Pre-operative Planning in Virtual Reality with Head Mounted Displays for Oral and Maxillofacial Surgery

Filip Kajzer

August 18, 2020

RWTH Aachen University

Master Thesis

Pre-operative Planning in Virtual Reality with Head Mounted Displays for Oral and Maxillofacial Surgery

for the degree of M.Sc. in Informatik

by

Filip Kajzer
Student Id.: 380 428

Prof. Dr. Torsten W. Kuhlen
Visual Computing Institute, RWTH Aachen University

Priv.-Doz. Dr. med. Dr. med. dent. Ali Modabber, MBA
Department for Oral and Maxillofacial Surgery, University Hospital RWTH Aachen

Supervisors: Andrea Bönsch, Behrus Puladi

Date of issue: August 18, 2020

Statement

Hiermit versichere ich, dass ich die vorliegende Arbeit selbständig im Rahmen der an der RWTH Aachen üblichen Betreuung angefertigt und keine anderen als die angegebenen Quellen und Hilfsmittel benutzt habe.

I guarantee herewith that this thesis has been done independently, with support of the Virtual Reality Group at the RWTH Aachen University, and that no other than the referenced sources were used.

Aachen, August 18, 2020 ....

Abstract

Introduction: Virtual reality technology is first depicted in the scientific literature as early as XXX. The upcoming of head-mounted devices is described since the early 1960s. With the emergence of consumer HMDs such as the Oculus Rift in XXXX, a widespread use of VR HMDs has followed. The use of VR in surgical training is described since XXX and has proven to bring advantages over classic surgical training. However, this is faced with two problems. First the developed surgical VR scenarios for HMDs describe specific applications. Second, the existing open-source frameworks for surgical VR do not support HMDs. Through the use of HMDs, an immersive and cost effective solution for VR surgical training could be provided. By using consumer devices, the barrier of entry for such VR surgial training software is rather low. Furthermore, the surgical VR training is strongly seperated from the intraoperative use of AR HMDs. In the course of this master thesis an open-source software application was developed for an VR scenario with HMDs embedded in an AR/VR surgical workflow in the field of OMFS.

Material and Methods: Unity 3D was used together with the Open VR Software Development Kit to develop an open-source software for a VR-scenario with the HTC Vive. The software was coded in C#. Additionally, the recently released Valve Index controller, which allow for tracking of the user hands in VR, were used for a more natural and immersive experience. A real operation room was captured with a 360 degree camera and used for more immersion in the developed VR software. Corresponding 3D models of true surgical instruments and a wide variety of surgical material like osteosynthesis plates were implemented. The developed VR scenario was evaluated by 5 OMFS trainees in a system usability scale study.

Results: The development of an open-source software for the use in an VR-scenario with an VR-HMDs in the field of OMFS is feasible. Furthermore, training with VR was percieved XXX. (TODO results of study)

Conclusion: The use of an open-source VR software with VR HMDs from the consumer market is a cost-effective application in the field of OMFS.

Contents

CHAPTER 1

INTRODUCTION

TODO: Jeden Absatz zitieren This master thesis is in context of a cooperation between the Visual Computing Institute at RWTH Aachen University and the Department of Oral and Maxillofacial Surgery (OMFS) at University Hospital RWTH Aachen (UHA). The goal of this thesis is to simulate a virtual operating room for oral and maxillofacial surgeons in Virtual Reality (VR). Workflows and procedures will be strongly oriented towards clinical practices of the oral and maxillofacial department in UHA.

Through the well established field of medical imaging, surgeons can get a very detailed view of patient's specific anatomy and pathology today. It is an essential part of preparing for surgery. Most common medical 3D image acquisition techniques (not exlusive) are computed tomography (CT), cone-beam computed tomography (CBCT) and magnetic resonance imaging (MRI). CT / CBCT makes use of x-ray measurements from different angles to produce cross-sectional (tomographic) "slices" of the scanned site. With this technique, bone structure and soft tissue can be displayed in medical imaging. The disadvantage of these techniques is the exposure to carcinogenic x-rays. In MRI, strong magnetic fields, magnetic field gradients and ultrasound are used to create tomography of the patients tissue. Since this technique makes use of hydrogen atoms, which is predominantly present in patient's soft tissue, bone structure is not imaged well. However, when studying mandibular joints for example, MRI is able to outperform CT [1]. The most recent one, CBCT, lowers radiation dosage of traditional CT and continually contributes to the accuracy of diagnostic tasks of the viscerocranium. It is able to produce images with isotropic submillimeter spatial resolution, which is ideally suited for isolated viscerocranium scans. The radiation dosage of CBCT is less than traditional CT and thus helps optimize health-to-risk ratio [2].

As discussed, there are a variety of ways to acquire medical imaging. However, the displaying methods of 3D medical imaging data is very limited for clinicians. After acquiring raw data via mentioned techniques, volume images are generated. Generally, data is reconstruced in three planes (axial, sagittal and coronal). Each plane is represented in "slices" which are 2D images of the volume image in an axis. The distance between each slice can differ but is usually between one and five millimeters.

OMFS is very diverse. It has to handle a complex arrangement of bones, teeth, vessels, cartilage, nerves, muscles, skin and gland tissue. These structures can be deeply complex, even more so in the viscerocranium. Therefore, OMF surgeons rely heavily on accurate 3D medical imaging to plan procedures. Even though three-dimensional objects are being analysed and also generated, they are viewed in a two-dimensional format on conventional computer screens. The generated slices from medical imaging are viewed in the mentioned planes to get volumentric understanding of patient's underlying anatomy and pathology. The problem with slices is that they are generally unsegmented and it is up to the viewer of the medical imaging to interpret them correctly.

To prepare for medical procedures, a number of preparational options are at the surgeons disposal. Each of those common practices will be discussed based on how well it is suited for the individuality of patients, the realism and the cost (time and resources) associated with preparing for the operation.

The most common preparation technique is the mental simulation in which the surgeon uses his imagination to get a mental image of the surgical site. This is solely dependant on the experience and spatial imagination of the surgeon. Hence it can be very patient specific, which is the goal in such an excercise. The realism however is low to medium and the costs are also dependant on the expercience and skill of the surgeon himself.

Another, yet very costly technique is a simulation on 3D-printed models. Since patient data is used here, it is an highly patient specific and highly realistic simulation.

In papersimulations, surgeons draw out treatment plans. This is usually little patient specific and not realistic, however the costs are very low too.

The last technique presented are operational textbooks and videos. They are not patient specific at all, but due to real operations being depicted the realism is generally low to medium. The cost is also almost zero since the hospital will generally own a number of textbooks and videos for training.

Each of theses techniques has major disadvantages. They all cannot actively reflect the underlying specific anatomy and pathology of the patient and lack spatial perception. Also, the 3D medical imaging, which gets viewed on 2D computer screens, has to be translated back onto the patient via the surgeons imaginative power. As discussed, there does not seem to be a trivial technique which all surgeons should use. Surgeons will often use a combination of mentioned techniques to get the best results. In the preparation stage, it is crucial that the operator gets a well defined mental image by 3D medical imaging data of the patient's anatomy and pathology. This thesis aims to improve medical imaging and pre-operational planning by using a modern approach with head-mounted displays. By using acquired 3D medical imaging in a virtual reality application, a very patient specific, highly realistic and only moderately costly technique with which surgeons can prepare for operations is pursued.

This thesis aims to achieve the following advantages over conventional methods:

(a) Familiarize the operator with the patient specific anatomy and pathology before operating
(b) The ability to simulate important operation steps
(c) Allow revision of the virtual operation as often as needed
(d) Recording and analysis of users and others virtual operations
(e) Test out procedures

Especially the imaging of voluminous objects is mentally demanding and this thesis hopes to eliminate this problem completely by providing realistic 3D medical imaging in virtual reality. This thesis is part of an applied virtual and augmented reality workflow for oral and maxillofacial surgery using head mounted displays (HMDs) as described in Figure 4.11.

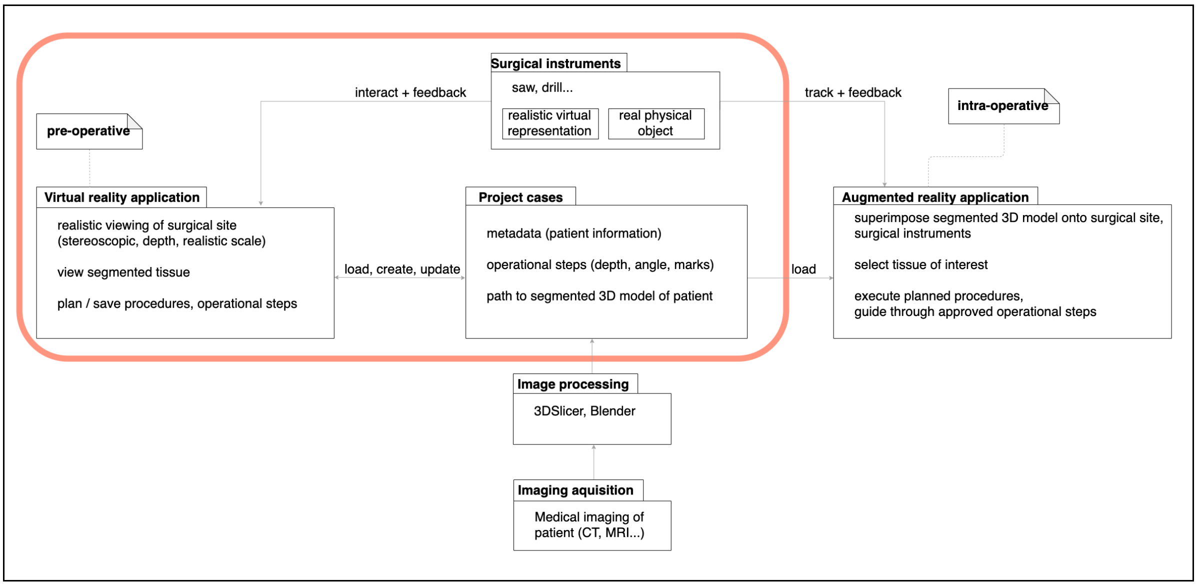

Figure 1.1: Complete VR and AR workflow for surgeons concept

The main goal of this thesis is to create a pre-operative assistance tool in VR with HMDs for oral and maxillofacial surgery as highlighted in Figure 4.11. In addition, the results of the pre-operative planning might be used intra-operatively to provide assistance via

Augmented Reality (AR) as described in the workflow. To provide a useful preparational tool, it is critical to simulate individual operation steps. Planned steps will be storable in a format in which they can be loaded and viewed in both the virtual and augmented reality applications bi-directionally as described. By planning the operational steps in virtual reality, planned procedures can easily be shown to other staff involved. Naturally, it will be of uttermost importance that we have medical equipment and an appropriate virtual environment recreated remarkably close to reality.

The remainder of this Thesis is structured as follows: TODO

Chapter 2

Related Work

A key part of this thesis is to advance the area of visualisation of medical imaging. Even though techniques exist, operations are still planned on two-dimensional images for three-dimensional surgical sites. In 2009, Swennen et al. discuss several improvements for three-dimensional treatment planning over conventional methods [3]. Cost reduction and better patient outcome were achieved with three-dimenstional treatment planning, even though the planning was still conducted on conventional computers with 2D screens. Especially the diagnosis, treatment planning and treatment communication were improved. Additionally, experts all over the world can be consulted since treatment plans can be send via electronic mail. As VR technology advances and entry costs are reduced, VR is considered more and more for a wide spectrum of applications. In surgery, the main focus of research is on surgical training with pre-modeled patient anatomy and pathology. By using state-of-the-art medical imaging and virtual reality technology and head mounted displays, this thesis aims to advance medical visualisation and surgery planning for patient specific procedures. In Section 2.3.1, a number of VR-based surgical simulations in different medical fields will be presented. In Section 2.3.2, the OMFS specific training tool "VR Surgery" will be presented. VR Surgery was developed as a visualisation aid for senior surgeons and as a practice tool for novices.

2.1 Medical Imaging

foo bar

2.1.1 Acquisition

2.1.2 Display

2.2 Virtual Reality in Medicine

foo bar

2.2.1 Training / Learning

2.2.2 Planning

2.2.3 Visualization

2.3 Surgical Simulations

In this section, a number of endevours for surgical simulations in virtual reality will be presented. This section gives a broad overview of previous VR-based simulations for surgeons in training. At the end there is discussion about lessons learned from this research.

2.3.1 General Applications

Parham et. al present a novel approach for a low cost surgical simulation to train novice surgeons for cervical cancer surgery [4]. The simulator aims to create pre-trained novices in resource-challenged countries. Cervical cancer is one of the world's leading causes of death [4].

By developing a low cost simulation, using commercially available VR software and the Oculus Rift HMD, they have succesfully helped surgeons to prepare for radical abdominal hysterectomy surgery procedures. A near identical representation of an operating theatre using 1:1 scale was used for immersion. 3D replica of human female pelvic anatomy and pathalogy including organs, veins, peritoneum and connective tissue was created. A huge focus while developing was to simulate reality as accurately as possible. Immersing trainees in the simulator is crucial so that they can focus on learning and practise without distractions. Putting them in a realistic operating scenario helps reducing anxiety and selfconsciousness before first time operations [4].

Parham et. al recognize a need for clinical testing to establish VR efficacy, since there is a lack of research for VRs clinical utility [5]. However, VR was already considered over 10 years ago as an important addition to surgical training, with a prediction for even more relevance in the future [6]. These low cost VR applications could be especially considered for resource-challenged countries where there is a lack of skilled workforce, mainly because of cost.

This simulator creates pre-trained novices by providing new ways to acquire the psychomotor skills, sensory acuity and cognitive planning abilities needed for sugery. Virtual reality based training is already proven to reduce the time to acquire surgical proficiency [7, 8]. In randomized control studies, VR trained trainees performing laparoscopic cholecystectomy, made fewer errors and were faster [9, 10]. VR trained trainees required only half the time to reach the skill level of intermediately skilled surgeons compared to standard training. Hence, it is proven that skills acquired in simulations can successfully be translated to the operting theatre (OT) [9, 10].

Parham et. al focus on high-quality visuals for immersion. All assets are represented in 1:1 scale and the correct visual reproduction of organs, tools and hand positions is ensured through thorough analysis of real world counterparts. Object materials are physics-based and organic materials approximated by an physics engine. The lighting emerging from medical equipment is based on their specifications. Lastly, the software would be developed with future expansion into other medical fields in mind [4].

The virtual OT consists of the open surgical area including organs of the patient, a tray for surgical instruments and a monitor displaying simulated patient vitals and procedure instructions. It was modeled after a real world OT located inside the University Teaching Hospital in Lusaka, Zambia. The assets were modeled after recieving reference photos and videos of locations and instruments and researching the female anatomy. It was argued that even though 3D scans of real human organs exists, they are too inefficient to run in real time VR [4].

In the virtual reality simulation, the trainee stands in the virtual OT with an operating table, tray of surgical instruments and the surgery awaiting patient with cervical cancer. The procedure is closely modeled after an actual surgical procedure, meaning the surgical site is exposed while the rest of the patient is covered. Instructions are given via a monitor above the operating table and audio feedback is given to guide the trainee through the simulation. The simulation lasts roughly 20 minutes and provides feedback on the trainees accuracy on various postions of the procedure and an overall score. To compare traditional surgical training versus VR, the trainees are assessed by expert surgeon-mentors [4].

It is mentioned how commercial VR will advance significantly in the future, allowing for an even better adoption of VR simulations in surgery. Surgical training enhanced with augmented and virtual reality will have wide applications according to Parham et. al. However, such technology has to be carefully build and clinically tested. VR and AR has the potential to help train the workforce and to ensure higher quality standards [4].

Another example for virtual reality training tools is the regional anaesthesia simulator (RASim) [11]. (TODO welche hardware wurde benutzt?) RASim focuses on physical accuracy using soft-tissue simulation and a haptic device to improve realism of interactions. It was developed out of the lack of training opportunities. Even though mannequins exist for training, they are too limited as they do not reflect the diversity of different patients and they wear from repeated use [11].

RASim allows for relevant tissue to be viewed. Tissue is segmented into skin, fat, muscle, blood vessels and bones. The simulation consists of two steps: First, the user performs a palpation using an extended index finger to sense the right puncture site for the procedure on the patients skin. Secondly, the user can switch the interaction mode to control a virtual needle. The needle can be moved freely until the patient's tissue is penetrated. When penetrating, only the depth of the needle can be varied. The user can trigger a virtual aspiration at any time to check whether the needle tip penetrated any blood vessel. If the needle tip is in emission range of any virtual nerve cord, according muscular motor responses are displayed in real-time. An interesting feature of RASim is the event logger, which remembers any given interaction step and thus allows to replay the whole procedure. This allows for further assesment by users themselves, but even moreso allows trainees to view the log of an experienced surgeon for learning.

A user study compromised of ten residents and consultants with experience between one and twenty years has been conducted [12]. The overall sentiment towards RASim was positive. Realism of the anatomy and identification of landmarks were highly rated. The majority of participants agreed that training with the simulator will be helpful to gain more confidence and increase the rate of successful nerve blocks. However, the majority of participants stressed that the haptic feedback has to be as sophisticated as possible.

A closely related work is the bilateral sagittal split osteotomy simulator (BSSOSim) [13]. (WElches gerät wurde benutzt?) BSSO is a major surgical procedure in maxillofacial surgery where training opportunities are rare and can be harmful for patients. Similar to RASim, this simulator compromises of realistic haptic feedback and tissue simulation. The simulator focuses on drilling and breaking, which are a subset of the operation steps in BSSO.

The main goal of the BSSOSim it the training of necessary motor abilities for a successful outcome of the operation. To achieve the required realism to train motor abilities, a haptic input/output device with 6 degrees of freedom is utilized. This allows users to get a feel for the exerted force needed in the operation. (TODO quelle)

NeuroSimVR is another training tool utilizing haptic devices [14]. This simulator allows novice surgeons to learn and practice a spinal pedicle screw insertion (PSI). Mostafa et. al recognize that most similar simulators perceive limited adoption by some medical experts. In contrast to related works, NeuroSimVR aims to optimize user interaction and user experience. The goal is to support medical experts with a training and learning tool that better satisfies their needs and expectations. (TODO quelle)

Mostafa et. al highlight that users, particularly novices, need an considerable amount of training before they can use and operate many of the existing simulatiors. Hence, NeuroSimVR has unique educational features and a simplified interface for ease of use. A key problem with NeuroSimVR as noted by numerous participants of the user study conducted [14], was that the simulation lacked realistic haptic feedback. Based on the feedback of their user study, Mostafa et. al concluded a number of key components which should be implemented in future works.

First, a flexible and simplified interaction is very important. Users especially liked the real-time x-ray visualization of different segmented tissue. Post simulation performance measures were also highly rated, although irrelevant for this thesis. Mostafa et. al strongly suggested simplifying the design of interactions when building surgical simulation as an important step towards providing more individualized independent learning. The ability to adjust the visualization of each anatomy part should be supported. This includes giving the user the option to hide or show various tissues as well varying their opacity. All participants of the conducted study stressed that performance measures beyond a simple numerical score provided by the simulation are important. Integrating feedback in a timely manner can be useful especially whenever something goes wrong. In NeuroSimVR this was realized by visual blinking if mistakes were made.

The goal of this thesis is to apply virtual reality in oral and maxillofacial surgery treatment planning. Haptic devices are a challenging aspect of most VR training simulators. Especially for training motor skills, haptic devices are a necessity. However, the percieved realism of such devices is still not accurate enough for most applications. Since the goal of this thesis is not an accurate physical representation of surgery, no haptic devices will be utilized. In contrast to the presented work, this thesis aims to provide a useful tool not only for learning, but also for planning patient specific surgery. Because of technology advancing rapidly, VR and AR become more and more affordable options. Mentioned limitations for patient specific 3D models are not an issue anymore. By using patient anatomy and pathology specific models, surgeons can profit from the mentioned benefits of VR simulation not only as a learning tool. Moreover, the goal is to give trained surgeons a useful tool which adds to the arsenal of existing planning techniques. However, trainees can also benefit immensely by studying and reproducing planned procedures of experts. Another aspect of VR is the ability to communicate on a global level. In fields where expects are rare, planned procedures by such experts could be viewed and studied to get greater insight.

2.3.2 Oral and Maxillofacial Application

VR Surgery allows trainees to virtually participate in a surgical procedure and interact with the patient's anatomy [15]. There is a huge emphasis to depict real surgical procedures and all related circumstances, such as a crowded operating table, as close as possible. The idea for VR Surgery came out of the global need for safe and affordable surgery. It is predicted that the global demand for surgeons can not be met with the current methods of surgical education [16].

Pulijala et. al describe how technical and non-technical skills have to be acquired in surgical training. Traditional means of surgical education though hands-on-practice has been around for more than a century. It was found that four out of ten novice surgeons are not confident in performing major procedures. VR Surgery aims to provide cognitive training for oral and maxillofacial surgeons [16].

After analysing existing methods of surgical training and identifying the need for their transformation, Pulijala et. all concluded that a simulation based learning tool can be benefitial for trainees. In VR Surgery, surgical trainees view pre-recorded stereoscopic 3D videos of real surgery in an OT and are able to interact with patient's anatomy via Oculus Rift and Leap Motion. The surgical procedure depicted in the videos is Le Fort I surgery. The software was designed in Unity 3D (TODO QUELLE).

Content of VR Surgery is split into four steps:

(a) Preoperative preparation
(b) Soft tissue incision and exposure
(c) Bone cuts, disimpaction and mobilisation
(d) Bone fixation and suturing

The 3D videos provide depth perception and realistic view of the surgical procedure, with other surgeons performing the procedure. This gives trainees the impression to be present during real procedures. It was found that such realistic scenarios improved learning. Users can zoom in and touch the 3D model of the patient's anatomy to visualise spatial relationshipts between the anatomy. Trainees get feedback through questions and tasks about procedures.

Pulijala et. al conclude how surgical education needs a major reform to meet future needs. Through continuously advancing commercially available hardware, VR became an affordable platform for high quality surgical simulations. They predict that applications like VR Surgery will provide an additional way of learning and in the best case reduce training time of surgical novices.

VR Surgery highlights how important realism is for training simulations. This is precisely why this thesis proposes a novel approach to existing methods. Since commercially available hardware today is able to produce high fidelity visuals and an immersive, stereoscopic view of virtual objects, the natural conclusion is to try out innovative approaches to existing problems with them. It also highlights how important a 1:1 real world scale is for visualizing the spatial relationships in patient's anatomy and pathology.

2.4 Discussion - Limitations

Chapter 3

Approach

As this thesis is a completely new project we will need to build an architecture from the ground up. Since the main focus of this thesis is visualisation and planning, we aim to provide a realistic feeling experience without being unnecessarily complex. This means that while our main goal is surgery simulation, we do not focus on realistic physical behaviour of tissue. The following anonymous, randomly selected data will be provided by the department of oral and maxillofacial surgery in the university hospital of the RWTH Aachen:

- (a) Imaging acquisition
    - (a) CT/CBCT scans, MRI scans
    - (b) provided by the UHA
- (b) Image processing
    - (a) Apply techniques to segment tissue from scans
    - (b) Create three-dimensional objects from segmented data
    - (c) Export data into conventional three-dimensional objects which can be used in the application

Furthermore, following key components will be designed and developed for this thesis to give an immersive experience:

- (a) Virtual operating room
    - (a) Based on real locations in the UHA
    - (b) If possible, designed via photogrammetry

(b) Provide an interaction system where the user can:
   (a) Freely move around
   (b) Interact with virtual model of patient:
      (a) Magnify and reset to original
      (b) Project another copy of the initial model for comparison
      (c) Set cutting planes
      (d) Mirror at symmetry line
      (e) Simulate cuts including depth by drawing
      (f) Measuring of the following attributes:
         (a) distance between two points
         (b) surface / volume area
         (c) angle
      (g) Transparancy slider for segmented tissue
      (h) Select which tissue to view
   (c) Grab surgical instruments
   (d) Use instruments for intended operational procedures (drilling, sawing etc.)
   (e) Start, undo, save recording movements of currently selected instrument
   (f) Start screen capture (Photo, Video)

(c) Surgical Instruments and materials
   (a) Create realistic virtual objects from real physical instruments and materials which are used in the oral and maxillofacial department of the UHA
   (b) Mechanism to plan and view procedures in relation to the patient including:
      (a) Angle of the instrument
      (b) Movements including direction of the instrument
      (c) Depth of the instrument if patient was penetrated
      (d) Markings on the patient
      (e) Inform if critical tissue was penetrated
   (c) Mechanism to start, stop, redo recordings of procedures for each instrument

(d) Provide an interface to the augmented reality application:
   (a) The user should be able to view all necessary patient data
   (b) The user should be able to view screen captures
   (c) The user should be able to load planned procedures in both applications by using an agreed format

TODO Implementation

Augmented virutality

Unity , most verbreitet

AR VR workflow

immer: WIE WESHALB WARUM

The software will be developed with commercially available hard- and software. The HMD in which this software will be developed is the HTC Vive. As user input, the Valve Index controller will be used. The software will be developed in Unity (LTS 2018.4) using the SteamVR (2.0) interaction system in the C# programming language. Since running virtual reality software is computationally expensive, a desktop pc with the following hardware is recommended for highest immersion:

(a) Graphics Card: Nvidia GTX 1060 or equivalent
(b) CPU: Intel i5-4590 / AMD Ryzen5 1500X
(c) Memory (RAM): 8GB+

TODO Implementation

The first step in realizing these requirements is to develop a software architecture with an interface to the augmented reality application in mind. Since this is a bi-directional data exchange which does not need to be real time, one obvious approach would be to use a simple object notation language such as JSON. A humanly readable format will be used so that operation plans can even be constructed without the need of an HMD. Different options will be explored and decided upon in the beginning phase of the thesis.

After deciding on a software architecture, the next step is to create a virtual operating room and first surgical instruments. The operation room will be designed after real operation rooms inside of the UHA. A photogrammetry approach will be evaluated in the hope to give the most realistic experience as possible for OMF surgeons. Virtual objects will be combined with a scan of the real world to give an interactive and immersive experience. After the operating room, the focus will be on developing a traversing mechanism which allows for free exploration of the operating room. Since operating rooms are not too large in general, it should be possible to traverse them in room-scale VR. However, a teleport function will be added for convenience. The surgical instruments will either be created in a 3D modelling software or exported in a similar way to how we obtain the segmented patient models from medical imaging. The full functionality of the instruments will be developed in a later stage, since we will first work on the more important planning tools.

The planning tools will be the most critical part of the thesis, since they have to behave as expected. There will be a mix of planning tools which are represented by virtual surgical instruments and basic features which will be mostly visualisation assistance. At this stage, it will be crucial that the user inteface (UI) is as intuitive as possible and does not distract in any way. Improving the UI however will be a continious effort throughout the thesis, and will hopefully become as intuitive and assisting as possible.

Each of the surgical instruments will have its own planning operations which can be recorded and saved. Since at this stage, the architecture and format will already be decided, there should not be too much to worry about when implementing this feature.

There are currently no plans to hold a user study, however an expert review by working surgeons is planned to evaluate the usability and percieved realism of the tool. Additionally, a small questionnaire will be used after surgery to determine if the new tool is preferred over conventional methods.

There are also possible optional features, such as an additional tool to view dicom data directly, which can be included in the scope of the thesis but will be decided upon during the development phase of the thesis and will be dependent on the progression of the core features of the tool. As of now, a basic prototype is already developed to showcase some of the planned functionality of the application.

3.1 Requirement Analysis

foo bar

3.1.1 Non-functional Requirements

3.1.2 Functional Requirements

3.2 Concept

foo bar

3.2.1 Available Tools

3.2.2 Medical Imaging Acquisition

3.2.3 User Interface

3.2.4 Features

foo bar

3.2.4.1 Project Case

3.2.4.2 Procedures

3.2.4.3 Training

3.2.4.4 Visualization

CHAPTER 4

IMPLEMENTATION

After the thorough requirement analysis in Section 3.1 on which a concept for the software was derived in 3.2, we can now discuss the implementation of the system components. We will start with the work- and interaction flow of the system. Afterwards, we will shortly discuss architectural components as well as utilities provided by SteamVR. Later, available commands and the concrete implementation details of surgical procedures and visualization tools will be discussed.

1.) Functionality FEATURES Visualization Procedures Training 1.1) What can this software do? (Features -¿ siehe Chapter Approach) 1.2) How was this implemented? (Technisch)

2.) Workflow JSON UML Foto 3.) User Interface 3.1) Graphical JEDES menü 1 FOTO 3.1) Voice Tabelle mit allen Befehlen + beschreibung was wie wo

Architecture Kapitel 4 Software mit Objektdiagrammen darstellen und textlich beschreiben SteamVR -¿ Architecture

4.1 Features

foo bar

4.1.1 Procedures

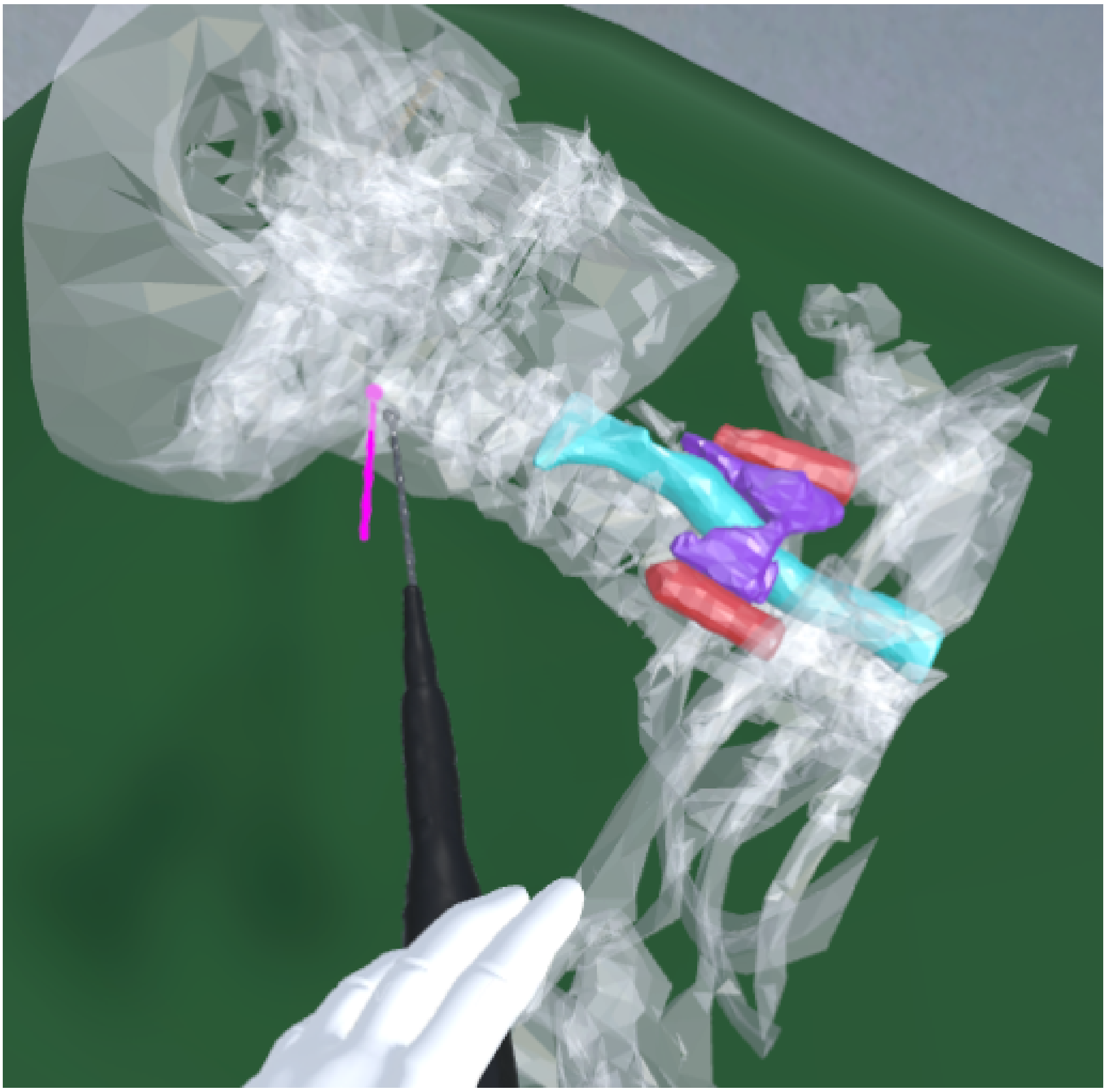

Figure 4.1: Drilling Procedure

4.1.2 Training

foo bar

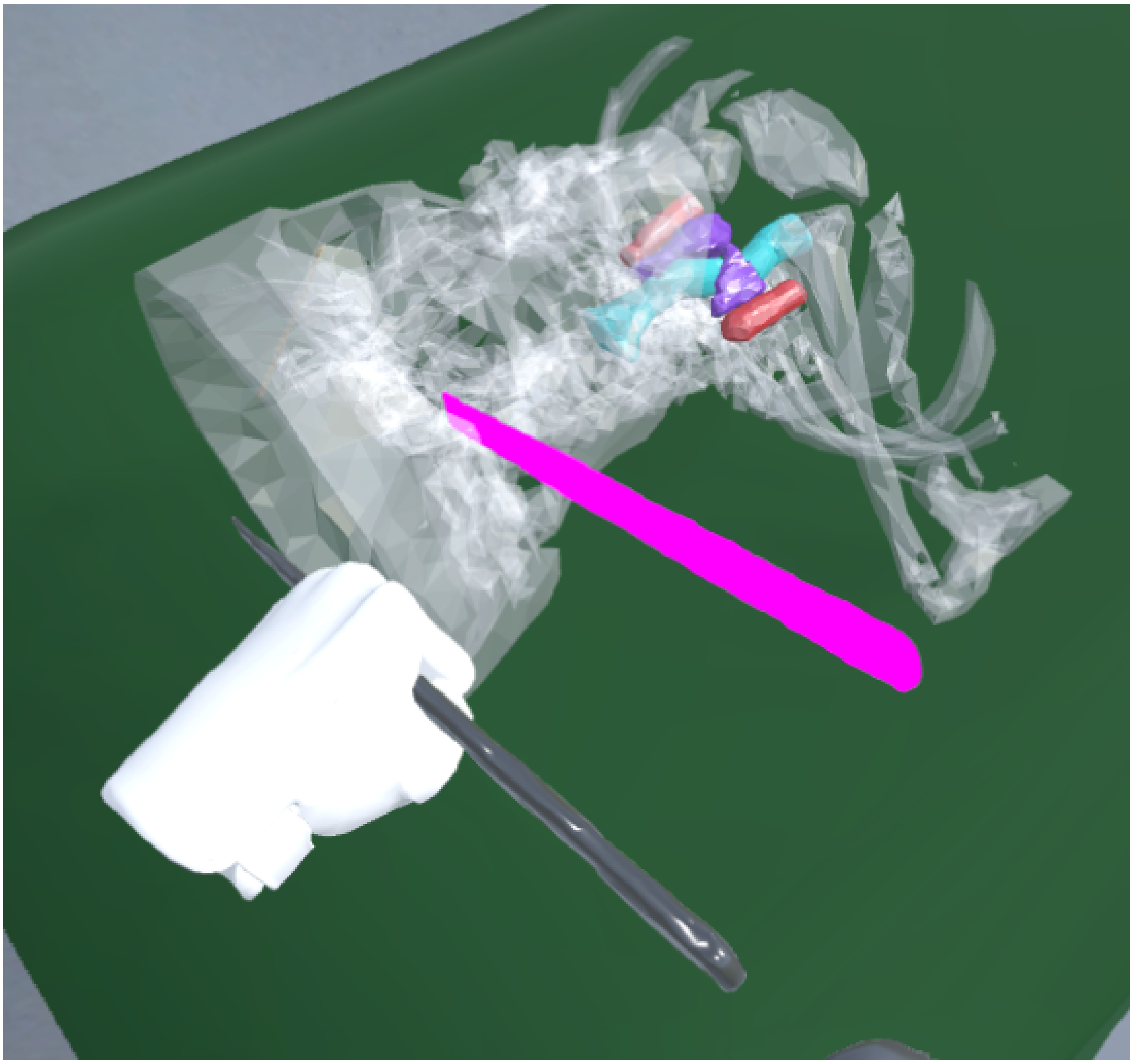

Figure 4.2: Hammer and Chisel Procedure

4.1.3 Visualization

4.2 Workflow

This VR-application is in the context of a AR/VR-based surgical workflow as depicted in Figure 4.11. OMFS-Surgeons can plan procedures with familiar surgical instruments on realistic representations of patients. Workflows can be imported and exported via a file in JSON-notation. The system uses a mixture of natural hand gestures like grabbing objects with voice commands for navigation. The patient can be freely scaled, rotated

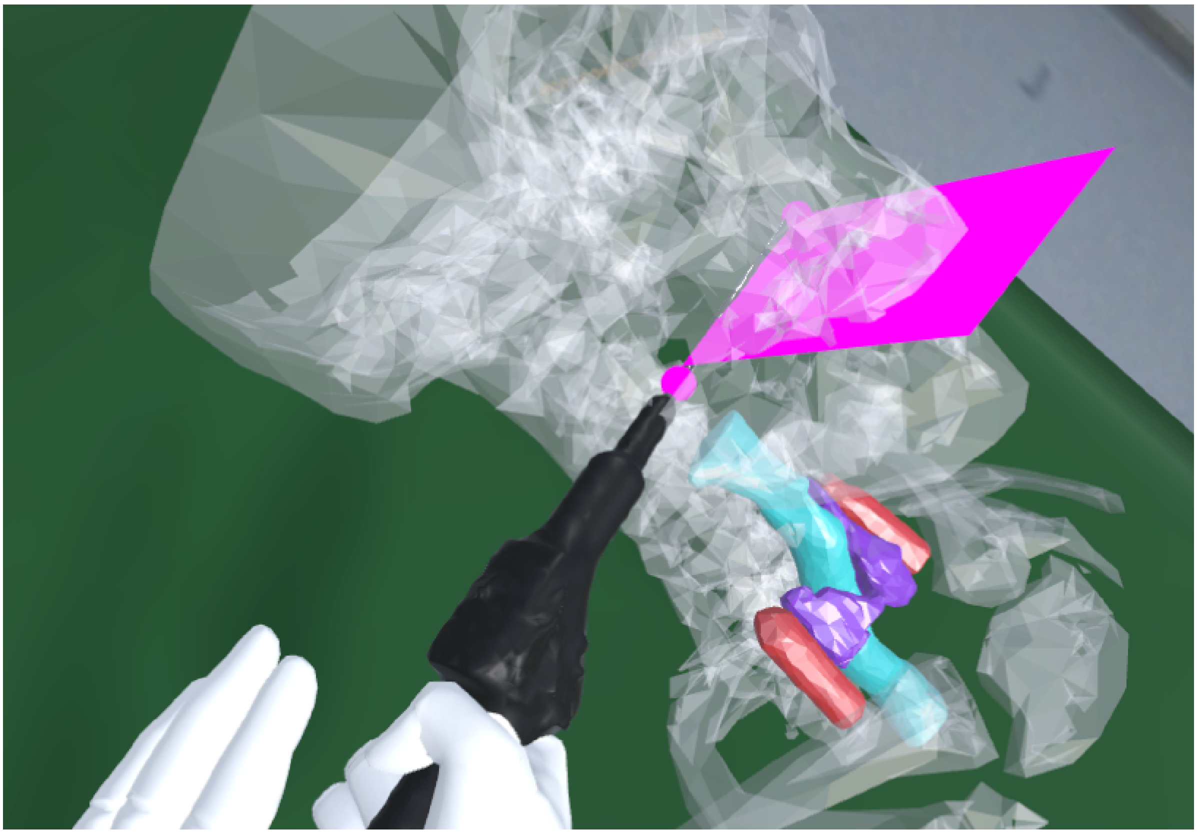

Figure 4.3: Bonesaw Procedure

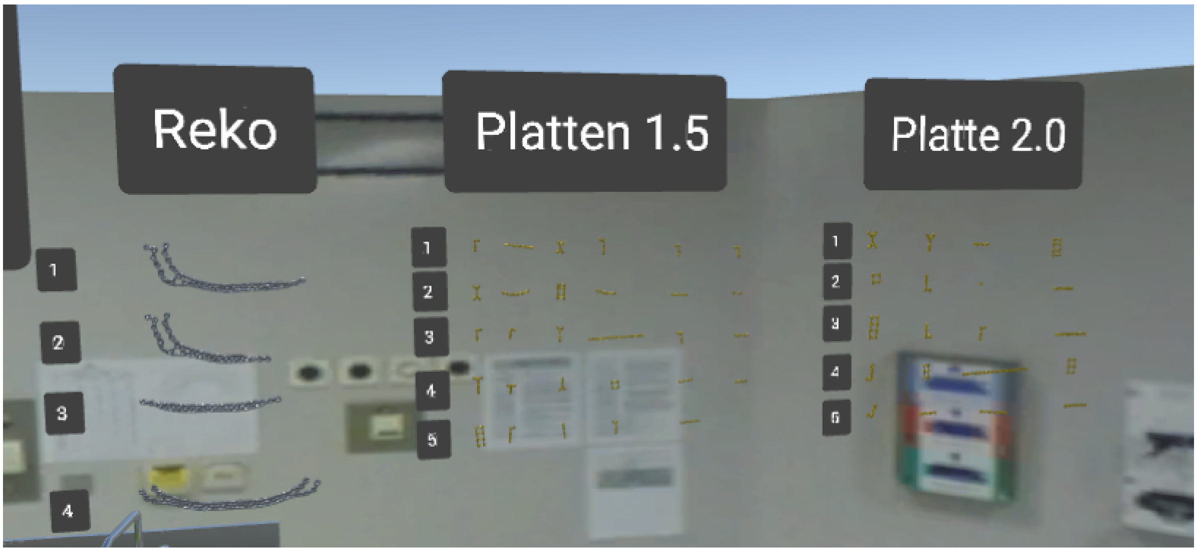

Figure 4.4: Osteosynthesis Plates Overview

and moved for visualization purposes. Patients can be resetted to the default position on the operating desk at any time.

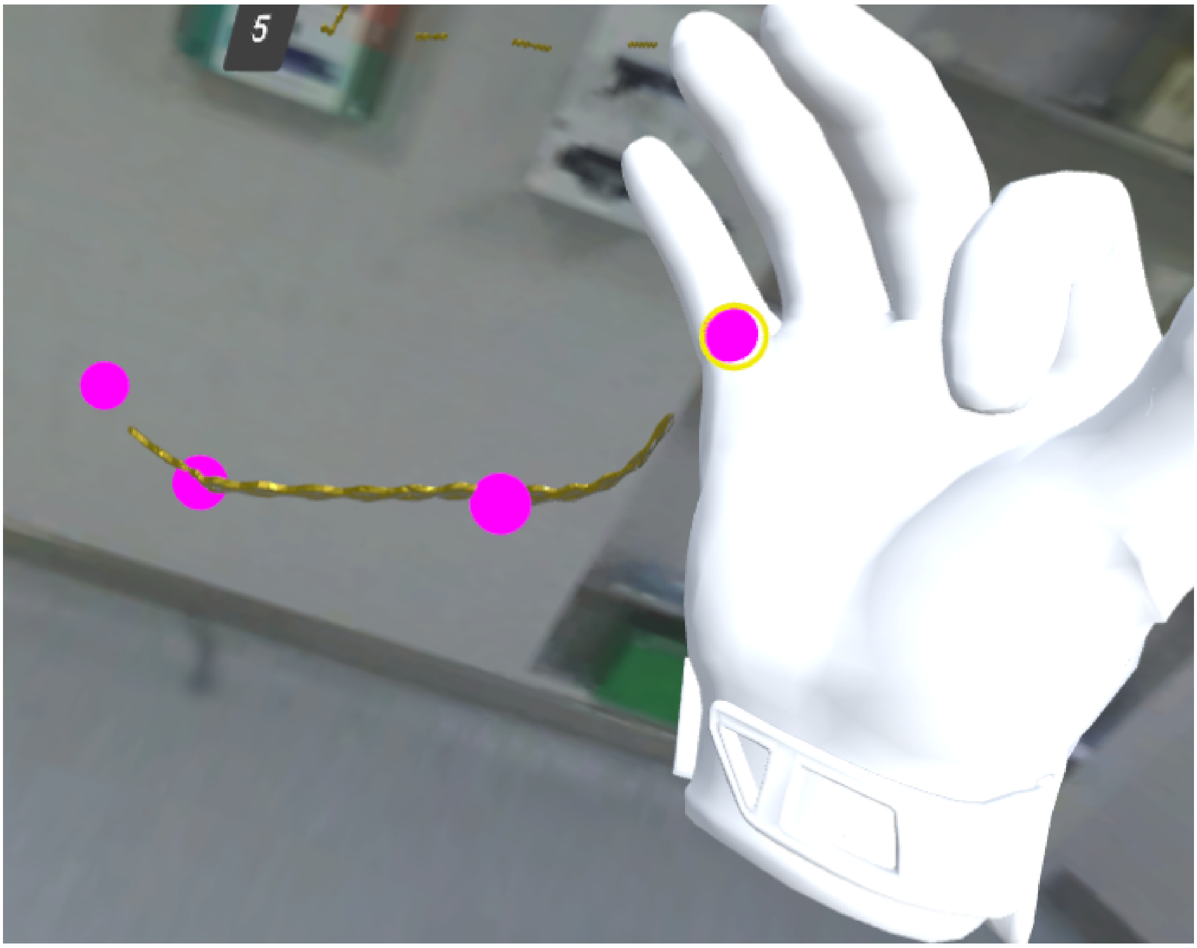

Figure 4.5: Osteosynthesis Plates Customizability 1

1. Acquisition of medical imaging (CT, DCT, MRT. . .)
2. Segmentation of volumetric data (DICOM) into 3D model data (STL, OBJ. . .)
3. Definition of project case in JSON-notation
4. Import of project case
5. Planning procedures in the context of project case
6. Optional: Simulate procedure for learning and training purposes
7. Save project case for use in AR or share with other surgeons

The workflow of the software is as depicted in the enumeration above. Important to note is that the first two steps of the workflow are not part of this thesis, as they are

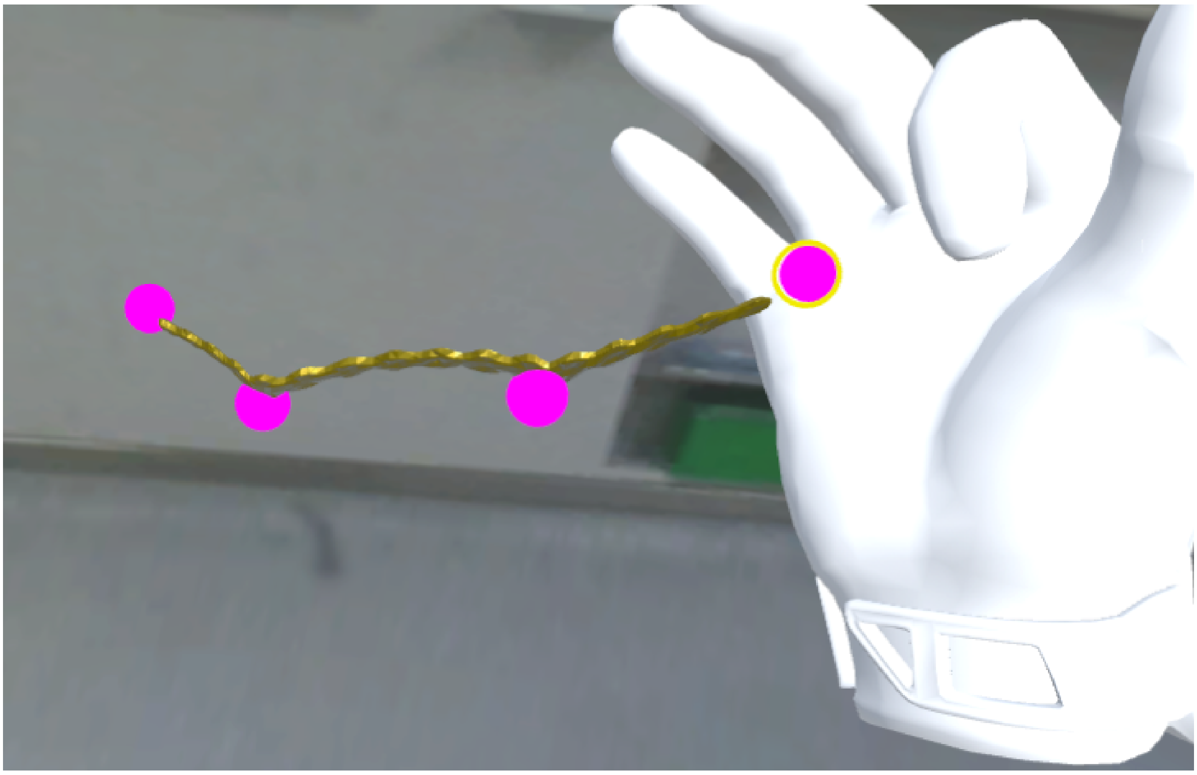

Figure 4.6: Osteosynthesis Plates Customizablity 2

kindly provided by the Oral and Maxillofacial Department of the UHA. Step one and two of the workflow are especially critical, as medical imaging techniques have their own advantages and disadvantages. Users performing the medical imaging acquisition have make expert decisions about which techniques to use to highlight the patient specific tissue. Also, while segmenting the medical imaging in step two, the decision about which tissue has which color and which tissue will be transparant is made. Specific features of the software are dependant on decision made in these two steps.

The project case is at the core of the workflow since it acts as the interface between the independantly developed AR- and VR-software. The specifics about the JSON-notation have already been agreed and decided upon in the conceptualization phase of the project, since it is critical for both of the applications to smoothly itneract.

The case info contains patient specific information which is important for the procedure as depicted in the listing above. These informations, aswell as the location of the patients 3d representation has to be manually registered by the user. Information about the steps will be automatically generated while perfoming procedures inside of the application, however the user can then later add additional information as he sees fit.

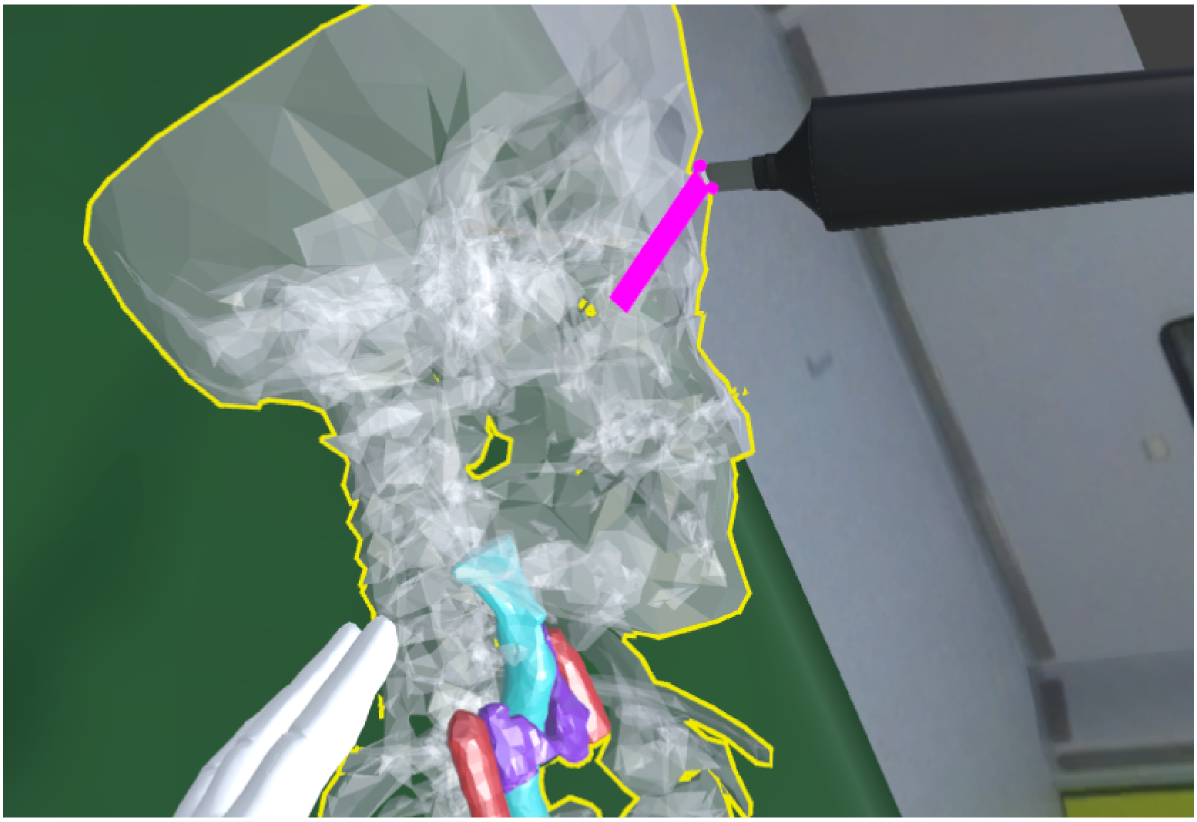

Figure 4.7: Marker Procedure

The thought process behind this decision is that only medical experts themselves can know about the fine details while performing certain procedures. Thus it is simply necessary to manually edit them with expert knowledge. The automatically gernated information about the steps contains only information about which instrument was used at which step of the procedure.

When a project case is saved from within the application, a copy of the current patient with all steps which were performed is made withing the root folder of the patient model. This way, the patients model is never lost and we can always start the procedure from scratch if desired. Also, the timestamp of the updated field inside of the case info will be set.

When trying out the different apporaches as depicted in Setion 3.2.4.1, we found that using this kind of approach is best suited for extensibility reasons. By simply adding the planned procedures as additional 3D-Data to the patient, we ensure extensibility and robustness of the software. New instruments and thus procedures can easily be added into the software without touching the project cases and everything will continue working as expected. In comparison, if we used an approach where procedures have to

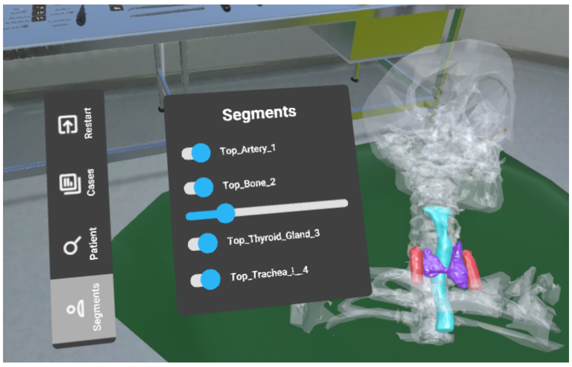

Figure 4.8: Segment enabled

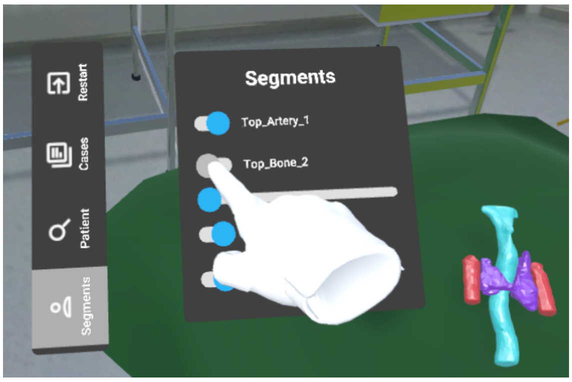

Figure 4.9: Segment disabled

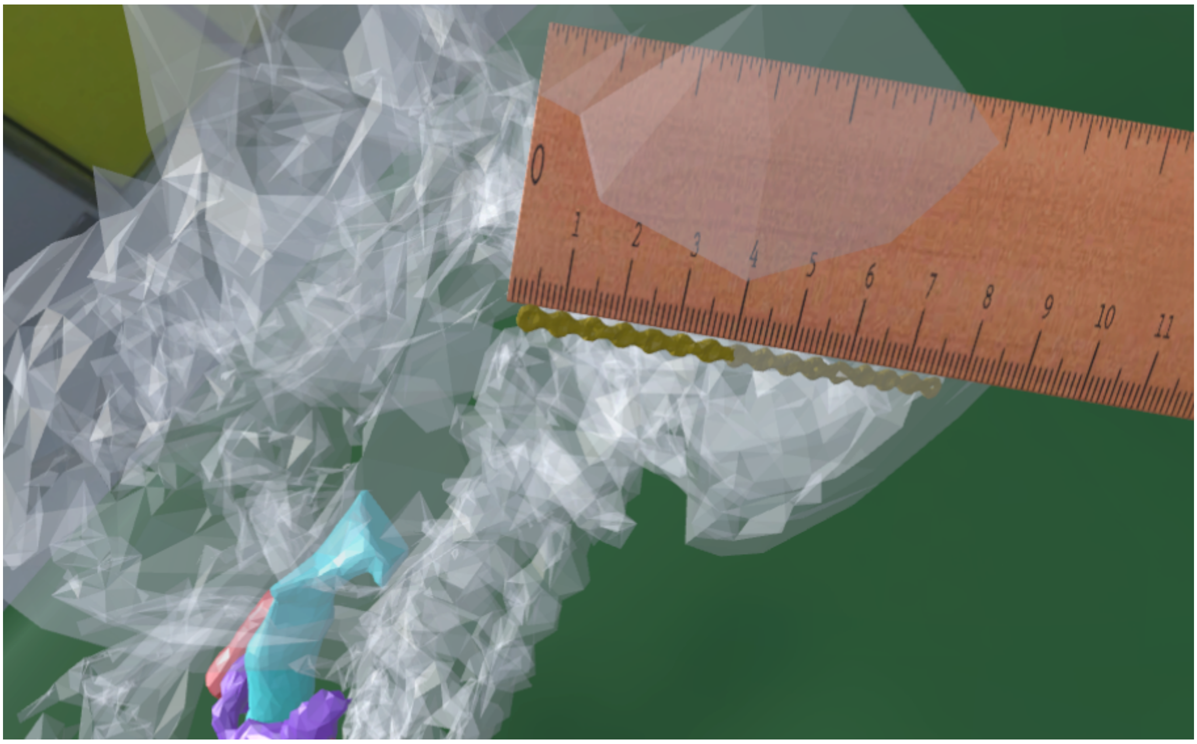

Figure 4.10: Ruler for Checking distances

be defined from within the project case, project cases would have to be updated every time we want to add new instruments to the application.

The tradeoff however, is that we can not adjust the procedures "on the fly" via text, but procedures have to be adjusted from within a 3D-modeling software or directly in the VR-application. (TODO in implementation nichts hinterfragen, nur beschreiben)

After setting up the project case, it can be loaded up at runtime inside of the VR-application. Users can then view, add and edit existing procedures or create new ones.

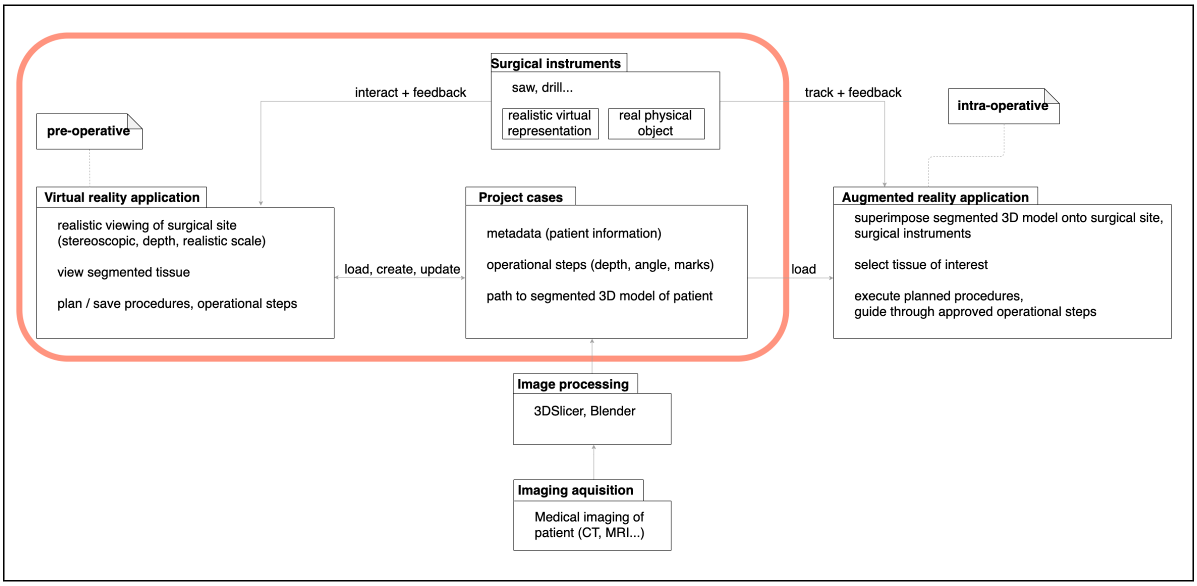

Figure 4.11: Complete VR and AR workflow for surgeons concept

If users wish to run through the planned procedure step by step, they can either navigate using the voice user interface or by enabling 'train mode' in which the user will be guided step by step through the procedure. Here, users will be visually guided by the outlines of a surgical instrument to know where a procedure has to be performed. Additionally, users will be guided via text inside of the application. The text which is shown will be automatically generated with information about the current surgical instrument when performing a new procedure. However, users are also free to edit the textual guidance manually via the JSON file in any way they see fit. To confirm if the current procedure is carried out in the desired manner, voice feedback will notify the user if procedures are carried out correctly or if errors are being made. The user can decide to save the current procedure for later use at any time of the process.

4.3 Interaction Flow

The basic flow of interaction for planning a procedure via the software is depicted in Figure 4.12. First, a user has to enable the graphical user interface via the click of a button on the controller. The user interface will be stuck to the left hand of the user, another click of the button will freeze the GUI in place. The user interacts with the graphical interface by perfoming virtual button presses with his virtual hands. Via the interface, the user first chooses a project case he wants to work on. This will load the patient into the virtual operating room, ready for planning the procedure via the available tools. From here on, the user can freely choose which procedure to perform and in which order. Tools can be selected via simply walking or teleporting to them

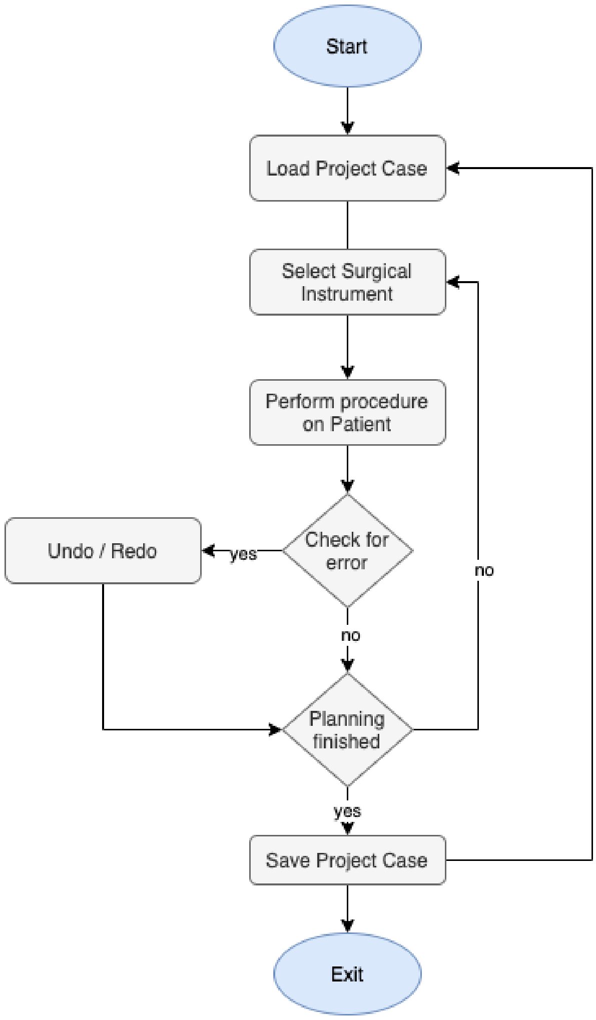

Figure 4.12: Simplified Flow of Interaction during the Planning Stage

and making a grab motion with the Valve Index controller. When holding a surgical instrument, the Trigger button has to be pressed to perform the procedure. By simply touching the Trigger button, the user gets a visual indication that a procedure is about to be performed. When performing a procedure step, the user gets auditory feedback that the step has been registered. At any point of performing the procedure, the user can choose to undo and redo the current step via the voice interface. Only the last performed step will be visible while planning the procedure for visibility reasons.
Not depicted in the flow chart is the selection of the operating theatre, which is the first scene the user will see when starting the application.
The training stage, which can be performed after a procedure has been planned, is almost identical to the planning stage. Here, the user has to follow instructions visible inside of the operating room and perform the planned procedure step by step as he is being told. Instructions correlate to the planned procedures, but can also be written manually from outside of the application. A visual representation of where the user has to perform the

step is visible at all times. The voice feedback will indicate whether the procedure has been performed correctly. Reasons for errors could be the usage of the wrong surgical instrument or incorrect placement.
Lastly, when a procedure is planned and the project case has been finished, the user has to save the project via the graphical user interface. This will create a copy of the current patient model including all procedure steps and save it to the users hard drive. This way, original data will not be lost and a project can always be redone from scratch.

4.4 User Interface

foo bar

4.4.1 Graphical User Interface

The first graphical interface which the user will see when pressing the button is depicted in Figure 4.13 The buttons for loading a case are created dynamically and depend on

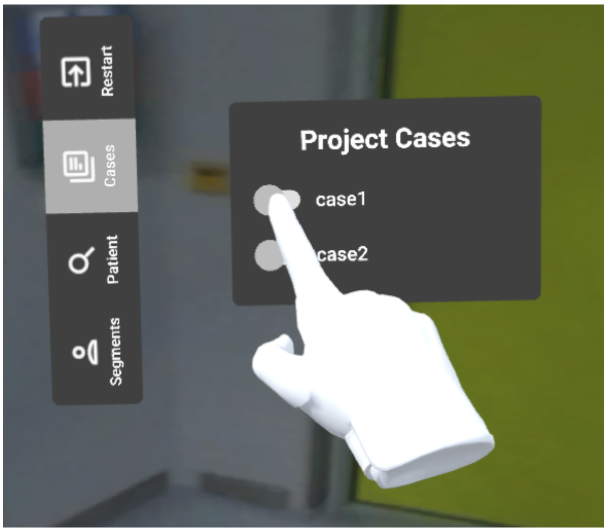

Figure 4.13: User Interface for the Selection of Project Cases

the number of project case JSON files found in the specified folder. As will be explained later, the evaluation consists of five distinct scenarios in which distinct procedures have to be performed via the available tools. By pressing the button by selecting it with the virtual hand, the project case will be loaded and the patient and information written down in the project case will be display from within the virtual operting room. On the left side, different submenus can be selected. Visualization tools can be selected via clicking on 'patient'. As depicted in Figure 4.15. Here, tools which are the same for any project case can be used for visualization purposes. Users have the option to scale the patient, look at the unprocessed patient for comparison and the ability to explode the 3D-Model to help with visualization. Project cases can also be saved from this menu.

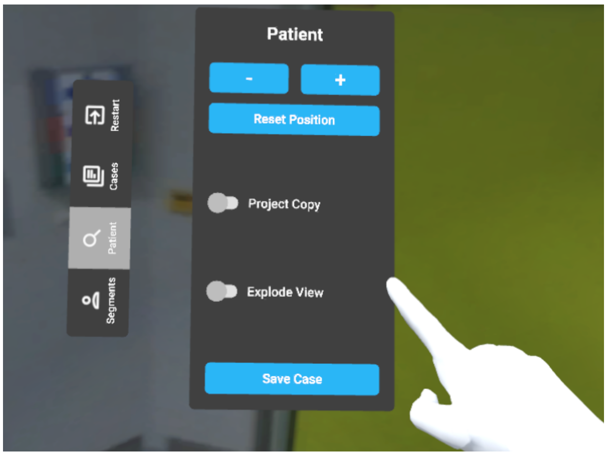

Figure 4.14: User Interface for Patient Visualization Tools

Figure 4.15: User Interface for Patient specific Segments

4.4.2 Voice User Interface

Command	Action	Comment
Start	Show first step of procedure	This command also does disables the 'show all' command.
Show all	Show all steps enumerated chronologicly	Gets shut duwn via 'start' command. Disables the use of 'step next' or 'step back'.
Step next	Show next step	
Step back	Show last step	
Undo	Undo current step	Last undid step gets cached and can be redone via 'redo' command.
Redo	Redo last undid step	Only one step can be redone.
Train start	Start train mode	Start at step 1 and navigate steps by following instructions and performing procedures in the correct manner. It also disables every other command except 'Train stop'
Train stop	Stop train mode	

Table 4.4.2 shows all Voice Commands.

4.5 Architecture

4.6 SteamVR

Chapter 5

Evaluation

foo bar. Was kann man genau machen? Hilfreich zum lernen, vorbereiten?

5.1 System Usability Study

foo bar

5.1.1 Preliminaries

5.1.2 Participants

5.1.3 Scenarios

5.1.4 Procedure and Data Collection

5.2 Results

foo bar

5.2.1 Quantative Resuluts

5.2.2 Qualitative Results

5.2.3 Think-aloud-protocol

Was it a concurrent think-aloud protocol or a retrospective one? Moved from 5.1.5 to here

Chapter 6

Discussion

CHAPTER 7

CONCLUSION

1. Satz: Was habe ich gemacht? (Zusammenfassend). Zb. Anwendbarkeit dieser App gezeigt / nicht gezeigt 2. Ergebnis Zusammenfassen (e.g. Major results of this thesis: Feasibility to develop virtual 3d surgical simulation...) 3. Stärken der Software: Open source, HMD for immersion, CHECK Paul Milligan paper Classes of immersion. 4. Schwächen: keine 100prozent immersion, kein feedback, patient bewegt sich nich Ausblick: Hardware wird besser, haptic feedback solutions sind in produktion 5. Software einordnen in vergleich zu anderen papern 6. Conclusion

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