LAPPEENRANTA-LAHTI UNIVERSITY OF TECHNOLOGY LUT
LUT School of Energy Systems
LUT Energy Technology
Master's Thesis

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UTILIZATION OF VIRTUAL REALITY IN LOVIISA NUCLEAR POWER PLANT

VIRTUAALITODELLISUUDEN KÄYTTÖ LOVIISAN YDINVOIMALAITOKSELLA

Examiner: Professor, PhD (Tech) Juhani Hyvärinen
Supervisor: MSc (Tech) Taija Solja

ABSTRACT

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The use of virtual reality technology in power plant environments has recently increased and the technology promises to bring improvements and benefits compared to work methods in use today. This thesis offers a theoretical and practical overview of the virtual reality technology in the context of nuclear industry.

Several virtual reality training applications were planned and built for Loviisa nuclear power plant during the making of this thesis. These applications were thoroughly tested and analyzed, providing insight on how to successfully use virtual reality technology in a nuclear power plant.

The results show that the technology is mature enough to gain widespread support from nuclear power plant personnel, yet the virtual reality content must improve before it can replace traditional methods of training.

TIIVISTELMÄ

Lappeenrannan-Lahden Teknillinen Yliopisto LUT

LUT School of Energy Systems

LUT Energiatekniikka

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Virtuaalitodellisuuden käyttö Loviisan ydinvoimalaitoksella

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Hakusanat: Virtuaalitodellisuus, Ydinvoima, Loviisan Voimalaitos

Virtuaalitodellisuusteknologian käyttö on viime aikoina lisääntynyt voimalaitoksissa ja sen luvataan tuovan useita hyötyjä verrattuna nykyisin käytössä oleviin ratkaisuihin. Tämä diplomityö esittää yleiskatsauksen virtuaalitodellisuuden teoreettiseen ja käytännön soveltamiseen ydinvoimalaitosympäristössä.

Tämän työn aikana suunniteltiin ja rakennettiin useita virtuaalitodellisuuden koulutuksen sovelluksia Loviisan ydinvoimalaitokselle. Näitä sovelluksia harjoitettiin voimalaitoksen henkilökunnalla ja harjoitteista saadut tulokset analysoitiin, saadaksemme selville, miten virtuaalitodellisuuden teknologiaa kannattaa tulevaisuudessa kehittää ydinvoimalaitoksella.

Tulokset näyttävät, että virtuaalitodellisuusteknologian käytöllä on laaja henkilökunnan tuki, mutta harjoitusten sisällön on kehitettävä ennen kuin koulutukset voivat korvata nykyisiä koulutusmetodeja.

FOREWORD

This master’s thesis was written as a part of my master’s studies in LUT University for Fortum Power and Heat Oy. Fortum has previously provided me with multiple interesting opportunities to work in Loviisa nuclear power plant during my studies and I could not have asked for a better workplace to write my thesis.

I would like to thank Niklas Hurmerinta for providing practical and theoretical help concerning the use virtual reality devices in Loviisa nuclear power plant and for spearheading the digitalization program in Loviisa for which this thesis was written. I appreciate my examiner professor Juhani Hyvärinen for great nuclear engineering lectures and for constantly driving the Finnish nuclear industry forward towards an ever-brighter future. I am also grateful for my thesis supervisor Taija Solja for helping with the structuring of the thesis and providing timely and accurate feedback to allow for continuous improvement of the thesis quality. I must also thank my supervisor Ismo Korhonen for his leadership ability and for creating a great environment for working and innovating. I would also like to extend thanks to colleagues Simo Kettunen and Aleksi Hassinen for providing endless amounts of interesting ideas during our numerous discussions and to Vesa-Pekka Vilpponen for strong words of encouragement and teaching me the value of having a great education.

No man is an island and none of this would have been possible without the support of family, friends, and colleagues over the years. Thank you.

TABLE OF CONTENTS

LIST OF SYMBOLS AND ABBREVIATIONS

Abbreviations

APROS	Advanced Process Simulation Software
CAD	Computer Assisted Design
CEA	Alternative Energies and Atomic Energy Commission
CR	Control Room
EDF	Électricité de France
HuP	Human Performance
HVRC	Halden Virtual Reality Centre
IDE	Integrated Development Environment
IFE	Institute for Energy Technology
ITER	International Thermonuclear Experimental Reactor
LOKS	Loviisa Koulutus Simulaattori
NPP	Nuclear Power Plant
MWB	Must Win Battle
PRA	Probabilistic Risk Assessment
PWR	Pressurized Water Reactor
R&D	Research & Development
UE	Unreal Engine
VIRSE	Virtual Reality Simulator Development and Evaluation
VVER	Vodo-Vodyanoi Energetischesky Reaktor

VR	Virtual Reality

1 INTRODUCTION

The ongoing process of increased digitalization is challenging Finnish industrial companies to reform their operating methods and practices. Finland is an advanced economy with an educated workforce and is recognized as a trailblazer in using electronic services which provides a great starting point for the increased digitalization of the industrial workplace. While great progress has been made, the full potential digitalization offers has not yet been achieved. For these reasons, the Finnish government has made productivity leap one of its medium-term objectives and is trying to support private companies by dismantling regulations and encouraging companies to increasingly digitalize their business. (Valtioneuvosto 2015, p. 27-29)

Successive governments have guaranteed that the digitalization program will continue at least till 2023 and that there is an increased public push to provide the necessary infrastructure, laws, and regulations to help companies succeed in the digitalization process. (Valtioneuvosto 2019, p. 9-12)

This thesis aims to contribute to the Finnish digitalization effort by providing the mostly state-owned enterprise Fortum Power & Heat with theoretical and practical information to apply new virtual reality methods for training and operation. The thesis was completed in Loviisa nuclear power plant for training organization during 2020.

1.1 Thesis background

While Fortum has always had an active interest in digitalization, it became a strategic objective during 2016 when the company identified digitalization as a global megatrend shaping the energy sector. "Digitalize our business to maximum scalability" -project was launched as a part of Fortum's Must Win Battle (MWB) -program. The goal of the program was to catapult Fortum into an industry leader in energy business digitalization. Sub-goals of the program were to create at least one new disruptive business model, energize and emotionally engage customer experience, create advanced business operations, power plants and trading and to create a competitive and attractive working environment. As a part of this MWB digitalization program plan, a subproject for gaining leadership in virtual reality (VR) and augmented reality (AR) technologies was launched. (Söderholm K 2016)

This subproject included nuclear power plant control room development, testing and training in virtual reality as well as creating 3D-models for VR use, 360-videos for training, digitalization of instructions, process simulation with Advanced Process Simulation Software (APROS) in virtual reality and multi-user mode for virtual reality. Evolving the control room design from old models to virtual reality enabled improvement of training efficiency and lower costs of control room design validation. (Söderholm 2016)

In 2017, applications developed with this project were used to improve operation efficiency in Loviisa nuclear power plant (NPP). Integrated system validation was done with the fully functional full scope control room virtual reality model in 2017 and different scenarios were used for control room operator training. Interactions between control room operators and field workers were done as part of the training. The results from the projects were measured as improved overall safety, increased production, lower maintenance costs and shorter outages. (Söderholm 2017)

Continuing this early success of the control room virtual reality pilot, Loviisa VR-room development started in October 2018 to offer a possibility of continuous virtual reality training and to further develop virtual reality scenarios with the power plant personnel. The early goal of the Loviisa VR-room development was to combine existing material with news ideas to develop training scenarios that could be used to further improve the efficiency and safety of the nuclear power plant. (Hurmerinta 2018)

1.2 Thesis scope and goals

This thesis aims to improve the utilization of virtual reality in Loviisa nuclear power plant by studying the theory and applications of virtual reality, especially within the context of nuclear industry. This knowledge is then used to build several quick-to-deploy applications to gather results from practical use of virtual reality. To provide background context for the work, this thesis also aims to briefly explain the organization and overall technical details of Loviisa nuclear power plant as well as the basics of virtual reality and the tools use of it requires. Applications of virtual reality in other nuclear power plants and nuclear industry are also examined presented as well as some relevant use cases that have not been used but are feasible to implement.

As a part of this thesis, several simple training scenarios for the power plant personnel have been built. Opinions and feedback from the plant personnel has been collected and analyzed to provide better understanding on how to develop better applications in the future. Combining the theoretical and practical part of the thesis explains how Loviisa nuclear power plant could utilize virtual reality for best results and shows a path forward for the Loviisa virtual reality development program.

1.3 Thesis outline

Chapter 2 provides background information about the Loviisa nuclear power plant. A simplified explanation for the process of nuclear energy production is given alongside Loviisa nuclear power plant process chart. Additionally, Loviisa nuclear power plant's organizational structure is introduced, and relevant parts described.

Chapter 3 explains the basics of virtual reality technology. The history of the technology is briefly overviewed and basic concepts of virtual reality introduced. The process of importing objects to virtual reality and technological obstacles are described. The potential of digital twinning in the context of virtual reality is also examined.

Chapter 4 focuses on existing and potential virtual reality solutions used by the nuclear industry. The chapter introduces some of the more notable examples in the industry and describes some of the potential virtual reality solutions nuclear power plants can use.

Chapter 5 discusses the previous virtual reality solutions used by Fortum and especially those built specifically for the purpose of this thesis. Virtual reality scenarios and software used in developing them are listed and described in this chapter.

Chapter 6 analyses the results of virtual reality scenarios done in the previous chapters. Feedback gathered from the experiments are analyzed and lessons learned from the experiments are discussed. Also, future application for Loviisa nuclear power plant are suggested.

Chapter 7 draws conclusions from all the previous chapters and provides the closing remarks for the thesis.

2 LOVIISA NUCLEAR POWER PLANT

Fortum Power and Heat Oy, a subsidiary of Finnish state-owned enterprise Fortum Oyj, fully owns and operates a nuclear power plant on the island of Hästholmen located in the Finnish municipality of Loviisa. The company produces nuclear energy with two westernized Soviet-built Vodo-Vodyanoi Energetischesky Reaktor (VVER) -type pressurized water reactors (PWR). These reactors have an operating permit that expires in 2027 (Loviisa 1) and 2030 (Loviisa 2). Both Loviisa 1 and Loviisa 2 currently have the net capacity of 507 MWe. The yearly net production of electricity is 7.79 TWh which is around ten percent of the annual electricity production of Finland. The annual usability and capacity factor of the power plant is world class reaching 88.4% in 2018. Loviisa NPP employs around 500 people but the personnel count can be as high as 1500 during annual outage. Aerial view of the power plant and some of the surrounding islands is shown in figure 2.1. (Fortum 2019)

Figure 2.1. Aerial view of the Loviisa NPP (Fortum 2019)

2.1 Nuclear power plant

The basic operating premise of a nuclear power plant is to generate heat through nuclear fission inside a reactor and to use this heat to boil water into steam. This steam then turns turbines which are connected into an electric generator. Nuclear fission is achieved by bombarding the nucleus of uranium atoms with neutrons. This splits the nucleus generating tremendous amount of heat and several new neutrons. Some of these neutrons cause new nuclear fissions which creates a chain reaction capable of maintaining constant heat generation. (Sandberg et al. 2004, p. 26-27)

The main process of Loviisa nuclear power plant and its most important systems are visualized in figure 2.2. Loviisa NPP reactor uses low enriched uranium dioxide as fuel. The UO_2 has been pressed into 1-cm wide pellets which have been encased in 2.5-4 meters long fuel rods. Fuels rods have then been assembled into 313 fuel bundles. One fuel bundle consists of 126 fuel rods. The reactor also contains neutron absorbing control rods which are used to change the rate of fission and circulating water which has the dual purpose of moderating neutrons and transferring heat out of the reactor core.

Loviisa NPP has two closed water circuits transferring heat around the power plant. Primary circuit pumps move the water from reactor to steam generators and back to reactor. Steam generators are connected to the secondary water circuit. Loviisa NPP is pressurized water reactor which means that the water pressure inside the primary circuit is so high (12,3 MPa) that despite the high temperature of 300 °C, the water inside the primary circuit does not boil.

Secondary circuit has much lower pressure inside the steam generator, thus the water boils and the resultant steam is drawn into high- and low-pressure turbine which are connected to the electric generators. These electric generators provide electricity through transformers to the power grid. After the turbines, the steam is condensed into water in the condenser, which is connected to the ocean through a tertiary circuit. Condenser- and feedwater pumps move the water back to the steam generator and the cycle continues. (Sandberg et al. 2004, p. 44-48)

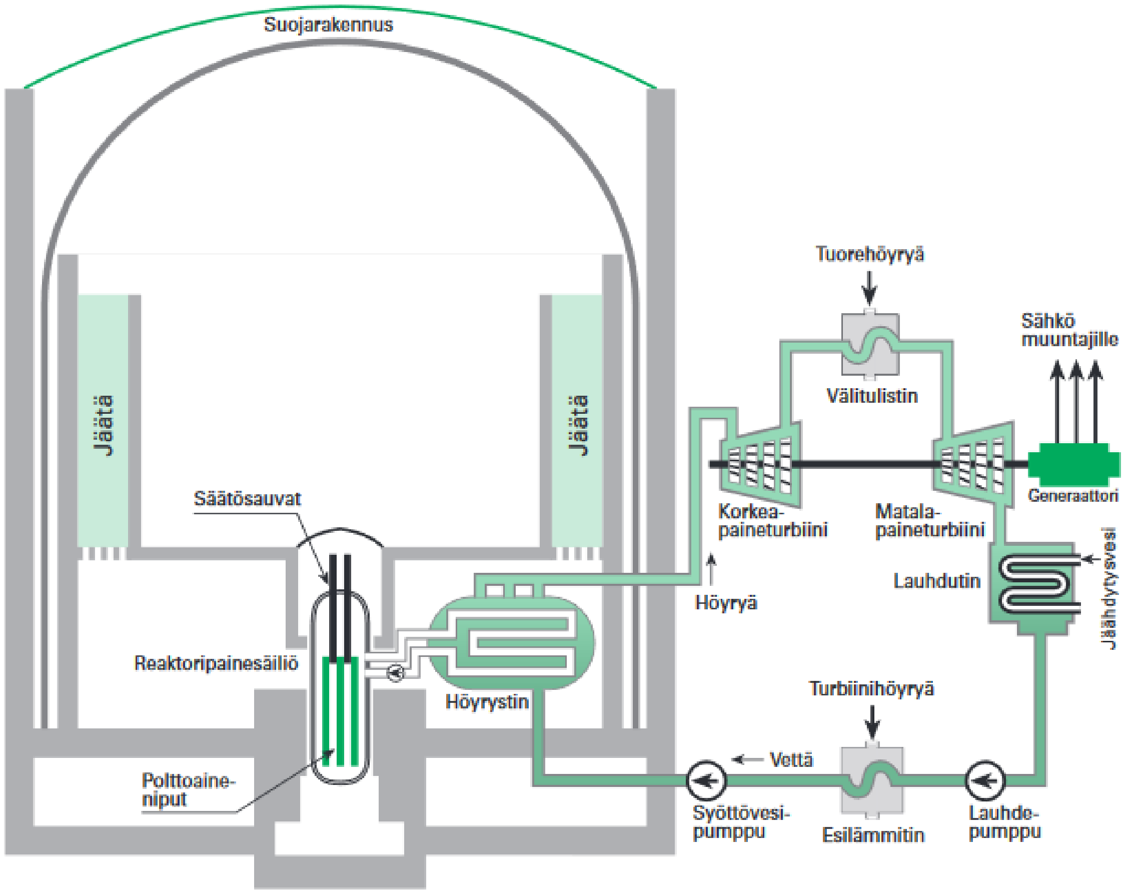

Figure 2.2. Loviisa NPP process chart (Sandberg 2004, p. 45)

Nuclear power plants need to limit the radiation exposure to the personnel and the environment and because of that the power plant has a radiation-controlled area which consists of both reactor buildings, auxiliary buildings, and a part of Loviisa social building. These areas are accessed through checkpoints where people and objects are monitored to ensure that no contamination exits the power plant. The release of radioactive materials during accidents is also prevented by multiple successive structural barriers and several independent safety systems. (Fortum 2019)

2.2 Organizational structure

Loviisa nuclear power plant organisation follows the traditional hierarchical model common in large power plants which resembles a pyramid-like structure. At employee level there exists a large amount of organisational groups that report to middle managers who in turn report to upper management. Loviisa nuclear power plant has a general manager responsible to the main company. Under the general manager are six department branches which perform the work required to operate the nuclear power plant. Upper level organization tree is shown in Figure 2.3.

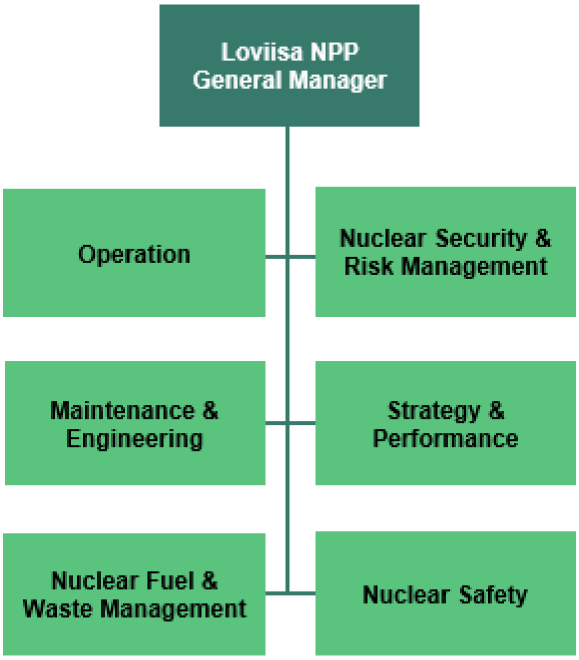

Figure 2.3 Loviisa NPP organization chart

This thesis was started for the Training and Operating Experiences group which was part of the People & Performance department. During the writing of the thesis Training and Operating Experiences group split into Training group and Operating Experiences group. The thesis was completed for Training group. People & Performance branch was reorganized into Strategy & Performance branch. Strategy & Performance organization tree is shown in Figure 2.4.

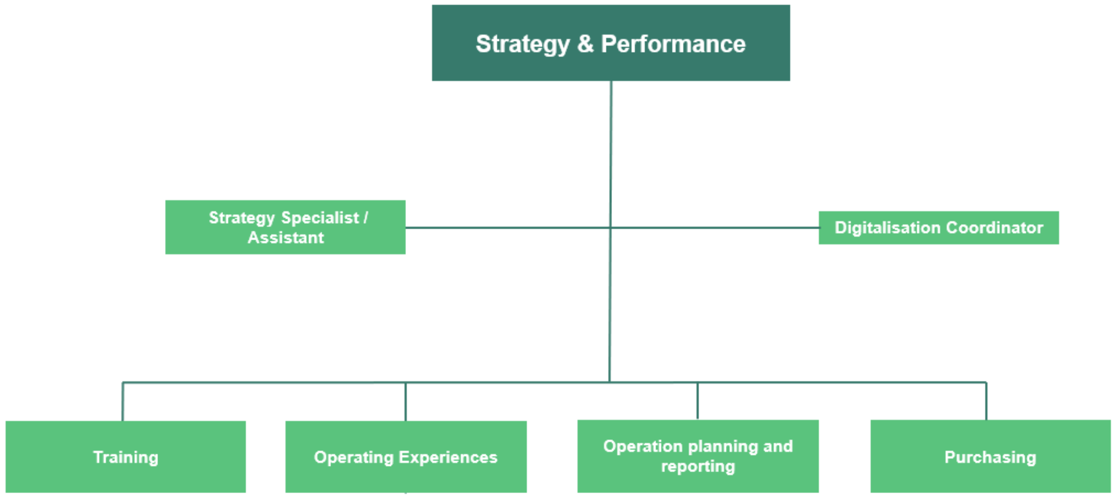

Figure 2.4. Strategy & Performance organizational chart

Strategy & Performance organization provides important support functions for other Loviisa NPP organizations. It is responsible for overall training of the plant personnel, gathering operation experiences, coordinating the Human Performance (HuP)-program, improving the safety culture of the power plant, small item purchases and developing the management system. Also, Strategy & Performance organization is responsible for evaluating administrative and purchasing guides and directives and maintaining plant-level action plan, goals, and indicators. Strategy & Performance organisation also creates high level strategies for the power plant management.

The Strategy & performance organization is divided into four groups. Training group, Operating experience group, Operation planning and reporting group and Purchasing group.

Training group is responsible for securing the long-term training prospects of the power plant personnel and to guarantee that the long-term competence levels stay high. Finnish nuclear regulation sets mandatory training requirements for personnel working in a nuclear power plant. These training regulations require enough qualifications, know-how and competence for nuclear power plant personnel and demand active work to achieve, maintain and develop these competences. The primary goal of Loviisa nuclear power plant Training group is to fulfill these requirements and thus allow the continued operation of the nuclear power plant in accordance with the Finnish law and regulations.

Operating experience group is responsible for HuP-tools, operating experience process development and reports, scaling INES -ratings in case of accident and reporting operating experience process and coordinating the development of operating experience material. Also, OE group is concerned about EHS investigations and researching OE experiences from other power plants.

Purchasing group is responsible to guarantee the success of economically significant purchases and that all regulations and laws are followed during the purchasing progress. It follows the specification progress and item delivery and gathers data and coordinates different purchases between other groups. It also provides support regarding purchases to other groups.

Two special roles exist under Strategy & Performance group. Strategy Specialist/Assistant and Digitalization Coordinator. Strategy Specialist/Assistant provides the group with extensive knowledge on strategy creation and implementation while also serving as the group assistant. Digitalization Coordinator provides coordination and sales support for digitalization projects across different groups in Loviisa nuclear power plant. (Päivärinta 2019)

3 VIRTUAL REALITY

Virtual reality is most associated with fixed or wearable technologies that can project an illusion of an immersive 3D-environment. This effect can be achieved by either providing the user with a stereoscopic head-mounted display or by projecting images around the user with projectors or a screen in a dedicated VR-room. Positional audio can be used to deepen the immersion to the virtual world. The concept of virtual reality is old, especially in science fiction where it was clearly defined as early as 1935 in the short story Pygmalion's Spectacles. Yet the technology required to manufacture and develop VR-devices has only been around since 1950’s. The invention of virtual reality cannot be attributed to a single person or company, but the term ‘virtual reality’ gained public recognition in 1987 when VPL Research, founded by Jaron Lanier, released their first commercially manufactured VR product. VPL Eyephone and Dataglove, shown in Figure 3.0, were revolutionary products for their time. Still, they suffered from low performance and high cost that eventually drove the company to bankruptcy. (Aukstakalnis 2016, p. 8-10)

Figure 3.0 VPL Research’s VR-system

During 2012 the display and graphical processing unit technology had matured enough that mainstream mass production of VR-devices could be conceived. Palmer Luckey founded Oculus in 2012 and created a Kickstarter campaign to build a cheap yet effective VR-device for consumer markets. Oculus Rift Development Kit 1 was launched in 2013 and Development Kit 2 was launched in 2014 culminating in commercial release during 2016. This attracted the attention of several competitors such as HTC which quickly launched Development Kit for HTC Vive in 2015 and launched a commercial version during 2016.

3.1 Technology

VR-devices work by tricking the user's brain into creating an illusionary world by sending light through the user's eye. This perceived scene projected by the VR-device is called visual space. Specific coordinates of objects and the shape of the models in virtual reality is called object space. Object space is crucial for the immersivity of virtual reality as every piece of content shown in visual space must be designed and placed with utmost care to maintain the illusion of reality. Any method that can supply data to the software tasked with creating the visual space can be used to create objects for the visual space. Most common way is to create 3D-models for virtual environment using a computer assisted design (CAD)-programs such as one shown in Figure 3.1. (Aukstakalnis 2016, p. 14-15)

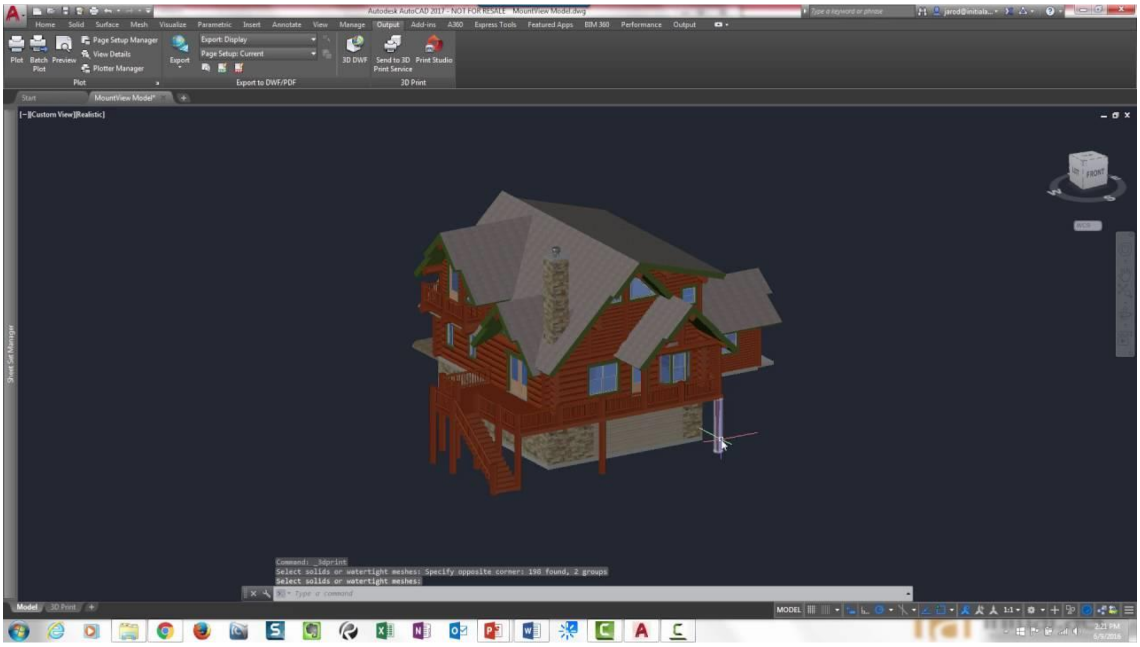

Figure 3.1 Creating a 3D-model inside a CAD-software.

Navigation inside virtual environment must be done in relation to the object space, thus some system of coordinates must be used for defining position, orientation, and rotation of objects in relation to the user and each other. Most common positional system is a Cartesian coordinate system using three variables (x, y, z), but there are some special cases where a non-Cartesian system proves useful. When the user is watching a 360 degrees video, he will always remain in the center of it, thus a spherical polar coordinate system which defines everything in relation to this center position is more practical for the designer. In some applications the user will not move in a virtual environment and their location is fixed in a cylindrical axis. In these cases, a cylindrical coordinate system could be used where everything is defined in relation to the longitudinal axis.

Usually knowing the coordinates is not enough; Tracking the orientation and rotation of objects in virtual environment is also needed. Since visual space is three dimensional, Tait-Bryan angles (Yaw, Pitch, Roll) provide 6 degrees of freedom and are often used for head orientation. Yaw, pitch, and roll are visualized in Figure 3.1. There exists a possibility to rotate the user’s head using Euler angles, but they fail to provide smooth movement and open the possibility of losing degrees of freedom if roll, pitch, or yaw overlap. This is known as a gimbal lock as it is impossible to separate the axes once they have overlapped. A 4-coordinate quaternion -system for rotation solves this problem.

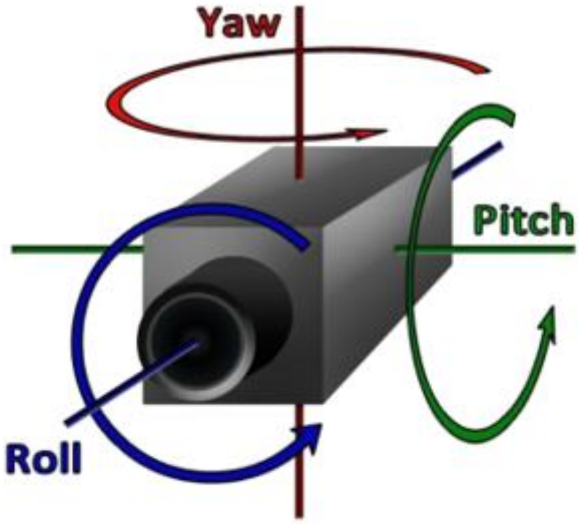

Figure 3.2. Camera rotation possibilities inside virtual reality.

Wayfinding in virtual reality can be done with physical movement, through control interface or a combination of both methods. Physical movement provides more realism, but it is limited by movement range and the tracking ability of the virtual reality devices. Movement through interface is easier to execute in practice, but naturally provides worse immersion than physical movement. Multiple methods of interface design solutions for wayfinding have been developed over the years: Keyboard, mouse, joystick, wheel, gloves, eye tracking and omnidirectional treadmill are some examples of navigation interfaces used in modern VR applications. Head-mounted displays nearly universally use same subsystems in their design, but the implementation specifications of those subsystems vary greatly. (Aukstakalnis 2016, p. 15-22)

Since virtual reality uses multiple senses, it also has a potential to affect those senses negatively. This can be due to natural tendencies of the user to feel nausea, deficiency of the hardware used or problems with the user experience of the VR software. Most common problems are headaches, dizziness, and overall nausea. To combat nausea, care must be taken that visual, auditory, and tactile senses do not unnecessarily conflict with what the brain feels is the correct response for the stimulus. When user is shown movement in virtual reality, optimally they should be able to move themselves at the same pace as the visual image moves. If an object is touched, there should be tactile feedback such as vibration from the controllers. Audio stimulus is rarely a priority for developers, but it has a potential to greatly enhance the feeling of immersion. (Lee et al. 2017)

Age, gender, vision, color perception or other demographic factors are not significant in causing nausea in virtual reality. The visual clarity of the virtual reality device has huge impact on potential negative effects; therefore, this phenomenon should decrease as the quality of the technology increases. (Geršak et al. 2018)

3.2 Digital Twins

Traditionally, physical, and digital products have not been linked together. Physical products could have been produced with the help of digital model or digital products could showcase some features of a physical products but for most part there has been no interaction between the two. Recent advances in data-driven product design have enabled a new option of digital twinning where both physical and digital products are intertwined. Data from the physical product changes the digital product, data from digital product changes the physical product or both change each other simultaneously. At minimum there must be a physical product, a digital product, and a data link between them. (Tao et al. 2018, p. 1-5)

Data fed to a digital twin from a physical product is extremely useful for feedback and improving the product. This data can be gathered from different use periods during the products lifecycle. Information about operation status, maintenance needs, correct behavior and optimum performance can be fed to the digital model for real time analysis by personnel who are in a different place physically. The information gathered can also include personal data from user such as physical details of the operator or their performance. Similarly, digital twin can make the physical version more ‘intelligent’ or responsive by sending data from the digital product to a single physical product so that the product can self-correct and optimize its behavior. (Tao et al. 2018, p. 1-4)

Creation of a digital twin requires more effort than building a single product. First a virtual representation of the physical product must be built using tools such as a 3D-modelling software. When the model is ready there needs to be collection of initial data from physical product to validate the virtual model. Simulation of physical products behavior in the virtual model must be rigorous so that correct behavior can be assured.

Then a data link between virtual and physical product can be established using secure two-way connections. At this point it can be tested whether changes made in digital model fully translate to the physical model and vice-versa. Data gathering and continual perfection of the model are then continued until required accuracy and performance is achieved. (Tao et al. 2018, p. 5-8)

For the safe operation of nuclear power plants, understanding the state of plant systems is paramount. Creating digital twin from a nuclear power plant can be used to visualize information in a clear way, especially if it is combined with advanced use of virtual reality. If the nuclear power plant is digitally twinned and moved to virtual reality, there is a capability for the plant operators to visit any room at the nuclear power plant without leaving the control room and see how the physical devices are functioning. The traditional method in older nuclear power plants is to use annotated layout images which always lacks some information a full digital twin would provide. Thus, having the possibility to view the plant in operation through realistic 3D-virtual model can deepen the understanding of physical layout of the plant. Reactor physics and reactor parts such as control rods can be digitally twinned which enables operators to have a better understanding of the phenomena such as neutron economy by seeing the effects through visualization in virtual reality. Data from accidents and operational failures can be gathered in real time which allows operators to ‘rewind and replay’ the events for better understanding of the phenomena. This data can also be saved for future reviewing and training.

During 2019, Fortum started a project to create a digital twin pilot for spent fuel lift training. The purpose of the pilot was to test if a realistic simulator of future spent fuel lifts could be used to improve the training of lift operators and to prepare for the future spent fuel lifts. This project was expanded for 2020 to create a heavy lift simulator for advanced training on the lifting of heavy reactor parts.

4 VIRTUAL REALITY IN NUCLEAR INDUSTRY

Virtual reality has been researched by several major companies and institutions in the nuclear industry since the 1990’s and recently the decrease in prices has allowed even mid-sized and smaller companies to develop VR-capabilities. One of the earliest examples is in 1996, when Institute for Energy technology (IFE) modeled and installed a VR laboratory for Oskarhamn nuclear power plant. It was a relatively simple VR pilot with a single stereoscopic projection screen.

In 1997, IFE formed Halden Virtual Reality Centre (HVRC) in Norway. HVRC researched ways to use virtual reality for control room engineering and Halden Reactor design. They have also worked with Leningrad NPP since 1999 and in 2003 provided them with virtual reality refueling machine for training Russian reactor operators as shown in Figure 4.1. (Skjerve & Bye 2010)

Figure 4.1. VR model of a LNPP refueling machine

In France EDF (Électricité de France) along with Framatome and CEA (Alternative Energies and Atomic Energy Commission) have developed CAD models that use 360° photos and laser scans to create maintenance tools that help improve outage preparation and pre-job briefing. These tools have been used to measure clearances or read component tags from distance. Machine learning tools have been used to map component tags automatically to help users find them in cramped conditions. This combination of 360° photos and laser scans can be visited using virtual reality devices to provide an immersive experience. (Morilhat 2018)

Model of a containment building used by EDF that can be viewed using virtual reality is shown in figure 4.2.

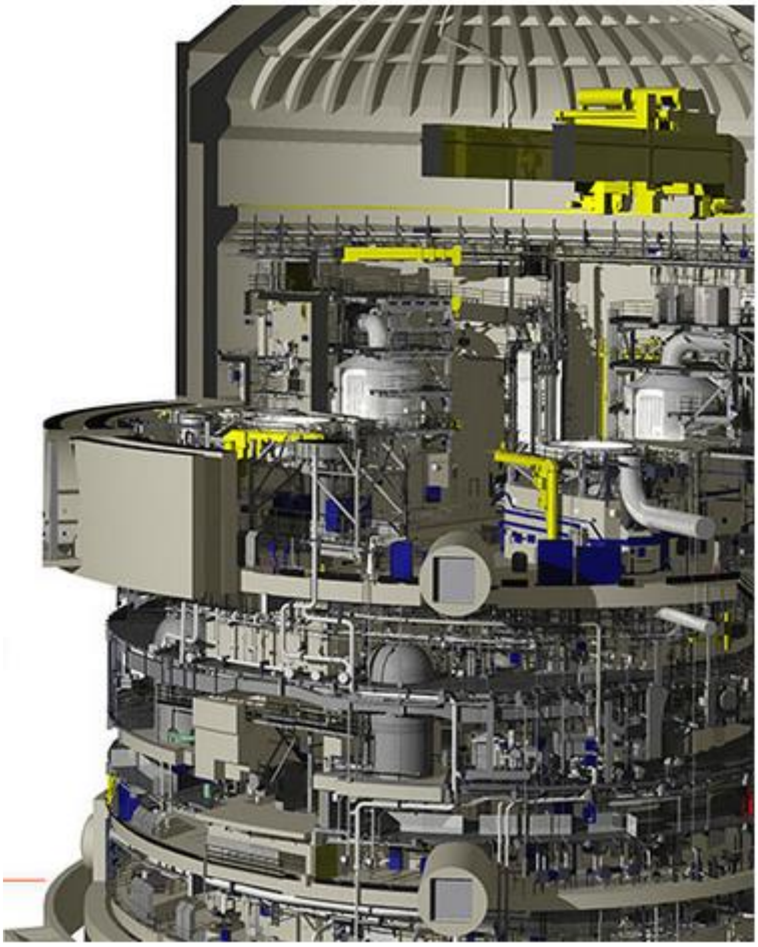

Figure 4.2 Model of the containment building used by EDF

ITER (International Thermonuclear Experimental Reactor) is a project to build a working nuclear fusion reactor in France. To help with integration and maintenance of different components, CEA has built a virtual reality platform. CEA VR platform has been in use since 2010 and has proven to provide results in the efficiency of integration and maintenance of components. The platform has been fitted to a single room where over dozen person can visit at the same time. It has a giant stereoscopic screen that provides a 3D effect when visitors wear 3D-glasses. Force feedback for controls and head tracking is used to create an immersive environment. (Keller et al. 2018)

CEA VR platform is also applied for accessibility testing. The platform has collision detection so that it is possible to verify that assembly clearances and functional gaps are built large enough for access. This is a more advanced way of verifying accessibility than automated CAD clash detection checks as the movement of users inside the VR-model is more natural. Collision coordinates in CEA VR are recorded and checked so that potential problems can be identified and solved. (Keller et al. 2018)

ITER worksite development has been tracked in virtual reality since 2016. Since the start of the project CAD models have been built out of every building and component which has enabled transferring those to virtual reality and providing the public a way to see how the construction process of the power plant is progressing. The site images and models are updated every three months. (Keller et al. 2018)

4.1 Applications of virtual reality in nuclear industry

Virtual reality technology is versatile enough to be of use in every aspect of nuclear power plant work. The technology can be used to either augment current methods of working or even try to completely replace them with a virtual application. One of the largest obstacles for the widespread adoption is the identification of use cases where the use of virtual reality creates most added value compared to traditional methods of working. This chapter lists some of the emerging or proven applications for virtual reality in the nuclear industry.

4.1.1 Personnel training

Current training methods for emergency situations, such as control room accident situations, require expensive modeling of real environments (mock-ups). While these mock-ups can accurately simulate real conditions, they can be quite expensive to build and disruptive to operate. Also, some risky training scenarios cannot be recreated in a meaningful way as the chances for potential accidents are too great. For example: contamination, fire and chemical accident training are often impossible to conduct safely and thus must be abstracted.

The advantage of using virtual reality for this kind of training is that there exists no realistic risk for the trainee, thus this type of training is by default safer than training in a non-virtual space. Users virtual avatar can be exposed to a simulated danger to create a more realistic situation, without risk of consequences for person in question. These scenarios are often relatively cheap to create and easy to scale as objects can be manipulated virtually to create different scenarios. (Mól et al. 2008, p 382-386)

4.1.2 Dose measurements

Virtual reality has some useful applications in the field of radiation measurements. Data from radiation monitors can be transferred into a virtual reality application which can then be used to model semi-realistic radiation conditions inside the NPP. Users can move in the virtual space and the radiation dose they receive can be tracked and reported. These results can then be used to provide training and feedback concerning the user's movement in radiation-controlled areas. These simulations can be also used to familiarize trainees to plant hazards and environments before any real work is done. Trainees can also see their dose rates and try to develop different strategies to minimize their accumulated dose.

One example of this kind of simulation has been done by Brazilian Laboratório de Realidade Virtual which has completely modeled their Argonauta research reactor using Unreal Engine (UE). Game engines such as UE provide enough accuracy for gravity and collision physics and their partially open code enables flexibility for the end-user to customize the game engine to fit their needs. Data provided by the radiation monitors is collected and fed to the Unreal Engine providing a real time dose rate for personnel running the simulation. In case a more accurate data is required, more radiation monitors can be added to the network. This kind of system is possible to replicate in any NPP with radiation monitors which can provide passive data over network. (Mól et al. 2008 382-386)

4.1.3 Nuclear decommissioning

Virtual reality can be used to minimize time and cost while maximizing the safety of nuclear power plant decommissioning. The dominating feature of NPP decommissioning is radioactive components, which largely affects the overall cost, risk, safety measurements and timetable of the project. Thus, planning for NPP decommissioning must start with gathering data about radioactivity of the plant and its components. This requires extensive sampling and measurement. Once the data has been gathered a realistic virtual reality model of the site can be designed and merged with the data. Also, existing design documents, reports and assessments done since construction of the NPP site can be used to perfect the model. Since this can amount to thousands of pages of information, data control and customization of data visualization is paramount for a successful application. The result allows for fast identification of contamination on a component and exact data associated with it and where the decommissioned part is supposed to be delivered and at what order they are supposed to be decommissioned.

VR also provides easier planning and changing of schedules should there be unforeseen obstacles with decommissioning. Hazardous operations can be planned and documented beforehand, and site personnel can closely work with decommissioning planning department to provide instant feedback for the decommissioning plan. During the decommissioning phase the site is operationally unstable as biological, chemical, and radiological defenses are torn down and temporary safety structures and safe zones must be built. Virtual reality provides a cheap way to test different safety configurations and to document potential problems for use in other NPP decommissioning sites.

Virtual reality simulation can be used to select the best field team for the decommissioning of the NPP based on their performance. For performance testing to be meaningful, tested team must be accurately briefed about the decommissioning work phase. At least minimum understanding of tasks, risks, safety, and some operational practice must be provided. All testees should be able to demonstrate knowledge and deep understanding of the work they are about to begin before doing the task in virtual reality. Tests should also include emergency situations should be included so that it is guaranteed the workers are able to handle situation in the field. If the decommissioning control room has virtual reality equipment, real time guidance can be provided with an audio link to the testees. This guarantees that if there is some unforeseen obstacle or unexpected situation, decommissioning personnel have instructions from control room operator who can look at the environment with his own eyes and decide the best course of action.

Once the given task has been completed, training instructors can provide feedback using virtual reality by repeating the task there and showing exactly what went right and what went wrong. This feedback can then be used to further improve the existing modeling and training of new team of workers in future tasks and future decommissioning sites. If the decommissioning personnel are tracked with a satellite tracking tool, the data can be included in virtual reality and compared with planned results and schedule. This data can also include other topics such as site weather and temperature at the site. Same work can be virtually done by a different team with no or little training and results can be compared and quantified for comparative analysis and qualitative feedback provided. (Szoke et al. 2008)

Loviisa NPP has examined the potential of applying VR for decommissioning work. Loviisa NPP has a cave for Low and intermediate nuclear waste and this cave has been laser scanned using a NavVis measurement device shown in Figure 4.3. This scan has resulted in a 3D-map of the cave which has been converted to a VR-capable format. Decommission engineers can visit the site and navigate it as they wish from a remote location. If the model is updated during future decommissioning, a real time progress of filling of the nuclear waste cave can be seen from virtual reality.

Figure 4.3. NavVis measurement device.

4.1.4 Virtual reality in NPP physical safety

Virtual reality simulations could help to improve physical safety in nuclear power plant if the models used are accurate representations of the actual physical environment. Facility's building dimensions, as well as site area must be mapped along with all the bigger objects including natural objects for the simulation to be meaningful. Users and personnel can then be represented with virtual avatars who can walk around the site with realistic speed and accurate jumping and climbing ability. With a good user interface, it is then easy to test for different security threats and scenarios quickly and with little costs. Illumination from manmade sources such as lamps and natural illumination such as sun or moon position should also be reproduced to provide more security scenarios. This also enables testing for blackout conditions where all artificial light sources will be removed Additional features can also be integrated such as day and night -cycles and natural weather phenomena such as rain and snow. (Silva et al. 2015, p. 19-23)

Virtual camera systems can simulate real camera behavior and the camera location can be easily moved inside the VR simulation. This allows testing and optimization of camera system locations. Camera systems can also be tested for multiple trespassers from several directions and locations. All the cameras outputs can be put into a single control room and realistic observation behavior of security personnel can then be observed.

If data is gathered about routes used and time spent to reach destinations inside the NPP site, they can be integrated to the virtual reality model. Avatar's walking and running speed can be iterated to match walking and running speed of a real person. This provides valuable data for evacuation and first response planning and for patrol route optimization. (Silva et al. 2015, p. 19-23)

4.1.5 Gaze tracking

Virtual reality offers a novel way to track the direction and duration of user's gaze inside a virtual reality simulation. This can be used to correct flaws in manuals, forms, and documentation by asking the user to read in VR and tracking the users gaze. This allows the observer to see if the user behavior is as expected and to correct potential flaws in the design. There exists a possibility to also create 'heat maps' of the users gaze to help in this task. The tracking of user's gaze in virtual reality scenarios can also be logged automatically as user participates in the use of VR-device. The movement path of the gaze can be logged and replayed to the trainer or user and they can see where the gaze was at each point of the simulation. (Wang et al. 2019, p. 1-5)

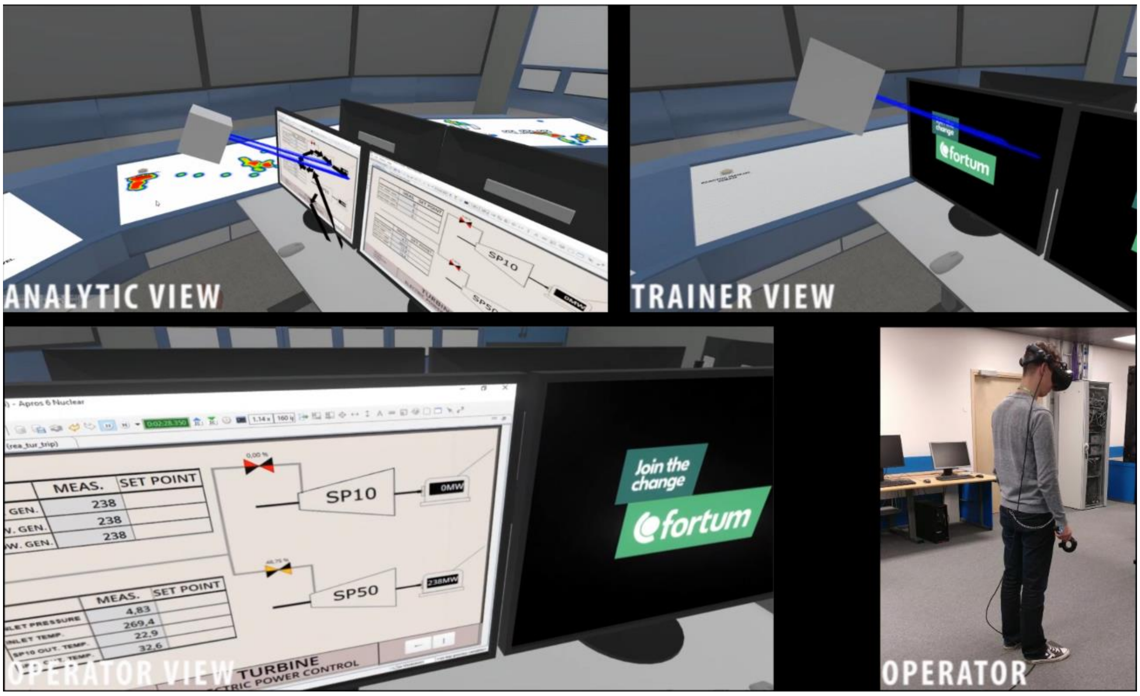

Figure 4.5. Gaze analytics demo (Fortum 2017)

4.1.6 **Validation**

Virtual designs and construction can be used to create computer-based descriptions of a project that can be used to validate the correctness of a physical model. There are three phases for extensive validation of a model in VR. At first a functionally correct 3D model of the product is created, and it is optimized by with the help of members of the organization which uses the product using performance metrics and predictions of the model behavior. Then a data-exchange is set up between model and analytics software so that data can be received and analyzed so that the 3D model correctly predicts behavior. Using industry standards is essential for easy data transfer. Finally, project methods are automated to increase the validation speed and efficiency pending model changes. (Kunz & Fischer 2009, p. 1-6)

Virtual reality improves this validation process by increasing the number of tested variables that can be validated inside the model. Some methods such as visual inspection of the real size model and practicing real life operations with it are only possible through virtual reality devices. This allows the designers to change the design following feedback from simulated real usage even before the construction of the physical model has begun.

Fortum has done validation testing for control room VR setup starting from 2016 to gain experience for this process to be adapted company wide. The validation pilot has been limited to control room personnel and field operators for the time being but once VR is more widely adopted and more 3D-models and VR-simulators the validation work will also expand. Fortum KESI and VR control room are shown in figure 4.6. (Olkkonen & Hurmerinta 2018)

Figure 4.6 KESI **and** NPP control room simulator inside VR (Olkkonen & Hurmerinta 2018)

5 UTILIZATION OF VIRTUAL REALITY IN LOVIISA NPP

The utilization of virtual reality in Loviisa nuclear power plant builds upon previous VR R&D projects by Fortum. These projects showed that virtual reality is a viable tool to use in nuclear power plants. Building upon knowledge gained from these previous projects, three small-scale projects were planned for this thesis:

1. Personnel training tools which allowed workers to train several different scenarios in the VR-environment.
2. Virtual model of the new chemical building which enabled personnel to visit and familiarize themselves in a building that is under construction.
3. Steam generator room simulation which lets new employees navigate and spot radiation hot spots in a cramped room that is normally inaccessible during operation.

Projects one and two were completed while the steam generation room simulator was postponed for a possible future date.

Loviisa nuclear power plant has a dedicated virtual reality -room which was finished in February 2019. Using primarily Oculus Rift and Varjo VR-1 -glasses, this cost-effective setup is suitable for small-scale training. It also allows fast testing and development of simple VR scenarios. All VR development for this thesis was done in Loviisa virtual reality training room.

5.1 Previous VR development by Fortum

Fortum started research into VR in January 2015 when funding was approved to research potential applications for industrial use. In February 2015, Oculus Rift Developer Kit 2 was rented and a tested with a static control room demo. During March 2015, VR-development of the control room pilot project began. Loviisa VR control room is show in in figure 5.1 Control room was chosen for the pilot because it had already been modeled in previous projects and existing 3D-model assets could be recycled. For the first year and a half, the development was done in collaboration with external developers. This period of external development also saw the Loviisa Polar crane cockpit virtual reality pilot which allowed Fortum to assess the viability of virtual reality in training crane operators. (Bergroth 2019)

Figure 5.1. VR control room training (Fortum 2018)

After both pilots were successfully completed, it became apparent that using external developers was not enough to satisfy the growing needs of the VR project and Fortum decided to commit to virtual reality by hiring a VR developer. This coincided with the release of Oculus Rift Customer Version 1, which started the current virtual reality revolution by providing inexpensive hardware and easy integration to existing game engines. The ability to develop applications internally gave Fortum's VR program a tremendous a boost and success quickly followed. November 2017 saw the validation of Loviisa virtual reality control room with plant personnel and June 2018 the full integration of APROS process simulation software to virtual reality. These were done alongside other numerous customer projects and consultation requests. (Bergroth 2019)

During 2018 Fortum decided that additional resources would be needed for Loviisa nuclear power plant virtual reality development as constant travelling between Loviisa NPP and Keilalahti headquarters was not a good use of limited developer time. Thus, a decision was made to acquire a virtual reality developer by commissioning a VR-focused master’s thesis. The initial goal of the thesis was to focus on aiding Loviisa NPP and laying the groundwork for further development. (Hurmerinta 2018)

5.2 Overview of software used in Loviisa VR -development

Developing virtual reality scenarios requires the use of dedicated software suitable for that purpose. More complex models require the use of more software and most programs have licensing fees which increase the development cost. For small-scale development four types of programs are needed:

1. 3D-modeling program which is used to create objects and environment used in virtual reality.
2. Integrated Development Environment (IDE) program that provides a platform to write code using a programming language. This code provides interactivity between objects, environment, and the user in virtual reality.
3. Game engine program where different 3D-models and code snippets can be integrated to create a virtual reality program.
4. Program that acts as a link and translates data between VR program and VR hardware used.

Primarily five programs were used for VR development during the writing of this thesis.

5.2.1 Oculus

Oculus is a companion app for Oculus Rift that provides vital features for configuring and using Oculus Rift hardware. It transfers information between the hardware and software, providing a framework that other software can access. Oculus also tracks the status and connection between Oculus Rift hardware and the computer so the user can view device status and health. Oculus sensor location and user height are stored in the Oculus app and must be set again if the location of the device or height of the user significantly changes. User can use Oculus to set guardian boundaries around the intended use area that manifest as a blue wireframe in virtual reality if the user approaches edges of the guardian boundary. The placement of guardian boundaries is highly customizable which allows the technology to be used in a wide variety of room sizes. At the time of writing there is no way to configure multiple Oculus Rifts to use the same account and the configuration must be done manually every time account or hardware is changed. (Oculus 2019)

5.2.2 Unity

Unity is a game engine and a real-time creation platform that developers can use to create runnable programs using assets and C# programming language. Unity editor provides a 3D-space where different models and code snippets can be added, and their properties changed. Unity editor provides many features that are useful in VR-development such as a rudimentary physics engine, graphics shaders and audio manager.

Assets and code that utilizes the game engine can be directly imported to Unity or purchased from the Unity Asset Store. Most 3D file formats are supported which allows easy importation of 3D-models from multiple CAD-tools to the editor. There exists integration support for Oculus Rift. The Unity version used in this thesis is 2018.2.19f1. (Unity 2019)

5.2.3 Visual Studio

Visual studio is one of the most popular integrated development environments in the world. It provides built-in support for C# code editing with intelligent code completion features. Most of the developers use standard code editor and debugger it provides, but Visual Studio also has compilers, graphical designers, and code completion tools to help programmers achieve increased productivity. (Microsoft 2019)

5.2.4 Blender

Blender is an open source 3D-graphics software which has been in development since 1998. The software and has recently transformed from a community project into a commercially viable 3D-modeling software. In this master’s thesis the release version 2.79b was used. Nearly all the 3D-models used in VR personnel training have been hand-made with the software. Unity has native support for Blender 3D-models allowing easy importation of models straight from Blender. (Blender 2019)

5.2.5 Bentley MicroStation v8i

Bentley MicroStation V8i is a powerful CAD software capable of designing realistic 3D-models of plant components. It provides advanced parametric 3D modeling capabilities; sis data driven and allows easy communication with other software. Bentley MicroStation is a popular inside Fortum for modeling work and most of the previous modeling work done by Fortum has used Bentley MicroStation such as 3D assets for the new Loviisa chemical building. (Bentley 2019)

5.3 Personnel training tools

Using virtual reality devices for the first time can be intimidating for plant personnel. A fraction of employees will always be fearful or resistant to using new technologies and even the enthusiastic might be frustrated with the lack of skill when trying new things for the first time. To combat these issues, proper training tools must be provided to teach necessary basic VR skills before more complex scenarios can be used.

For this thesis, three proof of concept personnel training tools were created for Fortum Loviisa NPP to introduce basic VR skills to personnel and to gather feedback and ideas for further development. These training scenarios were designed to mimic real problems that personnel might encounter while working in a nuclear power plant. Because of the experimental nature of these training tools and limited future usage, the scenarios were not designed with exact models of plant processes and equipment. Once plant personnel and organizations become familiar with VR-tools and their potential, more complex and realistic training scenarios will be developed.

5.3.1 Fire safety evacuation -training tool

Fire hazards are a serious safety risk that concerns all Loviisa NPP personnel. All the employees working at Loviisa NPP must periodically go through mandatory fire safety training. For this reason, it is practical to tailor a VR fire safety learning scenario for absolute beginners, as all personnel should already be familiar with the correct procedures. Movement inside virtual reality will be challenging for beginners so a familiar location should be used for first timers. In this scenario, all movement were done inside virtually simulated training building, which all employees recognize and know the layout of. First, they spent some time moving inside the training building to learn how movement and controls in the virtual space work. After a short period, a fire was lit in a random location inside the training building by the training instructor. The fire slowly spread around the building, destroying furniture and equipment as it progressed. When the user noticed the fire, either through happenstance or by hearing the fire alarm, they had several options on how to proceed. They could either try to extinguish the fire, by finding a nearby fire extinguisher or evacuate the building using designated emergency exit routes. If the user was slow to evacuate or failed to extinguish the fire, an evacuation alarm sounded informing the user that they must leave the building. The scenario ended once the user succeeded at extinguishing the fire, successfully evacuated, or failed to evacuate and was set on fire.

5.3.2 Valve operation training tool

Operating in virtual space efficiently requires the skill to manipulate virtual objects using one's hands. First time users often have problems with hand-eye coordination using controllers so any comprehensive training must address that. The purpose of this exercise was for the user to acquire these basic skills and to rehearse Fortum's human performance (HuP) methods. This training was done in pairs where one person was using VR glasses and other was verifying that the current task was being done. The person who wore the VR glasses took the role of a field operator. The second person represented a control room operator. First, the field operator spotted a pipe leaking liquid to a pool and a room full of valves. Second, the field operator communicated to the control room operator, which pipe is leaking to receive instructions on what valve to open or close manually. Valves were marked using obfuscated but realistic identification tags. There were both Loviisa 1 and Loviisa 2 valves with the same or similar tags mixed in the same space, so the field operator had to be careful not to turn a valve for the wrong plant. In case the field operator mistakenly turned the wrong valve, an evacuation alarm was sounded, and the exercise was ended as a failure. If the valves were successfully turned in the indicated order, the leak stopped, and the liquid drained from the pool. After draining, some puddles were left from the drainage of liquid and the operator given a possibility to use a nearby floor squeegee to remove them. In case the field operator decided to wipe the puddles, the training instructor reminded the operator that the floor might be contaminated and asked which actions were appropriate for the situation.

5.3.3 Tank container inspection - confined space training tool

One of the fundamental advantages of virtual reality compared to traditional video is the ability to perceive the environment around you by turning one’s head in the virtual simulation. Users who are used to watching static videos or playing games might not be familiar with the concept and it must be demonstrated in basic training. This exercise was done in pairs and required the user to inspect a tank container using a flashlight, while being careful not to fall inside it. The user had to first inspect the container’s work permit to assess if they could enter the confined space. User’s pair were given paper instructions on how to correctly check the container permit and they had to relay this information to the user. The room was poorly lit, so they had to pick up the nearby flashlight for improved reading visibility. If the permit were valid, the user could enter the tank container from a nearby hatch. If the permit was invalid and the user enters, an oxygen detector made noise indicating lack of oxygen in the container tank and the simulator was stopped. Upon valid permit, the user had to look for mechanical cracks with the flashlight in a tight space while being careful not to fall to the bottom of the tank container. Upon successful visual inspection, the user was also required to safely leave the tank container and notify the pair about the size and shape of the mechanical damage of the container. The limited image resolution of Oculus Rift VR glasses required the text on the paper to be unrealistically large to ensure proper readability. Testing using superior Varjo VR-1 glasses showed that improving the resolution fixes this problem.

5.4 Chemical building VR-simulator

Loviisa NPP chemical storage system was designed in a time when different, less strict, regulations were used. As such, there exists a need to upgrade the system to meet current requirements should the permit holders wish to operate Loviisa NPP in the future. During 2019, construction of a new building to store selected chemicals was started. To aid in the planning of the building project, 3D models used in designing the building were transferred to Unity engine to provide the possibility to experience the building in virtual reality. There were several identified benefits for completing this simulator. It allowed plant personnel to validate the new building and its equipment and request potential changes at a phase when changes are possible to make relatively cheaply, compared to last minute changes during construction. This allowed the project managed to review various problematic and un-ergonomic workflows which were discovered during this process.

6 RESULTS

One of the main goals of this thesis was to gather feedback and data from power plant personnel to further improve the utilization of virtual reality. The numerical data used in this thesis was collected from power plant personnel training days which were conducted over the period of three months. These training days provided the plant personnel the possibility to familiarize themselves with the VR-technology and to provide immediate feedback of the experience using a touch-screen survey. The results of these surveys were then transferred to Microsoft Excel for aggregation. Compared to the large volume of users in personnel training days, chemical building simulator had a significantly smaller number of users, so only qualitative feedback was gathered.

6.1 Feedback from personnel training day

After each personnel training day session, feedback was gathered from participants through large touch screens connected to a Webropol -survey site. The feedback was given anonymously. The Finnish language questionnaire form used for feedback gathering has been included as appendix 1.

Opinions about the training and the VR-training tools were gathered and the results are shown in the table below. The responses are graded from 1 to 5 where 5 means "fully agree with the statement", 4 means "partially agree with the statement", 3 means "I don't agree or disagree with the statement" 2 means "partially disagree with the statement" and 1 means "fully disagree with the statement. The results are shown in Table 6.1.

	5	4	3	2	1	Sum	Average	Median
	146	222	24	9	1	402	4,25	4
The training made me proficient in the basics of VR	36,32 %	55,22 %	5,97 %	2,24 %	0,25 %			
	76	215	73	32	7	403	3,80	4
The resolution of VR glasses was good enough	18,86 %	53,35 %	18,11 %	7,94 %	1,74 %			
	159	182	35	21	6	403	4,16	4
VR training was a pleasant experience	39,45 %	45,16 %	8,68 %	5,21 %	1,49 %			
	132	157	88	15	11	403	3,95	4
I wish for more VR training in the future	32,75 %	38,96 %	21,84 %	3,72 %	2,73 %			
	167	181	42	9	3	402	4,24	4
I would recommend VR training to others	41,54 %	45,02 %	10,45 %	2,24 %	0,75 %			
	66	119	133	56	28	402	3,35	3
VR could be used as an assisting tool in my current job	16,42 %	29,60 %	33,08 %	13,93 %	6,97 %			
Average of all questions						403	3,96	4

Table 6.1. Results of the feedback from personnel training days

Additionally, some power plant personnel completed the training during unscheduled extra sessions for training outside the original training day program. Feedback was gathered only from personnel who participated in the scheduled personnel training day virtual reality training sessions.

38% of the training participants had some previous experience with VR glasses and these participants had easier time completing the required tasks. The number of workers having prior experience in using VR-devices was higher than expected. This can be explained as a success of previous training efforts in utilizing VR 360° videos with devices such as Oculus Go and Samsung Gear VR. Clear majority had no previous VR experience, so a lot of time had to be dedicated for learning the controls. Especially personnel who had no experience holding a controller of any kind, had to be taught by holding hands and showing what each button and stick does.

98% of the plant personnel agreed that during the training they learned basic skills necessary to use VR-devices, which shows that the training achieved set goals successfully. Only 10% of the personnel felt that the resolution of Oculus Rift VR-glasses was not accurate enough for the purposes of training. This was mostly limited to users with poor vision and big eyeglasses who had trouble reading text inside the simulations. A high number of 85% felt that the VR-training was a pleasant experience and 71% of plant personnel wished for more VR-training, with only 6% being opposed to added VR-training. This shows that there is a demand for increasing the amount of VR-training and overall enthusiasm for new training methods. Many responders felt that supporting current training methods is the most appropriate usage of VR-training. Around, 46% thinks that there is potential to use VR to assist or improve their current work which shows the untapped potential of the technology. Only 15% experienced some form of nausea during the training. This can be improved with technical solutions, as well as better VR hardware with higher resolution. First time users typically experienced more nausea than users which had used VR-glasses previously.

Training participants also gave overall grade for the training using a 4-10 grading system that is usually used in Finnish schools. In this context, 10 and 9 means “excellent”, 8 means very good, 7 means “good”, 6 means “satisfactory”, 5 mean “sufficient” and 4 means “failed”. Overall grade from training is shown below in figure 6.1

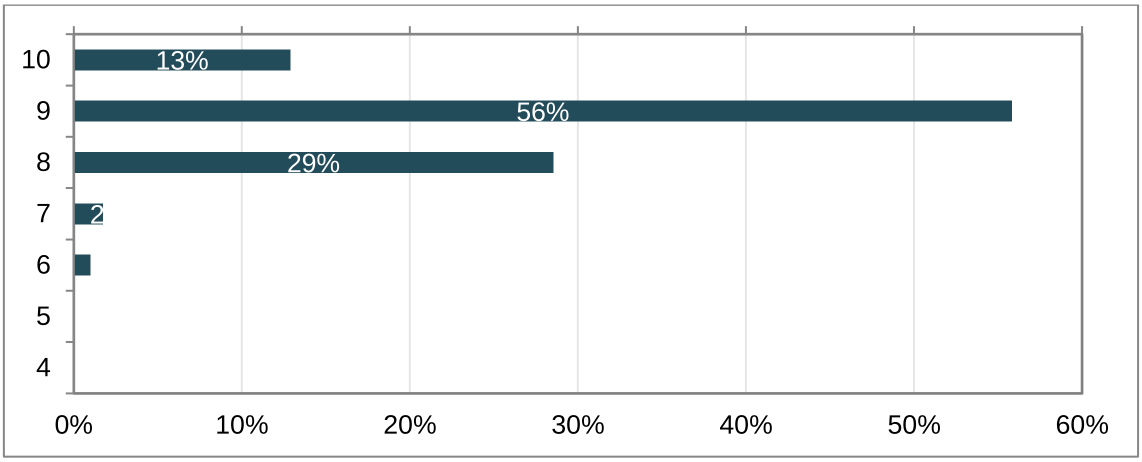

Figure 6.1 Overall training grade.

Overall grade was excellent, especially considering the time available and resources spent for the creation of the training tools. While overall grades from previous training were unavailable, training participants clearly showed enthusiasm about the increasingly physical nature of training compared to the traditional classroom -style lecturing. Laughter, excitement, and amazement where observed in all sessions.

Out of the three training scenarios, valve operation training tool received most approval with 68%, followed by fire evacuation 17% and container was least preferred with 14%. This was not surprising, as valve operation training tool was the longest scenario and most demanding for the user. Tank container inspection most likely suffered from low-light reading requirements, which proved especially hard for users with below average eyesight.

All the training scenarios additionally provided non-quantifiable information about plant personnel’s overall habits and many claimed that the training showed them the value of stopping and thinking before acting. A positive observation report for VR-training was submitted to NPP observation database by the plant management. The observation praised the HuP aspects of the training and the ability to further develop simulations to improve power plant safety. Additionally, Loviisa VR-training was submitted to Fortum's internal safety awards, which it won “for using Virtual Reality in safety training which demonstrates innovativeness and provides a totally new platform to practice situations that in real life are not possible or too dangerous to train. This solution can be distributed to other Fortum sites or sold to external clients through Fortum's new Virtual Reality start-up called e-Site. Loviisa also demonstrates a robust safety culture: during the 2018 outage over 400,000 contractor hours were worked without accidents."

6.2 Feedback from chemical building VR-simulator

Feedback from the new chemical building was gathered qualitatively by discussing with the project manager and other personnel involved in the construction and the future use of the chemical building. Personnel tested the simulator and then made comments and provided feedback. These comments were largely positive with users finding it useful to visit the building before it was finished and finding answers to some of the questions they had about the placement of machines and the architecture used. Once the building is complete, another round of evaluation will be done, and a 360°-introduction video is planned to help building operators familiarize themselves with the building and its machinery.

6.3 Future applications of virtual reality in Loviisa NPP

Fortum spends millions of euros for R&D expenditure every year. Some of these funds are allocated for research in Loviisa NPP to improve the future operation of the power plant and to conduct research that cannot be performed outside nuclear power plants.

This thesis has already provided multiple new ideas and possibilities for future research. Typical Fortum research path starts with basic research of the subject and finishes with the commercialization of the technology. Funding from R&D budget is typically applied for yearly.

6.3.1 Steam generator room VR -simulator

The steam generator room is a large room in Loviisa NPP reactor building, that houses all the six steam generators for the plant unit. The room is full of pipes and equipment and as such has limited space for movement and work. It is inaccessible during regular nuclear power plant operation, due to high heat and high radiation levels, which makes the ability to visit it virtually at any time valuable. Some use cases for virtual simulation of the steam generator room are training the users to successfully navigate there and optimizing workflows for outage time during operation before it is possible to visually inspect the room. Radiation data for steam generator room has been gathered over the years and it can be attached to all the important components inside the room, providing the possibility to have a semi-realistic dosimeter inside the VR-simulation.

The original plan was to have this project finished before the outage of 2019 and used to support the training of radiation protection personnel. Development of the VR-simulator was started, however before completion, it was decided that development time would be more beneficially utilized on the development of LoLayout tool, a visualization and navigation tool that shows 360° pictures and videos from all around the steam generator room. This tool was accessible from a 40-inch touch screen display, which was placed directly outside the steam generator room. A value case for the Steam generator room VR-simulator still exists, especially if advanced training is to be conducted for steam generator work.

6.3.2 Virtual Reality Simulator Development and Evaluation (VIRSE)

Virtual Reality Simulator Development and Evaluation -project was started during 2019 to further develop Loviisa main control room (CR) virtual reality simulator. The aim of the project was to turn the previously created successful simulator demo into a product that can be used in regular training for Loviisa nuclear power plant. This also opened a possibility of selling the simulator to other companies in the nuclear industry. The development of the simulator had a strong connection to SAFIR2022 BORS research project, which aimed to maintain and develop knowledge about control room usage. Some of the planned simulated control room error and accident tests were planned to run in VIRSE simulator. (Hämäläinen & Suolanen 2019, p. 8-9)

Control room VR simulator development is useful because they can be used to validate the room design before building a physical simulator, which brings significant cost and time savings. Having hundreds of panels, monitors and computers in a single room typically creates unanticipated problems. Major hurdles can be found out based of the results of virtual reality control room and pre-fixed before or during construction of the physical simulator. Fortum already has built two control room simulators for Loviisa nuclear power plant, Loviisa Koulutus Simulaattori 1 and 2 (LOKS 1 and LOKS 2) so some of the benefits of virtual reality control room are negated. Still, it can be used to test some of the scenarios that are harder to run in the real world, such as fire in the control room. VR CR also provides the opportunity to do design and planning work while the physical simulators are in use.

Varjo VR-1 glasses were selected for the hardware used in the VIRSE-project. It provides significantly better resolution than Oculus Rift or HTC Vive allowing greater fidelity of graphics. Having as good graphics as possible is important because it allows operators to immerse themselves on the situation at hand and helps when reading instructions, button labels and readings on virtual monitors. VR-1 also allows gaze and eye tracking and the associated analytics to monitor how operators use their eyes during the training. (WNN 2019)

6.3.3 Heavy Lift Simulator

According to the Probabilistic Risk Assessment (PRA) models created to assess the risks of Loviisa NPP operation, heavy lifts have the highest risk of severe accident out of any single operation. To combat this risk of accident, heavy lift operators must be thoroughly trained and experienced professionals. Accumulating enough practical experience from heavy lifts is problematic as heavy lift operations are done only a couple of times in a year. This affects especially newer operators as it delays the accumulation of experience from heavy lifts. Virtual reality can alleviate this problem by providing extra opportunities to practice heavy lift operations and create scenarios that cannot easily be trained in real life such as lift malfunction.

To be useful as a training tool, VR heavy lift simulator must be precise, which makes building the simulator harder than most other training tools, where some inaccuracies can be tolerated. Discussion and testing with experienced crane operators and PRA engineers are required for a project to succeed as inaccurate training can create extra risks for the heavy lift operations.

Building 3D-models of objects lifted during heavy lifts is not difficult but calculating the realistic physics of lifted objects and the lift is challenging. While it is technically possible to build a physics engine with the specifications of the heavy lift and lifted objects, previous experience from lift simulation project shows that the accuracy is not good enough for serious training use. Physical measurements and properties must be used for the simulation to accurately mimic physical operation.

Before the outage of 2019, the decision to measure the heavy lifting process was made. Especially the amount of swaying of the lifted objects was of great interest for decision makers. Finding the right way of measurement proved to be non-trivial. At first, laser-based measurement of movement was researched, but this proved too capital and manpower intensive for this project. Second solution was a measurement device attached to the lifted object, yet suitable measurement device was not found and getting permits to use such a device during heavy lifts would have delayed the project. Finally, stereophotogrammetry was selected as the technique used to measure heavy lifts as it provided a way to measure the heavy lifting effectively and accurately, without interfering with the lifted object.

Stereophotogrammetry means the measurement of movement in three dimensions using two cameras taking pictures synchronously of the object. Since the distance between cameras, time between each picture shot and the specifications of the lifted objects are known, the 3D-coordinates can be calculated from the change of object position in the pictures. Figure 6.2 clarifies the technique.

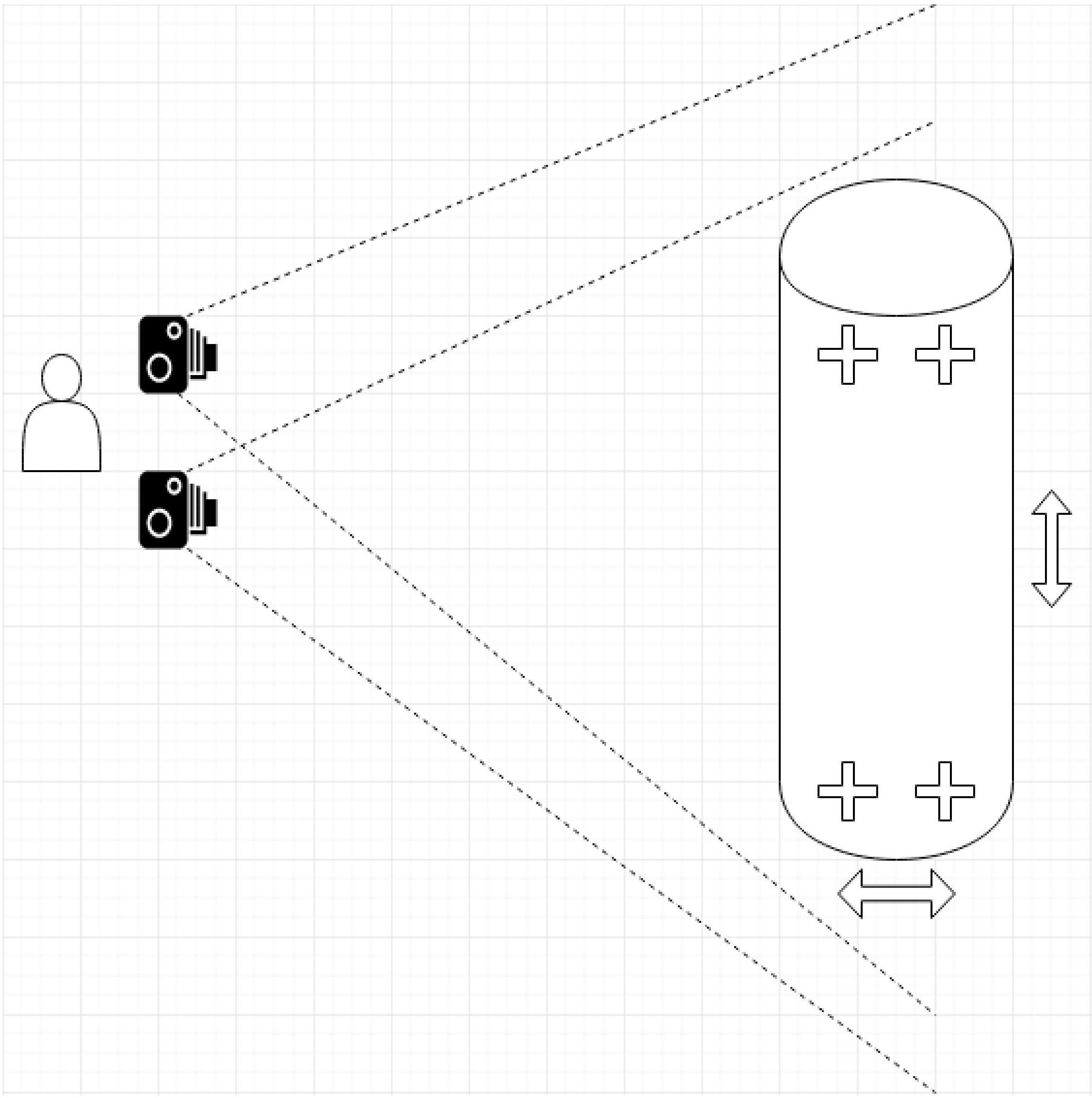

Figure 6.2. Measuring movement with stereophotogrammetry

To help with the object movement measurement, several markers were attached to the lifted object. At first reflective stickers were planned for the project, but gaining the chemical specifications required for approval proved hard as providers did not or were unwilling to supply the data of the material and glue used. In the end it was settled that crosses out of pre-approved PC 624 Premium Nuclear Grade Cloth Duct Tape (also known as yellow tape) were used as a marker.

Since there are thousands of pictures taken from the lifted object, an algorithm was required to analyze the movement and provide the required data in an easily understandable format. This algorithm was commissioned from a third-party developer, who built it using MATLAB computing environment. The algorithm detects yellow tape crosses from the pictures and provides pixel accuracy of the movement of the object. The results from this initial project will be used in the future when VR heavy lift simulator will truly begin.

7 CONCLUSIONS

The purpose of this master's thesis was to examine emerging virtual reality technology in the nuclear power plant industry and to find the best ways to utilize it at Loviisa nuclear power plant in the future. The first four chapters of this thesis provided the necessary background to understand the context of this thesis, while the fifth and the sixth focused on work accomplished during this thesis and tried to provide clarity on the proper utilization of virtual reality at Loviisa nuclear power plant.

To this thesis, several training scenarios were developed and tested with power plant personnel. To keep the scope of this thesis manageable the training scenarios were quick to build and small in scale. This was compensated by using a large amount of personnel to test the scenarios and thus gathering a large amount of data from the participants. Over four hundred out of five hundred of the nuclear power plant personnel participated in this virtual reality training so the results can be assumed to be representative of the overall opinion in the nuclear powerplant. Due to the large amount of personnel working in Loviisa NPP, this was likely the most extensive virtual reality study ran in Finland so far measured by the number of active participants.

The results show that virtual reality has a bright future at Loviisa NPP and there is a case for further use virtual reality as the technology matures and it becomes more commonplace. VR has already shown that it can provide cost-savings compared to traditional training methods as it provides an easily scalable and flexible solution for different training needs.

The results of the work done during this thesis have been used as a justification for further development and research of virtual reality technology inside Fortum, which shows that the information gained has been valuable and the thesis has been a success. More results will be gathered in the future as more complex and complete scenarios are developed. While Loviisa NPP is a great environment to conduct large-scale VR tests, further studies can also be done with less personnel using statistical techniques that provide statistically significant results from smaller samples.

Many companies in the nuclear industry have recently launched virtual reality projects of various sizes. At this point, it is not clear which single virtual reality application provides the most value for nuclear power plants or what will be the future scale of VR utilization in the nuclear industry. Most of the current applications are focused on training of power plant personnel, but the unique benefits that virtual reality provides can be easily applied to other aspects of nuclear power plant work. Modeling processes and plant equipment such as heavy lifts and control room in virtual reality can bring significant safety benefits if the work is done with piety. Validation and planning with virtual reality can lower the costs of operating nuclear power plant if the tools are used correctly. As virtual reality is a currently bleeding edge technology, the potential for further research on the subject is tremendous. The utilization of virtual reality in nuclear power plants has only begun.

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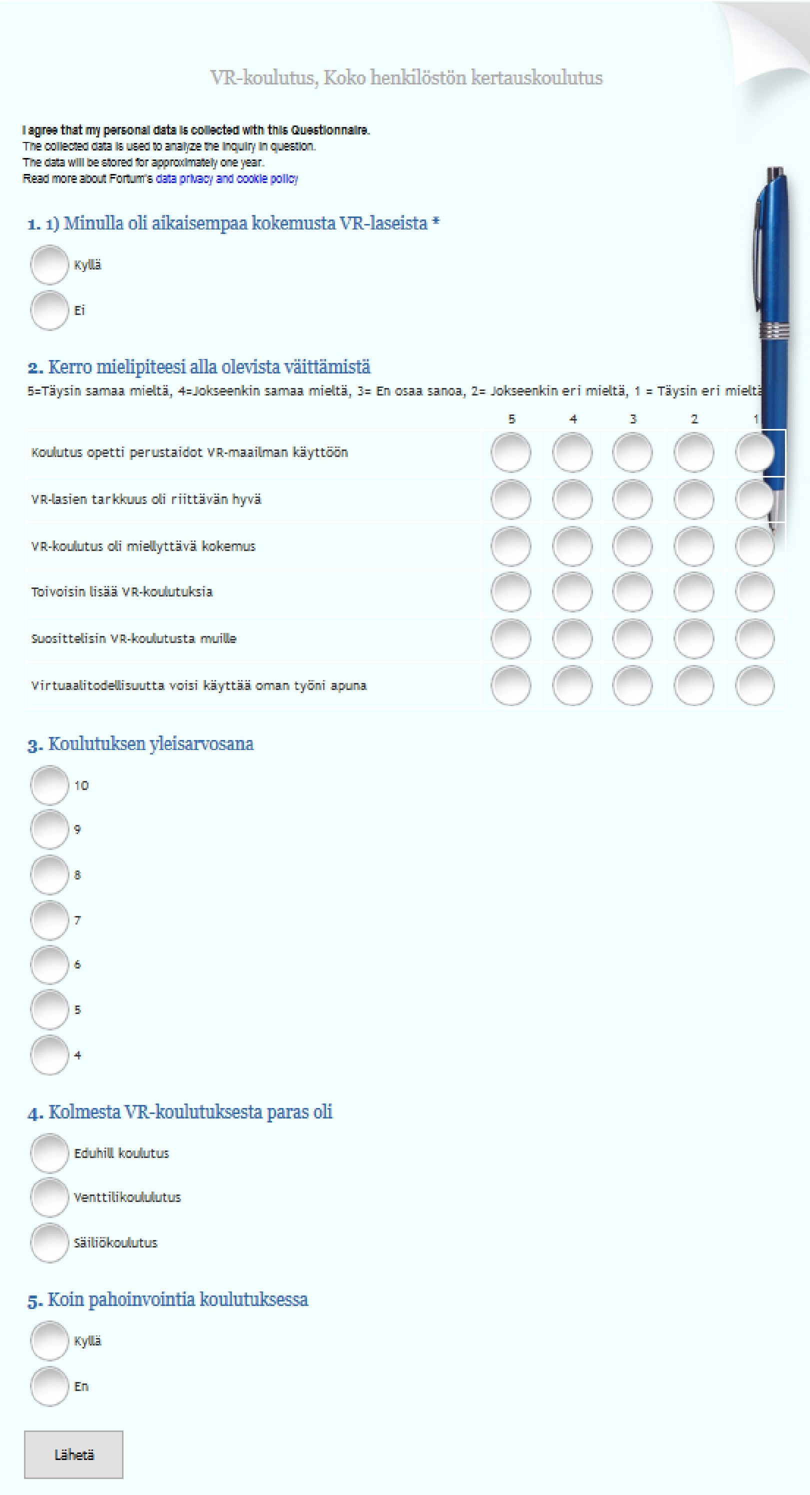
APPENDIX 1. PERSONNEL TRAINING SURVEY DOCUMENT



VR-koulutus, Koko henkilöstön kertauskoulutus

I agree that my personal data is collected with this Questionnaire.
The collected data is used to analyze the inquiry in question.
The data will be stored for approximately one year.
Read more about Fortum's data privacy and cookie policy

1. 1) Minulla oli aikaisempaa kokemusta VR-laseista *

- Kyllä
- Ei

2. Kerro mielipiteesi alla olevista väittämistä

5=Täysin samaa mieltä, 4=Jokseenkin samaa mieltä, 3= En osaa sanoa, 2= Jokseenkin eri mieltä, 1 = Täysin eri mieltä

	5	4	3	2	1
Koulutus opetti perustaidot VR-maailman käyttöön					
VR-lasien tarkkuus oli riittävän hyvä					
VR-koulutus oli miellyttävä kokemus					
Toivoisin lisää VR-koulutuksia					
Suosittelisin VR-koulutusta muille					
Virtuaalitodellisuutta voisi käyttää oman työni apuna					

3. Koulutuksen yleisarvosana

- 10
- 9
- 8
- 7
- 6
- 5
- 4

4. Kolmesta VR-koulutuksesta paras oli

- Eduhill koulutus
- Venttilikoululutus
- Säiliökoulutus

5. Koin pahoinvointia koulutuksessa

- Kyllä
- En

Lähetä