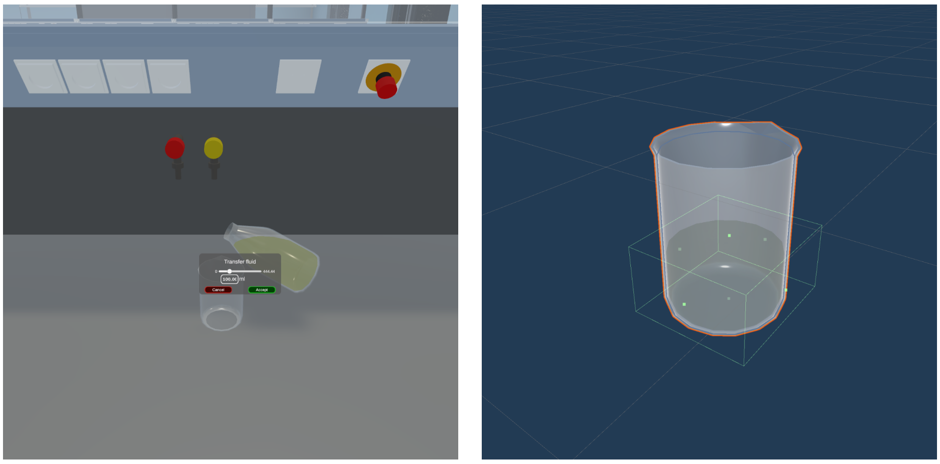
The ideas of different components that comprise the virtual lab are described in the following.

4.4.1 Handling Liquids

In the desktop version, the interactions already existed as a combination validation when two liquids are combined. On a valid combination, a slider with an input field is displayed (see Figure 4.6a). This technique serves well for the desktop since entering direct values on the liquid transfer is much easier than manually rotating a beaker to pour liquid. However, a similar idea could be challenging to interact with in VR and be an unnatural way of mixing liquids. Therefore, the following concepts are presented for different apparatus, i.e. fluid containers such as a beaker and flask, and an automatic pipette.

Besides, the idea of avoiding random mixing liquids should be realized in both variants. Since it leads to countless outcomes based on the liquids and their proportions, the limit has to be set on which combination of liquids can be mixed.

Fluid Container: A better way to have an interaction that resembles reality would be to grab the liquid in a container and pour it into another container. Furthermore, validation should be performed to avoid random mixing of two different liquids to check if two liquids can be mixed. Finally, since it could be challenging to define a precise amount compared to the desktop, an alternative should be provided to transfer the required liquid. This can be achieved via a pipette to dispense or absorb additional liquid, just like how it would be performed in a real lab.



(a) Liquid Menu on Desktop (b) Adaptable Liquid Collider

Figure 4.6: Liquid Menu and Adaptable Collider

Pipette: A pipette[3] is a laboratory tool used to absorb or dispense liquid of measured volume. It is handled by connecting a tip used to hold the liquid. Submerging the connected tip into a liquid enables absorbing, and pushing the liquid from the tip using the piston will dispense the liquid. For both kinds of transfers, the piston is driven. A natural way would be to grab the pipette and emulate the scenario of driving a piston.

The pipette tip should be used to absorb or dispense the liquid. During absorption, the tip should be in contact with the liquid. For the contact, a collider is required to adapt to the liquid level. Once the tip is in contact

[3] https://www.youtube.com/watch?v=QGX490kuKjg

with the liquid, the absorption is enabled, similar to real-life. The tip must be pointing down to a liquid container for dispensing the liquid.

4.4.2 Personal Inventory

While working in a lab, one would need to switch to different workplaces. At the same time, they might need to carry the equipment from one workplace to another. For this reason, a mechanism to carry items over to different workplaces is provided. Generally, a tray is used in a real lab to collect objects and move them. Therefore, combining the objects to be moved and a tray object seems natural. However, the user must move to different workplaces during the experiment frequently. Hence, having to combine objects each time with a tray can be time-consuming. Therefore, a simpler alternative is needed. Instead of a tray, the user can collect items in easily accessible slots.

Desktop The desktop variant was already comprised of inventory slots from the existing architecture. The user had to drag objects from the workplace to one of the inventory slots to collect them. On the flip side, the user can drag an object from the inventory slot to the workplace. The maximum available slots were five (see Figure 4.7a). The limit was placed to reflect a tray used to move objects between workplaces, and this tray has limited space.

(a) Desktop (b) VR

Figure 4.7: The personal inventory in both desktop and VR.

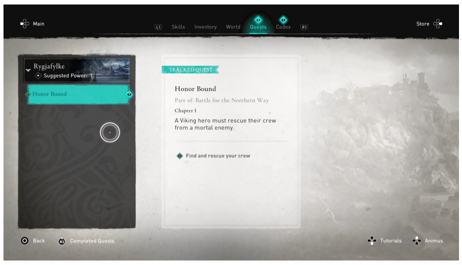
VR Since UI-like inventory seems unnatural in VR, slots attached to the player body, specifically the torso area, are provided (see Figure

4.7b). In this way, the player can always check with a glance which objects are in the personal inventory. In addition, slot insertion and removal can be used via direct interaction and snapping. However, the number of slots is limited to two to avoid a distorted view while working with collected items.

4.4.3 Task Display

Students or trainees need to know the tasks that need to be performed to complete the experiment. Considering that the chosen experiment is quite exhaustive with 81 steps to perform, a step-by-step guide helps the learner accomplish the tasks in front of them. In video games, such tasks are translated into missions or quests. It is a common practice to display the player's tasks as mission quests. Additionally, the task must always be viewed as a reminder of the player's current objective. However, it should not cause the user to lose concentration while playing the game. Therefore, it is essential to strike a balance between always providing the user with enough information about the task at hand and avoiding user distraction. This is typically realized via a preview pane and details pane. A preview pane is always present on the user's head-up display (HUD), and the detail pane only appears on demand. The Figure 4.8 shows an illustration of one such quest from the video game Assassin's Creed Valhalla.

(a) Preview Pane



(b) Details Pane

Figure 4.8: The two panes showing the same quest from the game Assassin's Creed Valhalla.

Desktop A similar approach to the preview and details panes is followed on the desktop. In some situations, when more than one active quest is active, multiple quests can be shown simultaneously in a vertical view (see Figure 4.9a).

VR The preview and details pane strategy is also applicable to the VR version. However, adding an overlay to the player UI in VR and making it always visible can distort the user's vision. Alternatively, the player could check the tasks on a board like object in the lab. However, going to the board position to check the details each time might be straining. To solve this, it might be simpler for interaction to have a portable board in the lab that can be held in hand and resembles a journal pad (see Figure 4.9b).

(a) Desktop (b) VR

Figure 4.9: The task display technique in both desktop and VR.

4.4.4 Time Simulation

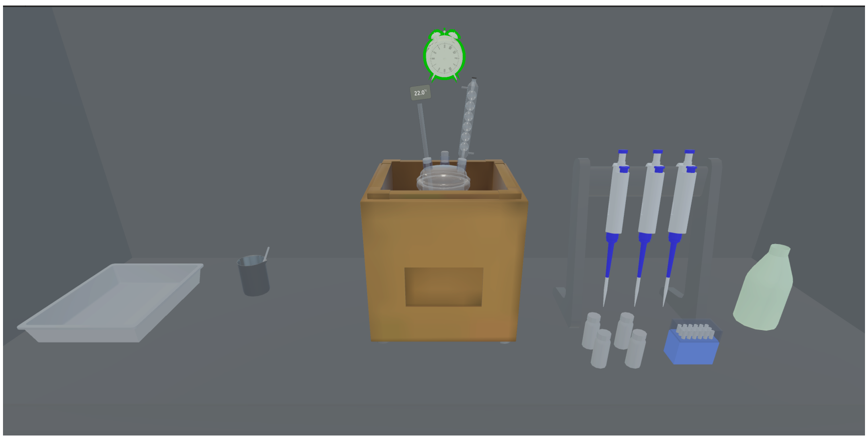


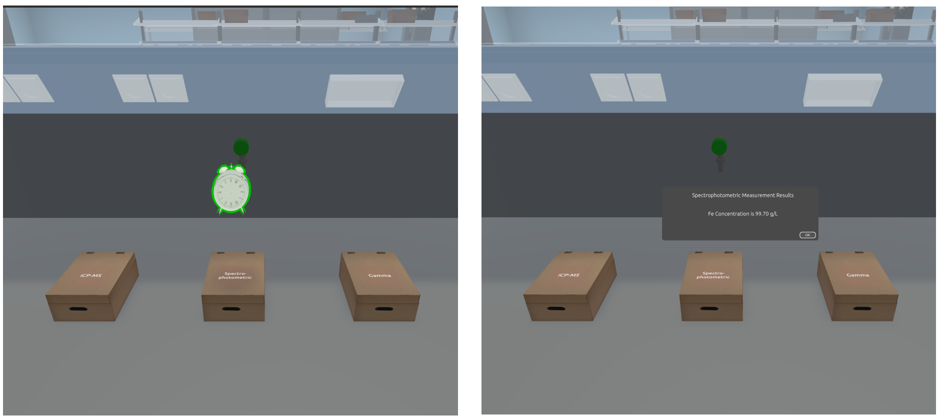
Figure 4.10: Timer clock on a device indicating a time consuming task.

Some tasks from the experiment have a waiting period for completion. For instance, it takes some time for water to reach its boiling point. Similarly, it takes time for an analysis to characterise a liquid by measuring it. These intervals between tasks in the experiments can last anywhere from hours to days. However, real-time waiting for a period of this length is not ideal for the user. Therefore, the waiting times should be brief but give the user the impression that some time has passed. A clock representation that indicates when a task is taking time can be used to implement this feature. The waiting period expires once the user activates this clock representation (see Figure 4.10). Additionally, adding fade effects that show something has changed over time, like blinking, can enhance the interaction. In both variants, ray interaction can be used to invoke the time simulation.

4.4.5 Sample Measurements

Few of the experiment's tasks consist of analyzing the solutions or materials obtained during the procedure. Mass spectrometry, gamma counter, and spectrophotometry are the various analysis types required. The sample results are obtained in a physical lab after one day of handing it over to a technician. However, as discussed previously, implementing such a waiting time is not the best scenario. Therefore, time simulation is utilized here as well. However, the receiver for the sample to measure is still to be conceptualized.

The sample receiver can be represented as a box with the measurement type written on it. The sample can be placed inside the box, after which the results are obtained by clock activation. Finally, the results can be displayed on a textbox, as shown in the Figure 4.11.



(a) Different measurement boxes. (b) Measurement results on a pop-up.

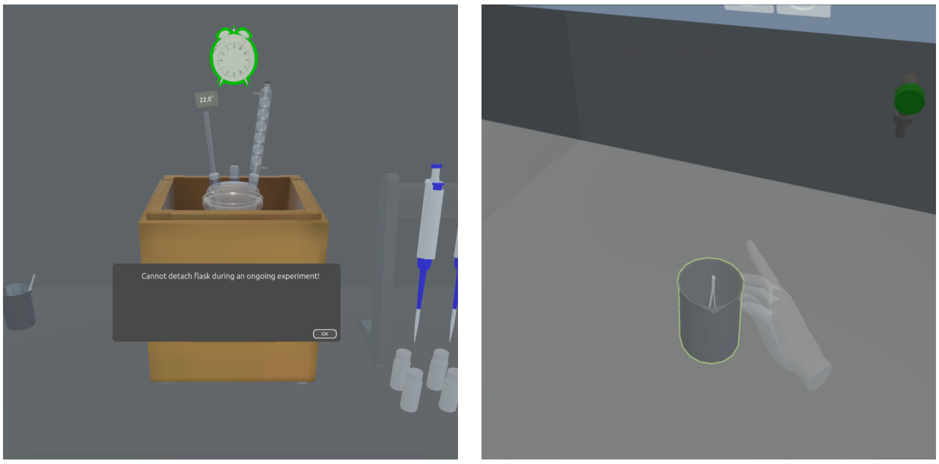
Figure 4.11: Different measurement boxes, with one of them with a sample (*left*), and the results of the measurement box with sample (*right*).

4.4.6 Waste Separation

During the experiment, many of the containers used will be dirty or get contaminated. For example, the pipette tip after liquid transfer, and condenser after pickling process. These unclean equipment must be handled carefully. Moreover, they have to be separated as either contaminated waste or non-contaminated waste. For this reason, multiple options to discard these objects have to be provided. Additionally, these options should be distinctive in signalling the user of their purpose. One such distinction is the use of a bottle to collect pipette tips, which is a common practice. On the other hand, the contaminated waste can be collected using a tray reserved for only contaminated objects. Objects such as beaker and other fluid containers can be placed inside a box for disposing.

4.4.7 Feedback System

Feedback is critical to understanding whether or not an action or interaction is valid. It can come in many forms. Here, the methods used to realize the textual and visual feedback is discussed.



(a) Textual feedback via message box. (b) Visual feedback via object outline.

Figure 4.12: An example of textual and visual feedback.

Visual Feedback: During selection, it is also essential to let users know that an object is activated upon the action. Feedback of some kind is therefore necessary. Therefore, the object outline should be highlighted. When selection or combination is possible, the highlight is green, otherwise, it is red. Additionally, the visual feedback during selection should exclusively exist during teleportation in VR and workplace selection on desktop.

Textual Feedback: Textual feedback is required in various situations in the virtual lab. These situations are described below

1. **Selection:** During selection, it is essential to let the user know what is being selected. A tooltip can be employed to assist with the selection, which gives the information of the selected object.

2. **Errors:** Errors made by the users are categorized into critical and non-critical errors. Critical errors should only warn the users indicating that their action was incorrect, such as pouring a liquid with a cap closed. On the contrary, non-critical errors are invalid actions for which the experiment cannot progress. For instance, choosing the wrong temperature required for the pickling process. Based on both these errors, textual feedback should be provided.

3. **Results:** When the user completes a result-based procedure such as analyzing a sample for gamma measurement, the output has to be presented. The user can be presented with textual feedback on a pop-up like UI as part of the output after the procedure is finished.

4. **Tasks:** A type of feedback must be implemented after a user completes an experiment task in order to determine whether the action was part of the experiment or not. This type of feedback can be as simple as removing a task from the task display in response to an appropriate user action.

4.5 Experiment Setup

As discussed previously, the experiment involves two stages, pickling and oxidation, wherein a special flask system has to be built in each stage. The same interaction of combining and snapping objects is used to build the flask system in desktop and VR, respectively.

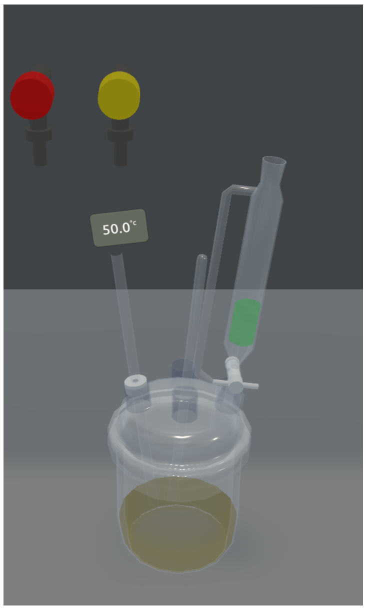
4.5.1 Pickling

In the pickling stage, the flask system must contain three objects - a thermometer, condenser, and rubber cap. These objects can be placed independently of each other. However, the flask must be closed with its cap before any of them are connected. The final assembled flask system for the pickling stage is shown in the Figure 4.13a.

4.5.2 Oxidation

Like the flask system in the pickling stage, multiple objects are required for the oxidation process. These comprise a thermometer, dropping funnel, rubber cap, and an elongated stirrer. The Figure 4.13b shows an illustration of the flask system design for the oxidation stage.

(a) Pickling Stage



(b) Oxidation Stage

Figure 4.13: The flask system required in the decontamination procedure.

5 Implementation

5.1 Software

The application implemented in this work was fully realized using the *Unity*[1] game engine. Moreover, external libraries were required to assist and fasten the application development. The details are described in the following.

5.1.1 Unity

Unity is a multi-module game engine software that offers various functionalities for building and manipulating 3D environments. The game engine uses C# as the programming language to drive the logic behind the applications. Besides, it includes components such as animation, audio, physics, and rendering to support world-building. Moreover, the game engine provides the ability to build for multiple platforms, which is highly desirable with the many existing platforms today. Correspondingly, the application was developed for desktop (WebGL) and VR in this case. Additionally, the existing A-CINCH virtual lab architecture was already developed using Unity. Therefore, using Unity to build both variants was a practical choice.

A significant advantage of working with Unity includes accessibility to various asset modules or libraries that can be directly integrated into a project. For example, a readily available asset can be used instead of building a liquid rendering system from scratch. Such assets used in this work have been discussed in the next section.

[1] https://unity.com

5.1.2 Libraries

Various systems have to be integrated into the virtual lab. One is the rendering of liquids, which are primary actors in a chemistry lab. In order to realize the liquid rendering, *LiquidVolumePro*[2] was used. The asset renders a liquid in a container based on parameters such as level and density.

Besides, to build spline-like structures such as tubes and pipes, *SplineMesh*[3] was used. It is a node-based system that defines multiple waypoints and connects all tiles as a combined mesh. Furthermore, users need to know which tasks to perform in sequence. Therefore, a quest system is needed to handle such requirements. The *QuestMachine*[4] asset was used to support the quest system architecture.

Unity already provides an XR toolkit to ease the time required to implement common VR interactions such as teleportation, head tracking, and grabbing. The toolkit is called the XR Interaction Toolkit (*XRITK*[5]). Although the XRITK offers fundamental interactions, another library, the Virtual Reality Interaction Framework (*VRIF*[6]), was used. VRIF offers much more features than the default XRITK. For example, snapping, hinge mechanics, and UI interactions are readily available in VRIF. Furthermore, with the help of VRIF, the interaction are easily transtlated to any commonly available VR system such as the Oculus Quest, and HTC Vive.

5.2 Hardware

Both the variants were developed using a computer running Windows 10 and equipped with Intel(R) Core(TM) i7-8700K CPU @ 3.70GHz plus 32,0 GB of RAM. Additionally, the Nvidia RTX 2060 graphics card was utilized, with the visual rendered on a Dell LED Monitor.

The additional hardware required for the applications are discussed in the following.

[2] https://assetstore.unity.com/packages/vfx/shaders/liquid-volume-pro-2-129967
[3] https://assetstore.unity.com/packages/tools/modeling/splinemesh-104989
[4] https://assetstore.unity.com/packages/tools/game-toolkits/quest-machine-39834
[5] https://docs.unity3d.com/Packages/com.unity.xr.interaction.toolkit@0.9/manual/index.html
[6] https://assetstore.unity.com/packages/templates/systems/vr-interaction-framework-161066

Desktop

The desktop application was mainly targeted at the WebGL platform. Although WebGL could technically run on mobile phones, considering the size of and the interactions realized in the application, it is not a suitable platform. Therefore, a computer with the aforementioned specifications and a keyboard and mouse for input is recommended.

Head-Mounted Display

A head-mounted display (HMD) was used in the development of the virtual reality variant. Several HMDs are commonly available, such as the HTC Vive, Oculus Quest, and the PSVR. The Oculus Quest was chosen for this realisation, which can also run standalone. Additionally, each hand has a touch controller, which can be used as an input device. The hands of users are also tracked using these controllers. Oculus Quest also has head tracking enabled, enabling room-scale movement for the user.

5.3 Technical Details

In the following, technical details of some of the critical implementation aspects of the applications are presented.

5.3.1 Interactable Objects

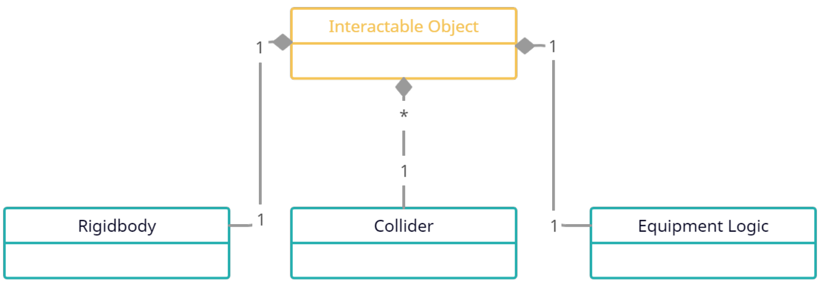


Figure 5.1: The object composition of an interactable object.

In the virtual laboratory, the user can interact with different types of equipment, such as beakers, pipettes, and balances. However, they have certain aspects in common for both desktop and VR. For example, each object consists of an object type to define the equipment type, an outline component for visual feedback, colliders and rigidbody components to enable physics. Along with these components, specific equipment logic is also included. For example, a balance would be composed of an additional component handling the weight calculation and balance display. In comparison, entities such as acid bottles contained liquid-related components detailing liquid properties. An example of such composition is provided in the Figure 5.1. In the virtual lab, any object that can be interacted with is built as a interactable object.

5.3.2 Flask System

A flask system is required during the pickling and oxidation stages. For both these stages, the composition of the flask system is very similar. The objects required to complete the flask system are combined with the flask. Furthermore, the logic in both systems is the same, although their interactions in desktop (drag and drop) and VR (snapping) are different.

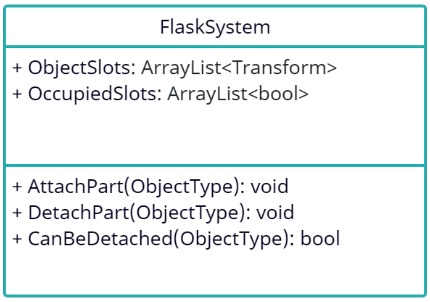


Figure 5.2: The class diagram of the flask system.

A class responsible for the flask system was created and attached to the flask interactable object. The class contains methods to attach and detach the object. Furthermore, methods are added to check if a particular object can be detached from the flask system. This ensures that object such as the flask cap is not removed before the objects connected to the neck. The class diagram represents the implementation details in the Figure 5.2.

5.3.3 Experiment Processes

The stages of pickling and oxidation both require certain criteria to be met regarding the flask system, before these stages can be initiated. These criteria, for example, ensure enough acid volume, close all flask cap necks, and combine only valid objects with the flask system. Although these criteria are shared, their details differ. For example, the acid type and volume differ for the pickling and oxidation process. Hence, abstraction is used to share a standard code for the experiment processes and allow for the implementation of specific details separately, such as in the example of acid properties difference mentioned earlier. The inheritance is demonstrated in the Figure 5.3.

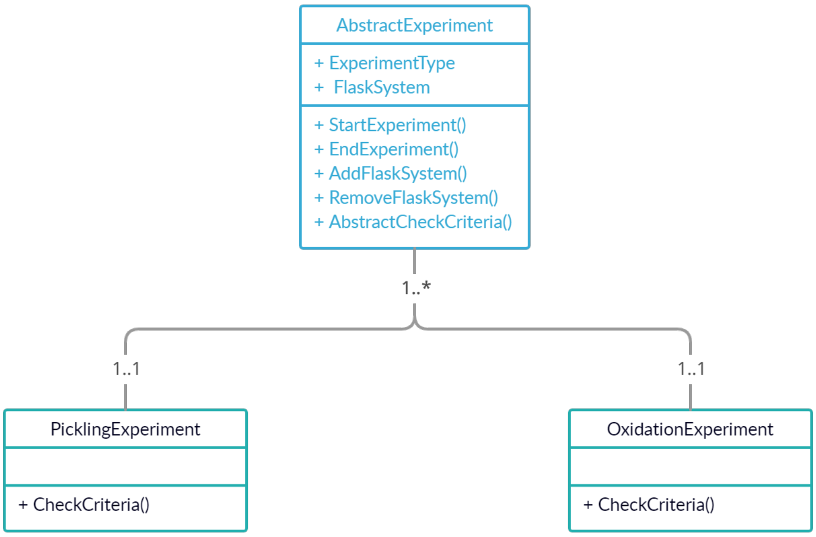
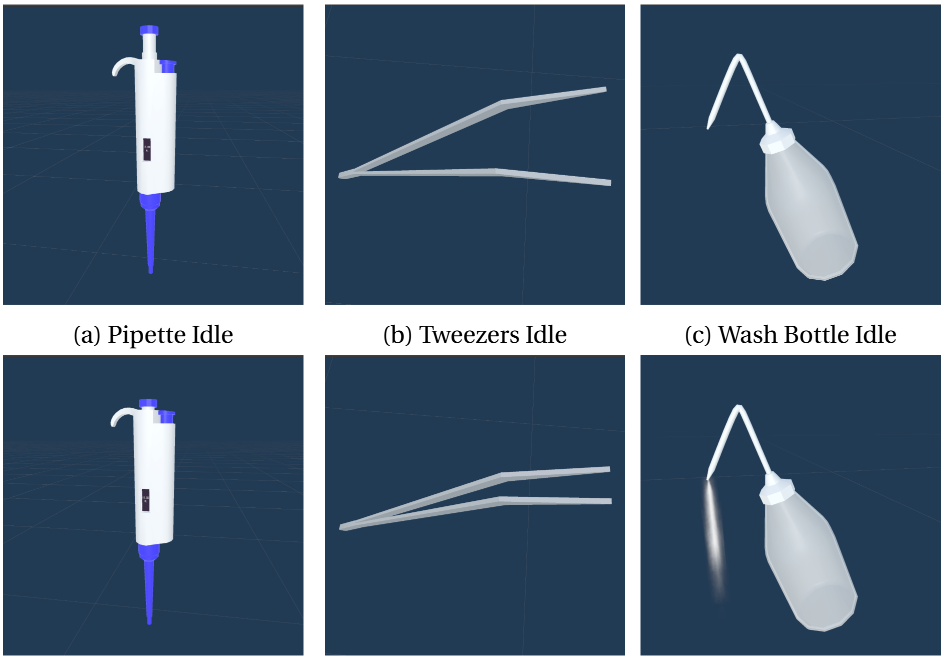


Figure 5.3: The inheritance of the pickling and oxidation experiments.

5.3.4 Special Equipment

In the virtual lab, after selecting (primary interaction) an equipment, such as a pipette, it is put to use by secondary interaction to activate it. In the pipette's case, the secondary interaction is the transferring of the liquid. The desktop variant already comprises these secondary interactions in the existing architecture. The secondary interactions were realized via animations automatically triggered upon a valid combination. The following shows the special equipment's usage in the lab for the VR variant.

Automatic Pipette: The pipette contains two controls, the piston and the tip ejector. The piston dictates the release or absorption of the liquid, while the tip ejector is used to eject the tip. On grabbing the pipette, the secondary button on the controller is used to trigger the tip ejection. On the other hand, the trigger button is used to control the piston. All liquid in the pipette is ejected with the maximum push (trigger value of 1). During the trigger button press, the piston is animated as a response to the user's action (see Figure 5.4d).



(a) Pipette Idle (b) Tweezers Idle (c) Wash Bottle Idle

(d) Pipette Pushed (e) Tweezers Clenched (f) Wash Bottle Squeezed

Figure 5.4: The devices with special interactions when grabbed in VR.

Tweezers: The tweezers, when grabbed, can either be clenched or unclenched based on the amount of squeeze applied. The trigger button push value [0, 1] on the VR controller was used to achieve these states, with 0 denoting an idle unclenched state (see Figure 5.4b) and 1 denoting a fully clenched position. The animation is continuously refreshed according to the value of the trigger button touched in a frame. Compared to a two-state button, the continuous value from the trigger button gives the user more control in handling the tweezers in VR.

Wash Bottle: The wash bottle emits water from its pipe when squeezed. Like tweezers, the squeeze is applied when the user presses the trigger button while grabbing the wash bottle. The water is released upon the trigger button press, which is represented using particle effects (see Figure 5.4f).

5.3.5 Quest System

The task display was realized using the quest system architecture. In this architecture, each task would represent a node and belong to a group called *Quest*. Available libraries were explored, and the *Quest Machine* asset was chosen. Although the library offers the required architecture of modelling each task as a node and consequently grouping them to *Quest*, it still needs a further extension to determine at what point a specific task should be marked complete.

For example, a task could be “Upload sample data on PC”. To complete this, the user should go to the PC area, open the PC and click the upload button, after which the task is marked complete. Such completion events had to be realized for both variants’ pickling stage (81 tasks) and the oxidation stage (57 tasks) on the desktop.

To realize this, the observer pattern was used. In this pattern, three entities are present: publishers, subscribers, and notifications. The publisher notifies the subscribers of the events (notifications) for the objects that the subscriber is interested in. Using this model, the quest system is made to subscribe to events for all the different components in the lab, such as equipment, inventories, and workplaces. When these components are modified, a notification is sent to the quest system along with the details. Afterwards, the quest system processes the task completion using the received details. For example, if the active task is to “Switch on balance”, and the user switches on balance, the quest system will be notified of the “switching on event”. Once the notification is received, the task is marked complete. This example is illustrated via the sequence diagram in the Figure 5.5.

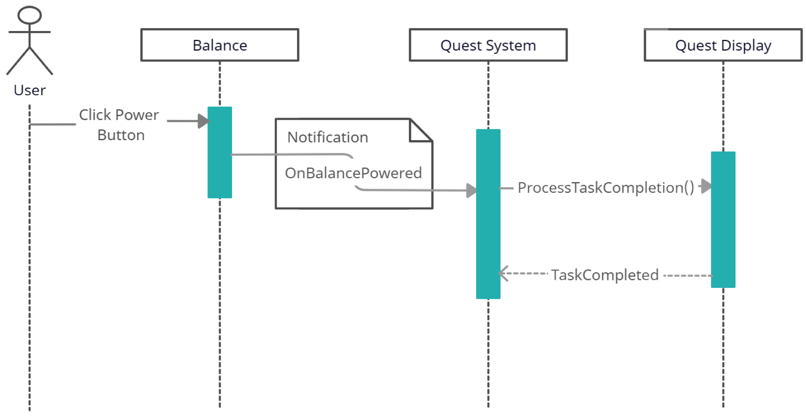


Figure 5.5: The simplified notification system between the interactable object (balance) and the quest system.

An advantage of such implementation is that loose coupling is established between the quest system and other systems in the virtual lab. In the future, even if the quest system is removed for some reason, none or very minimal changes are required to keep still everything intact. Such a result is highly desirable from a software development point of view.

5.4 Challenges

In the following, frequent challenges faced during the implementation are described from a software development point of view.

5.4.1 Translation to VR Variant

The VR variant was implemented after the completion of the desktop variant. Since the desktop variant already had many interactions with the existing A-CINCH architecture, it was chosen to be built first. However, many components from the desktop version could be reused since the same game engine was employed to build both variants. For example, the lab setting is one component that could be reused in its entirety. The following list provides the components that were directly reusable with a little or no changes.

1. **3D Models** The 3D models already part of the desktop variant could also be directly used in VR. Since the measurement units of the model reflected the real-world values, it was not an issue in the VR variant. In addition, the materials associated with the model containing information such as textures and colours are also directly reusable. Furthermore, shaders for the liquid rendering could also be reused without any adaptation.

2. **Environment** The lab environment consisting of workplaces, doors, and cabinets placed according to a floor plan in the scene could also be reused directly. Moreover, a few of the colliders of these entities could also be reused with little to no changes. Besides, the lighting data from the desktop variant is also reusable in the VR variant without any changes. The lighting data consists of light type, positions, and intensity. In order to use the lighting in VR, the lab scene has to be baked for lighting, especially when there is a change of equipment placement.

3. **Text Contents** Text elements such as message displays and pop-up dialogs could also be reused in VR. However, their position has to be changed from screen space to world space to avoid overlaying text on the user view in VR.

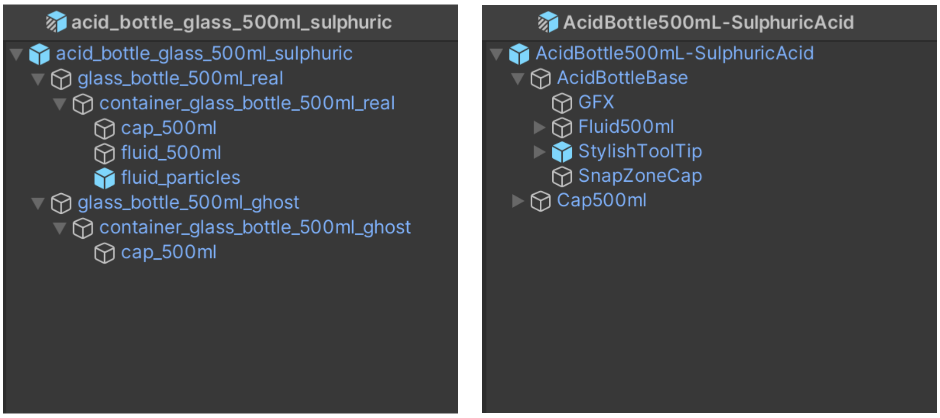
4. **Code** The interaction-independent code, such as the acid amount calculations, balance weighting logic, and flask building system, required little to no changes and could be directly reused. On the other hand, code related to fluid transfer logic on the desktop required moderate changes since the fluid transfer was not based on a slider value anymore but rather using the direct rotation of the spilling beaker. To conclude, the equipment logic that is loosely coupled with the interaction can be reused with a few adjustments.

When an application is already on a different platform, translating it to VR takes more work. However, this effort can be drastically decreased if the VR variant is developed using the same software and can reuse the elements from the above list. However, even with a significant reduction in effort, more time must be spent conceptualising and implementing particular VR-related aspects.

Although many of the components from the desktop variant could be easily reused, some could not be. The following presents the key elements that were majorly adapted or have to be recreated entirely for VR.

Prefab Hierarchy

A reusable asset entity in Unity is called a *prefab*[7]. In a lab, it is typical to find multiple units of the same piece of equipment. A beaker, for instance, can be found in various locations throughout a lab. The project makes use of prefabs to achieve this. However, due to the different object hierarchies between the desktop and VR, the prefabs from the desktop cannot be reused in VR. For instance, the desktop variants use the ghost copy technique for previews, whereas in VR, there is no preview. For this reason, the preview components are unnecessary for a prefab in VR.



(a) Desktop (b) VR

Figure 5.6: Prefab configuration on desktop and VR variants for an object.

The prefab changes pose a translation challenge since the prefabs have to be recreated or adapted to the VR variant. Therefore, all the necessary object prefabs from the desktop were translated individually into VR. Besides, appropriate naming conventions were followed in VR, similar to desktop. An example showcasing the prefab hierarchy is shown in the Figure 5.6.

Interaction Framework

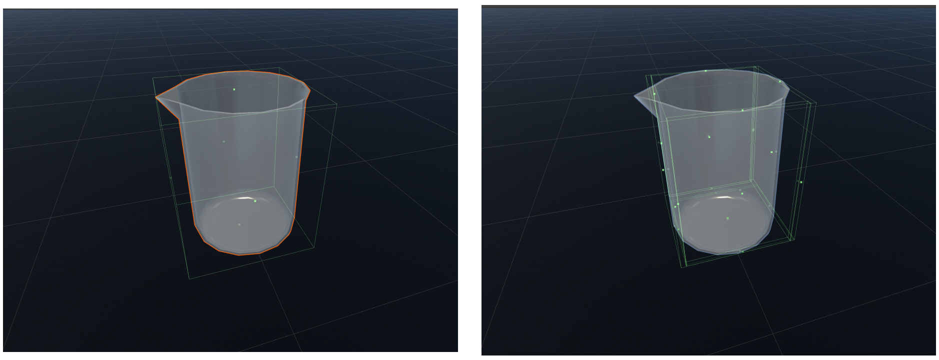
The mode of interaction is one key distinction between the desktop and VR versions. This difference also presents a challenge during translation

[7] https://docs.unity3d.com/Manual/Prefabs.html

regarding the scripts used to steer the interaction. Although many desktop scripts that do not directly deal with interaction can be reused in VR with some modifications, the scripts that target desktop interaction would not be very useful in VR. As a result, the necessary adjustments are made, and scripts for the VR version of the interaction framework are produced. Besides, equipment such as balance which was combination based on desktop needed a new approach in VR because of physics-based interaction. This, in turn, also led to the generation of new scripts.

Object Colliders

In VR, the interactions were physics-based. This meant objects were also physics-based, unlike the kinematic objects on the desktop. Additional changes are required from the desktop to simulate appropriate physics. Unity already provides physics simulation for object collision. However, the colliders outlining an object still have to be set.



(a) Desktop (b) VR

Figure 5.7: Colliders setup on desktop and VR variants for a beaker.

Consider the beaker model, for instance. On the desktop version, a simple box collider was sufficient because there was no actual physics based collision. To reflect the concave surface from the mesh in VR variant, multiple colliders must be present for the same beaker. Of course, a single collider like the one on a desktop could be used, but that cannot simulate a hollow surface. As a result, more specific colliders must be set. The Figure 5.7 illustrates the variations in the configuration of the colliders. For performance reasons, only primitive colliders were used instead of mesh colliders. Similarly, a collider setup was performed for various other objects in VR.

5.4.2 Integration to Existing Architecture

As mentioned previously, the A-CINCH virtual lab already contained an architecture at the start of this work. One of the goals of this thesis is to integrate the realized development for the desktop version into the A-CINCH architecture. In the following the different methods involved during the integration is described.

Merging

The A-CINCH architecture was continuously updated since there were simultaneously ongoing developments with other Hands-on-Training experiments. This thesis' work and the A-CINCH architecture had to be merged frequently as a result. The merge is completed by using pull requests and reviews to merge code bases, which is a common practice in software development. Git merging techniques[8] were used for this.

Prefabbing

In Unity, all the objects are contained within an entity called a scene. The A-CINCH architecture consisted of a single scene containing the objects for the entire lab. This implies that there is a high likelihood of a merge conflict[9] if any changes were made to this scene at the same time on two different computers. As a result, the integration process takes a long time, and the merge conflict must be resolved manually.

It was necessary to use a method to ensure that conflicts with the scene file do not arise during integration. If not, manually comparing the scene files from two different code bases can be difficult. This is particularly true for files with rapidly growing file sizes, like the A-CINCH lab scene file. Therefore, the workplace area objects of this thesis were transformed into prefabs in order to avoid the whole scene conflict during integration. This way, any changes to the workplace areas were made in a prefab rather than the actual scene. In addition, this made it clear during integration which

[8] https://www.atlassian.com/git/tutorials/merging-vs-rebasing
[9] https://www.atlassian.com/git/tutorials/using-branches/merge-conflicts

element of the scene was altered. This prefabbing technique of breaking down a large scene into smaller prefab objects is a common practice in larger game development teams where many people are working on the same scene at once.

5.5 General Comparison

In the following, general comparison of different aspects from both the desktop and the VR systems is made.

1. **Freedom of Interaction:** The user has more freedom in interacting in VR than on the desktop. For example, the user can only move the object in the selected workplace. The simple movement of an object to the neighbour workplace requires the user to take the object to inventory and then go to the new workplace and place it. On the contrary, the user in VR can just move the item by repositioning it. Moreover, the user can freely move in the lab as in real life. In comparison, on desktop, the user's position and view are locked once the workplace is chosen.

2. **Interaction Fidelity:** The interactions on both variants are developed to be intuitive. However, when compared, the interactions on the VR are much closer to real-life actions than in the desktop variant. For example, absorbing liquid from a container using a pipette on a desktop needs the user to drag the pipette onto the container and define the amount to be absorbed. On the other hand, in VR, the user should take the pipette in hand, dip it in the container with liquid, push the control button, and then release it to extract the liquid. These are the same actions a user would perform in a real lab.

3. **Error Potential:** In the desktop variant, user interactions were limited to a certain extent. For instance, the user could not throw an object on the floor or could not randomly put one object on top of another. Both the aforementioned examples are possible in VR. This implies that the type of errors the user can make is higher than on a desktop. Moreover, to handle these errors, more effort is also required. For instance, to avoid randomly spilling liquid on the work-

place or the floor, the liquid transfer is enabled only when there is a receiver directly below the spill point.

4. **Technical Configuration:** Although both variants are graphics and memory heavy, the VR variant requires a better-configured machine and a HMD to run the application. Unfortunately, this also limits the accessibility aspect of the VR since it cannot run on all machines that run the desktop variant. On the other hand, although it does not create a bottleneck at the current state of the application, elements such as colliders in VR are more detailed, requiring higher computations than desktops. Such details can negatively impact the performance when scalability is considered.

5. **Testing Effort:** The testing effort required for VR is higher than for desktop. On the desktop, the application can execute and be ready to be tested without additional apparatus. However, in VR, the headset must be worn and connected to the computer via a cable to access the application. In other situations, a VR simulator could reduce the testing load, but the interactions must inevitably be tested using the VR system. Since the interactions also involve frequent movement of the user, fatigue could also be induced during testing.

Summary

Based on the desktop and VR systems comparison, it can be seen that each system has an advantage over the other in different aspects. Therefore, it cannot be determined certainly that one of them is better than the other. For example, the desktop system is more accessible and requires less testing effort than VR. However, the VR system offers perception and interactions closer to a real-life lab than the desktop system. Hence, further investigations are required to assess the system's suitability based on the requirements.

6 Evaluation

The evaluation of the developed system is performed two-fold. One, the application was assessed to find if there were any learning outcome differences between both platforms. Additionally, factors such as presence, usability, and cybersickness were evaluated. Second, an interview with a specialist in the field of NRC was organized. During the interview, details related to the uses and potential of the applications were discussed. This chapter presents the user study first, followed by the expert interview.

6.1 User Study

The user study to assess the desktop and VR application was conducted at POLIMI, Italy. The details are as follows.

6.1.1 Task Design

The tasks performed by the participants consisted of the steps in the A-PHADEC decontamination experiment. The experiment's first stage (pickling process) was considered, which comprised 81 steps. The experts designed the breakdown of the steps for the experiment. The exact number of tasks were presented in both desktop and VR.

6.1.2 Sample Design

Two study groups were necessary for the user study. Each group participated exclusively in a desktop or VR study, making it a between-subject design [CHARNESS et al., 2012]. Because the experiment is based on NRC concepts, a pre-requisite of NRC knowledge was set for participant recruitment.

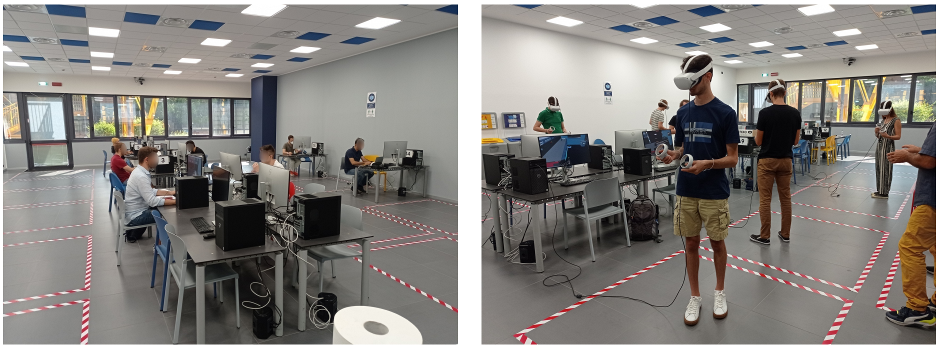
6.1.3 Questionnaires

Standard questionnaires and a knowledge test were used to document the participants' experiences. Additionally, the questionnaire was split into pre- and post-study sections. Participants were required to respond to a knowledge test based on the experiment in the pre-study questionnaire. Participants responded to the same knowledge test and other questionnaires listed below in the post-study questionnaires.

- **Knowledge:** To evaluate the knowledge acquired using the application, an NRC expert designed 11 *true* or *false* test questions, where each belongs to either group of the experiment procedure or contamination safety measures. Both the pre- and post-study versions used the same questions. Participants in the pre-study were questioned about whether or not they were familiar with the decontamination process. If they replied "no", the procedure group questions were skipped. However, questions about safety were still answered. Both procedure and safety group questions had to be answered in the post-study. Each correct answer counted toward one point, and the maximum achievable scores were 6 and 5 for the procedure and safety-based questions respectively.
- **Presence:** The Igroup Presence Questionnaire (IPQ) [IGROUP, 2020; SCHUBERT et al., 2001; SCHUEMIE et al., 2001] was used to gauge the presence factor associated with using the application (IPQ). There were 14 questions on a 7-point Likert scale in the questionnaire. Additionally, each item belonged to a potential dimension of *Experienced Realism*, *General Presence*, *Spatial Presence*, and *Involvement*.
- **Usability:** To evaluate how convenient the application was to use, the standard System Usability Scale (SUS) questionnaire [BROOKE et al., 1996] was used. Ten items on a 5-point Likert scale, from *strongly disagree* to *strongly agree*, made up the survey.
- **Cybersickness:** The standard Simulator Sickness Questionnaire (SSQ) [KENNEDY et al., 1993] evaluated potential cybersickness in-

duced by using the application. It consisted of 16 items on a 4-point scale. Each item accounts for a typical symptom of cybersickness. Additionally, each item represented one of the groups of *Nausea* (N), *Oculomotor* (O), or *Disorientation* (D). Moreover, all of them combine to provide a *Total Score* (TS).

6.1.4 Procedure



(a) Desktop (b) VR

Figure 6.1: Participants performing the virtual decontamination procedure during the user study sessions.

For both study variations, a similar process was used. First, a briefing on the study was conducted. Following the briefing, the participants completed a pre-study questionnaire form with questions about demographic information and experiment knowledge. Shortly after, the participants were given a tutorial introducing them to the applications. While a PDF file containing controls was handed over for the desktop version, participants were allowed to get inside the environment to learn only the fundamental interactions such as movement and object manipulation in VR. Participants in both groups were instructed to read the theoretical introduction to the experiment on a user interface in the virtual lab after the tutorial. They were able to use the theory whenever necessary. The investigation then began with the experiment's tasks. Participants must complete the experiment tasks listed in a quest journal during this period. Beforehand, they received instructions not to stray from these tasks. Following the experiment, a post-study questionnaire was presented, containing the same experiment knowledge questionnaires. Finally, the presence, usability, and cybersickness questionnaires were answered. The organization of the participants from both the sessions can be seen in Figure 6.1.

6.1.5 Technical Specifications

The Dell Precision 3640 MT workstations were used to conduct the desktop and VR variants study. The workstations ran Windows 10 Enterprise and had an Intel(R) Core(TM) i7-10700 CPU clocked at 2.90 GHz, 32 GB of RAM, and an Nvidia GeForce RTX 3070 graphics card.

Participants perceived the desktop version's graphics on a Dell Monitor U2722D while running a WebGL application. On the other side, the VR visuals were viewed on the Oculus Quest 2, connected to the workstation through a link cable.

6.2 Results

The results from the user study are discussed in the following.

6.2.1 Participants

A total of 15 participants took part in the study. The desktop variant had a total of 9 participants — 8 males and 1 female. Their ages ranged from 22 to 26, and they were studying energy, nuclear, and physics engineering (3 bachelor's, 6 master's). In contrast, the VR study had 6 individuals (5 males, 1 female), 5 of whom were enrolled in master's programs and 1 in a doctoral degree. They were all trained in radiochemistry and either studied or conducted chemical or nuclear engineering research. None, however, claimed to have experience using a VR headset. Data shows that the participant's demographics were similar between the two groups.

6.2.2 Data Preparation

The knowledge test answers were first compared to their ground truth and divided into pre-test and post-test. Additionally, each response was categorized as either procedure or safety-related. The average and standard deviations for each group were then determined. Similarly, the values were segmented into dimensions for the presence questionnaire. Three items had their outcome values reversed because, on the Likert scale, their higher values indicated a negative result. Similarly, the SSQ answers were categorized and graded using the system described by BIMBERG et al. [2020]. Finally, the SUS scoring was carried out using an adjective rating scale based on percentages [BANGOR et al., 2009]. The scale values were transformed into a percent range from 0% to 100% - ([0, 50]% - not acceptable, [51, 67]% - poor, (67, 69)% - okay, [69, 80]% - good, [81, 100]% - excellent).

	Desktop		*VR*	
	M	SD	M	SD
Knowledge				
Procedure (Pre)	1.34	2.18	2.50	2.94
Procedure (Post)	4.67	1.41	5.67	0.81
Safety (Pre)	4.78	0.44	4.84	0.41
Safety (Post)	4.89	0.34	4.84	0.41
Presence				
General Presence	5.00	1.50	5.83	0.98
Spatial Presence	4.13	0.80	4.90	0.90
Involvement	3.13	0.97	3.58	0.75
Experienced Realism	3.08	0.65	3.33	0.94
Usability				
Total Score	68.1	13.5	75.0	12.6
Cybersickness				
Nausea	15.50	30.95	27.03	33.27
Oculomotor	19.89	20.44	64.43	46.16
Disorientation	12.18	27.64	67.28	47.74
Total Score	19.16	26.83	60.46	47.27

Table 6.1: Statistical data showing the mean (M) and standard deviation (SD) values of the questionnaire responses.

6.2.3 Technical Faults

The desktop group in the study reported multiple times that the application was unresponsive. It is possible that this problem arose because they could complete tasks that were not in line with the quest system, although they were told to follow the quests. The need to restart the experiment also affected how long it took the users to finish it. Furthermore, two users from the desktop group discontinued the study at unknown points of time in the experiment (one due to extreme cybersickness). However, they still completed the post-study questionnaire. This might have slightly had an impact on the average time taken to finish the experiment and also on the post-study knowledge test scores.

6.2.4 Statistical Analyses

The participants took, on average, 67.5 minutes on the desktop compared to 44.7 minutes in VR. In the following, the questionnaire responses are statistically analysed and presented through table and graphs.

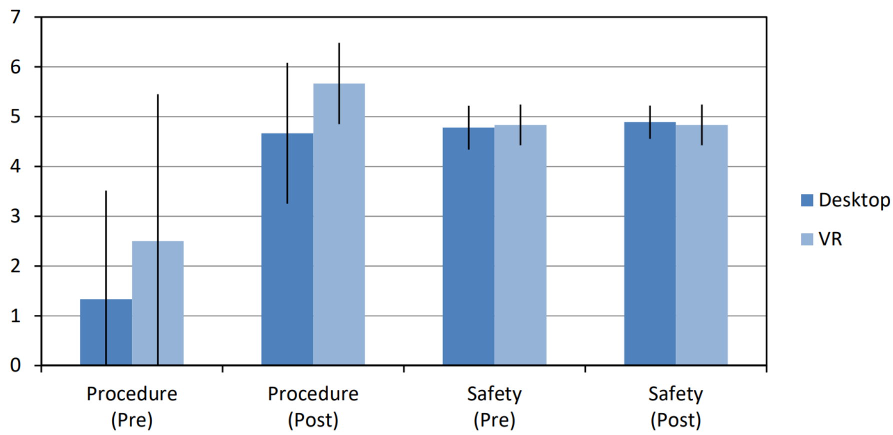


Figure 6.2: Knowledge gain scores comparing both groups.

Knowledge Gain The differences in the knowledge test, as well as its mean and standard deviation indication for both study groups, are shown in Figure 6.2. Additionally, the values are shown in the Table 6.1. Both study groups had lower pre-test scores for the procedure related questions. Compared to the VR group, the desktop group scored slightly lower. However, the post-test results showed significant gains in test scores for both groups, with the VR group slightly outperforming the desktop group. Comparing pre and post-test results of safety-related test for both groups revealed no improvement. However, the pre-test safety scores were already relatively high.

Presence The values of the presence assessment are shown in Table 6.1 and are visualised in Figure 6.3. The minimum possible score is 0, and the maximum is 6. The graph demonstrates that both groups exhibit the same kinds of outcomes, with the VR group demonstrating higher scores across the four dimensions. The *General Presence*, which is in the middle range on desktop and high in VR, received the highest ratings in both groups. Then, for both groups, *Spatial Presence* produced medium ranges. Additionally, the participants indicated an average range of *Involvement* in both groups. The lowest rated attribute was *Experienced Realism*, indicating a closer relationship with the *Involvement* attribute.

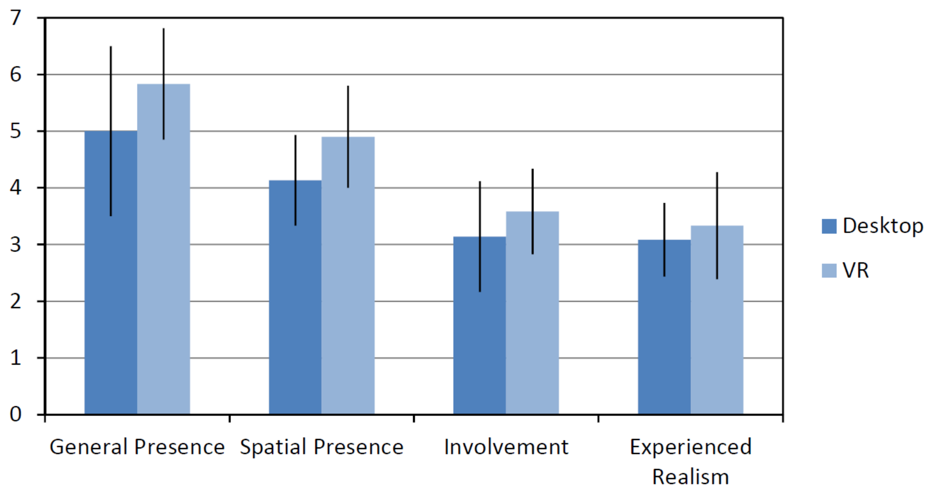


Figure 6.3: IPQ scoring comparing both groups.

Usability The comparison of the usability scores for both groups are shown in the Figure 6.4. Additionally, the mean and standard deviation values can be seen from the Table 6.1. Both groups reported usability scores that were above average. However, the VR group outperformed the desktop group in terms of score. The desktop group received an adjective scale rating of "okay," whereas the VR group's score positioned the application's usability in the "good" range.

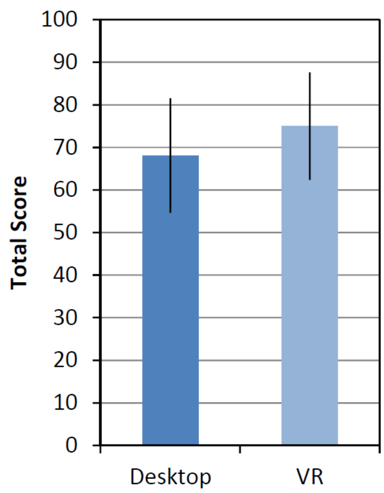


Figure 6.4: SUS scoring comparing both groups.

Cybersickness The results of the cybersickness factor is shown in Figure 6.5 and Table 6.1 shows the mean and standard deviation values. The graphic shows that the application, particularly when used in virtual reality, has induced cybersickness. While the effects are slightly less severe in the desktop group, they are moderate to severe in virtual reality. The least common symptom in both cases was *Nausea*. *Oculomotor* symptoms were more prevalent on desktop than on VR, with *Disorientation* as a more prominent symptom. Based on average and in comparison with the maximum achievable score for each dimension, the VR cybersickness measures are not extremely high. However, the score distribution shows that some samples are on the higher end of the spectrum. Despite the fact that the values for *Nausea* are not high in VR, the *Oculomotor* and *Disorientation* values still demonstrate a larger difference in cybersickness compared to the desktop group.

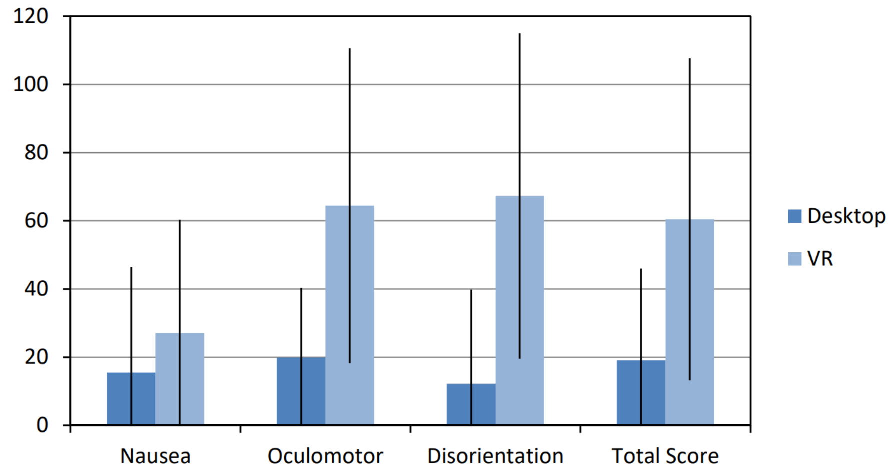


Figure 6.5: SSQ scoring comparing both groups with possible score ranges: *N* [0, 200.34], *O* [0, 159.20], *D* [0, 292.32], *TS* [0, 235.62].

6.2.5 Further Remarks

Participants were also asked to describe what they liked and did not like about the application in open-ended questions during the post-study questionnaire.

Both platforms' attention to detail and realism in the virtual lab environment impressed the students. They also thought the interactions, particularly in VR, were natural and simple to understand. Additionally, they valued how using the lab encouraged them to comprehend the experimentation process. One even claimed, "*virtual lab allowed me to use the experimental technique that I couldn't perform as a student in a physical lab*". Finally, even though the statistics do not strongly support this, many people found it to be simple to use.

Participants did not like that the tasks in the process had to be completed in a specific order, whereas there is much more flexibility in real life. Additionally, considering this is a time-consuming experiment, it was suggested to permit pausing during the procedure and continuing from the checkpoint. A save system could be employed to address this. Furthermore, a few desktop group users reported dissatisfaction with the application crashes while performing the experiment.

6.3 Informal Expert Interview

An informal interview lasting approximately 45 minutes was conducted with an NRC specialist with more than 18 years of experience, three of which were spent in decontamination procedures. During the interview, the expert was questioned about the application's advantages, disadvantages, targeted use cases, and future work. In the following, each of the target aspects of the interview is described.

- **Benefits:** The main benefit of the developed application is that it will be directly used as a training tool to help students learn about the decontamination procedure using the A-PHADEC process. Expert outline that students are invited to labs on a fixed period basis, and the fixed period is generally limited. During this period, if they spend time explaining the whole experiment, it takes much more time than if they knew something about it already. Therefore, the expert mentioned that the application developed can be used as a first approach for students before bringing them into a physical lab. Furthermore, while the expert appreciated the easy access of the desktop version, the VR version's immersive ability was noted. Furthermore, the expert also mentioned that students would feel much more comfortable and confident handling items in a lab if they were already acquainted with it before, even digitally. Participants' comments from the study can also prove this.

- **Drawbacks:** The expert also noticed some drawbacks with the application. Firstly, for the VR, the expert felt that the target users (NRC students) might require technical support and a VR lab environment to access it. On the other hand, although accessibility is not an issue for the desktop, its user experience compared to a physical lab is less resembling than in VR. However, despite the drawbacks of both variants, the expert feels their benefits outweigh the disadvantages.

- **Use Cases:** It was also suggested during the interview that the application may be used in both the industrial and a university setting. It is preferable to conduct such an experiment with interactions rather than reading it when a supervisor needs to know how long it will take to complete an experiment or how hard it is. The expert also suggested the idea of using such training programs for professionals who wish to change their area of specialization within the sector in order to gain a general understanding of the experiments.

- **Potential:** The expert applauded the application's present state of development and believes it provides a solid foundation. More experiments, particularly those involving spent nuclear fuel, will be planned to be digitally operated in the future. Although the expert believes that applications in VR are much more akin to the actual lab, the accessibility of the gadgets must be taken into account because VR may not be as convenient as desktop. Therefore, before considering developing another application for an exclusive platform, several factors must be considered.

6.4 General Discussion

In the following, the results of the study and their potential causes are discussed.

1. **Learning Outcome:** The knowledge test trend is consistent with the earlier discussed studies, where post-test scores indicate an improvement over the pre-test. The VR group scored higher than the desktop group, however, their scores were also higher during the pre-test. The amount of time spent with the application does not correlate with the scores achieved since the desktop group spent more time than the VR group.

   In this test, the experimental questions showed higher positive differences than the safety-related questions. The safety-related scores were nearly identical between the pre- and post-tests. It is possible that the participants were already aware of the decontamination safety precautions. It is also possible that there was not much room for improvement because the achieved values were already very high.

The experimental questions targeted the general principles of the process. It could be argued that this knowledge could have been gained via theoretical introduction, but not all questions were directly based on it. It would have been helpful to learn the participants' methods of knowledge acquisition. However, the positive effect is evident.

Even though using the application has improved knowledge tests, relying solely on true or false type tests might not be accurate due to their probability-based nature. A more accurate way to assess the impact would be to interact with experts after a participant has finished the study. In addition, including qualitative tests might also be beneficial. Therefore, further investigations are necessary to determine the platform's true impact on the acquired knowledge.

2. **Presence:** Both user groups think they felt present, judging by the scores, in terms of general and spatial presence. The higher scores could be mainly possible because the user was in a first-person view. This view might have given the user that they were not controlling an avatar but rather themself. In VR, where spatial presence is moderately higher than desktop, users' immersion in the virtual lab would have improved the score.

   Even with a different mode of perception, it was intriguing to see that both groups rated an average level of experienced realism. Since both the mediums comprised of the same environment and models from a graphics standpoint, the realism could have been affected. Furthermore, interactions such as cleaning equipment, which were simplified might have also affected the score since they did not completely resemble the actual real world.

   Similarly, both groups rated the involvement factor, with the VR groups scoring slightly higher than the desktop score. It is likely that even while using virtual reality, the participants were frequently aware of their surroundings because the user study was conducted in a lab with everyone present at once. This should not be a problem, though, because coworkers and students would work together in a real lab on experiments.

Both application variants seem to give the user a sense of being there in their current state.

3. **Usability:** It is clear from the usability scores that both groups found the application to be usable in their respective media. However, the VR group outperformed the desktop group by a modest margin. Although both groups thought the interactions were simple to use, their freedom of movement was constrained. For instance, they had to adhere strictly to the tasks from the quest system.

   Besides that, the numerous application crashes in the desktop group might have frustrated the participants. Their responses to the questionnaire do also support this. Additionally, some members of both groups felt that they needed technical support. It could be caused by their initial use of a VR system. On the desktop, however, it might have been because the application was unresponsive at the time of the crash.

   Additionally, the scores might have been impacted by the absence of a progress saving system and an interactive tutorial. Also, using the application for a longer time could be considered. However, the participants' ratings indicate that the application is usable, and the score may increase with additional improvements.

4. **Cybersickness:** From the data, it is indicated that cybersickness was induced in the participants. The impact was also confirmed by the study facilitator, who mentioned that participants reported uneasiness shortly after using the application. It was unexpected to see that the desktop version also showcased a mild level of discomfort. One participant who used the application on desktop said it was extremely uncomfortable. Further research revealed that the camera transition and screen fading during the time simulation were important contributors to the induction.

   On the other hand, VR participants indicated larger discomfort levels than desktop group. It could be due to two reasons. First off, everyone who took part was using VR glasses for the first time. They might therefore require some more time to get adjusted to it. Second, the experiment in virtual reality lasted, on average, more than 45 minutes. This extended period may have caused eyestrain through the

VR glasses, which is also indicated by the oculomotor factor in the graph from Figure 6.5.

Nevertheless, the considerable impact of cybersickness is a problem that must be solved, especially if all four experiment stages must be completed in short intervals. It might be interesting to investigate whether implementations such as the *VR Nose* [Wienrich et al., 2022] could lessen VR sickness in this application. A checkpoint save system was also suggested by a few of the participants as a way to take breaks from the experiment without losing any progress. Such measures might also alleviate the cybersickness to an extent in both variants.

Summary

Students and experts' reception towards both application variants has generally been encouraging and positive. It allows the introduction of students or trainees that are not confident with handling radioactive elements and also to the radiochemistry lab activities without the pressure of contaminating something. Additionally, it can simulate the first-time approach in a radiochemical lab for decontamination procedure and shows promising results for computer-aided learning.

7
Conclusion

This chapter summarizes the work involved in this thesis, along with a conclusion. It is followed by future work that can be expanded upon this work.

7.1 Summary

This work presents a novel application to virtually perform decontamination of superficially contaminated materials based on the A-PHADEC process. Moreover, the application is developed for both desktop and VR platforms. The application enables students or trainees to learn about the decontamination procedure step-by-step.

Interactions specific to a lab are also demonstrated for both desktop and VR. Interactions such as using an automatic pipette, fluid containers, building flask systems, and others are presented. Moreover, the feedback system comprising multiple variations is also discussed. Besides, the interactions presented are also compared between the desktop and VR variants to provide a succinct view.

Additionally, different techniques used to integrate the developed work into the existing A-CINCH lab architecture, such as merging and prefabbing, are presented from a software development point of view. Furthermore, different challenges faced during the translation of interactions and lab environment from desktop to VR variant are discussed.

Also, an evaluation consisting of a user study and an expert interview is discussed. The user study assessed multiple factors such as knowledge gain, usability, presence, and cybersickness. For all factors except cybersickness, the VR group overall performed better. The expert interview provided insights on application benefits, drawbacks, use cases and potential.

Overall, both desktop and VR applications have their benefits and drawbacks, as seen from the general comparisons and evaluation. Although the VR system is better compared to the desktop system from the statistical analyses, in general regard, it cannot be determined which system has the edge over the other altogether. However, both systems demonstrate great potential to be used as computer-aided learning tools.

7.2 Future Work

The application on both mediums still has room for improvement. The suggestions from the expert's interview and user study are considered. Furthermore, the extensions from a general view are also listed.

Improving Desktop Variant Users in the desktop group of the study reported numerous application crashes. This mainly happened when the users deviated from the quest system's tasks. To provide a stable user experience, the crashes must be investigated and fixed. Also, the user must still be flexible in completing tasks outside the quest system. Additionally, to assess the application's robustness and stability, the final virtual lab architecture with all of the practical training experiments, including the decontamination procedure discussed in this work, must be thoroughly tested across a range of user groups, browsers, and technical configurations. Besides, the motion sickness caused by camera transition and fading effect, as reported by one participant, should be investigated. Furthermore, the desktop variant could be improved by introducing auditory feedback and multi-language support.

Improving VR Variant The cybersickness scores for the VR group were higher than the desktop group. Although all the users were first-time using VR, and the length of study might have impacted them with VR sickness, it would still be worth introducing proven features such as the *VR Nose* [WIENRICH et al., 2022] to reduce cybersickness. In addition to reducing cybersickness, introducing auditory and haptic feedback in the VR system can significantly enhance the user's immersion in the virtual lab. Furthermore, these feedback extensions can heighten realism in certain situations. For instance, liquid sounds when pouring and controller vibrations when grabbing an object. Similar to desktop, multi-language support can also be included in VR.

Additional Experiment Stages The application currently only supports the first step of the A-PHADEC process on VR and the first two steps on the desktop. Therefore, extending the steps mentioned earlier beyond their present state would be the logical next step in this work. The *oxidation* step, for instance, must be included for VR. Additionally, both variants need to include the *precipitation* and *vitrification* steps. This way, trainees and students can virtually experience the entire decontamination process.

Presenting Interactive Tutorial The tutorial was presented as a PDF file to the desktop group during the user study. On the other hand, fundamentals such as navigation, selection, and manipulation were enabled for the VR group. A specific tutorial about the virtual lab and its interactions was missing for both groups. Hence, an interactive tutorial that explains the lab environment, equipment and its uses, and the control could be helpful. For instance, guiding the user through a step-by-step procedure to weigh an object. Furthermore, it would be helpful to introduce first-time users to the virtual lab. Moreover, a tutorial specific to the virtual lab could improve user confidence in performing the decontamination process virtually on both variants.

Extensive Assessment for Knowledge Gain The user study conducted in this work also assessed if there was knowledge gained by using the application. Although the results suggest there is knowledge gain, the extent of it and the impact of the medium (desktop or VR) is not clear. For instance, the knowledge test consisted of a colour-based question. However, the user demographic did not question users' colour disabilities. Such drawbacks from the assessment have to be resolved. Therefore, an extensive user study with significant analysis of the medium impact on the knowledge gained of the users can be interesting. Furthermore, using techniques such as interviews with experts and users can be more robust than the true or false questions used to test the users' knowledge.

Including Save System Based on the findings, the participants have voiced their dissatisfaction with the lack of a system for saving their progress and allowing them to carry on from the last checkpoint they left. The save system can be helpful when a user does not want to complete the entire experiment in one sitting. However, due to the substantial amount of data to be saved, adding such a system must be handled carefully. Elements such as text, liquid properties, and object transform are example components that can quickly add up to create a sizable pool to save. Runtime elements that are created or removed must also be monitored. Additionally, tracking numerous components might result in a bigger save file and needs size optimization. Although including a save system can enhance user experience, adding it could be difficult.

Collaborative Virtual Lab Currently, only one user at most may use either variant. In contrast, several students, trainees, or employees would be present at once in a real lab. Furthermore, enabling collaboration support allows a group of students to learn together. Therefore, adding multi-user support can improve the usability of the application. There might, however, be several issues that need to be resolved. For instance, one user should not handle equipment under the control of another user. Furthermore, it is also necessary to address the network connection disruption and latency issues caused by synchronising the objects. Besides, avatars must be used to represent the users. Given these considerations, adding multi-user support could be challenging but something to consider.

Student-Teacher System Although the application has a feedback system, it still misses a student-teacher like interaction mode. Moreover, the application only assumes the user's role of being a student or trainee. There could be situations when a teacher would like to explain the process to a student or when the teacher would like to test a student's knowledge of the decontamination process within the virtual lab. Hence, adding the roles of the teacher and student would expand the capabilities of the presented applications.

A
Appendix

A.1 Knowledge Test Questionnaire

In the following, the questions used for the knowledge test is provided. All the question were based on *true* or *false*.

A.1.1 Procedure Based

1. In the pickling process, the acid used is able to dissolve the contaminated layer and bring the radioactive contaminants in solution.

2. In the pickling process, low temperature favors the dissolution process.

3. In the pickling process, fixed the surface to volume ratio, by choosing the proper temperature and pickling time it is possible to remove the desired contaminated layer.

4. In the pickling process, it is not possible to control the thickness of the dissolved layer.

5. In the pickling process, at the end of the process the acidic solution contains iron (mainly in the oxidation state +2), the other elements present in the metallic material and the radioactive contaminants present in the contaminated layer.

6. In the pickling process, at the end of the process the ferrous solution is green due to the presence of iron in the oxidation state +3.

A.1.2 Safety Based

1. If you are working with radioactive liquid samples, you need to pay attention not to contaminate your hands.
2. If you are working with radioactive liquid samples, collect contaminated glassware and plasticware with other dirty objects and wash them very carefully with soap.
3. To safely manipulate contaminated solid samples, you have to use gloves and tweezers.
4. To safely manipulate contaminated solid samples, you hold firmly with hands and avoid tweezers.
5. To safely manipulate contaminated solid samples, you can put solid samples directly on the balance or benchtop but remember to clean at the end.

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Declaration of Academic Integrity

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I hereby declare that I have written the present work myself and did not use any sources or tools other than the ones indicated.

Magdeburg, 29th August 2022 ....

(Signature)