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VR SAFETY TRAINING FOR FAB LAB

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ABSTRACT

With advancements in both hardware and software, virtual reality has become more common in homes, offices and other workplaces. As with all new technologies, it is important to find uses that are best suited for VR. Education and training are the most common professional applications for VR. In this thesis we describe ways that VR has been utilized by others, and introduce an application developed by us to display the possibilities brought by VR.

We developed an application to teach safe behaviour when using a laser cutter, to aid in the education of new users of a Fabrication Laboratory (Fab Lab). The application was built using Unity3D game engine for the Oculus Quest 2 VR headset, and was tested in an evaluation by staff at the University of Oulu Fab Lab. There were four test users in total, all of them with limited experience using VR. A member of our team was there to guide them in the use of the application. After the evaluation was complete, the participants answered a questionnaire containing multiple-choice and open questions.

From the evaluation with the staff and questionnaire responses, it was concluded that the application was a mixed success with positive feedback but caused VR sickness in many. In addition, the evaluation resulted in suggestions for improvements from the users. We had planned to add other features, which were not possible to include due to the tight schedule. The application showed a lot of potential for future improvement such as including other machinery and features located in the Fab Lab such as 3D Printers and vinyl cutters for safety training.

Hiitola S., Karjalainen R., Malo T., Veijola V. (2021) VR turvallisuuskoulutus Fab Lab-ympäristöön. Oulun yliopisto, Tietotekniikan tutkinto-ohjelma, 42 s.

TIIVISTELMÄ

Tietokonelaitteistojen ja ohjelmistojen kehittyessä virtuaalitodellisuudesta on tullut tavallisempaa kodeissa, toimistoissa ja työpaikoilla. Uusien teknologioiden, kuten VR:n, ilmaantuessa on tärkeää löytää käyttökohteita, jotka parhaiten hyödyntävät kyseistä teknologiaa. Tässä työssä kerromme tavoista joilla muut ovat hyödyntäneet VR:ää, ja tuomme julki kehittämämme sovelluksen, esittääksemme asioita joita VR mahdollistaa.

Kehitimme sovelluksen opettaaksemme turvallisia toimintatapoja laser-leikkuria käytettäessä, helpottaaksemme uusien Fabrication Laboratoryn(Fab Lab) käyttäjiä. Sovellus on kehitetty Oculus Quest 2 -VR-laseille käyyttäen Unity3D pelimoottoria, ja sitä on testannut Fab Labin henkilökunta. Testikäyttäjiä oli neljä, ja heillä kaikilla oli hierman kokemusta VR:n käytöstä. Yksi ryhmämme jäsenistä oli mukana testaustilanteessa, opastamassa sovelluksen käyttöä. Käyttäjätestauksen jälkeen testaajat vastasivat kyselyyn jossa oli monivalinta- sekä avoimia kysymyksiä.

Käyttäjätestauksesta ja kyselyn vastauksista tulkiten sovelluksen menestys oli keskinkertainen. Käyttäjät antoivat positiivista palautetta ja ehdotuksia sovelluksen kehittämiseen, mutta käytöstä aiheutui pahoinvointia useille. Tarkoituksenamme oli kehittää enemmän toiminnallisuutta, mutta rajoitteena oli tiukka aikataulu. Sovelluksella on paljon potentiaalia turvallisuusopetuksen laajentamiseksi, ja siihen voisi lisätä muita Fab Labissa sijaitsevia laitteita, kuten 3D-tulostimia ja vinyylileikkurin.

Avainsanat: virtuaalitodellisuus, VR, teleoperaatio, simulaatio, virtuaalinen opetusympäristö

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FOREWORD

We would like to thank D.Sc. Paula Alavesa and M.Sc. Arash Sattari for their advice and guidance throughout this project. We wouldn't have been able to get through the development without their help. We are especially thankful towards Paula for making the 3D models and importing the Fab Lab environment.

This projects has allowed us to learn a lot about virtual reality, the unity game engine, and ourselves. Thank you to University of Oulu and the Faculty of Information Technology and Electrical Engineering for making this possible.

Oulu, June 10th, 2021

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LIST OF ABBREVIATIONS AND SYMBOLS

VR	Virtual reality
VE	Virtual environment
AR	Augmented reality
HMD	Head-mounted display
CAVE	Cave automatic virtual environment
BIM	Building information model
PVC	Polyvinyl chloride

1. INTRODUCTION

Virtual reality (VR) has been used in industry for decades [1] and it has gained mainstream popularity since the early 2010s. Affordable head mounted displays aimed at the consumer market have become increasingly popular, which has helped the entire industry grow and develop. Multiple manufacturers have started producing competing and unique products, and development is faster than ever. Virtual and augmented reality has found use in places ranging from hospitals to living rooms. VR can be thought of as an immersive simulation of a virtual environment. The level of immersion is dependent on how well the person experiencing can feel themselves as being a part of the environment.

VR has been widely used as a teaching tool in industry, especially in the medical, military and construction industries. The strength of VR is that it is possible to simulate situations that could be life threatening or very expensive, with little danger of accidents [1] [2] [3]. With the advancements and cost reductions in head-mounted displays, VR can also save floor space. In the past, immersive simulation meant room-sized CAVE systems[1] while now only a small open area is needed for an immersive virtual environment.

To explore the possibilities of VR we developed a technical demonstration of a virtual safety training environment. We created a safety training simulation of a laser cutter, teaching proper methods of use and what to do when something goes wrong. The simulation takes place in a virtual Fabrication Laboratory(Fab Lab) environment modelled after the University of Oulu Fab Lab. Fab Labs are shared spaces where people can openly do small scale fabrication of products using tools and machines provided by the Fab Lab. [4] Many Fab Labs contain 3D printers, laser cutters, CNC machines, soldering stations and similar equipment. Many of these machines can be hazardous to the user or others, especially by causing fires due to high heat output, and should not be used without training. Due to the open nature of Fab Labs, most users are amateurs, and do not have formal training to use the machines. At universities correct procedure is usually taught to students, but in large crowds learning outcomes are often sub-optimal[2] [5]. In addition to being a possibly more active form of learning for each individual user, the COVID-19 pandemic has shown that there is a need for alternatives to face-to-face teaching. Taking these things to account, our aim was to develop an effective, low-cost way of learning safe usage methods of a laser cutter. Ideally, students or other users of Fab Lab could train with the machines even before their first visit.

1.1. Individual Authors' Contributions

Discussion between members was continuous and the work was spread to different members to help reduce overlapping work. Every member did research and writing regarding the related subjects, found in the second chapter. Timo Malo tried to implement a way to show the status of the real-world machine in virtual reality, but was faced with difficulties. Santeri Hiitola and Roope Karjalainen were in charge of developing the application, with some work done by Veli-Matti Veijola as well. Veli-

Matti and Timo worked with creating the questionnaire for user testing and analyzing the evaluation results, with Timo overseeing the user testing.

1.2. Structure and Contents of This Thesis

In the next chapter we will take a look at prior research on the subject and related subjects, such as VR, mixed reality, gamification and the iterative development process that was used in our applications development. The third chapter contains the results from the initial questions to the Fab Lab staff regarding the safe procedure of a Laser Cutter, which were used as a guide for the development. We also ´give details about the design process and decisions that were made during the implementation. In the fourth chapter we get into more detail about the actual implementation details, as well as tools used for the development. The fifth and sixth chapters go through the evaluation process, starting with what was being evaluated and why our evaluation was done the way it was. We then go through the results of the evaluation and draw conclusions from them. In the discussion chapter we further discuss some details from the evaluation, and talk about the issues and difficulties that limited the scope and outcomes of the project, especially the ongoing pandemic.

2. RELATED WORK

VR has become more mainstream in industry in the early 2000s. With lowering costs it has also found its way to homes starting from the early 2010s. In education VR has slowly gained more use-cases. Many study fields, such as medicine[6] have managed to find ways to take advantage of VR in presenting subjects that are difficult to construct or describe in the real world, such as anatomical structures, by showing 3D modeled versions of the desired objects and structures.

The aim of this thesis is to explore the possibilities of VR in safety training and examine previous, current and future uses of virtual reality in safety training of different systems and machinery in the context of small scale manufacturing. S. Grassini and K. Laumann explored articles regarding the results of VR safety training programs conducted between years 2014 and 2019 on different fields of industry and found that VR systems were effective learning tools in a majority of the cases. Especially chemical industry workers reported a positive effect of VR training on their work. [7]

2.1. VR in Safety Training

VR has been widely tested as an alternative safety training environment. It has been utilized in normal workplaces like construction sites [8] and retail stores or possible emergencies like flooding [9], tunnel accidents [10] and cabin safety [11]. It has been used to simulate even everyday life situations like pedestrian safety [12]. VR allows people to learn how to behave in dangerous situations without possibly life-threatening danger and identify the possible hazards in the simulation environment [13]. Studies have found VR safety training sometimes to be more engaging than traditional safety training methods. [8] [11] [14] More engaging training has lead to better learning outcomes right after the training [8] and in the long run [8] [11]. However, there are also some exceptions where gains using VR as safety training method were minimal compared to traditional methods [14]. VR safety training has also been proven to be very effective in increasing self-efficacy for users having undergone virtual safety training. [11]

Standalone head-mounted displays (HMDs) allow the user to experience virtual environments without additional hardware or specific space requirements. The cost of the HMD or how immersive the virtual environment is has shown to not be very important in regards to learning outcomes. When testing three different types of HMDs with different levels of fidelity, results showed no difference in knowledge acquisition or self-efficacy. The results have also shown only a little difference in engagement and sense of "being there" i.e. presence with different types of HMDs. [11]

A study by Eiris et al [3] compared OSHA approved construction site safety training to safety training using VR. In the training utilizing VR, 360° images were used in conjunction with HMDs, while the formal training was lecture based. Virtual safety training achieved the same results as formal training, with those having trained using VR also more correctly identified the risk level of potentially hazardous situations [3]. Another study found that virtual training achieves the most benefit on those who have the least amount of experience, comparing medical students in different stages of their masters studies [2]. We could assume that VR training could benefit first time users of machines in Fab Labs.

2.2. VR in Teleoperation

There has been research exploring a connection between the real world and a virtual world, using sensors in the real world to inject features into the virtual world. [15] The mixing of reality and VR has been described with names such as dual reality[16], mixed reality[17] and hybrid reality[18]. A system like this can be used by remote workers to show the status of a worksite, and could be utilized to oversee multiple locations simultaneously from a remote location. Lifton and Paradiso [16] suggest that while the boundaries between reality, augmented reality and VR are clear, a sensor network can seamlessly connect the real and virtual environments. They also suggest that a virtual representation of a real world location could change to meet the demands of the use case. They propose a virtual campus that becomes larger with more people, to give more space to the users[16]. This style of blending also has alternative paradigms, where the real reality and digital reality are mixed, for instance virtual continuum [17] and hybrid reality [18].

A study performed in 2011 by S. Cho and Y. Hahn[19] investigated how practicing robotic surgical training using a VR simulator influenced performance in using a da Vinci surgical system.[19] In the study the students were randomized into two different groups where one of the groups used a VR simulator for practicing using robotic surgical system for a month while the other group acted as a control group, who did not practice at all. After two tests, the group who had partaken in VR training between the tests had improved their scores compared to the control group, while there were no differences for both groups in the exercise completion mean time.[19] From the results we can draw conclusions which may suggest VR training to be beneficial for initial training on relevant concepts and procedures, as a way to reinforce the learned techniques by partaking in VR training sessions to maintain routine usage with the equipment and during off-work periods. It could possibly even function as an environment for training for lowering the threshold for participation to face-to-face training due to the increase in self-efficacy[11].

2.3. Gamification

Reaching sufficient knowledge and understanding concerning the safety when using a laser cutter is fundamental to our project. We came up with an idea to use gamification as a way of speeding up the learning process. Definitions for gamification range from *use of game design elements in non-game contexts* by Deterding et al.[20]to *applying game-like accelerated user interface design to make electronic transactions both enjoyable and fast* by Pelling[21], who was the first to use the term. In practice, it is a persuasive approach that uses game design elements for technology to influence user behaviour in a desired way. It has been used with positive outcomes for multiple different applications, such as reducing speeding, reminding people to take their medicine, and encouraging physical exercise. [22] Different design elements, such as scoring systems, time limits, trophies, rankings and virtual avatars can be used in conjunction with each other, to influence the user in different ways. Gamification has become commonplace in some aspects of society, namely frequent flyer points and status levels are a gamified way to encourage customers to continue using a specific airline. [22]

Traditionally motivation to do something is either intrinsic, such as wanting to do something because it brings joy, or extrinsic, like wanting to perform well to get praised by a superior. However, gamified experiences can arouse the intrinsic motivation in users by visualizing the progress in learning or mastering a new skill. [23] [22] This is valuable when trying to teach a skill that requires continuous study or exercise over a long period of time. In fact, gamification has become a core part of business for many companies in the past decades, especially in those specializing in education. Duolingo, a language learning app, rewards users when they complete lessons every day, and points are given to users when they know the right words.[24] To teach users how to code, Codecademy has made the learning path into a game-like experience.[23] These examples border on something called serious games, which are games with a purpose other than entertainment, such as physical activity or safety training[22][20].

2.4. VR Heuristics in Evaluation

For VR applications and simulations, evaluating has not always been as straightforward as in the early days of when first VR HMD devices were built. The concept of having the user view into the virtual world through a head mounted display, while optionally using special controllers in each hand to manipulate the objects in a virtual world, was very clunky at the start. The first head-mounted devices developed in 1960s were used for displaying video feed from another location to the user's visor, which responded to the user's head movements. Until 1985, the first commercially viable HMD was developed by NASA, featuring head-tracking features[25], which was a feature which became an integral part of the HMD devices.

As VR applications are a lot more complex than normal computer software and has the human element implemented in closer interaction, using existing evaluation methods from different evaluation targets and adjusting them to fit into VR is a good way to start, as is dividing VR into separate categories to be evaluated separately[26].

Sutcliffe's and Kaur's article describes how VR user interfaces can be evaluated with using different models covering different aspects of operating in a virtual environment[27]. The analysis included three different models: goal-orientated task action, exploration and interaction based approach. Each method were evaluated by using Nielsen's standard evaluation methods and guidelines[28] with minor changes as Nielsen's method did not take navigation and object manipulation in a virtual world into account[27].

In goal-orientated task action the user decides beforehand what they want to do in the environment and formulates a plan based on the task and proceeds to on the observations of the environment and if the environment does not offer any clues for how to achieve performing the task, it may result user guessing. In exploration method the user explores the environment without any specific goal decided beforehand and scans the environment for any interesting objects the user might want to interact with.

In interaction method the user starts with a target to interact with, scans the environment to figure out what they can do in it and proceeds to interact with the objects one by one to see how they react to the interaction until they have reached their target object[27].

Each model approached the evaluation with a different starting goal, but used a walkthrough evaluation method for each model based on interaction models for user behaviour, which were categorised under specific design properties. Each model provided similar results for potential issues with evaluated VR environments and when the heuristics were given to the VR designers to be tested, the overall ratings of the guidelines were high. In a different test 16 users were tasked to explore and analyze a virtual environment. The walkthrough method had identified that about 80% of the users correctly identified problems with the environment, and common problems that the method had missed were related to moments where users had issues with locating objects and navigating in the virtual environment. [27]

2.5. Iterative Development Model

Iterative development model has often been mentioned to be a modern and revolutionary software development model, but it dates to pre-1970s. The core idea is that development is done in cycles of planning and implementation, and with each iteration the project gains new features and can adapt to changing needs quickly. The earliest description of iterative development is from 1968 from B. Randell and F.W. Zurcher in a report for IBM [29]. Since this initial description parts of iterative development have been suggested many times as alternatives to more classical development models like the waterfall method. Modernization of iterative development model began in the early 1970s "under the leadership of Mike Dyer, Bob McHenry, and Don O'Neill and many others during their tenure at IBM FSD".[30] The "evolutionary" term was attached to iterative development model by Tom Gilb in 1976. These early versions of iterative development have even been used in NASA's space shuttle program from 1977 to 1980. In the 1980s iterative development was highly used in the attempts of creating artificial intelligence and expert systems. Barry Boehm's "A Spiral Model of Software Development and Enhancement" was definitely one of the most remarkable texts of the 1980s in iterative development. And other publishes worth mentioning in the 1980s was Gilb's "Principles of Software Engineering Management" in 1988 [31], which was "the first book with substantial chapters dedicated to IID discussion and promotion." [30] From that point forward the awareness of iterative development rose quickly and the model has been modified slightly here and there, but the most significant change has been in the planning phase. From the 1990s and forward the methods have been trying to avoid any specification and focused on the "evolutionary analysis approach". [30]

Iterative development is known to be a very flexible development model since it does not require much planning up front. It was developed to fulfill a need for a different approach than waterfall model in which almost all the planning is done up front. This results in the waterfall model being inflexible, not customer friendly and hard to track the origins of mistakes or errors. Iterative development model's strengths are waterfall's weaknesses. It is very flexible and it contains every step of the development process in small iterations, so the project can be designed, implemented, tested and maintained in every step of the creation process. This also helps the client to get exactly what they need, since they can see and test each iteration and ask for changes.[30] [32]

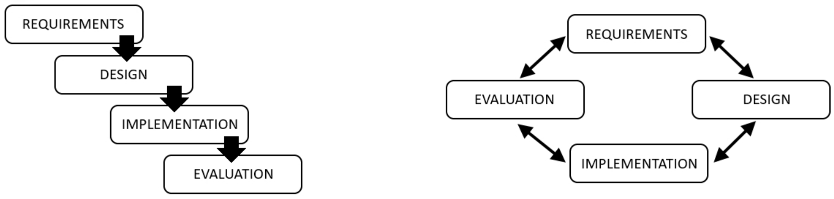

Figure 1. Waterfall model compared to iterative development model. Figure (c) Authors

3. DESIGN

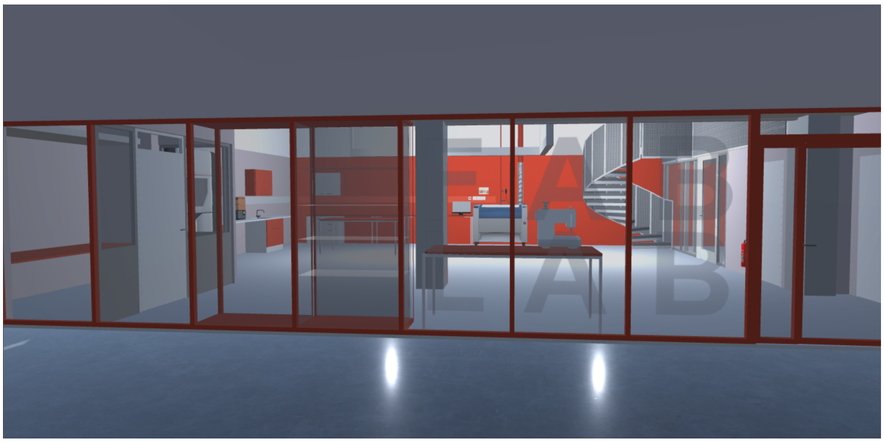

Figure 2. Screenshot of the initial Unity scene used as a basis for the simulation. Figure (c) P. Alavesa, used with permission.

Our goal for the design was to create a virtual reality scene that can be used to teach users about safety when using a laser cutter. The starting point four our project was a model of a Fab Lab brought into Unity from a building information model, which freed time that might have been spent on environment design to the development of the VR and educational aspects. To help with the design, we asked the staff at the Fab Lab for things to take into consideration, and they provided us with a list of potential risks when using the cutter, and links to additional resources. We believe that being involved with the final users of the product at the early stages of design was beneficial. This is called user centered design, and it helps with reaching design goals and reduces bad design directions. Consulting the users in the design process results in more efficient and effective implementations of products[33]. Additionally, we also gained valuable information from the related work researched in the previous chapter, especially the articles concerning VR based safety training and gamification.

The risks described by the Fab Lab staff were as follows:

- Material bursting into flames.
- Leaving the laser cutter unattended. Strictly forbidden because of previous risk.
- Using forbidden types of materials that produce hazardous fumes, such as vinyls.
- Forgetting to turn on the exhaust system, or it not working properly.
- Forgetting to turn on the compressor that activates the air assist.
- Opening the lid while working, which should stop the laser, but the mechanism could fail.
- Opening the lid after a job is finished, but without leaving enough time so the exhaust system can remove all nasty fumes.

- Leaving some objects, such as a piece of metal used as weight when stock material is bent, in the laser headers way. If it hits the laser at high velocity it might damage the header.
- The tray is too high and the stock material hits the header of the laser.
- Cut outside stock material. It might burn the small pieces of materials that are below the tray and might produce a fire.
- Trying to move the laser lenses with hands. Motor might be damaged or lenses might get dirty.

From here a rough image formed, where a user would have to choose a material, turn on the ventilation and then stay in the vicinity of the machine while cutting. We decided to cut out some of the details that would have been difficult to reproduce in a natural way due to the limitations of VR, such as the positioning of the laser and cutting tray inside the machine. Normally, the laser would have to be positioned in the machine using a joystick in the control panel. Instead of teaching all the intricate details in using the machine, we decided to focus on teaching only about safety when using the machine. Making every part of using the machine very accurate to the real world could derail the focus of the application, and distract users from its purpose.

The initial design plan included sensors that would make it possible to visualize the real world status of the laser cutter in the VR simulation. The laser cutter would then become unavailable for use in the simulation if someone was using it in the real world. This implementation also included gas and pressure sensors which would have allowed visualization of fumes inside the cutter if the sensor in the real world detected them. The sensor would send the data to Unity in the local network using CoAP protocol over WiFi. This idea was later abandoned due to complications between Unity and CoAP and focus was shifted on the simulation.

3.1. Scenario

In the beginning of implementation we did not have a clear image of what the final product would look like, but the final goal started to become clearer during the process of implementation. In the end we came up with a training scene that utilizes features found in game design to aid in the teaching process. Our application can be considered to be a teaching tool utilizing gamification, or a so-called serious game. The difference being that a serious game is a game with a purpose other than entertainment, and gamification is the use of game-design in any non-game application to reach certain goals. [22] [34] In our case, gamification shows up as a score system that rates the user's performance based on how many mistakes they make while cutting different materials.

The application is focused on a single scenario where the user wants to cut something using the laser cutter. Before beginning the cutting, a user must turn on the exhaust system and air compression, to make sure fumes emitted by cutting are removed. After this, a sheet of material is chosen and dropped into the machine. The materials available are aluminium, wood, plywood, polyvinyl chloride (PVC), and acrylic, with different materials having different properties. PVC is a material that must not be cut, as it emits chlorine gas that damages both the machine and the user. There is also a piece of wood that is clearly too large to be inserted in the machine, and there is a warning notifying the user that they shouldn't insert too large items in the cutting bay.

After a sheet has been chosen and the machine turned on, the machine will run for 30 seconds, and then stop. After the machine stops the cutting process, the user must not open the cover for an additional 10 seconds, after which the fumes will be exhausted. Opening the bay cover too early will deduct some points from the user. Point deductions are made if the cover is opened during cutting, or when the fumes have not yet been completely exhausted.

After the cutting process is finished, the user is given a score depending on how many mistakes were made during operation. Points are immediately reduced when the machine is turned on when the cutting bay is empty, or when cutting PVC, for the reasons described earlier. The user must also never leave the machine unattended, and the ventilation system must be turned on before cutting. Points are also reduced if the cut material catches fire and extinguishing it takes longer than 15 seconds. Only sheets made of wood or plywood can catch fire. The maximum number of points per cut is one hundred, and a user must reach a total of three hundred points to pass the training and be allowed to exit the application.

3.2. Design Details

We wanted to add a visible element of danger to the implementation, that requires the player's reaction. Having interviewed the staff, we knew that it was possible for material to catch fire, which seemed like a natural choice. To make this part authentic and usable for our safety training session, we wanted the player to be able to extinguish the fire. For this we landed on adding a fire extinguisher to the scene. The extinguisher was definitely the best solution in our opinion, because we already had an existing model of it in the Fab Lab assets, and we felt we could make using the extinguisher realistic and stylish. We made the decision to start developing the fire and the extinguisher side by side, so we could see what problems each part of the development brings.

Having interviewed the staff at the Fab Lab we knew that generally there are two materials used that can catch fire when cut: wood and plywood. In our minds it was clear that the cutter could only be ignited, when one of these materials were put in by the player; e.g. having aluminium catch on fire would be unpredictable and confuse users. What we decided to change a little bit was the size of the fire. Originally we had planned the material only to ignite with rather small flames, but we changed this to larger flames on the whole machine for the sake of simulation. We believed that larger flames would make it clear to the player to act quickly to solve the issue, instead of thinking that the flames were a natural side-effect of cutting wooden materials. Smaller flames might also have been hard to see, when the bay already has fumes being emitted by the cutting.

We planned on using the existing fire extinguisher prefab in the Fab Lab assets. Prefabs are Unity elements that can consist of multiple static or animated meshes and other objects, bundled into a single asset. When we started working with the extinguisher we realised the prefab was not what we had hoped and decided to make some changes to it. The hose of the extinguisher was static and faced an awkward direction. We had a clear vision that our player would be able to use the extinguisher with two hands, with one hand on the handle and the other hand on the hose. As a result we added armature to the mesh in Blender, to allow for the movement of the hose in Unity.

After the changes made on the fire extinguisher, we realised that it was too difficult for us to add the two hand functionality and it was not worth the effort considering the limited time. At this point we made a decision to shorten the hose so the player would be able to control the hose with the same hand he is holding the handle. While the solution is not as elegant as we had hoped, it works well in practice and is very usable.

Figure 3. Our original idea of the extinguisher Figure (c) Authors

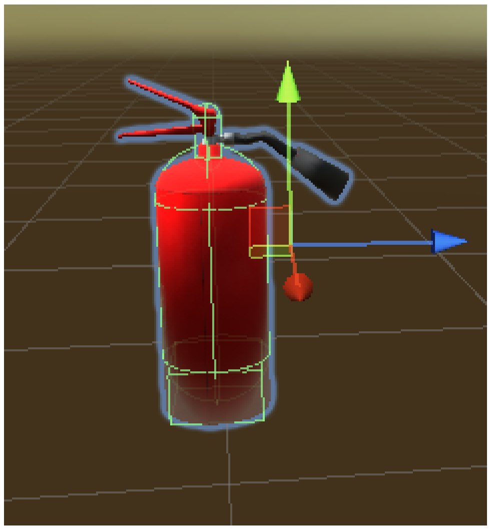

Figure 4. Our final model with shorter hose. Figure (c) Authors

In the middle of developing the fire and the fire extinguisher, we landed on using particle system carbon dioxide (CO_2) spray as an extinguishing element of the fire extinguisher. At that point in development, we had already used particle systems to create the fumes and smoke emitted by the cutting, as well as the fire. This made it easy to implement the particle system for the CO_2 using the same particle textures made for the smoke, and making it white and opaque.

3.3. Environment Setup

Before the implementation process of the teaching tool could start, we had to setup the environment for the scene. The model of the Fab Lab had been imported from a building information model, and it introduced some occurrences of overlapping meshes, which caused an issue called Z-fighting. Z-fighting is seen as flickering on a plane in the 3D environment, and happens when the 3D engine tries to render two or more planes at the same location. The flicker caused by Z-Fighting would be found irritating by most users of the application. It is most prominent when moving around in the 3D environment. [35] In VR the effect is especially prominent, due to the viewpoint being changed constantly as the user moves their head. The effect caused by Z-fighting can be avoided by eliminating overlapping meshes and faces.

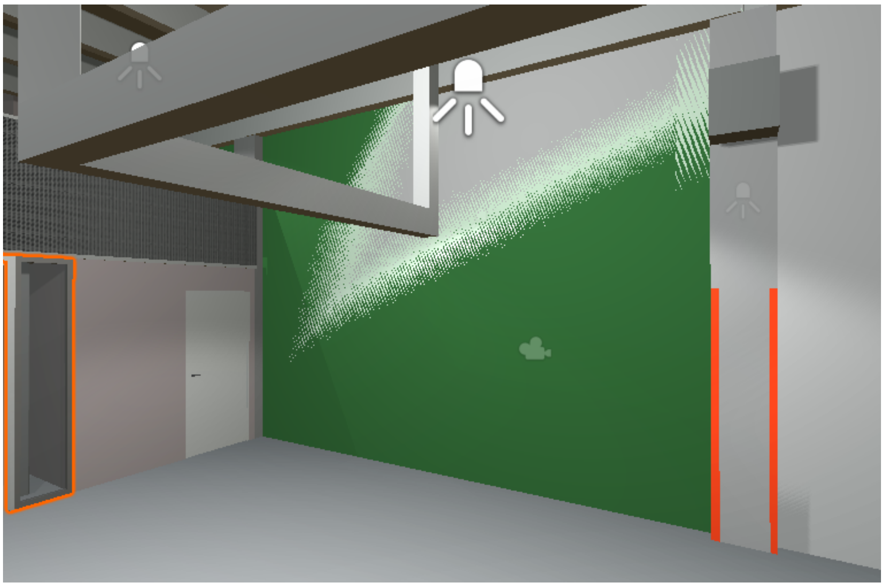

Figure 5. Z-Fighting occurring when 2 identically sized planes share the same position. Figure (c) Authors

To increase the immersion and sense of realism of the scene, some additional changes and adjustment were made. Collision boxes were added to the walls, tabletops and floors to prevent the user from walking through objects. It is also possible to walk up the stairs and open the front door. Grabbing objects such as the cover of the laser cutter, or the different sheets of materials can be awkward for first time VR users.

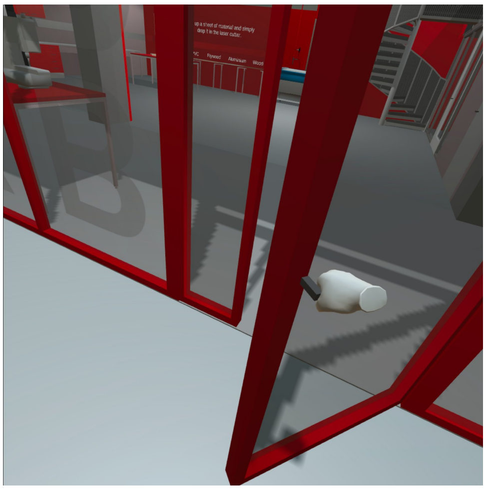

Figure 6. Opening the door to FabLab

Figure 7. Opening the cover of the laser cutter. Figure (c) Authors

To help users get used to VR, opening the front door also works as a small introduction to interacting with objects in the scene. The user must grab the handle and then pull the door open, as they would in real life. The awkwardness comes from having to hold the controller even while not grabbing anything, and using your middle finger to control whether to grab objects or not. The grab mechanics are specific to the Oculus Quest 2, and might be different for alternative hardware configurations.

4. IMPLEMENTATION

When we started the development process, we did not think of any special methods or development approaches we could take. Naturally we started the development in small sections we knew we wanted in the simulation. Simultaneously we tested and got used to the environment we built our product into.

This kind of development process is called an iterative development. In iterative development you divide your development process in many small steps and you separately do the whole development process for every step. In our project this kind of approach worked perfectly because we had no previous experience in Unity programming and did not know the steps before-hand. Also we were not sure what we are capable of doing in our time frame. We could just take a small portion of our project and do the planning, designing, implementation and testing for that part of the project. This really helped our whole development process because we had no clear picture in the beginning, what the final product will look like and this kind of method helped us design our idea at the same time we worked on the implementation part.

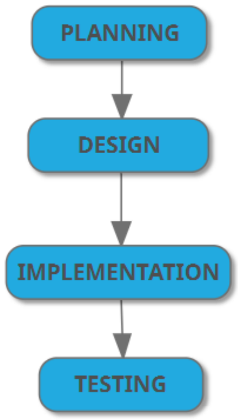

Figure 8. Our development process for every iteration of the implementation. Figure (c) Authors

4.1. Technical Implementation & Setup

The training scene was built for the Oculus Quest 2 HMD, using the Unity3D game engine and scripted in the C# programming language. Unity Teams and Collaborate platforms were used to co-develop the application. Unity Teams platform allows multiple people to get access to a shared repository, and Collaborate is a built-in version control system in Unity. Oculus Quest 2 is a standalone HMD, which means that it can be used without a connection to a computer. It runs an Android based operating system, which means that the application build was targeted for Android. For the Unity VR integration we used Oculus VR integration package, instead of Unity's built-in XR Interaction Toolkit. 3D models were modeled in Blender, as was adding the armature to the extinguisher. Particles were first made in Paint.NET, by making black and white sheets of four by four particles using the built in cloud rendering function, and taking cuts of random clouds. The textures were then brought to GIMP and made transparent by using the color-to-alpha function and changing the black values to alpha values.

4.2. Implementation Process

With the environment ready to be used, the actual implementation could begin. With VR creating a new layer of complexity, testing at every stage was fundamental to the successful implementation of features. The initial goal before having an image of the final product ready, was to simply get the laser cutter working in virtual reality.

We made slight changes to the 3D models of the laser cutter and its ventilation system, to allow for operation in virtual reality. The cover of the laser cutter was made maneuverable in VR, as were the controls of the ventilation system. Since the knobs that control the ventilation are quite small, an abstraction was made to the usage where a user only has to put their hands into a collision box in the vicinity of the knobs to make them turn. The front door was made to swivel around a hinge and can be opened in VR by grabbing the handle, simulating real world interaction. Since only the safety features are being taught, the rest of the details in using the machine are simplified: The sheets that are being laser cut don't need to be aligned in the cutting bay by the user; we created a so-called snap zone, where sheets can be dropped and they will be automatically oriented correctly. The laser cutting head doesn't need to be aligned either, and the machine is turned on by putting your hand on the screen normally used for aligning the laser and turning on the machine.

We needed to create a feeling to the user that the laser cutter is running and working. To do so, we decided to make the head that moves the laser inside the cutter shift to random positions. This movement is continuous when the cutter is running, and when the cutter stops the head moves back to where it started. Creating this kind of simple movement should be quite straight forward, but again the lack of experience with the tools and the imported environment provided some difficulties.

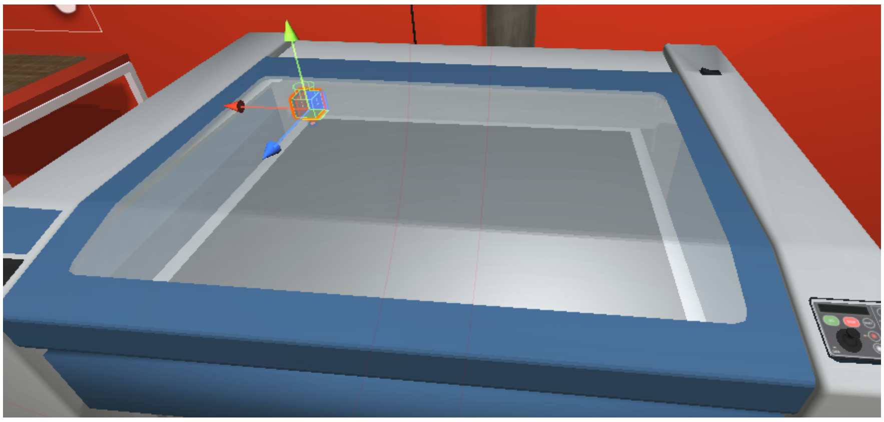

Figure 9. The head always begins its movement from the top left corner and returns when the cutter is not running. Figure (c) Authors

Unity provides a component for objects called nav mesh agent, that allows the object to move inside a predetermined nav mesh. This nav mesh has to be baked to a game object, for example a plane that we used in this project. The baking of the so-called laser field where the laser is able to move proved to be somewhat problematic due to the scaling of the environment. With the basic settings that worked in an empty project appeared to be dysfunctional in our project, so the minimum baked fields had to be modified.

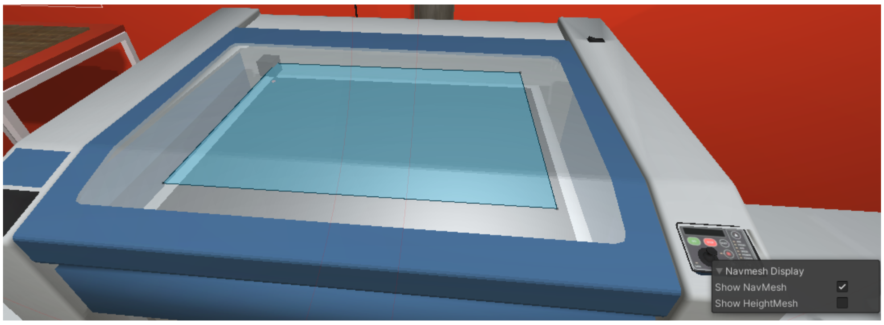

Figure 10. Baked mesh inside the laser cutter. Figure (c) Authors

After baking the laser field, the next step was to create a simple random movement script with the nav mesh agent. This was surprisingly straight forward and with little tweaks we made it look adequately smooth. This kind of approach is not exactly how the cutting actually looks in real life, but for the simulation purposes it looks fine and fulfills its purposes. When cutting objects, fumes will be emitted. In our scene we simulate this with a smoke-like particle system. Also, when a user cuts a sheet made of polyvinyl chloride which emits chlorine gas and is thus not allowed to be cut, the fumes emitted are yellow-green, which should be quite alarming to a user. If a user has turned on the exhaust system, these fumes will be removed from the machine after it has finished cutting.

When cutting sheets made of wood, the sheet can catch fire at a chance of 33%. This was done by checking what the material of the object in the bay is, and then running a script once in the middle of a run that turns on a fire particle system if a random range from one to one hundred is below 33. When the laser cutter bursts into flames, the user should be able to put out the fire. The solution was to add a working fire extinguisher to the environment, which can be picked up and moved and shoots carbon dioxide that kills the fire. The Fablab environment had an existing fire extinguisher, which was modified slightly to make it suit our purposes.

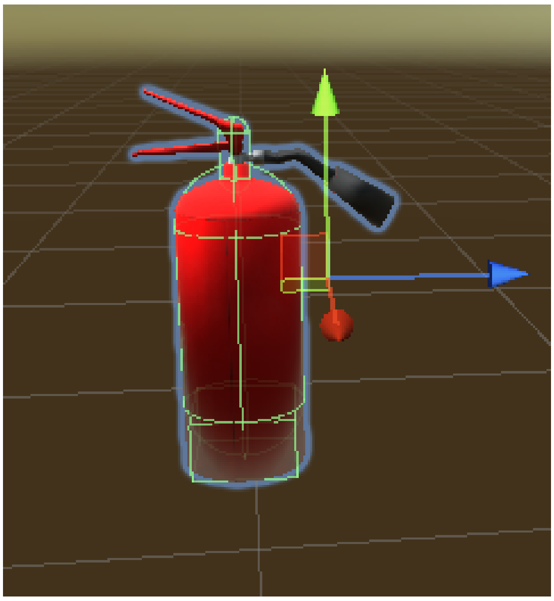

Figure 11. Our simple fire extinguisher model. Figure (c) Authors

The implementation of a working fire extinguisher with this working model was divided to three different parts. Step one was to make the extinguisher grabbable so you can move it and point it towards the fire. Step two was to create the carbon dioxide particle system, that can be shot from the hose. Final step was to actually make the carbon dioxide particles to put out the fire.

Enabling the extinguisher to be movable and grabbable with this limited experience we have gathered about Unity programming can be done with either a very simple, or a very difficult method. Oculus provides very useful asset packages for Unity, which you can use for these exact purposes. The downside of using these packages is that the final implementation can often look quite unpleasant and feel clunky. Also, it has proven to be difficult to produce smooth and intuitive results with these movable objects which requires writing situation specific scripts for different object, which is time consuming and requires know-how our group do not have at this time. We tried to find the middle ground between these options and used the packages Oculus provides with little modifications in the grabber script. We created an invisible handle to the extinguisher, so when the user grabs the handle the extinguisher should snap in the hand facing the correct direction instantly. There are definitely still some imperfections and strange movement, but for the purposes of the scene this behaviour is adequate.

To make it possible to position the hose and the carbon dioxide stream, we added armature to it in Blender. Initially we wanted a user to be able to grab the hose and aim it towards a fire, but in the end decided against it for simplicity. However, this could be changed in later revisions of the scene. The carbon dioxide is simulated with a particle system that has physics applied to it to make it collide with the fire, and fall towards the earth. After the particle system had been created, we had to write a script, which checks if the extinguisher is in user's hand or not and if the person is shooting carbon dioxide (pressing A). Scripting in this case did not generate any major problems.

Extinguishing the fire is a similar problem to damaging an enemy in a video game so there was a lot of data for similar functions to what we wanted. We wanted to use the carbon dioxide particle system for this, so we used the collision module, which is provided inside particle system game object. We created an invisible fire surface, which is not interacting with any other object in the game except the carbon dioxide particles. With this implementation we could count particles that are hitting the fire. These hitting particles act as damage done to fire, which has its own health. To extinguish the fire user must get the fire health go below zero. The fire should extinguish with 3-4 seconds of continuous carbon dioxide.

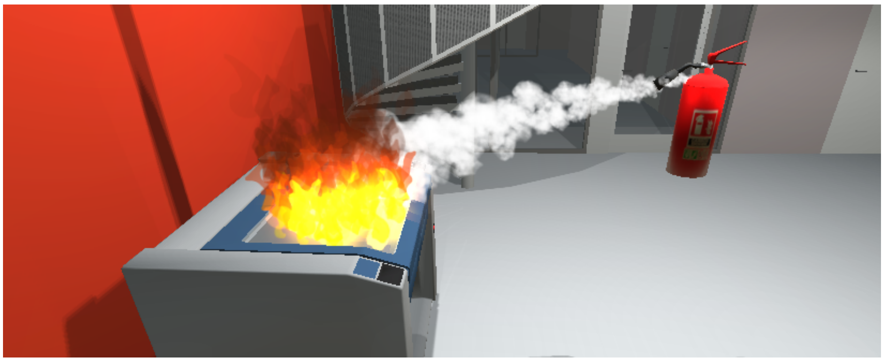

Figure 12. Fire extinguisher shooting carbon dioxide to the flames. Figure (c) Authors

4.3. Difficulties with Implementation

Since Unity and C# were quite new for the whole team, there were many difficulties developing the application. Some members had difficulties getting the scene from the Unity Teams platform, which was used for collaborative development. There were a lot of problems with the Oculus VR integration package, such as difficulties with positioning objects held in one's hand, and interacting with the cover of the cutter. The cutter's cover uses something called a hinge joint, and it's not built to be interacted with in VR. As a result the joint behaves in unexpected ways without modifications, such as bouncing back after being let go. Another issue with the cover was it feeling either very heavy or alternatively floating up. This was finally fixed by setting the mass of the cover nearly zero, and making another object to behave as a handle, with a larger mass but no gravity. The cover was then made to rigidly follow the position of the handle object.

4.4. Final Prototype

The scene can be played using an Oculus Quest 2 headset with the touch controllers. Upon starting the scene, the user will be outside of the FabLab and they need to use the analog sticks to move to the door, open it, and move inside. On the outside wall is also a text telling the user that they can reset the scene with the Y button in the controller. The user must now start cutting the sheets. The machine will turn on if the cover is closed and the user touches the control panel of the laser cutter, but starting the cutter with nothing in the bay will result in a deduction of points. The user should choose a sheet of material to cut, but choosing a forbidden material will again result in a loss of points. At this time the only forbidden material is PVC, which will emit chlorine gas and cause harm to the machine and the user.

Figure 13. A selection of materials. Figure (c) Authors

After choosing a material, the user has to drop it in the cutter, and it will automatically align correctly. Then the machine can be turned on, but if the ventilation systems have not been turned on, a point deduction will be made. After 20 seconds the cutting will finish, and if the ventilation system is on, after 5 more seconds the fumes will be exhausted. When cutting objects made of flammable materials such as wood, there is a chance that the object will burst into flames at the midpoint of the cutting. If at any point during the 20 seconds of run-time the user leaves the vicinity of the machine, points will be reduced and a message telling the user to not leave the machine unattended will be displayed. Other messages are shown when the user makes mistakes, such as not turning on the ventilation, cutting forbidden material or cutting when there is nothing in the bay. If the user makes no mistakes, they will get 100 points per sheet of material, with points going as low as negative 100 if the user cuts a strictly forbidden material such as PVC.

5. EVALUATION

The evaluation was initialized by inspecting the VR specific heuristics and from the perspective of how we could take advantage of the VR's unique quirks and possibilities, which are not possible via traditional means, such as presenting situations which would be hazardous or difficult to reproduce in a safe environment. The goal of the evaluation were to explore the viability of using our application for educational purposes, small-scale manufacturing and use expert evaluation[36] queries to gather feedback from users, who are experienced with the laser cutter, which we were trying to implement in the simulation.

5.1. Evaluation Goals

5.1.1. VR Heuristics

On the VR specific heuristics our priority aspects would be ensuring the simulation be glitch-free and minimize the possibility of motion-, or more specifically, VR sickness during the simulation. As the simulation has been developed from an educational aspect, we are not intending to make the simulation completely realistic, but rather have enough similarities with the real-world counterpart to be effective. As the user is capable of manipulating objects and devices in the simulation, our approach for the interaction aimed for simplicity and ease of use over realistic behaviour as it would increase the possibility of bugs and issues in the simulation.

By ensuring the simulation's stability and minimizing any possible glitches, we can provide the user the experience we had envisioned and have designed. Any glitches that happen during the simulation would interrupt or distract the user and possibly make them think the glitchy behaviour is intended behaviour in the simulation and might lead to false assumptions. Glitches can also make the user feel insecure or doubt the stability of the simulation which would affect how the user approaches the simulation's interactions.

Another heuristic we plan to follow with our application is minimizing the VR sickness during the simulation, which is a very common problem with VR applications. Some of the causes of VR sickness can be linked to the user experiencing motion in the simulation while the user is standing still outside the simulation. Other factors that can cause VR sickness in the simulations are: the time exposed to the VR simulation, HMD device's specifications: field of view, resolution, frame rate and device's ergonomic features and simulation's content, which may increase or reduce the VR sickness[37].

Our ways to minimize such occurring with our application we try to keep most of the interactable and non-interactable objects static, minimize controller joystick-based movement and avoid making drastic positional changes in the environment. With the help of the experts, who are experienced with using and handling the equipment we have implemented in VR, we can get valuable user testing experience regarding how our project usability matches the real-life counterpart equipment and find functionalities where the immersion would need more adjusting. For the experts we have prepared a questionnaire, which gives us feedback regarding the simulation's performance from a user perspective.

5.1.2. Education Tool & Small Scale Manufacturing

For FabLab VR to be used as a potential education tool, it will be important to find any potential discrepancies and inaccuracies from the application as any misleading or lacking procedures would weaken the usability of the application, such as missing safety features, incorrect text elements or inconsistently occurring object behaviour. Any feature, teaching element or unintended simulation behaviour, which is not correct, could potentially mislead the user into learning behaviour that might end up being the opposite what the simulation had originally intended to teach, and in the worst case, teach bad habits which could lead into severe accidents when learned practices are put into actual use in a real work situation.

With the plan to implement a point system as part of the gamification of the simulation, it would be used for grading the player's performance based on successful actions and penalizing points from safety related mistakes. The aim for the system would be trying to be as informative as possible and adjust the focus direction based on the expert evaluation and feedback.

Small-scale manufacturing wise we are approaching to design the application to be as user-friendly and as simple to use as possible. Another possible direction for the design would be constructing the application to be easily modified for different machinery located in the Fab Lab, such as 3D printers and welding machinery. The plan to expand the application's range to implement other devices would require a lot of testing and gathering feedback, but we would want to keep that opportunity open in mind for the future.

5.1.3. Expert Evaluation Query and Testing

To gather further feedback of the application's performance and state, we arranged testing sessions in the Fab Lab with the Fab Lab personnel to test out the simulation in the intended environment. The simulation has reached the state where it can be tested with users and while the users are testing the application, our team members guide and supervise the testing session while taking notes how the users perform in the simulation. After the users have used the application at least once, they are instructed to fill a query, which we have prepared for the testing session consisting of various questions related to the users' information, experiences working at the Fab Lab, the VR specific questions, such as motion sickness and open questions for any possible feedback. The questionnaire aims to find the most impairing flaws in the simulation in addition to major differences between the real laser cutter and the cutter in the simulation. We also ask users if they agree with gamification as a viable way to teach safety precautions of equipment, and how well this simulation performs in teaching safe use of the laser cutter. All of the answers will be handled anonymously and the results of the query will be presented in the Results-chapter with in-depth detail.

5.2. Experimental Setup

After the users were given a brief introduction in using the VR headset, they were instructed to first explore the surrounding areas in the simulation to get familiar with the controls. Before being able to use the laser cutter, the simulation places the user outside the FabLab room, where the user navigates to the FabLab by opening a door. This functions as a brief tutorial for grabbing and manipulating objects in the virtual space and as most of the objects in the simulation require grabbing the object by hand, the door handle is the first object for the user to interact with before using the laser cutter or any other object in the simulation. The reason for using a door handle as the first interactable object for the user is to take advantage of the already known behaviour of the objects in the real-life and in this case using a door handle is one of the common actions most people are familiar with and this behaviour should transfer to VR intuitively.

While the user was playing the simulation, our supervising member was observing the user's actions during the simulation without stepping in or telling the user what they were supposed to do in the simulation, unless the user requests help or the simulation starts breaking or malfunctions. Minimizing our team member's interaction with the user during the simulation allowed the user fully focus on the simulation itself and prevented any outside influence on users' decisions during the testing.

Once the user had successfully opened the door and entered the FabLab work area, they were instructed to use the laser cutter to cut a piece from one of the available materials located on the nearby desk. The user had full freedom for choosing any of the materials in any order. Once the user had selected the material they planned to use for the laser cutter, they could perform the optional, but mandatory safety procedures for using a laser cutter in real-life before continuing. If any of the safety procedures had been bypassed and an error had happened, a penalty would have been given. As an example, if the user were to leave the laser cutter unsupervised while the cutting was in progress or opened the lid before fumes had been exhausted, the simulation's scoring system would have penalised the user from the mistakes by redacting the user's score.

After the cutting is finished and the user takes out the material from the laser cutter, the user is given a score based on the performance with a maximum of 100 per cut, with deductions given for any mistakes made. The user was then instructed to proceed to cut a different material and repeat until the user had reached the required score amount of 300. The users used the VR application one at a time and at their own pace until the required tasks in the simulation were completed.

After the participants had used the simulation at least once, they were instructed to fill a questionnaire based on their experiences from the simulation. The questionnaire had various questions, which included the following: any earlier experiences with VR applications, general questions related to their working experience in the FabLab and with the laser cutter, scale-based questions how they agree or disagree with sentences related to the VR simulation and a few open-ended questions related to motion sickness. After the questionnaire was filled by all participants, we used thematic analysis to analyse the answers and the observations from the testing sessions.

Normally there would have been multiple project members assisting with the testing sessions and more participants to test the simulation. However, due to the ongoing COVID-19 pandemic, we had to take into account the safety guidelines set by the university and we only were able to use a smaller testing group for the session, with a single supervising team member.

6. RESULTS

Our test users consisted of people aged from 35 to 45 with an evenly divided gender ratio. Their work experience in FabLab ranged from 3 months to 6 years. All users had former experience of VR headsets but most had only tried VR a few times in the past, or used VR semi-regularly few times a year. All of the test users were familiar with safety precautions related to the laser cutter.

The simulation was tested with people who have experience with using the laser cutter and are familiar with different safety precautions related to the usage of the cutter. Testing revealed quite significant differences in usability of the simulation when compared between our own group and new users. Users had some trouble not only with the features of the simulation, but also with features of the VR equipment itself. Most users had used VR devices before, but not this particular device. Due to this, they took some time getting used to this device and its controllers. Users had to be guided through what each of the controller buttons does and how to grab and use different elements in the simulation. Users were also quite new to moving in VR and a few of them tried to move around the virtual environment by taking steps in the real world, as one would in the real world. Using the analog stick of the controller for movement seemed to be counter-intuitive, and movement caused motion sickness for users. These are common symptoms for first-time-users of VR and usually diminish when the user regularly spends time in VR environments.

In the simulation, feedback is given to the user by displaying text on the wall next to the laser cutter. When testing, often the users were so engaged with activities they were performing that they rarely paid attention to the text displayed on the wall or their score changing. Presence of new feedback could potentially be emphasized by getting the attention of the user by sound notifications or by moving the feedback text to a more relevant position. Users also reported that the movement speed could be a bit slower as it caused some disorientation and users found positioning themselves in the correct spot in front of machinery difficult.

6.1. Data Analysis

We received useful information from the user questionnaire and the answers from the users were fairly consistent. All of the users experienced motion sickness to some extent during the simulation due to linear movement in the simulation handled by using the controller's joystick input. Some users did not notice the textual information on the wall and nearly all of the users had some problems with grabbing and handling the cover of the laser cutter and various other objects in the simulation.

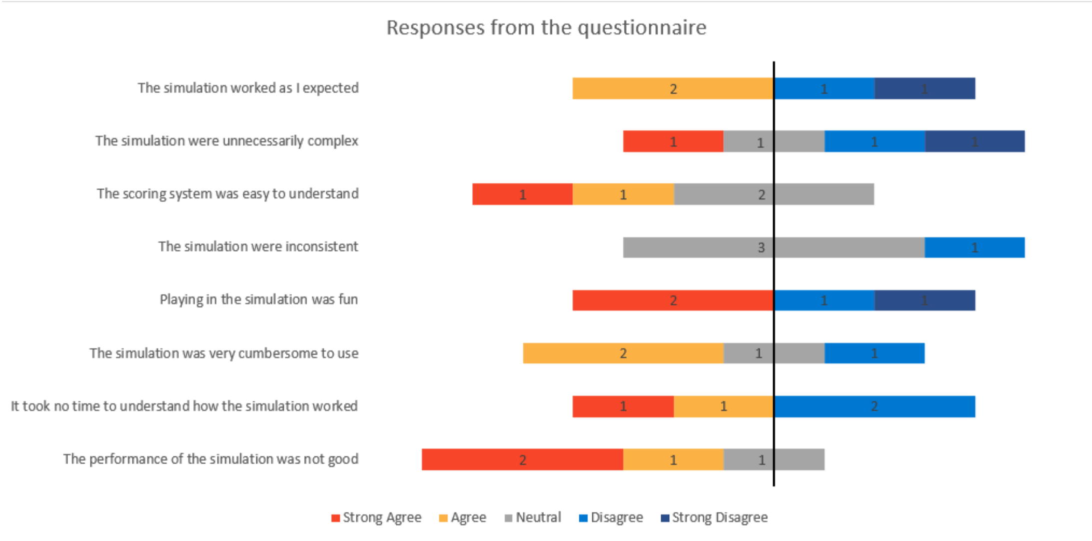

Figure 14. Questionnaire responses from multi-choice questions

Based on the questionnaire results which the figure above represents:

- Users' expectations on simulation's functionality varied a lot between users
- Users had mixed responses on simulation complexity, but some of the users thought the simulation was not unnecessarily complex
- The scoring system was easy to understand
- Most of the users could not decide if the simulation was inconsistent
- Some of the users enjoyed using the simulation, while the other half did not
- Some of the users found the simulation cumbersome to use
- Understanding how the simulation worked varied a lot between users
- The simulation's performance was not good

While the users had varying responses on how the simulation translated to using a real laser cutter, all of the users thought gamification could be a viable way for teaching safety precautions and to learn to use different types of equipment and machinery. In the current version of the simulation, the aspect of learning did not meet our initial expectations, as the simulation had some shortcomings related to general usability.

A portion of users did not find this particular simulation very educational, since a considerable share of time spent went into trying to properly close the cover of the laser cutter or grabbing different items in the virtual space, and not into the actual use of the machinery. These types of generic usability issues have a major effect on the educational quality of the simulation. The user should have to pay minimal attention to technical details of the simulation, and be able to give full attention to the task being performed.

Results of the questionnaire was analyzed using thematic coding[38] and then confirmed using agreement testing and Cohen's Kappa to indicate level of agreement.

The themes we used for categorizing feedback from the test users were as follows:

- Basic Usability Issues
- Precision
- Legibility and Layout
- Simplicity
- Educational Quality
- Support for Learning
- Novelty Effect
- New Idea

Categorizing feedback from users like this allows us to more reliably see which areas in the simulation need the most attention regarding future development. It also tells which parts or features of the simulation get the most feedback from users.

6.2. Interpreting the Results

Based on the questionnaire results we are able to find aspects of our project which have worked, and which have not. Even though the user group size is very small and we are unable to draw any conclusive results, there are still a few areas where improvement is clearly required and some areas where we have managed to succeed.

For the users expectations on the simulations functionality, the responses were divided between the users greatly and the possible reason might have to do with the simulation's incompleteness. While most of the features were implemented in the simulation, users noticed lacking features at crucial parts of the simulation, which we had not taken into account during development. Another question that was divided between the users were related to simulations complexity, where some users rated simulation to be unnecessarily complex while the other users did not think the simulation were too complex. Some of the users found the simulation to be cumbersome to use, which we were not expecting, but it could be caused by the HMD VR headset or by lack of frequent VR use.

An important feature that was missing was that it is not possible to remove an object from the machine while the object is on fire. In the real world this is the first thing that should be done. While in our simulation, the user can only use the extinguisher to put out the fire. Doing this in the real world would cause additional damage to the machine, and is not the right thing to do in most cases. This is something that was completely overlooked by us, and must be corrected before the application can be brought to public.

Questions where the users' responses were the most similar were at easy understanding of the simulation's scoring system, finding the simulation to be consistent and rating its performance to be not good. We already were expecting the simulation's performance to be somewhat average as we were mostly focusing on the features of the simulation and performance was left with a low priority.

Questions that we hoped to receive positive responses from the user, but instead received mixed responses were finding the simulation fun and understanding the simulation's functionality. One factor that could contribute to the varying results of finding the simulation fun would be the motion sickness, which was reported by most of the users. Alternative movement methods could be added to mitigate this.

Motion sickness was reported by all of the users and the most common cause for it was related to moving around in the simulation either with the grip controller's movement inputs or by walking around in the simulation. One of the users also reported the motion sickness to hinder the simulation so much they had to take an half hour break to fully recover. One of the users suggested to implement an alternative movement method to the simulation featuring warping to specific locations instead of using manual controller inputs. This type of warping-based movement in VR environments is widely considered more friendly for new users as it induces considerably less motion sickness symptoms.

6.3. Qualitative Agreement Testing Results

In order to perform thematic coding [38], we divided user feedback into 32 separate lines of feedback. When categorizing these comments into aforementioned categories, the most prevalent category was 'Basic Usability Issues' by a significant margin. This was expected since most of the feedback received was related to technical issues and flaws in the simulation. Nearly half of the comments from the users were categorized into 'Basic Usability Issues' category by both of our observers. (14 and 22 out of 32) With these categorizations we got a Cohen's Kappa value of 0.390.

	A	B	C	D	E	F	G	H	Total
A	14	3	1	0	0	0	0	4	22
B	0	0	0	0	0	0	0	0	0
C	0	0	1	0	0	0	0	0	1
D	0	0	0	0	0	0	0	0	0
E	0	0	0	1	0	0	0	0	1
F	0	0	0	1	0	0	0	0	1
G	0	0	0	0	2	0	3	0	5
H	0	0	0	0	0	0	1	1	2
Total	14	3	2	2	2	0	4	5	32

Figure 15. Matrix of categorizations for Cohen's Kappa

In the graph above, letters from A to H represent the themes mentioned earlier as follows:

- A = Basic Usability Issues
- B = Precision
- C = Legibility and Layout
- D = Simplicity
- E = Educational Quality
- F = Support for Learning
- G = Novelty Effect
- H = New Idea

We agreed on 19 out of 32 of our categorizations, which gives us an agreement rate of 59.38%. With Cohen's Kappa value of 0.390, we can conclude that we are in fair/moderate agreement.

6.4. Other Observation

Here we would like to bring up some things that were necessarily not clear in the questionnaire, but came to light in the testing event itself. Even though all users had some previous experience with VR, none had used this particular device before. Due to this, the users were not familiar with controller buttons and did not know which button is which. Some users stated that it would be beneficial to have images of the controllers and buttons with their respective labels inside the virtual environment. Since this was overlooked by us, outside help was needed by the users to use the controllers.

Some users started instinctively walking when inside the virtual environment and they had to be guided to use the analog stick in order to move around the environment. While this is a common thing that happens to first time VR users, it could have been solved by implementing a tutorial that goes through movement and other controls. The need for a tutorial and options for movement style and speed is clear. These features are the first things that should be implemented for the next version of the application.

Users get feedback for their actions by text appearing on the wall behind the laser cutter. Usually users were so engaged with their activity that they rarely noticed the text appearing on the wall. Feedback could be emphasized by using sound notifications or moving the text to a more relevant place where it could be noticed more easily. The cover of the laser cutter was very difficult to close for a majority of test users.

7. DISCUSSION

7.1. Accomplishments

As we were working on the project we set certain goals, which we aimed to fulfill with our project. As an education tool we aimed to make the simulation perform as if you were handling a real laser cutter in the real world without going into too much detail that might take away from the learning goals. To make the tool more engaging and useful, we leveraged gamification to make training sessions more entertaining and enjoyable to the users.

While there was some negative feedback, the users were overall happy with the application. The aspects that worked were the simulation's stability, scoring system and simplicity of the simulation. The VR application had no performance or hardware issues during the testing and the scoring system worked as it was intended without feeling too demanding or easy to reach for the users. Surprisingly, users managed quite well in maneuvering the VR avatar, even though there was some hardship in the beginning due to limited experience with VR, and the HMD used being unfamiliar. We were positively surprised that test users had numerous improvement ideas for the project.

Aspects that did not meet the requirements set for ourselves were inaccuracies in the simulation, and nausea experienced by many users. Most of the features, which the simulation lacked, were tied to the user experience which we had not thought to implement when designing the laser cutter operation. Features such as seeing a cut object after having used the cutter, or being able to hold an object using both hands at the same time are features which seem small but can do a lot for immersion. Another issue which the users encountered was handling the laser cutter's protective cover, which was difficult to properly close as the detection range for detecting when the cover was closed were too narrow. The motion sickness was a much bigger issue than we had originally thought and every user had experienced VR sickness during the simulation ranging from minor nausea to experiencing motion sickness, which took one user 30 minutes to recover from. The simulation also lacked a tutorial for using the VR device and hand controllers, which the users had difficulties to learn when they started to use the simulation.

7.2. Similar Projects

There is a decent amount of similar projects or works available in the field. Because of the fact, that we do not know how long these projects have been developed and how much earlier experience the developers have had with these kinds of implementations, it is unnecessary to compare the refinement of the projects and the precision of the movement. Here we focus on the actual purpose of the project and other choices we made, during this project.

The VR safety training simulations are used for several of purposes. They can be used as a tool to learn in certain areas, for example in the work place. Simulations can also be used as a more immersive and engaging tool to demonstrate safety instructions.[9] [10] [12] An additional way is to use the simulation as a practical exercise, where the player can get some hands-on experience with the possibly dangerous situation or device.[8] [11] Our implementation is definitely supposed to be a learning tool, but it can also work, if expanded, as an introduction tool for the entire Fab Lab space. Compared to other projects that are trying to deliver the same purpose, our implementation lacks some key elements not present in the simulation. The instructions are missing in many cases, and it can be pretty confusing for the player to figure out what he or she is supposed to do. Also, in other known simulations, there are visible goals that the player tries to achieve. In addition, as a learning tool the usage of the laser-cutter is different from the real world usage and it works best as an interactable introduction for laser-cutting.

When observing the usage of gamification in the simulation, we can detect some differences. Many different projects we present in our Related work use some kind of gamification. These simulations use different game mechanics and game design elements to access next level or next task. This is actually really different approach compared to our point system. In our project players have to use the laser-cutter in such manner, that he or she obtains enough points to pass the level. There are also some projects that do not utilise gamification, when it could provide much needed excitement to the simulation.[8] [9] [10] [11] An improvement that could be made to our application is a staged learning system seen in other projects.

One issue we noticed, in comparison to existing applications, was in the style of the movement. In our simulation player can move with the joystick freely around in a style called "free locomotion". In the evaluation phase we noticed, that this can be a major factor causing nausea for our test users. We also got some feedback, stating that we could have used teleportation as our moving method. From other projects we can see, that some people have decided to go with teleportation option. We can not say with certainty that the teleportation is the superior method, but while possibly difficult to implement, it may have been a good idea to make it an option for users that prefer it.

7.3. Limitations

In past years, the project has lasted through both the autumn and spring semesters, while this year only the spring semester was used for the project. This made a large impact to the development process, since there was a short amount of time for testing and polishing of the application before it was given out to the test users. Time constraints also impacted other areas of the project, such as the gathering of information from related articles, and the evaluation. Had there been more time, we could have done two rounds of testing, with improvements in between, to help get the application to a state where it matches the requirements more closely.

At the time of writing (2021) the world has been in a state of pandemic for over a year due to a coronavirus outbreak. The COVID-19 pandemic has made it impossible to work face-to-face, and greatly effected the evaluation of the application, since only a small number of people could be in the same space together at any time. This slowed down the evaluation that already had issues due to time constraints. As a result the amount of outside testing and query answers are very limited, and it is difficult to interpret the results with certainty.

Originally, there was also an idea to show the state of the real machine in virtual reality. However, due to skill and time limitations, this did not come to fruition. There were issues getting the data from the sensors into the Unity game engine that is used for the development of the application. It would have been necessary to write our own libraries to do so, and at this point our know-how wasn't at a level that doing that would have produced results in this time-frame.

7.4. Future Work

If the project is expanded in the future, there are some features and other improvements that could be made. Many of these are things that we would have been happy to implement, had there been more time and/or less restrictions in place due to the pandemic situation. Most importantly, all bugs and immersion breaking details should be polished out. The feature that gained the most negative feedback was detecting if the cover is open or closed. This issue rose from the fact that the Unity built in Hinge Joint is not made to be used in VR, and bounces back after being brought to an extreme position. We have already improved upon this feature, and the cover is detected as being closed, even if it bounces back. Another thing that the test users felt was needed was a tutorial, which could be added as a separate scene where a user can get a better feel for picking up objects and moving in VR. Additional movement methods could also be introduced, such as a warp-type movement, to counteract nausea experienced by some users.

To help teach users of the Fab Lab more broadly, additional machines could be implemented in the future. Machines in the Fab Lab include a vinyl cutter, CNC mill, 3D printer, etc. All of these could be implemented in VR in some form, and be used for education. It may also be possible to teach the usage of these machines in a more general sense, instead of only teaching the safety aspects of the machines. Adding additional machines may allow a simulation of producing complete items in the Fab Lab using different machines in the process. In order for the application to be an effective learning tool, even before the user has set foot in the Fab Lab, the application should be ported to other HMDs, to improve the possibility for a user to have a supported device.

As described in the design section, there was originally a plan to make it possible to see the current state of the real world machine in VR. This is something that could still be done, and the sensors to detect the state of the machine are already in place. IoT-VR-integration would allow more use cases for VR tutorials. IoT-AR interconnection has been a subject of multiple research papers, but is still underutilized outside of research environments[39]. A connection between Unity and the sensors would have to be made.

8. SUMMARY

We developed a VR application that includes a virtual environment that represents the premises in the University of Oulu Fab Lab. The purpose of the application is to be used as a safety training tool for the laser cutter in the Fab Lab, and to help new users become more familiar with the space and the safety precautions related to the machine. The application runs on Oculus Quest 2 VR headset and uses Unity3D game engine at its core. To find out the most important details regarding safety when using the machine, we queried the staff at the Fab Lab, to make sure the simulation was factually correct and represents correctly how the laser cutter is operated.

After learning about the safety precautions from the personnel of FabLab, we developed the simulation to correspond to those requirements. In order to evaluate that the simulation works as a learning tool, we ran a small scale evaluation in the FabLab with the personnel. Although our findings are inconclusive, they suggest that gamification can be used as an enhancing tool in teaching safety precautions and teaching how to operate machinery. Gamification often makes learning experiences more engaging and interesting, as it allows the users to feel a more clear sense of accomplishment. Gamification-based learning experiences also make progress easier to present quantifiably using points to indicate the users' progression.

Our evaluation concluded that the users, for the most part, felt immersed in the virtual environment and had fun with the simulation. The educational aspect of the simulation was somewhat hindered by technical issues and some factual inaccuracies between the simulation and the real laser cutter. All in all, the current state of the simulation offers a good base to continue further development of the simulation, potentially including other machinery than the laser cutter down the line.

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10. APPENDICES

Appendix 1 Work Hours

Roope: 40h research and writing, 6h setting up the project and problems with it, 25h working with the scene, about 2,5h meetings

Veli-Matti: 62h subject research and writing, 6h texture and modelling work, 5h work with the scene

Santeri: 51h research and writing, 83 hours with the scene

Timo: 57h research, writing and analyzing test results, 14h working with sensors and trying to export the data, testing session related work: 15h