

Ask Jentoft

Augmented Reality for Neurosurgery Training on the SphenoBlock Procedure

Master's thesis in Computer Science

Supervisor: Ekaterina Prasolova-Førland, Gabriel Kiss

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Department of Computer Science



Abstract

This study aims to utilize Augmented Reality technology to create and application for training medical personnel. Training is done to improve for the *SphenoBlock* procedure, a research project at St. Olav's University Hospital in Trondheim, that aims to treat migraines by injecting sedatives using a specialized tool called MultiGuide. Techniques for aligning the real world with the virtual are researched and developed, enabling usage of a physical mannequin head to provide tactile feedback when training for the procedure.

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Acronyms

- AR** Augmented Reality. 1–3, 7, 9–11, 17, 28, 32, 64, 65
- ASR** Architecturally Significant Requirement. 28, 34
- COVID-19** Coronavirus disease 2019. 49
- DOTS** Data-Oriented Technology Stack. 27
- ECS** Entity Component System. 27
- FOV** Field of View. 57
- GPU** Graphics Processing Unit. 36, 38, 42, 46
- HMD** Head Mounted Display. 2, 9, 12, 42
- HSR** Hidden Surface Removal. 42
- MVP** Minimal Viable Product. 31, 34, 35, 59
- NTNU** Norwegian University of Science and Technology. 1, 6
- OOP** Object Oriented Programming. 27
- OST** Optical See Through. 9
- PCF** Persistent Coordinate Frames. 61
- SDK** Software Development Kit. 44, 60
- SPG** sphenopalatine ganglion. 1, 28, 30, 36–38, 45, 46, 50, 51, 65, 73, 74
- UI** User Interface. 28, 32, 61, 62
- UX** User Experience. 32
- VR** Virtual Reality. 6

Glossary

"Zorro" Face mask protecting parts of the skin from touching the headset. See figure 7.1. 54

anchoring Spatial recognition of some physical object to align virtual space. 3, 64

Architecturally Significant Requirement Requirements that have a measurable impact on the choice of architecture. xiii, 34

culling The process of removing hidden geometry in 3D computer graphics, also know as Hidden Surface Removal. xiv, 42

Hidden Surface Removal The process of removing hidden geometry in 3D computer graphics, also know as culling. xiii, xiv, 42

MonoBehaviour Base scripting class in Unity for the C# language.. 27

polygon Basic data structure used in computer graphics, consisting of three edges and three vertices forming a triangle. 42

retopology The process of simplifying the topology of a mesh. 42

shader Programs that run on the GPU which affect the rendering of objects.. 36

spatial perception Computer awareness and sensing of surroundings. 9

St. Olav's University Hospital The hospital in Trondheim, Norway, closely related to the Norwegian University of Science and Technology in research and education. iii, iv, 5, 7, 17, 40, 47, 63, 66

Stakeholder 1 . 17, 38

Stakeholder 2 . 17

transfer problem Problems that require application of knowledge from one context to a new situation. 10

Chapter 1

Introduction



Figure 1.1: QR link to a video demonstration of the final product. *Or click here.*

1.1 Motivation

Augmented Reality (AR) is an emerging technology that has seen big investments by major technology companies in recent times. Since its inception, AR has shown potential to enhance human perception[1], as well as improving training by allowing users to be immersed in combinations of live and virtual simulation[2]. Devices that solve the fundamental technical hurdles are readily available and research is ramping up to find practical real world applications.

One such area of application is in the field of medicine. There is a huge potential to improve existing procedures, and in many cases, AR can enable entirely new approaches. A research group in Trondheim is developing a tool called MultiGuide, that uses image guided navigation to enable procedures requiring high precision. Among their possible use-cases, SphenoBlock is a procedure for treating headaches by botox injection into the sphenopalatine ganglion (SPG), a nerve located deep into the skull. In collaboration with Norwegian University of Science and Technology (NTNU), two previous master projects have focused on implementing AR technology in the SphenoBlock procedure.

1.2 SphenoBlock AR



Figure 1.2: SphenoBlock AR 2018.

This project is a continuation of the previous SphenoBlock AR projects at NTNU. The first project was in 2018, and utilized the HoloLens 1st generation AR headset, hereby referred to as a headset, to aid in training the Sphenoblock Procedure [3]. This first iteration ran a training simulation utilizing a physical mannequin head, with a holographic model of the human skull (figure 1.2). The project used images in the form of small cards for anchoring the virtual models to the physical model. The application featured a guidance system for the injection, providing multimodal feedback in the form of sound and color changes. However, this first iteration was limited by the power of the HoloLens 1, and could not render more complex 3D models, thus only essential anatomy could be displayed.

The next iteration aimed to improve upon the previous by utilizing newer and more powerful headsets, as well as improve on the functionality for training [4]. For this project, students used three AR HMD: The HoloLens 1, Meta 2, and Magic Leap One (see figure 1.3). This application featured three modes: injection guidance, exploration mode, observer mode and additionally a tutorial to demonstrate the injection procedure. The injection mode featured the anatomical skull, with the SPG nerve highlighted. The user controlled a 3D model of the MultiGuide, that could be seen following the controller when wearing the Magic Leap headset. The HoloLens version of the application on the other hand, used image tracking to control the MultiGuide. The exploration mode allowed the user to grab and view the skull from different angles, to improve understanding of the anatomy and points of contact in the procedure. Finally, the observer mode was a way to let another user view through a second headset, to observe the trainee doing the procedure.

The second project found that the Magic Leap was the best suited HMD, with its superior performance, enabling high refresh rate for higher definition models. This would enable more anatomically detailed models, for a better spatial



Figure 1.3: The headsets used in SphenoBlock AR 2019.

understanding. They also concluded that to make it fit for use in training, it would be necessary to have some form of haptic feedback. As a suggestion for further work, it was proposed to combine the use of Magic Leap and improved anatomical models, with a mannequin head for haptic feedback [5].

1.3 Research Objective

The purpose of this project is to continue where the previous project left off, and show that this AR application, *when paired with physical objects for haptic feedback*, can be a valuable tool in training for the SphenoBlock procedure.

The main objectives of this thesis have been formalized in the following questions:

1. **RQ1:** What is the value of augmented reality technology in training, especially in the medical field?
2. **RQ2:** What solutions exist for alignment of real and virtual space (a.k.a. anchoring)
3. **RQ3:** Would a training app using the Magic Leap and head mannequin for the Sphenoblock Procedure a viable solution?

1.4 Outline

This thesis opens with a look at the background of technology and previous work, that has formed the foundation from which this project has developed. It takes a look at the medical research and expansion into new areas where technology can be applied. The previous work and research lays the basis for the requirements that have been formulated in chapter 3.

From there we take a look at the technical design, consisting of the software architecture and the design frameworks and principles that were used to shape the solution. Chapter 5 discusses the process, from the development model, to describing the different stages of development and the tools used for process

management.

Chapter 6 looks at the more technical details of the implemented solution, and the tools that were used during development. Chapter 7 and 8 describes the testing that was done during development and results that were obtained respectively. Finally we the discussion in chapter 9, which explore all the interesting aspects and lessons from the project, before the thesis is concluded in chapter 10.

Chapter 2

Background

2.1 The MultiGuide Project

The basis for this thesis is the work started by researchers at St. Olav's University Hospital, developing a tool for use in a variety of medical cases. The goal in developing this tool is to create an alternative to invasive surgery in hard-to-reach anatomical areas.

A minor operation lowers patient risk and recovery time. It also takes up less time for surgical professionals. Another advantage of the minimally invasive procedure is the flexibility it offers: interventions have fewer restrictions on location and patient sedation, enabling treatment on awake patients under local anaesthesia in an "*outpatient office-based setting*" or clinic [6, 7].

MultiGuide significantly lowers the cost and complexity associated with image guided interventions. As a result, MultiGuide may represent a shift from highly specialized procedures performed by few, to easy-to-perform procedures within the reach of junior surgeons or physicians. Additionally, it facilitates a shift from general to local anesthesia, increasing intervention accessibility [8].

2.1.1 MultiGuide Tool

The MultiGuide tool itself is a pistol shaped injection device (see figure 2.1). A handle carries the piston that guides the user in pushing a hypodermic needle to perform the injection. The syringe is attached at the back, and holds the medical compound used in the procedure.

Three infrared (IR) reflector balls are attached at the top, for high-precision tracking of the MultiGuide. [9] [10] The IR balls are tracked by the Brainlab surgical navigation system, that includes a camera and a touchscreen monitor. The equipment is positioned to the side of the operating table, standing on a cart with wheels (see figure 2.2). Tracking works by using infrared LEDs and multiple

cameras, that optically tracks the IR balls to determine their position.

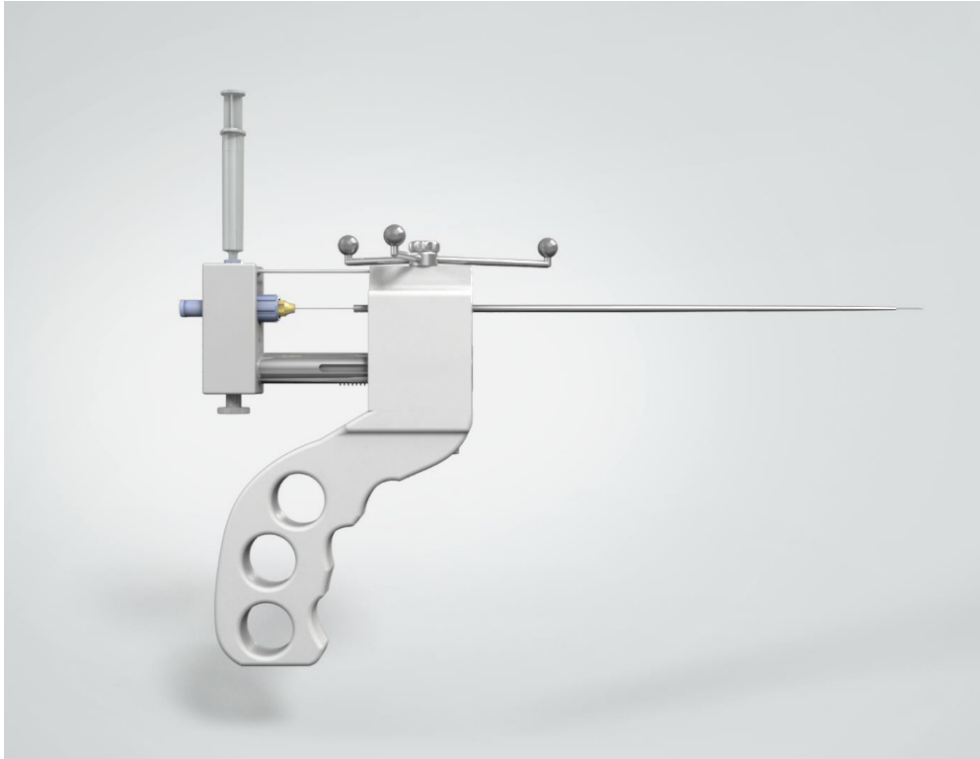


Figure 2.1: A render of the MultiGuide tool. At the center top are the IR tracker balls used in combination with Brainlab. A long needle covers a thinner needle that connects to the syringe at the top left.

2.1.2 Sphenoblock Procedure

The sphenopalatine ganglion (SPG), also known as the pterygopalatine ganglion, is a parasympathetic ganglion found in the pterygopalatine fossa. According to the MultiGuide website [8], the SphenoBlock procedure is a unique approach for the treatment of cluster headache and migraine. Neural activity through the sphenopalatine ganglion is believed to be involved in creating migraines and cluster headaches [6]. Transmission of these signals is dependent on the release of the neurotransmitter acetylcholine (ACh) in the ganglion. Botulinum toxin, as for example Botox, can inhibit the release of ACh, thus blocking the signals. Duration of autonomic blocks with botulinum toxin is expected to be in the range of 3-9 months, and needs to be repeated regularly.

Parallel to developing the MultiGuide and test its efficacy, an offshoot project spawned in collaboration with Norwegian University of Science and Technology (NTNU), and the IMTEL Virtual Reality (VR) lab at NTNU. The goal of this collaboration has been to research and develop new and improved ways of



Figure 2.2: Brainlab's Kick Surgical Navigation System.

surgical navigation. Augmented Reality (AR) has been recognized as a promising technology for various medical applications (see 2.2.4), and potentially something that could improve the SphenoBlock procedure. The use of surgical navigation systems such as Brainlab's Kick, require the surgeon to look at a screen to the side. AR has been identified as an option that can serve to move the navigational imagery into the field of view of the surgeon [11].

Another aspirational goal for the team at St. Olav's University Hospital was to provide the surgery in an outpatient office-based setting. Being able to provide training for the procedure, lowers the barrier to entry and potentially opens for non-specialists to the practice and broader availability of the procedure [6].

The collaboration has spanned multiple master thesis projects, with many iterations that continue to evolve along with developments in AR technology. As innovations in AR continues, the research is less limited by available hardware and software solutions. It is therefore still a relevant research question in a field that is reaching a level of maturity that is becoming appropriate for mass adoption.

2.2 Augmented Reality

¹Augmented reality (AR) is a field of technology which allows for interaction with the real world, *augmented* by computer generated sensory information, most commonly visual objects and sounds, but also haptic perception and smell. AR attempts to blend in with the real world environment to create an immersive

¹Section cited from my project thesis [12]

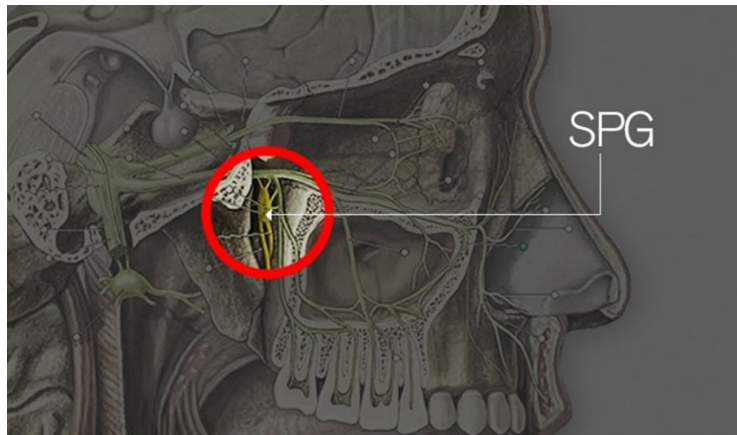


Figure 2.3: The sphenopalatine ganglion (SPG).



Figure 2.4: A surgeon performing the SphenoBlock procedure.

experience for the user.

AR can be defined as a system that fulfills three basic features: a combination of real and virtual worlds, real-time interaction, and accurate 3D registration of virtual and real objects.

2.2.1 Hardware

As AR technology is mostly centered around the visual aspect, most hardware in AR uses computer graphics. This is typically in the form of a wearable computer with some form of display, and the necessary sensors for spatial perception. Thus, the definition of AR normally includes the use of smartphones that map and film its surroundings, while rendering objects in a shared 3D space. This is displayed on a screen to the user, where the combination of virtual and real image appears.

The focus of this thesis is the use of a different class of hardware, namely *Immersive Devices*. Contrary to smartphone AR, these devices aim to create a surrounding sensory feeling, the most important of which is the visual sense. This is achieved by equipping the user with a Head Mounted Display (HMD), that typically has one Optical See Through (OST) display per eye. Separate displays for each eye allows the user to see in full 3D, as separate images are rendered for each display, enabling depth perception.

The combination of virtual and real space is a result of a number of sensors that map the environment, also known as spatial perception. A combination of sensors are used for mapping the environment, mainly multiple cameras and depth sensors. Additionally, change in the headset's position is measured with cameras, as well as an accelerometer, a gyroscope and a magnetometer. The headsets are equipped with speakers on each ear, to allow immersion through sound. Modern headsets are normally capable of hand tracking and may optionally use a controller.

2.2.2 Software

To display holograms, the AR devices run 3D graphics software. Controlling the rendering is usually a game engine, that simplifies control of objects and the logic of their interactions. Depending on the hardware, the rendering performance is limited by the geometry (mesh) and texture detail of the holograms, as well as the calculations done by the game engine. A central part of AR software is the combination of real and virtual objects, and to do so the software runs spatial perception algorithms to understand the positioning relative to the surroundings.

2.2.3 AR and Learning

The case for Augmented Reality (AR) as a tool to improve learning, is older than the technology itself. Since the dawn of time, animals have used play as a tool for cognitive development, allowing them to practice their skills in a simulated scenario. The use of technologies to assist in simulation became increasingly necessary, as humans ventured further away from their natural habitat. Notably, the Apollo missions had extensive simulation training, and Neil Armstrong have said they would not have been successful without them. AR is in this context the digital support system that facilitates the simulated scenario. The main advantage of simulation, is that it allows training in a realistic environment, where exploration and troubleshooting is safe.

Additional benefits of computer assisted simulation can be found in the ease in which performance metrics can be obtained, and the ability for real-time feedback on performance. Performance metrics can also be useful to adapt the environment to the learner, either in terms of difficulty or what information is presented.

Learning that makes use of these adaptive techniques, are more generally referred to as augmented learning [13], where the focus is on context and adaptive learning techniques.

In an even broader sense, Augmented Reality (AR) is a medium that has the potential to fully use rich media, utilizing most of our senses. Current research is somewhat lacking when it comes to the effects of Augmented Reality (AR) in education, but if the educational content is considered multimedia, theories in *e-learning* can be applied. E-learning is the cognitive science concerned with effective learning using multimedia technologies. The theory provides some empirically established principles that can be applied to the design of AR applications [14]. The principles are based on cognitive load theory, that describes the different types of mental effort it takes to complete a task, where learning can be made more efficient by minimising effort for an equivalent outcome.

Out of the principles that have been formulated, some of the more relevant for AR applications are:

- **Multimedia principle:** Combinations of relevant graphics, audio and text, are better for learning than any one alone.
- **Contiguity principle:** Relevant bits of information should be in proximity.
- **Coherency principle:** Avoid distraction by only including relevant media.
- **Learner control principle:** Learning is enhanced when when users control their learning, in terms of pace and focusing on areas of special interest.

Evidently, Augmented Reality (AR) is a suitable platform for to deliver multimedia content, not only for traditional video, text and audio, but also with interactive 3D objects. Research remains to be done in e-learning to prove whether this principle applies to the 3D imagery in AR. However, images in combination with text have been shown to increase correct solutions to transfer problems by between 55 to 121 percent [14].

A central function of AR is spatial perception, which is a device's ability to see and understand its environment. As a consequence, AR devices are spatially smarter than other computer interfaces, and will always be incentivized to continue innovation in this area. This ties in with our remaining three e-learning principles.

First of all, the *learner control principle* is uniquely enabled by spatial understanding in AR. Learning can happen spontaneously as sparked by the learners interest. Imagine being intrigued by a flower, only to have the device recognize it, retrieve its information, and seamlessly display and narrate relevant information. As a side effect, such as system naturally satisfy the contiguity and coherency principles. Holograms can be displayed in a way that information is superimposed on real objects, or be arranged such that they overlay and stay attached to their relevant area. This system also lends itself to dynamically displaying only relevant information, such that the learner does not experience sensory overload and

become distracted by sensory details [15] (coherency principle).

2.2.4 Augmented Reality in Medicine

The medical field has been of interest for Augmented Reality applications since early on in the technology's life. Many aspects of AR are immediately attractive from a medical standpoint. The ability to view 3D images is especially useful, as medical work is concerned with a localizing disease and defects, where information must be gathered through various imaging techniques to minimize intrusive procedures. Imaging techniques such as CT, MRI and ultrasound, are originally 3D imaging techniques that are normally projected to a 2D screen. AR enables viewing of this data in its original format, saving all spatial data in projection. Such a system functions as an enhanced visual sense, and has been described as X-ray vision.[16]

A systematic review on the effectiveness of AR in medical training [17], concludes that "AR allows trainees to understand the spatial relationships and concepts (...) Moreover, AR helps to create authentic simulated experiences. It is thought to increase trainees' subjective attractiveness, enhancing learning retention and performance."

Simulation is another area where AR excels, enabling simulated scenarios of medical procedures to be played out. As mentioned in 2.2.3, simulations are useful when training on real situations is unfeasible due to expense, patient safety or availability. Practicing on real patients can be difficult when medical care is more concerned with patient safety, leading to scarcity in real situations for rarer medical procedures. Simulations are also more flexible in AR, as training exercises can be done in combination with their normal physical environment, through the use of real equipment and mannequins. In fulfilment of the learning principle 2.2.3, simulation also allows trainees to safely explore and fail without consequence. Some studies have found that simulations increase in confidence, comfort, technical skill and knowledge. [18–20]

2.3 Previous Work

A body of work has been devoted to AR applications since its inception [21], for surgical training, planning and navigation. For a comprehensive meta study, see [11, 22–26].

Abhari et. al. [27] found AR beneficial to aid in perception and mental transformations, using a stationary AR application for planning and visualizing a procedure. This was represented as 3D images projected on the head of a mannequin. The system used the Vuzix Wrap 920AR glasses, which requires a wired connection to a computer, as well as external IR tracking sensors for object

alignment. The use of a mannequin enabled touch and manual handling of the head, but the system did not emulate any surgical intervention. Thus no actions were enhanced with haptic feedback, as nothing except hands were used with the mannequin. It still represents the closest example that could be found of similar work, apart from the work of other master students that have worked on this project.

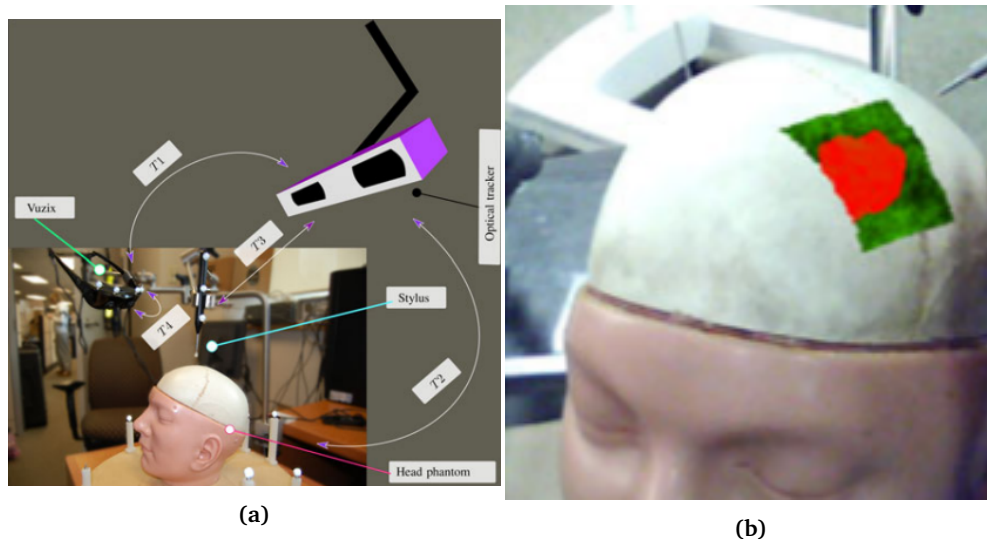


Figure 2.5: System setup in (a) and AR visualization in (b), from Abhari et. al. [27].

2.4 Commercial Work

This section looks at more commercial solutions.

2.4.1 Microsoft's Dynamics 365 Guides for HoloLens 2

Microsoft is betting big on their flagship augmented reality HMD, and has recently launched an application for creating guided processes without writing code. This application involves creating annotations and spatial understanding relevant objects, to guide users through a step by step procedure to completing a task. They claim to maximize training effectiveness by “Integrate[ing] photos, videos, and 3D models to personalize training and turn institutional knowledge into a repeatable, interactive learning tool.” [28]



Figure 2.6: Microsoft Dynamics 365 Guides for HoloLens 2.

2.4.2 AR for Live Surgery

An interesting area of research is the with the use of AR during live surgery. Some examples of this is CTrue and Xvision (figure 2.7 and 2.8). These projects utilize more active tracking with external sensors that yield higher precision. This is used in combination with scanning of real patient tissue, that is rendered in 3D over the patient. The hope is to improve efficiency and cut time during invasive procedures, leading to less complications during surgery. [29, 30]

2.4.3 Brainlab's ExacTrac Dynamic

Brainlab's ExacTrac Dynamic is an example of state of the art anchoring and real-time scanning of patients with specialized equipment. Using multiple sensors from many different angles, while restricting patient movement, the tool is able to provide extremely accurate imaging and anchoring the data. See figure 2.9.

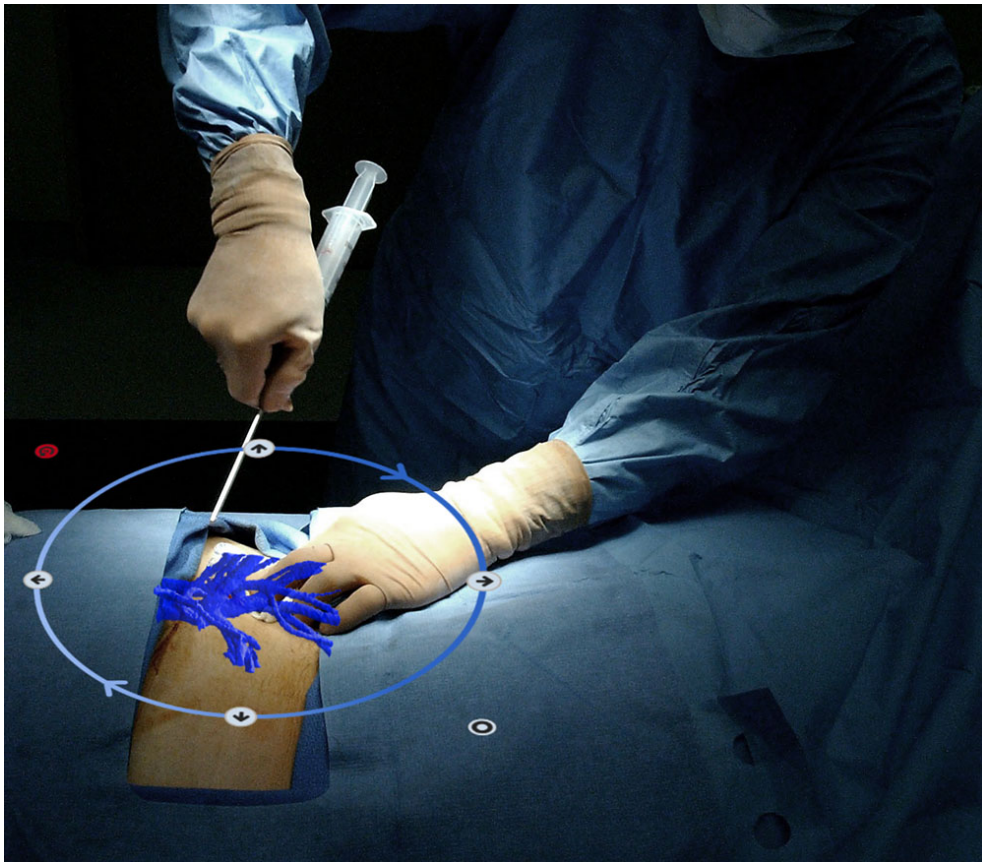


Figure 2.7: HoloCare's CTTrue.



Figure 2.8: Augmedics' Xvision.

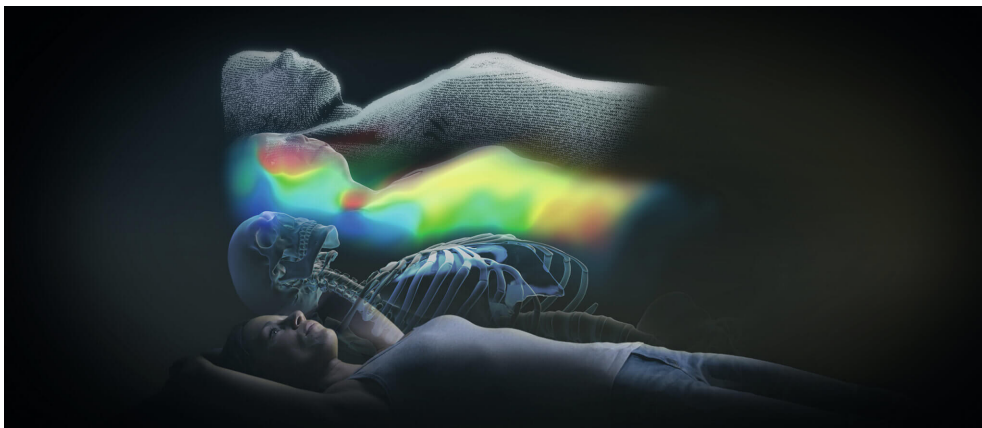


Figure 2.9: Brainlab's ExacTrac Dynamic.

Chapter 3

Requirements

This chapter lists the project requirements in their various forms, discusses their origin and when they appeared, as well as the different stakeholders to the project. With this chapter I try to convey how the seemingly simple project goal has changed over time, reflected in how requirements change and sometimes appear unexpectedly during development. I will try to explain how a relatively simple elevator pitch of a project can evolve in complexity and quickly grow in scope.

3.1 Types of requirements

The projects requirements take different forms to best reflect the different stakeholder's values and viewpoints. User stories are a way to directly compose requirements based on the type of user it originates from, and is therefore a good starting point. They reflect both the different types of stakeholders, as well conveying a generalised description of their needs. The user stories can then be converted into functional requirements, which is a more direct look at what the system needs to do. This is useful for the developers, as it narrows the problem down to more discrete tasks that need to be solved. Functional requirements are limited in that they only describe the technical details, but fail to capture the more human aspects of the system. Emotions tied to the user experience can depend on many aspects of the system, which is why non-functional requirements are included in this project and especially important in a user-centered system.

Name	Description
User Story (US)	-
Functional Requirement (FR)	-
Non-functional Requirement (NFR)	-

Table 3.1: The different types of requirements used in this project.

3.2 Requirements Gathering

The requirements were collected and formulated based on interviews and meetings with the various stakeholders. Previous projects on the same subject were also a source of requirements, as their work had already explored different areas and done testing. The results of these projects provided a good source of knowledge about the project and a good foundation for which requirements could be formulated. The impact from the pandemic has meant that meetings were banned, and this resulted in that the requirements were formulated and kept only for the developer, while more informal meetings were held to communicate them with the stakeholders.

3.2.1 Initial Requirements from Previous Work

The project began in February of 2020, and was offered as a possible master project by Stakeholder 1 as part of the IMTEL-Lab at NTNU. It was pitched as a project that had been worked on by previous masters students as part of a collaboration with St. Olav's University Hospital. It had sparked interest with the medical researchers, and there was a desire for further research and development. Unfortunately, the main customer and collaborator, hereby referred to as Stakeholder 2, was quite busy and could not meet until the middle of May. This meant that the project needed to start somewhat unconventionally by not having a meeting to start the project off. It would prove to become more unconventional yet, as the COVID-19 pandemic was spreading. However, the previous master project had laid good foundation for further work, so Stakeholder 2's needs and feedback from previous prototypes were already well documented.

Despite some issues in development, the previous project had uncovered a major design requirement for the product. They had found it very lacking trying to practice the procedure without something physical to push against. The user would be pointing in the air trying to perform an accurate procedure that would normally be done on something physical. Haptic feedback, or simply the tactility of the procedure, is an important part of simulating the experience, as well as an important aid in performing it correctly. The most important requirement was therefore to add tactility by using the mannequin head, a head already used to practice the procedure, except it is normally used without any AR guidance.

The second requirement that was uncovered was to use an AR headset, the Magic Leap One, which was the most modern headset the lab possessed at the time. The previous project had briefly attempted to port their application for the Magic Leap, but this was done late as they got their hands on the headset near the end of the project. They had performance issues with the older headsets, and spent a lot of time optimizing their application. As they received better hardware late in the projects, they never got to fully utilize and test the potential it brings.

3.3 Requirements List

**As a <role>
I want <goal>**

Figure 3.1: The user story cards used in this project.

User Stories	
#	Story
US1	As a medical professional I want to practice SPG injections in a simulated environment
US2	As a medical researcher, I want to test the viability of AR guided surgery
US3	As a patient or family relative, I want to benefit from the treatment
US4	As a learning researcher specialized in immersive technology, I want to study the practical applications of AR where learning is an element
US5	As a researcher who sees the potential of AR, I want an application that can impress others and demonstrate its value

Table 3.2: User Stories

Functional Requirements	
#	Description
FN1	The app must superimpose a virtual hologram to a physical mannequin
FN2	The app must show where the SPG nerve is located
FN3	The app must show relevant anatomy for the SphenoBlock procedure
FN4	The app must track the MultiGuide

Table 3.3: Functional Requirements

Non-functional Requirements	
#	Description
Functional Suitability	
NR1	The app shall meet stakeholder's functional requirement to such a degree as to which the viability of the proposed solution can be evaluated
NR2	Training with the app shall be better than without
NR3	Skill practiced with the app shall transfer to real scenarios
NR4	It should be very easy to locate the target, navigate and get a good spatial understanding of the geometry
NR5	Navigational functions should make performing actions accurate easier
Performance Efficiency	
NR6	The performance of the app shall yield sufficient FPS to avoid stuttering and nausea
NR7	The app shall feel responsive and accurate
NR8	The app shall use as little resources as possible, so as to minimize battery drain
Compatibility	
NR10	The app shall be a complete standalone product running on only one headset
NR11	The app shall be able to share a common environment with other products, and be able to share a mannequin head
Usability	
NR12	The app shall follow the lean development principle to minimize waste
NR13	The app shall be intuitive and easy to use
NR14	The app shall be forgiving of errors
NR15	The UI shall be as minimal as possible and practice the contiguity principle
NR16	The holograms shall add to the experience and not be distracting of the real world
NR17	The anatomical holograms shall be pleasant to look at
Reliability	
NR18	The app shall not crash constantly
NR19	In the event of a crash, rebooting shall fix all problems
NR20	The app shall be usable with some margin of error in terms of accuracy
Maintainability	
NR21	Should be easy to make changes to source code
NR22	Classes and functions shall practice separation of concern and be loosely coupled
NR23	Functions shall have descriptive names that can easily be understood
NR24	Classes and functions shall be documented with comments
Portability	
NR25	The product shall be able to integrate with different tracking solutions in the future
NR26	The product shall be able to be used with different mannequins
NR27	The product shall be portable to a different AR headset

Table 3.4: Non-functional Requirements

Chapter 4

Technical design

4.1 Architecturally Significant Requirements

A set of key requirements have been selected and ordered by category. They make up the architecturally significant requirements, and constitute the requirements that have shaped this project's decisions the most:

Hardware Solution

1. **FN1:** The app must superimpose a virtual hologram to a physical mannequin
2. **FN4:** The app must track the MultiGuide
3. **NR10:** The app shall be a complete standalone product running on only one headset

User Experience

- **NR4:** It should be very easy to locate the target, navigate and get a good spatial understanding of the geometry
- **NR12:** The app shall follow the lean development principle to minimize waste

Software Architecture

- **NR18:** The app shall not crash constantly
- **NR21:** Should be easy to make changes to source code
- **NR22:** Classes and functions shall practice separation of concern and be loosely coupled
- **NR23:** Functions shall have descriptive names that can easily be understood

4.2 Physical and Hardware Solution



Figure 4.1: A live demo of the final product in use by a surgeon.

4.2.1 All-in-one Hardware

The proposed solution uses only a single Magic Leap One headset and the accompanying controller, for all its computational and spatial perception needs. It does not rely on any external base stations for tracking position, and does all its computing needs locally. As such, the solution is completely self sufficient, reducing complexity and minimizing cost. This reflects the desire to test the viability of the AR in this context, meaning that it is not a requirement to provide the best-in-class tracking solution, but to be a pathfinder for further development. The all-in-one solution reduces complexity for both developers and users. To set up a practice session, all a user needs is a table, a mannequin head, MultiGuide and a Magic Leap One running the software.

4.2.2 Mannequin Practice Head

The solution integrates with the tools that are already being used by surgeons and researchers to practice the procedure outside of augmented reality. A mannequin head simulates the head of a patient and provides the physical resistance when performing the procedure. It has an outer shell of hard plastic, a softer rubber for the face, with an opening on the side of the cheek that exposes the innards, which is filled with foam rubber.

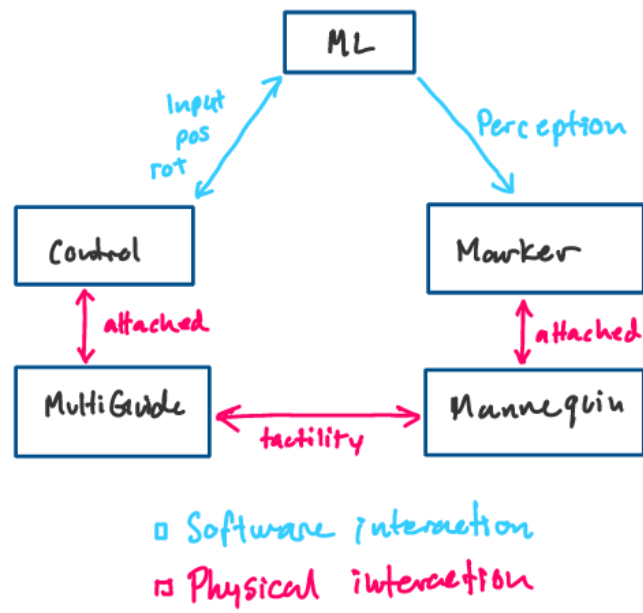


Figure 4.2: A diagram showing the interactions between hardware, or the physical components of the solution.



Figure 4.3: The practice head as used by surgeons for practicing the procedure.



Figure 4.4: The complete custom MultiGuide.

4.2.3 Custom MultiGuide

An early prototype of the MultiGuide has been stripped down to the bare essential components, including a handle, a needle and a metal piece that connects the two. Grooves at the top makes it possible to attach equipment, such as the controller in this case, but also IR emitters and reflectors.

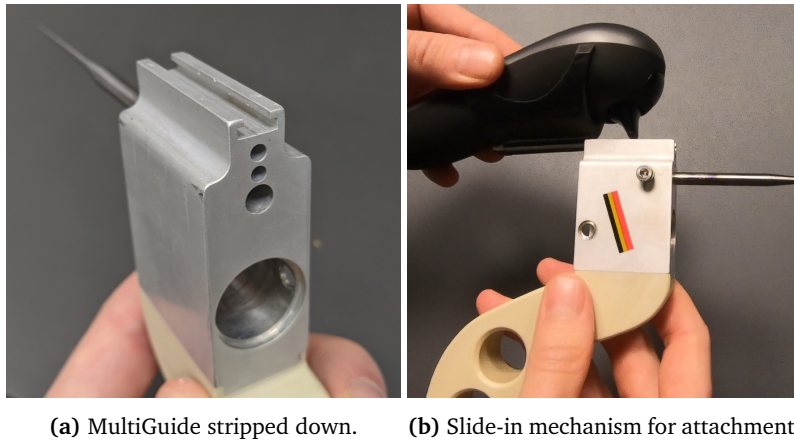


Figure 4.5: Attachment of the controller.

A custom attachment piece has been created, that enables the Magic Leap controller to sit on top of the MultiGuide. The piece is special made for this purpose, and can be 3D printed in 7 hours depending on printer. It features a secure bottom ring and arms that hold the controller firmly, so that it can sit tight when held in all orientations, while still being easy to insert and remove. This enables precise relative positioning for a constant offset and accurate tracking of the needle.

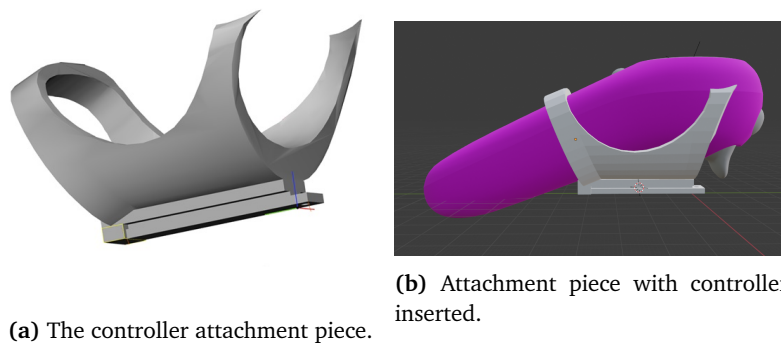


Figure 4.6: The custom made 3D printed attachment piece and controller.

A bar is positioned at the bottom of the 3D printed piece that fits the MultiGuide grooves, and slides in effortlessly for quick attachment. Easy removal is important when navigating the Magic Leap menus with the controller alone, as the MultiGu-

ide should be used carefully to prevent injury from the needle. Users can start the application from the menus, and from there the user simply attaches the piece to the MultiGuide to perform the procedure simulation.



Figure 4.7: MultiGuide and virtual needle as seen through the Magic Leap glasses.

4.3 Tracking Solutions

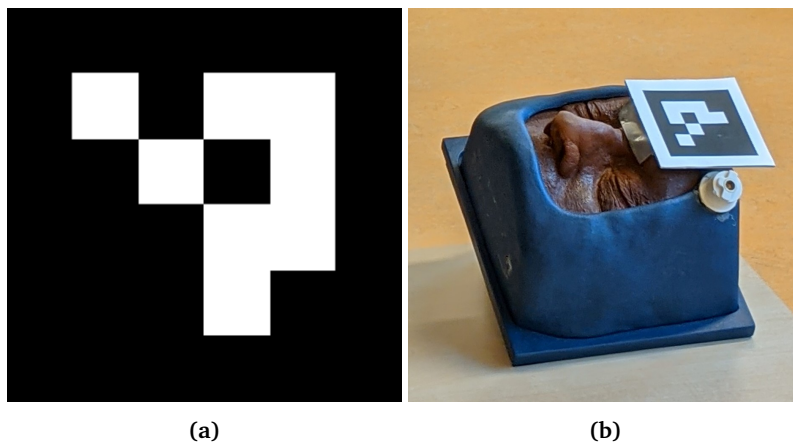


Figure 4.8: The mannequin head with the ArUco marker attached.

Central to the project is the task of combining the real and virtual into a mixed reality. While spatial perception is evolving rapidly, it is still lacking when it comes to tracking individual objects' orientation. For the AR device to do this accurately, aid in the form of a tracking solution is necessary. A combination of methods were used to form the complete spatial understanding solution, where both magnetic and visual sensors were used (see 6.3.1).

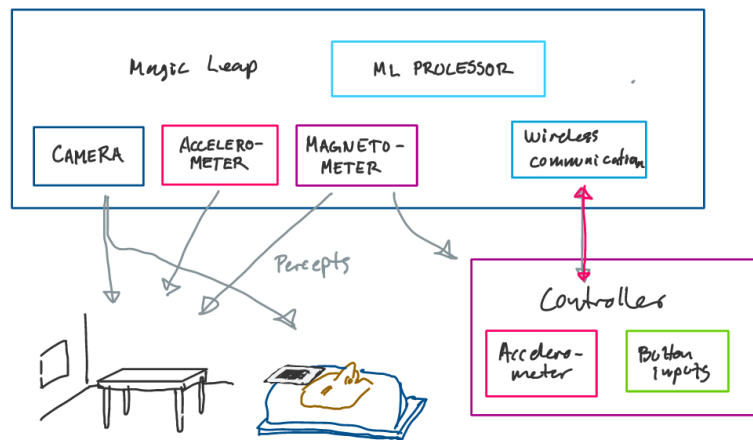


Figure 4.9: The different perception sensors and their input.

4.4 Software Architecture

4.4.1 Unity Game Engine

The program that runs on the Magic Leap is a Unity application, which is a game engine that offers decent performance and good utility. A key aspect of this game engine is the community that surrounds it. It makes it trivial to access a huge library of online resources and learning material. Examples are also readily available, as well as large number of users in various chat rooms. This fulfills some of maintainability requirements, as maintainers are more likely to be proficient or find help with a popular game engine.

Unity also offers support for many devices and platforms, opening up the potential to port the application to headsets and add support for external tracking solutions. This aids in satisfying the goal of portability (NR25-27) in a rapidly changing hardware environment.

4.4.2 Prefab Pattern

The solution makes use of the Unity pattern called prefabs, short for prefabricated. It is a pattern that allows game objects to be composed in the game engine, and be instantiated independent of the scene it resides in. This is a way to loosely couple the code and enable quick changes to game object without directly changing the scene (NR21-22).

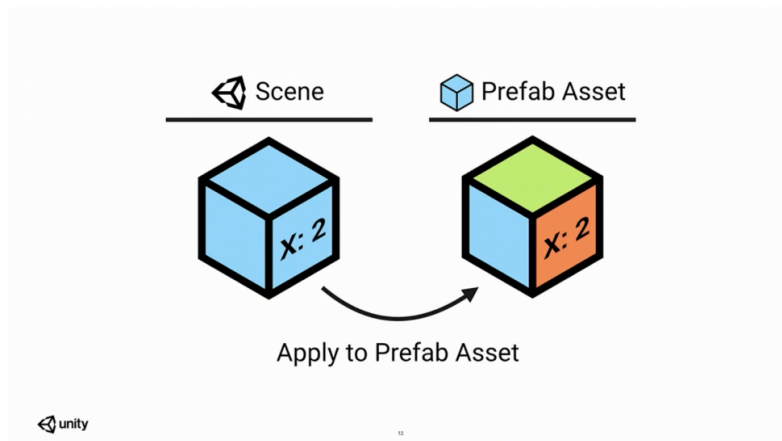


Figure 4.10: Illustration highlighting the difference between normal scene game-objects and prefabs.

4.4.3 Events vs. Direct Coupling

Direct Coupling is used between prefabs. This is a way to expose interfaces between objects at a top level. The references are then passed down to classes in the hierarchy under the prefab root. A system like this is quick and efficient in a project of this size.

With the potential for the project to grow, a natural result is that the linking between objects increase. To mitigate this, an event system was implemented. This is an implementation of the built in C# event system, a pattern which facilitates communication from one object to many. Ultimately, the event system was not used in the delivered product, but it remains in the source code in case the project is to be extended.

4.4.4 Object Oriented vs. Entity Component System

The software architecture of Unity is often mistakenly assumed to use an Entity Component System (ECS). This is not true in most cases, as Unity only got support for ECS in recent years. Unity's ECS, called Data-Oriented Technology Stack (DOTS), is highly performant, but requires a different setup in code to be enabled.

The benefits are also minuscule when the number of objects in a scene is as few as this solution requires. Therefore, the methodology utilized in this project is the default paradigm in Unity, Object Oriented Programming (OOP), with game object scripts inheriting from a base class called `MonoBehaviour`.

4.5 User Experience Design

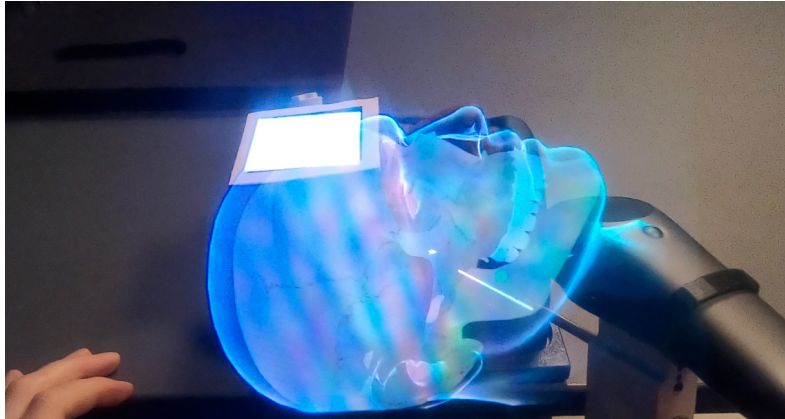


Figure 4.11: The mannequin head with the hologram overlaid. Picture taken through the Magic Leap glasses.

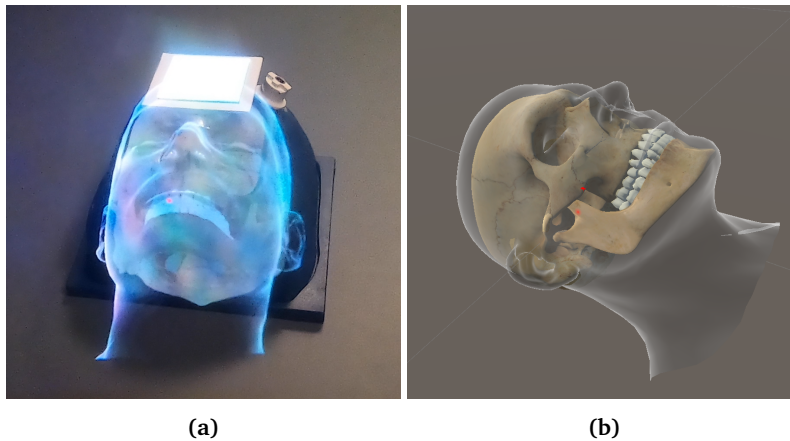


Figure 4.12: Comparison of visuals through the Magic Leap glasses and the Unity editor.

4.5.1 Esthetics and Visualization

A key ASR for the design of the UI is NR4, which says that it should be easy to locate the target, navigate and get a good spatial understanding of the geometry. This led to the decision of making the SPG visible at all times through the anatomical layers. With the 3D capabilities of AR and the depth perception it provides, it becomes naturally obvious where the SPG is located. This is true despite the SPG anatomical layer of skin and bone in front of where the SPG. In a realistic setting, the SPG would be occluded by the outside. In this app, use of a



Figure 4.13: The view through the glasses of the custom MultiGuide and the hologram needle in white.

special shader enable viewing it through 3D geometry from all angles, unoccluded by any geometry.

4.5.2 UX Design Principles

The application follows a set of principles to facilitate learning and user satisfaction. As this application is centered around a real world process, a key design principle has been that the augmented reality should only add to the real world experience. What this means for the application is to avoid a typical pitfall of AR, where the virtual images becomes distracting to the real world process. Whatever benefits are had by augmenting, are quickly lost in applications that overload the user with information and options.

E-learning Principles

This is closely tied to the e-learning principles (see 2.2.3) of *coherency*, where the best learning happens when the learning environment only includes relevant media to avoid distractions. As the application only enhances the user's perception visually, it embodies the *Learner Control Principle*. This is an attribute that is inherently present in the traditional method of using only the mannequin head and MultiGuide, as it can be played with at the user's will. As with physical objects, the user simply interacts and learns at their own pace, without any external force guiding their attention or pushing for action. This reduces stressful factors, which can be a detriment to learning, and empowers users to explore at their own pace. It also means that there is no system in which the user can fail, as goals are inherently self-defined. As a result, curiosity functions as a driving force for learning when focus can be shifted to any point of interest at the users will.

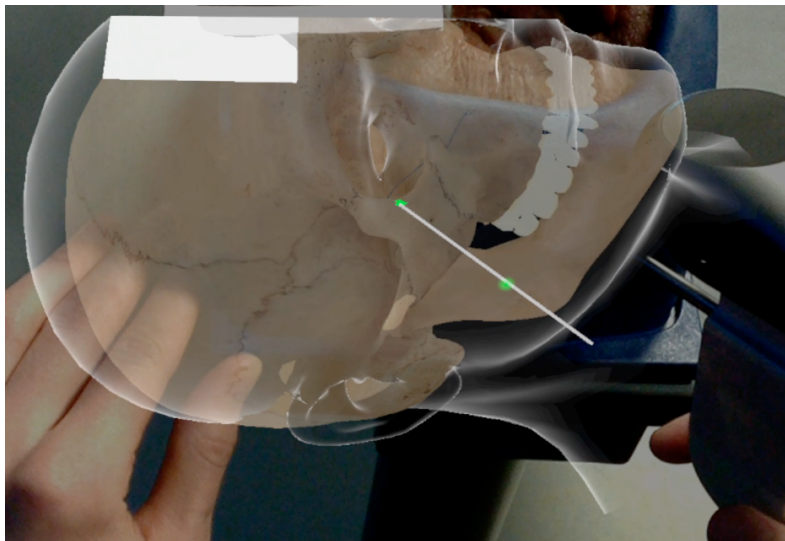


Figure 4.14: Image taken through the glasses when performing the procedure. Here, the entry point and SPG is visibly green as they are hit by the needle.

Lean Development Principles

The project also follows the *Lean software development* principles, and key among them is the focus on eliminating waste. What this means for the design of the application is that extra features are a distraction for both the developer and user. Focus should be on the core set of features, as partially done work is also seen as waste. The result is that the features which are present aim to be as solid as possible and part of the integral whole.

Chapter 5

Development Process

5.1 Process Model

For a relatively small project, having many frameworks and process models to adhere to can be daunting, especially in a one-man project like this. Many of the formalized methods are partly methods for facilitating collaboration between team members, where certain traditions are to be followed strictly, such as breaking up work into sprints or having daily stand-up meetings.

Such practices have not been strictly applied in this project. According to my personal experience, there is a trade-off between the amount of time spent in managerial tasks and the benefit they reap, and the rigidity in processes is especially difficult in projects with fewer team members and a shorter project time span. It is therefore the philosophy of this project that the overhead in work associated with following any software methodology to the letter would be a detriment to the project's success. Rather than following any one method strictly, a set of principles and practices have been adopted as long as they benefit the project and as far as circumstance would allow (see 7.1.2).

5.1.1 Agile Development

A core guiding principle is that of agile development. In this project, this means a focus on iteration, early delivery of Minimal Viable Product (MVP), rapid testing and awareness of changing requirements.

This project is a mix between research and development. Questions as to whether this combination of AR and physical reality can be reasonably done, and whether the product ends up being exactly what the customer wanted are two different questions. The former is a more technical challenge:

Is it possible to implement with the current technology?

The latter is more focused on the human part of the equation:

Will the proposed design benefit humans?

The project has therefore shifted from a *waterfall* software development method in the beginning of the project, to a more agile mindset in the second half, as a prototype materialized and incrementally improved.

The divide is not so clear however, as iteration and cyclic processes are central to agile, where this project only has three meaningfully distinctive phases. It has always been the intention to keep iterating rapidly, but a number of factors have played into longer and fewer development phases. Part of the reason is the focus on a core set of features that are hard to implement, which can not be meaningfully tested by users before near completion. While the I has some experience in the field, it is an entirely different tool set and hardware for me as a developer. It is therefore difficult to estimate the time it will take to implement features, and a rule of thumb is that it usually takes 2-3 times as long. Among other reasons is a fairly busy stakeholder, who could not meet regularly as perhaps an agile method would advice. However, the most severe impacts were felt due to the the COVID-19 pandemic and the extra restrictions that places on visiting medical researchers and their facilities.

Nevertheless, most of agile's concepts are preserved, and this is done for a number of reasons. First of all, the application is inherently user facing, and therefore has a human element at the core. Agile methods tries to expect changes in requirements and direction, which is to be expected in any project. It is however especially true in projects that involve human interaction, which is why interaction design is fundamentally a user oriented practice. Predicting human interaction in regular 2D UIs is hard. AR is a different level of uncertainty when it comes to UX design. Modern AR has not been present for more than a few years, and is still far from mainstream adoption. There is therefore no recipes for success to build on. Major uncertainty in decisions for UX design needs to be accounted for, which is why an iterative design process is best suited when venturing into AR territory. In some contexts, this process is referred to as *Design Thinking* or a *Human Centered Design Process*.

5.1.2 Lean Development

One agile method that has been followed more closely is the *Lean Software Development Method*. It consists of 7 principles for success in software development. While they all have been implemented to some extent, I wish to highlight the ones listed below.

- Eliminate waste
- Amplify learning

- Decide as late as possible
- Deliver as fast as possible

5.1.3 Kanban

Kanban is a method of visualizing work, by placing cards representing task in categories of level of completion. The method serves many purposes in a larger project, but in this project it is mainly used for two reasons.

1. Organize tasks in simple and clear manner
2. Visualize progress for motivation

5.2 Development log

This section details the events that transpired during the entire time the project was active, from initially taking it over, to delivery and handover of the final product. That includes the specialization project the first semester, also done as part of the same project. It details which plans were made, which tasks were focused, analysis and feedback from testing, and decisions made to improve and iterate on the product. In essence, it serves as a log, and should reflect how the process model covered in the previous section 5.1 was implemented, but also how circumstance at times required me to deviate from the model.

5.2.1 COVID-19 Pandemic

It is important to note that the COVID-19 pandemic became a global problem during the entire span of this project. This affected the project in many ways, by limiting social contact, and at times closing the entire university and research lab. This meant little access to both equipment and stakeholders.

5.2.2 Project Initialization

Project Scoping

After the initial project pitch and takeover, a familiarizing phase started. The goal was to research the MultiGuide procedure, the previous project's research and software, as well as the Magic Leap hardware and software libraries. A deep dive into the state of the art, similar work in the field, and getting familiar with the tools are important steps to take early on. This would give greater insight and understanding of the project's scope and set more realistic expectations. Rough estimation is an important aspect of software development, and it needs information and experience for accuracy, although large inaccuracies in estimation

is to be expected. Familiarity with especially software libraries for the Magic Leap, but also the legacy code of the previous project have potential to cut down development time if any prebuilt solutions can be applied. Making the right decisions is also important, as the decisions made will have an impact on the rest of the project. This is true even for an agile project, as certain requirements are *Architecturally Significant Requirements (ASRs)*, and matter especially in choice of hardware, software framework and tracking solutions. This includes questioning the requirements that was handed to me.

Design Fundamentals

To evaluate the initial requirements and set the course ahead, a first principle analysis was performed. The goal of this activity is to get to break down a problem into its individual first principles, the foundational propositions or assumptions about the problem. When left with only the basic elements, they can be rebuilt to verify your reasoning and serves as a tool to improve clarity about a problem.

The initial requirements were the use of the mannequin head for haptic feedback and the Magic Leap headset to handle the simulation. Using the mannequin head is based on two assumptions. First is the result from the previous master project that found that simulating a procedure without the physical interactivity between objects was insufficient. This assumption can not be further tested or verified without implementation and testing. Second is the assumption that the mannequin head would be a fitting physical object to provide this resistance.

The other requirement is the use of the Magic Leap headset. This assumes that the headset will satisfy visual information, sensory and computational needs. The visual and computational aspects is tested and satisfied in previous projects. Providing haptic feedback from physical objects that are also represented as virtual objects, would require some calibration between the two realities. Calibration can only happen through the use of some sensory capability. The typical solutions for this type of calibration is through the use of sensors in the visual spectrum, infrared spectrum or magnetic field. If only the the Magic Leap is to be used, best supported methods are visual spectrum sensing using a camera and magnetic field tracking using the controller. It is potentially possible to use the IR capabilities of the Magic Leap, but this is not an officially supported option. Other options would require external sensory equipment.

5.2.3 First Implementation Phase

At the start of development, there was a clear goal set of reaching an Minimal Viable Product (MVP), and the basic requirements were also set. The requirements consisted mainly of utilizing the Magic Leap and integrating the mannequin head into the simulation for haptic feedback. The first problem that needed to be tackled

was the tracking mechanism. Researching options for the Magic Leap led to the somewhat disappointing discovery that very few options were available for Magic Leap and provided as part of the Unity SDK. Alternatives would require a third party solution, such as Vuforia or and OpenCV package for Unity. Finally we had the option of using an external tracking solution, such as Brainlab Kick (2.2). With the very limited access to the hospital and its hardware, this was a hopeless alternative at that moment. As discussed previously in section 5.2.2, it was not immediately obvious why the application would not be better suited in VR, as that would provide very accurate tracking solutions.

I ended up choosing the image tracking feature that had the best integration with Unity, to build the first prototype. At first, only a basic test was done where a cube was spawned over the image. The image recognition worked relatively well, and boosted confidence in the method. It was not completely flawless, as when it was actively tracking the image, the accuracy would fluctuate, resulting in a *jittery* tracking. A quick solution to this was to only use the image for placing the cube initially, then use the spatial mapping to lock the cube to that position. This is still problematic in some ways, as the placement algorithm was very simple at first, as it only triggered on a timer after the image was initially discovered. If the tracking was inaccurate at the moment it locked, the placement of the cube would happen at an offset position. This problem was left for later as it functioned well enough for an MVP.

Next on the list was the procedure simulation and visualisation part. This part consists of the anatomy visualisations and surgical navigation. The easiest and first step to an MVP is adding the anatomy head. When doing this, some work was done by looking at the previous students work and their code, hoping that some parts could be salvaged. Some of the 3D models they had created was extracted from the project, but otherwise it seemed hard to work with the legacy project, and probably easier to create the rest from scratch. This was also a result of not being able to see the result of the previous project in anything but pictures, as no video or build of the project was left. The models that was extracted was a detailed skull, a head with several anatomical layers, and 3D scans of the MultiGuide and mannequin head. At first, the anatomically layered head seemed like the most fitting model, and it was added to the project as a replacement for the cube. The virtual head would be offset from the tracking image, and the mannequin would be positioned at a fixed location relative to the image marker. In this way the offset could be manually adjusted to where the virtual and real head was aligned.

The first prototype used directional lighting, which is computationally expensive and not really fitting for mobile devices. While not ideal, the Magic Leap proved to be a powerful device that could handle the workload for testing purposes. It did also help reveal some problems with the models, as their normals appeared to be wrong, resulting in shadows that would look wrong. It was unclear at the time why and how to best fix this, so this was ignored for the time being.

Next task was to make the target of the procedure, the SPG, visible through the model. For this purpose, the rendering of objects can be modified through the use of programs that only run on the GPU, called shaders. The effort started by looking for shaders available online, more specifically for a type of highlight shader. They are fairly common, but it was problematic to get them to run on the Magic Leap, as they would look perfect in the editor window on the computer, but would only render on the left eye when wearing the Magic Leap. Figuring out a solution to this problem was difficult, the shaders that were tested did not work as intended. Luckily, one malfunctioning shader ended as a workable result. The intention was that it would highlight the edges of the SPG, it instead colored the entire SPG in white. Although unintentional, this was a good enough result for a first prototype.

Unfortunately, the pandemic made it difficult to demonstrate the current prototype, so more fixes were made. A sphere was used temporarily as a placeholder for the SPG. This was not a good solution as it did not show the SPG anatomy at all. When studying the anatomically layered head, it was discovered that the skull in this model was extremely inaccurate, and could not be used as it did not even feature an opening where the procedure should be performed. On the other hand was the 3D model of a standalone skull, and this even featured the nervous system and a fully modelled SPG. It was decided to combine the two models, by removing the old skull and inserting the anatomically accurate skull and see how they fit. As someone with little experience working with 3D models, this proved to be more difficult than expected, and it required a lot of time learning the basics of Blender. The skull ended up not matching perfectly, and part of the skull would protrude out the back of the head, but it was better than the alternative. Since managing the models ended up being difficult, the sphere remained as a placeholder for the time being.

At this point it became uncertain if an in person demonstration would be possible, so focus shifted towards making a video that could demonstrate the prototype for the stakeholders. A problem with this is that filming video from the Magic Leap's built in recording functionality resulted in all the holograms being offset from their position when viewed from inside the glasses. This meant that a core achievement of the prototype, the alignment of real and virtual objects, would not be possible to view on video. Despite this a video was made, and the resulting video can be seen at [this YouTube link](#), or by following the QR code in figure 5.1.

A video call was held in place of a meeting, and the video demo was showed. The feedback and consensus from this demo was that this was a good first step, and that going forward the focus should be on integrating the MultiGuide and the controller to track the needle. The second priority should be to add some sort of guidance to help the user navigate and perform the procedure correctly. Third and fourth priority that could be addressed, was a better 3D model and an exploration mode respectively. Despite the pandemic, an in person demonstration was scheduled a week after this video call, but no new noteworthy feedback was



Figure 5.1: QR link to the first video. Alternatively [click here](#).

received during the demonstration.

5.2.4 Second Implementation Phase

The first task for this phase was the combination of MultiGuide and controller. Since the controller is already tracked by the Magic Leap by default, the problem then becomes how to attach the controller to the MultiGuide. The three methods that were identified were

1. Loosely attach with some tape and rubber bands
2. Tightly attach with lots of tape
3. Create a 3D printed attachment piece

The first two options would be relatively easy, as they only require readily available tools and little skill. The difference between the two is the degree to which they can be disassembled. A loose attachment might also not be able to provide sufficient sturdiness to prevent shifting, something that would ruin the alignment. The third option was also problematic, because I had no skill in making 3D printed parts and no ability to estimate how much time doing that would take.

It was therefore decided to do the second alternative, as it struck a balance between simplicity and ability. It would take some time to assemble, and would be awkward to use when navigating Magic Leap menus during boot, but it would have to make do. A piece of foam was cut out and taped tightly, and grooves for the controller was cut out. Despite expectations, it did not require tightly taping the controller to the foam to get it to be sturdy enough, so small rubber band was strapped around to keep it in place.

The next step was implementing the visual feedback and navigation aid. The first step was to remove the old sphere that functioned as a temporary SPG. The SPG model was then cut out and extracted from the detailed skull model. A MeshCollider was added to the model in Unity, something that would allow for raycasting and checking if the model is pointed at.

Now that the controller had been attached to the MultiGuide, it was time to

create a virtual needle. This would serve as the point from which calculations could be made to figure out if the needle was hitting the SPG. A cylinder object was also added to visualise the position of the virtual needle.

Surgical navigation would be provided by a feature that was initially described as a "lighthouse" system, where the SPG would change color when pointed at. The problem was the shader that unintentionally worked to highlight the SPG, provided no method to set the color. It was therefore necessary to study shaders more and figure out a way to write one that allows it to change color. Some guides were followed online to learn about shaders, and a highlight shader was implemented in a Unity test project. This resulted in the same problem as earlier, where the object with the shader would only render on the left eye.

After some research, the problem was found to be a special mode of rendering called single pass stereoscopic rendering. This is a way for the GPU to minimize overhead when rendering from two virtual cameras, one for each eye, thus increasing performance. This was incompatible with the standard way of writing shaders. First I tried to switch to dual pass rendering, but this caused more issues. Eventually, with the help of a Unity wikipege, and a template shader provided as part of the Magic Leap SDK, a functioning highlight shader that would make objects visible through other objects was made.

As research had gone into the development of shaders, a special kind of shader called a Fresnel shader, or rim light shader, was discovered. This was a potential solution to the next problem of improving the visuals. At this point in development, very little work had gone into the look of the models. It was a problem that the outer anatomical layers overpowered the more relevant bone layer beneath. The Fresnel shader made it possible to only color objects around the contours of the geometry, reducing the distractions and visual clutter. Some experimentation was done with this method, and it was attempted to have the skin be translucent and the skull have the Fresnel shader. This was scrapped in favor of showing the full textured skull and surrounding it with the skin layer with the Fresnel shader applied, as Stakeholder 1 thought it was a negative tradeoff.

With the virtual needle and the updated SPG shader, it was now time for adding the surgical navigation indicator. This would be a simple mechanism to help guide users to the right angle by changing the color of the SPG when the angle of the needle was right. This was implemented with a simple raycast that changed the color of the SPG when a hit was registered.

A problem at this point that became apparent, was the lack of indication of where the entry point of the procedure is. The solution to this was a texture that was place at the entry, and similar to the SPG, it changes color when being hit. The demo video from this phase can be seen in figure 5.2, and a demo video created shortly after illustrates the MultiGuide attachment piece, and can be seen in the video linked in figure 5.3.



Figure 5.2: QR link to the second video. Alternatively [click here](#).



Figure 5.3: QR link to the third video. Alternatively [click here](#).

5.2.5 Third implementation Phase

The more informal user testing and demonstrations that were done after the second phase, was a good opportunity to learn. It was a great moment in the project, as it seemed to demonstrate actual usefulness in its more complete form, and provided some relief by proving the design viable.

One problem that became apparent was that the current tracking solution where an image was positioned next to the mannequin was very flawed. Users would accidentally push the head and ruin the alignment, so a marker attached to the mannequin would be the ideal option. Testing was done with smaller image markers, but the effectiveness of the images really diminished with smaller sizes. The more common fiducial marker for AR applications, are ArUco markers. These were well known, but no official method of using them was found, and using a plug in for Unity was discussed. As a stroke of luck, Magic Leap released v 0.25.0 of their SDK for Unity in January of 2021, and this included support for ArUco markers. The marker functionality was added and markers were printed and attached to the mannequin.

The next most pressing problem was the attachment piece created from foam and tape. It functioned well to verify the viability of using the controller for tracking, but was far from a solution that could be delivered to a customer. Thus, the remaining development time was spent learning modelling in Blender, and

eventually a piece was made ready for printing. This was the first 3D print I had ever done, so with the help of a research lab at St. Olav's University Hospital, the piece was finally printed. It came out surprisingly strong and accurate, but the inexperience led to one big mistake: the piece did not have enough room for the controller to fit nicely. This was due to not adding margins to the measurements, as well as non-smoothed curves that were displayed as smooth in Blender. In addition, the 3D printed material appeared to expand slightly outside the boundaries. While a new 3D print could have been made, this would require organizing with the research lab, and this would take time. Instead, sand paper and scissors did the job of grinding down the excess material, and after about 10 hours the piece finally fit. The virtual needle was then realigned to the new position.

At this point, development was close to an end, but a problem remained from early on in the project. The tracking and placement of the hologram would still happen as a poorly implemented automatic feature, but this gave no control and would often result in misalignment. The ideal automatic placement feature had been considered for a long time now, and some work had gone into finding the best way to average out the jittering, and find a value as close to the real position as possible. While this feature had potential to be great, time was running out and it was decided to make a simpler solution that could potentially be just as powerful if the users could handle it. Spending time on such a feature would also be unwise before further testing. The solution then was to add linear interpolation to the change in position of the hologram. This resulted in a smooth movement of the hologram. The final piece was a simple locking mechanism that would toggle the tracking on and off. This allows the user to manually decide when the hologram is in the right position and then lock it there.

5.3 Tools

5.3.1 Task Management (Kanban board)

- Trello
- Post-its & Whiteboard

5.3.2 Documentation

- OneNote
- Overleaf
- Git & VCS

5.3.3 Communication

- Slack

- E-mail
- Video Conferencing i.e. Zoom

5.3.4 Demonstrations

- YouTube
- The Lab Streaming

Chapter 6

Implementation

6.1 Equipment

6.1.1 Magic Leap

The previous project used both the HoloLens 1st generation, and later the Magic Leap. The choice of hardware was made based on results from the previous project and the technical constraints. Part of their project was to test out the various kinds of Head Mounted Displays, where the Magic Leap came out on top.

The Magic Leap has a much more powerful Graphics Processing Unit (GPU) than the HoloLens 1, making it ideal for visualising 3D models with a higher polygon count. The more polygons a model has, the more computational resources are necessary for a smooth experience. This makes it possible to use existing 3D models without having to do extra work, such as retopology and use of culling and Hidden Surface Removal (HSR) algorithms.

Another deciding factor is the inclusion of a controller with the Magic Leap, making it an easy way to track the Multiguide.

6.1.2 Multiguide and Mannequin Head

The Multiguide is an injection tool developed at St. Olav's University Hospital. See figure 2.1. The mannequin head is a dummy head used to practice with the MultiGuide, see figure 4.3. It provides the physical feedback to simulate using the MultiGuide.

Table 6.1: Hardware specifications for the Magic Leap 1

Hardware	Details
CPU	2 Denver 2.0 64-bit cores + 4 ARM Cortex A57 64-bit cores (2 A57's and 1 Denver accessible to applications)
GPU	NVIDIA Pascal™, 256 CUDA cores Graphic APIs: OpenGL 4.5, Vulkan, OpenGL ES 3.3+
RAM	8 GB (4 gigabytes of memory available to applications)
Storage Capacity	128 GB (approximately 95 GB available to applications)
Audio Input	Voice (speech to text) + real world audio (ambient)
Audio Output	Onboard speakers and 3.5mm jack with audio spatialization processing
Connectivity	Bluetooth 4.2, WiFi 802.11ac/b/g/n, USB-C
Power	Built-in rechargeable lithium-ion battery. Up to 3 hours continuous use. Battery life can vary based on use cases. Power level will be sustained when connected to an AC outlet. 45-watt USB-C charger.

Table 6.2: Hardware specifications for the Magic Leap 1 Control

Hardware	Details
Haptics	LRA Haptic Device
Tracking	6DOF (position and orientation)
Touchpad	Touch sensitive
LEDs	12-LED (RGB) ring with diffuser
Power	Built-in rechargeable lithium-ion battery. Up to 7.5 hrs continuous use. 15-watt USB-C charger
Other Inputs	8-bit resolution Trigger Button, Digital Bumper Button, Digital Home Button

6.2 Software Tools

6.2.1 Unity

¹The main tool used for creating the 3D application was Unity, a popular cross-platform game engine. Magic Leap supports various platforms and game engines, that have different advantages and characteristics. The choice of Unity as the development platform, was made mainly based on two reasons. Firstly, the previous SpheNOBlock projects had used Unity, so to make it easier to continue the project, Unity was a must. Secondly, Unity is the platform that I have the most experience with. Unity is also the most popular game engine, and therefore is the most supported among AR developers.

6.2.2 The Lab

Development for the Magic Leap platform is centered around their proprietary software, called The Lab. This piece of software consolidates several tools and utilities in one place. Features include:

- Device management
- Software package manager
- Zero Iteration
- Magic Leap SDK

Device management consists of connecting and detecting the Magic Leap headset, creating a connection over WIFI, and managing installed apps on the headset. The package manager lets developers download and install the necessary software for development conveniently in one place. This includes installing Unity, the Magic Leap SDK, as well as utilities like Zero Iteration, Device Stream, emulation software and various debugging software.

6.2.3 Magic Leap SDK and Toolkit

Through The Lab (6.2.2), developers are provided the SDK necessary for programs made in Unity to run on the Magic Leap. This SDK comes as a package that is downloaded through The Lab's package manager, and is installed through Unity's package manager.

¹Section reworked from my project thesis [12]

6.2.4 Blender

Blender is an open source, versatile 3D modelling and rendering software. It has become more popular over time, and has great compatibility with the other tools used in this project. Use of the software was mostly modifying the 3D anatomical model that would be superimposed on the mannequin. It was used to adjust, combine and organise the 3D models, so that each part of the model could be easily addressed. Blender has the option of importing files directly into Unity as a .blend file, or to export it as an .fbx file, which is the current industry standard.

6.3 Core Components

6.3.1 Fiducial Marker Tracking

The goal of combining real and virtual objects is achieved with the on-board camera and a reference point positioned in a fixed position relative to the physical object. This reference point is called a fiducial marker, and it is a marker that can be recognized by image processing. The marker features a distinct black and white color scheme, and has an encoded ordering to its pattern. This means that many different markers can be individually recognized based on their pattern. For best recognition, the marker features a clear white border around its edges. As the marker is of a known size, the image processing can calculate the distance and orientation of the object, relative to the camera. An advantage of the ArUco markers compared to image recognition is that it is less computationally expensive and works at more sizes.

6.3.2 3D Anatomical Models

The anatomical 3D model used in this project is a combination of two models. The first one provides different anatomical layers of skin, muscle, and various veins and nervous systems. The second is modelled more accurately after a skull, and also features some nerves and various nerve nodes, called ganglia. Most important is the Sphenopalatine Ganglion, or SPG for short. These individual meshes are separated and grouped, as well as collected with scripts in Unity as prefabrications, also called Prefabs. This lets each layer be easily addressed for simpler scripting.

Additionally, photogrammetry has been used to scan the mannequin head, providing an at scale 3D model. This model is useful when markers are changed and recalibrating the offset is needed.

6.3.3 Shaders

Special shaders have been made for various purposes. One shader helps with highlighting the SPG through external geometry that would normally occlude it. This lets the user see its exact position with both eyes through all the anatomical layers in front. This is implemented by moving the rendering further back in the queue so that it is drawn on top of all the other geometry. The shader also allows scripts to set the color of the SPG through a parameter, which is used as a form of visual feedback. This is a simple parameter that changes the fragment value in the shader.

Another shader that was implemented is the Fresnel shader, also known as a rim highlighter. This shader enable visualizing objects without cluttering the users view with graphics. This calculates the angle between the camera and the surface normal of polygons. The closer the angle is to 90 degrees, the brighter the color. A parameter sets the intensity of the shader, which affects how big the angle needs to be before it colors the object. The fragment color of the Fresnel shader can be set with a parameter.

The shaders used in this project supports single pass stereoscopic rendering for increased graphical performance. This lets the GPU render the scene in a single pass from two cameras, without instantiating objects twice from memory.

6.3.4 Surgical Navigation

The surgical navigation that was implemented helps users achieve the right angle when penetrating the skin. This is done by changing the color of the SPG when the user gets the right angle and the needle is pointing straight at it.

This is implemented as a simple raycast going from the tip of the needle to the SPG, travelling a bit further than the distance from the entry point on the skin to the SPG, to give the user room to aim before the skin is hit.

Chapter 7

Testing

This section details the testing part of the agile development project. Details about methods and strategies used are explained here, and should highlight why this testing methodology was chosen.

7.1 Stakeholder Meetings

As an agile project, testing has been important role in ending a development phase and gathering feedback and results. As there were three development phases, one meeting was held at the end of each period with the main stakeholder as the only participant. This stakeholder is a neurologist at St. Olav's University Hospital and involved in the development and commercialization of the MultiGuide. Here, the participant got to play around with the product in an informal setting.

7.1.1 Consent

For the sake of the participants privacy rights, a consent form was filled out granting rights to use the results of the test in this project. The form used can be found in appendix B.

7.1.2 COVID-19 Precautions

Due to the COVID-19 pandemic, all gear had to be prepared meticulously. The first step was to run the Magic Leap headset through a UV cleaning machine, specially made for wearable mixed reality headsets. If the test was held at a remote location, such as St. Olav's University Hospital, this step needed to be prepared in advance. The gear would also be carefully sprayed and rubbed with disinfectant, and clean hands when handling the gear was important. A special mask for wearing mixed reality headsets was provided to the participant, visible in figure 7.1.



Figure 7.1: Mixed Reality "Zorro" masks, as part of the COVID-19 measures taken.

7.1.3 Demonstration

With the prerequisites out of the way, the demo would start. It would be recorded and transcribed after, so that every detail would be preserved. The application would be started and the participant was handed the gear and instructed on how to put it on. Instructions would be given on how to operate the application, which depended on what stage in development the demo was given.

7.1.4 Interview

After the application had been tested, an interview followed. The participant was asked a series of questions, some of the regular for each demo, and some unique to a feature or task that was new at that version. The regular questions was framed to give some level of satisfaction with the current prototype, as the best means of gathering quantitative data.

Interview Questions

1. How would you describe the overall experience?
2. What did you like?
3. What did you not like?
4. Any surprises?
5. Any annoyances?
6. Any recommendations?

Unstructured Interview

A more free discussion followed after the questions. The key topic that was discussed were to what degree our goals had been met, whether this is still the right path forward and any potential changes in priorities.

7.2 Usability Testing

Near the end of the project, the application had reached a level of maturity where it was deemed wise to do more user testing. This section details the steps that were taken to let 5 participants do user tests. The goal of these usability tests were to test the application and figure out how ready it is for release, by testing it on several people in hopes that design flaws are revealed. Usability test usually have users and observers. Users are the test subjects who perform the tasks given by the observer. It is often common to have the observer in a different room, to avoid any influence from a second person on the users behaviour. This is referred to as *remote testing*.^[31] It prevents users from having subconscious feelings of wanting to please the observer, by for instance not failing, among other effects.

This type of setup would not be possible in this test, as observing an ongoing test in AR provides many challenges, and can be a technical limitation that requires development time. It was therefore considered sufficient to only observe the user's actions and live commentary.

Extra care was taken when communicating with the participants. To remain as objective as possible, only the strictly necessary information should be given. The principles that were used are as follows:

- **No leading questions:** Avoid leading questions at all cost to not give the user clues. Leading questions will only lead to reinforce the observer's preconceived understanding.
- **No helping the user:** If any problem arises where the user struggles to complete the task, no help should be given and giving up is OK. The only exception is when the user gives up and completing the task is necessary for the next step.
- **Do not give feedback:** No communication should be feedback on how well a task is done. This includes letting the user figure out if the task is complete alone.

7.2.1 Participants

The usability test was intentionally performed on non-medical professionals. The group of five were students in their twenties with no medical background and little to no prior experience with augmented or virtual reality. Due to the COVID-

19 pandemic, participants were in limited supply, so the five participants that participated were known to the observer.

7.2.2 Test Setup

The tests were held in a room where the participant could be alone and undisturbed with the test organizer. All the contamination precautions due to COVID-19, detailed in the previous section 7.1.2, would also be taken here. The user would then be given an introduction of what is about to happen. A checklist would be followed by the observer before any testing happened.

Introduction List

1. Introduce yourself
2. Explain that the purpose of the test is to test the application, not the user
3. The test can be exited whenever the user wants
4. Describe the equipment and any limits of the application
5. Instruct the user to commentate themselves and their actions
6. Explain that no help will be given
7. Describe the exercises and introduce the application
8. Ask for approval to record audio.
9. Ask for any questions

Test Purpose

The purpose of the test was described like this:

- To test the usability of the application, for non-medical personnel
- To learn about any flaws in the application

7.2.3 Tasks

The user was given six tasks:

1. Lock the hologram in place. Move the head to a new location and make sure the hologram ends up locked in the new position
2. Check if the entry point indicator is where the physical entry point is. If not, do step 1 again
3. Point out where the SPG is located on themselves
4. Attach the controller to the MultiGuide
5. Perform injection procedure on SPG
6. Change anatomical layers

Chapter 8

Results

8.1 Stakeholder Meetings

8.1.1 Phase 1

It must be noted that this procedure is a novel technique that only a select few experts are able to properly test, so a limited number of test subjects would be available even without COVID-19. Our test participant was such an expert at St. Olav's Hospital. When testing in person, the participant was able to setup and use the simulation with verbal instructions.

The interviewee commented on the choice of anchoring solution, that it seem like a simple and straight forward approach, that was easy to understand. As the solution utilized a separate picture that was placed near to the mannequin, a question was put forth of whether it would be possible to have the head be sufficient on its own for anchoring. Shaking or stuttering of the hologram was also a concern, but the interviewee seemed to be pleased with the result demonstrated in the video. About visibility, it was commented that it looked realistic, and that for educational purposes, the realism was interesting and could increase anatomical knowledge. On whether it would be ready for training in its current form, it was stated that a visual feedback on performing the procedure right would be necessary, and that the prototype should utilize the Multiguide and Mannequin Head.

Impressions of the prototype was that it was responsive and anchored sufficiently accurate to use in training and demonstration. The participant was particularly impressed with the visual fidelity of the model when displayed with several anatomical layers, as well as the ability to see the sphenopalatine ganglion (SPG) nerve from all angles.

8.1.2 Phase 2

The feedback from the in person demonstration and interview are listed in note-form below:

General Comments

Visuals:

The stakeholder commented that the tool was really great at conveying information. As would be expected from 3D, it gives great depth perception. The stakeholder asked about the needle tip. Should it be always visible or should it occlude? Wants it visible. Would be nice if it looked more like a real needle tip as well. Likes the red and green light in the current iteration. Wants to avoid visual clutter.

Accuracy, potential and improvement from past projects: The app is clearly not completely precise and accurate, but there is a potential for use as surgical navigation system here. Stated that although it is quite good now, it is not viable for use with real patients. The current demonstration is a huge improvement from the previous prototypes.

Using the Hardware:

Entry Point: Struggles with hitting the entry point. Finding it is difficult when the hologram is overlaid. Hits rubber with the needle that has loosened at the entry point of the head.

HoloLens vs. Magic Leap: Likes the simplicity of only using a Magic Leap for demo purposes. In a potentially more realistic setting, HoloLens might be more suited when proper external trackers are used.

Estimated Usefulness

Is it comparable to doing the real procedure? Real procedure uses CT scans, so the visuals are quite different. This application is more an abstraction for visualization purposes, while the real CT scans are more raw data.

Can it be use like it is now?

- Can be used to show patients as an introduction to the procedure.
- Can be used as a demo for other surgeons.
- Can be used at conferences to test the procedure and get an understanding of the difficulty.
- Can be used as an intro to the procedure for medical trainees.

Likes, Dislikes and Surprises

Likes: The stakeholder likes the result of anchoring the hologram and the tactility it provides. **Dislikes:** Does not like having to find the entry point every time you start the procedure. **Surprises:** Better than expected.

8.2 Final Evaluation

8.2.1 Participants

ID	Occupation
P1	Neurologist
P2	Neurosurgeon
P3	Neurology PhD Researcher

The final application was tested by several medical professionals and given an evaluation. The feedback that was received after testing, ordered by the corresponding aspect follows.

8.2.2 Combining real and virtual

All participants noted that the combination of real and virtual was good. Only P1 and P2 had experience with practicing the procedure on the mannequin head, as well as tried the previous master projects, and both said that the combination made the experience significantly better. Although having no experience with the real procedure, P3 said the resistance felt appropriate.

As a surgeon who actually does the real procedure, P2 expanded on the benefits, saying the practice head makes it much more realistic. P2 said pushing against air, like in the previous master project, felt completely different. When using the mannequin head, the needle is locked to one point as it penetrates the rubber foam. This completely changes the moves you can do and how the MultiGuide handles.

8.2.3 Hardware

Magic Leap Headset

It became clear that there was a huge difference in experience between the users and the ease in which they used the headset. P1 and 2 both had previous experience with the headset, and had little problems with wearing it. P3 was new

to the experience and struggled with putting it on and getting the right angle for the screen. This problem was exacerbated by both face and "Zorro", as well as hair that made the headset slide down on the back of the head. P2 was pleased that the headset enabled looking straight ahead, as opposed to previous prototypes that used different headsets, which forced them to look down when performing the procedure.

Head Angle

When giving P2 a demo, they would immediately tilt the mannequin head sideways, and asked for something to support it in this position. A duct tape roll was provided as an improvised support for the head the remainder of the demonstration. This was because, as P2 said, "*the angle needs to be the same as when the procedure is performed.*"

8.2.4 Visuals

Visual Quality and Anatomy

P1 and 2 was impressed by the improved visual quality in the new headset. P2 said the resolution was significantly better, making it easier to see the structures. P2 was however a little dissatisfied with the anatomical layers, saying the accuracy of the model was so bad they could barely recognize the different anatomical parts. P3 said the head was quite anatomic, but could be more accurate. It was a nice middle ground they said: Not too scary for relatives, while still somewhat accurate. The mannequin head on the other hand, with a very accurate casted rubber head, was "*creepy*".

Navigational Indicators

P2 said the navigation indicators were not intuitive and did not immediately understand their function. It was however, understandable with an explanation. P2 was unclear about what triggered the green color, saying that it seemed like a radial distance from the target. From P2's testing, it appeared it was green shortly before it hit and green some distance after, stating that it should only be green where you want to perform the injection.

P3 expressed frustration with the flickering color of the indicator, as the needle would barely miss and rapidly change color.

Alternative Navigation Systems

P2 suggests that maybe a guiding line would be beneficial, although it could be confused with the needle. P2 went on to explain the current navigation system, called *Autopilot*, which is displayed in 2D, using crosses for the three points (needle tip, target and entry point), and rings that stretch between to indicate distance. If it would be possible, this system could be implemented in the AR application as a transitional step to learning the real procedure. The depth perception of AR would make the distances of the rings obvious, and perhaps serve as an easier bridge to understanding the 2D navigational system. Alternatively, P2 said, the two systems could be combined, where the mannequin head could be placed as a patient and set as the target in the real *Autopilot* system, at the same time as the AR application is used. This would give both perspectives at the same time.

Skin Visibility

P2 commented that the skin was only visible tangentially, and that it was invisible on the side facing you. This made it hard to see where the skin actually started, which is important when the needle first enters, but not so much after. Currently it is hard to see when the needle enters the skin. P2 suggested to maybe have the skin visible where the *MultiGuide* points or when it gets close to penetrating, then "crop" it away after.

Virtual Needle

The feedback on the virtual needle was mixed. P2 said it was useful since the real needle is not easily visible with all the visuals that fills the users view. The participant inquired about the possibility of a black virtual needle. P2 explained that what you really want to see, is only the internal anatomy and the target. The physical needle is already there, so having a virtual needle is perhaps redundant. Elaborating further, P2 said it is especially true when even a millimeter difference between the virtual and real needle can be disturbing. This, is because the needle is the center of focus and therefore subject to extra scrutiny. If however, it would not be visible without any aid, then the virtual needle is definitely necessary.

Some further comments were shared about the functionality that made the needle visible. P2 asked if there is a larger volume surrounding the head, maybe 2 meters in diameter, inside of which the virtual needle is visible. This was at least how they interpreted it, which led to some confusion.

8.2.5 Hologram Placement

Stability

When asked about the visuals, all the participants commented that the hologram was nice and steady. P1 and 2 commented that it was especially steady compared to previous master student's projects.

ArUco Marker

All the participants were able to learn the controls for placing the hologram when given instructions. It seemed it was not immediately obvious to the users that the ArUco marker needs to be visible to be tracked. After the P2 had run the demo, P1 was next, and therefore continued the procedure in the angle that P2 had set up. When P1 then tried to reposition the head, the marker was facing away making it impossible to track. P1 then awkwardly had to stand up and lean over to get the marker in view. P2, being in the room, said that the marker should probably be on the side where you will sit when performing the procedure.

8.2.6 General feedback

P3 said the 3D aspect was interesting, and that it gave a different level of intuition about the procedure. The combination of real and virtual was also well executed, and said that the procedure felt less frightening after doing the demonstration.

P2 was impressed with the improvement from the previous project. The visuals were crisp and stable, and the resistance felt from the head made the experience much better.

P1 had played a closer role in development and could therefore not say much that had not been said before. P1's feedback was mostly a general satisfaction with the project reaching its current state. Most new was the 3D printed attachment piece, which seemed to satisfy requirements.

Current Use Cases

When asked about the possible use cases in the current state, all agreed that it was great as a demonstration tool, either for patients or relatives, but also to surgeons in training as a first exposure to the procedure. P1 also seemed interested in using it as general tool for demonstration, and asked for opportunities to show other what the user sees. This would be useful in situations like lectures or conferences where the procedure and MultiGuide tool is demonstrated.

8.3 Usability Test

This section details the interesting finds from the test. All the data from the tasks given during the usability tests, as well as the participants likes, dislikes and recommendations, are listed in appendix A.1.

Locking and Unlocking the Hologram

All participants complete the task, but there were some issues with understanding that the locking mechanism works both ways, meaning that the hologram can be unlocked after being locked. When tested on the accuracy on the placed hologram, it seemed only 2/5 got it right the first time when checking the entry point.

Virtual Needle Offset

After much confusion on the part of the observer, it became clear that the virtual needle was offset from the real needle by a whole centimeter when all the participants tried the application. This was not immediately known, as the application was not tested by the observer in the test environment to minimize contact and virus infection.

The offset made it near impossible to make both indicators green, something all participants found hard and very frustrating. They were also confused about the intention of the indicators, as their intuition was that they should both be green, while being unable to achieve that.

Controller Mapping

Mapping the locking functionality to the trigger on the back of the controller, led one of the participants to push the MultiGuide into the point where the trigger was pressed, and thus unlocked the hologram mid procedure. The trigger also led one user to repeatedly press and hold the trigger to perform the hologram placement. The two buttons to enable and disable anatomical layers was evidently not easy to use, as 3/5 participants struggled to use it.

Headset Angle

One aspect there were no tasks aimed at testing directly, were general comfort when using the Magic Leap. This became an unexpected source of frustration for all of the participants in the usability test. At the beginning of testing, the participants would consistently complain that only the top part of the hologram was visible. The relatively small FOV of the Magic Leap was not communicated to

the participants in advance, and so they had put the headset on, but at an angle where the screen was too far up, making holograms in front of them to only display from the middle up. Apart from communicating this problem, no participant independently solved the issue by adjusting the headset angle. Informing the participants that the headset angle could be adjusted by moving the position on the back of the head, solved the issue for all of them except one. This participant had problems fixing the angle issue, even after instructions were given. As the back of the headset was lifted further up, it would cause hair to bunch up and subsequently cause the headset to slide back down. This was an issue noticed to some degree among all the participants with longer and slippery hair.

Comfort

It became clear that the angle was not the only problem, as general discomfort was expressed about putting all the equipment on, including the masks. One participant complained that the headset was heavy and especially uncomfortable where it rests on the nose.

Unexpected Techniques

With little instructions on best practices when performing the procedure, participants exposed certain weaknesses when using techniques that are not intended, and in some cases not well supported. Observed techniques that broke the *intended* procedure are as follows:

- **Performing the procedure standing**, leading to a steep angle.
- **Pushing the MultiGuide too far**, causing the controller trigger to activate.
- **Holding the MultiGuide sideways**.
- **Not working near the edge of the table**, making a steep angle necessary as the bottom of the MultiGuide would hit the table.
- **Not holding the MultiGuide handle**.

User test 4 (UT4) demonstrated that attaching the MultiGuide with the custom 3D printed piece was easy, as all participants completed the task with no instructions other than to connect the two parts.

8.3.1 Likes, dislikes and Recommendations

The full list of likes, dislikes and recommendations is in appendix A.4. Participants seemed to like the visuals and anatomical layers. They also expressed having fun trying AR and doing the procedure. The dislikes point out the needle offset was a major problem, which is also reflected in the participant's recommendations.

Chapter 9

Discussion

This chapter discusses all the aspects of the project, from technology, design to methodology. To begin the chapter, I share my thoughts on the state of the technology and the ecosystem that surrounds it, from hardware and software, to the design guidelines that exist. I spend a section evaluating my process, then move on to free form discussion of the developed solution. The rest of the chapter is spent discussing the research questions and how well they were met, before finishing up by listing my contributions.

9.1 State of Technology

AR is a quickly developing technology, with constant improvements that make developers' lives easier. In this section we discuss how the current state of the technology impacts the goals of this project, in terms of how it benefitted the project, but also where it has room for improvement.

9.1.1 Hardware

Processing Power

One advantage in this project compared to its predecessors, was the sole use of the Magic Leap and its superior computing power. This made a number of aspects easier during development, such as not having to be an expert game engine programmer to quickly get testable prototypes. Time that would have been spent optimizing graphics and algorithms, could rather be spent making rapid prototypes. More prototypes meant a quicker feedback loop on design, making the potential for iterative improvements higher. As with most user facing software, it is essential to get an MVP in the hands of users quickly. One example of this is the real-time directional lighting that was used in the beginning of the project, a

feature that is graphically expensive and wasteful. With uncertainty about how to do the lighting properly and other concerns that needed to be tested, it was not fixed until much later in the project, as the Magic Leap could handle the work just fine.

Hardware User Friendliness

While some of the more technical problems may have been solved, major challenges lie ahead in solving the human part of the equation. All the users that were tested had some minor issue with putting the Magic Leap headset on properly. This was mainly a problem with the headset sliding up and down the back of users' heads, leading to difficulty with seeing the whole screen. This was especially true with those who had no prior experience with AR headsets, as they had no concept of that there was a screen to be seen properly. In contrast, those who had prior experience knew to correct the headset to where they could see the full screen. This means that there is a slight learning curve to using the Magic Leap.

This leads to a question of whether this is a problem that will remain in AR. One could postulate that AR headsets will increase in popularity, and with it users' knowledge might mitigate this problem entirely. There will however be a period in which users will have their first exposure to AR, and a solution is needed for this period. One solution may be in the design of the hardware itself, ensuring that the design is fool proof and comfortable to use. In my personal opinion, the more modern HoloLens 2 achieves much better usability and comfort, so early indicators may point to this being a problem of the past. At the time of writing, Magic Leap has also announced a new headset which aims to increase comfort. If another iteration of this project were to be made where there are many new users, such as the use case of patients and relatives, or demonstrations given to users at a conference, a more active solution is necessary. This can be in the form of a tutorial or a simple visual indicator of where the edges of the screen are.

9.1.2 Spatial Understanding

Fiducial Marker

Perhaps the most central motivation of this project, that emerged as requirement from previous students' work, was the need for haptic feedback. What remained to be solved then was the alignment of real and virtual spaces, something which is not a simple problem and an area that seems to lack the same amount of focus from the headset manufacturers. This is illustrated by the fact that ArUco tracking was only released as part of the Magic Leap's SDK in early 2021. Before this, the best official choice for tracking was using image recognition, something the manufacturer seemed to intend to be used for context aware interactions and not

real time tracking of objects. This is unfortunate, as effort into better tracking solutions will help enable many areas of application.

Object Detection

The choice to use a fiducial marker turned out to be a relatively good solution for the scope of this project, yet it leaves a desire for better solutions that might require no markers at all. It is easy to imagine functionality that rivals that of our own spatial understanding. Our ability to map the geometry of objects and store them internally, lets us project those objects quite accurately onto our surroundings from the perspective of only two eyes. Some variant of this ability is already present for more static objects, mainly in the form of the spatial mapping feature that maps the user's surroundings, and can recognize an environment. The environment can then be assigned a unique ID, upload some metadata to a server and remain as a reference for future use sessions in the same space. In Magic Leap this is called Persistent Coordinate Frames (PCF), and in Microsoft's case they are called Spatial Anchors.

More relevant for this project is an experimental feature that exists for the Magic Leap called *World Understanding*. This feature aims to recognize objects in the surroundings, categorize them and provide properties such as position, orientation and extents of the object. This would have been an interesting feature for this project, if it was not limited to only five categories of objects, namely couches, chairs, tables, posters and screens.

In general, the reason for lacking features in this area is that these problems are longstanding computer science problems, under the umbrella of computer vision. Neural networks have caused a significant improvement in the field of computer vision, and the problem of joining spatial point clouds (point set registration) is no exception. It remains problematic to run these algorithms on portable devices when they can be computationally expensive, but I expect this to be an area that will see great improvements in the future. The option for running it on servers are always there, but currently there are few options, so this is an area that could see great benefit from more development.

9.1.3 UX Design and Best Practice

An interesting aspect of this project was the design of the visual elements and usage patterns that were envisioned. With the technology being relatively new, it is difficult to find literature and industry standards when approaching this problem. The area of 2D user interfaces has had more than half a century of development and refinement. Even still, a UI made a decade ago is often very different from those made in the present. This may reflect another aspect of UI, which is that it may perhaps only be described as an art form, and that expecting a form of

rule book is a hopeless endeavour. Many guidelines do however exist for 2D, and exploring the possibilities in AR remain an interesting area of research. Questions like what interaction modes work well across 2D and 3D, what works only in 3D, how hand and controller tracking should be approached, as well as combinations of physical and virtual objects, are largely unexplored questions.

A subset of this problem is when real objects virtually tracked, and as expected, this introduces additional complexity. It became clear during this project that a mismatch between tracked objects in the two realities, can cause significant problems for the user. However, users were able to adapt and overcome those issues, and so a complete 1 to 1 may not be necessary for all types of physical objects.

9.2 Process

Perhaps the biggest problem was encountered doing testing without help, as this became a major workload that negatively affected the useful feedback that was received. It became difficult to listen to feedback, while taking notes and asking thoughtful questions. This was partly because of strict privacy laws and a mistaken idea that recordings should be avoided. For later interviews, both recordings and notes were taken, but it is clear in hindsight that the quality of the questions were lacking due to multitasking.

Testing should also ideally have been done sooner, maybe sometime after the second phase, as this would have revealed issues with the project earlier. Unfortunately there were a number of obstacles that prevented running a simple user test. First of all was the fact that early prototypes did not have the locking feature, and rather relied on an automatic placement mechanism. This would often result in misaligned holograms, and as the test observer could not see what the user was doing, it was difficult to know if alignment was done properly. The only solution for this was restarting the application, which required knowledge of the Magic Leap UI and the controller in hand. Since the product in phase 2 used a more permanent solution of attaching the controller, removing it meant the alignment of the virtual needle would be lost. Not removing the controller put the user at risk of accidentally hurting someone or themselves, as focus would be taken away from the sharp needle they were wielding. Moreover, COVID-19 demanded strict procedures, so the observer could not wear the headset shortly before the user and set up the procedure without taking steps to disinfect. Most of these problems went away when a 3D print was created, but the rather simple solution of a locking mechanism would solve them all and was significantly simpler than making the 3D printed model. This is obvious in hindsight, but at the time I had my eyes set on improving the auto-placement feature. Undervaluing the feedback from users unexposed to the project may be another error, as if it was prioritized higher, it may have resulted in testing sooner. That does not necessarily

mean that priorities would change, as the only differences would probably be the positioning of the ArUco marker.

9.3 Stakeholder's Evaluation of the Proposed Solution

The proposed solution did turn out good enough for the customer to justify the price tag on hardware, and the researchers at St. Olav's University Hospital expressed an interest in acquiring the solution for their own use. Somewhat unexpected is their desire to use the solution for demonstration, and while this was an intended use case for patients and relatives, it was not intended as a demonstration tool for external observers not wearing the headset. They asked for the possibility to share the view from the users perspective, as this would enable demonstrations.

9.4 Research Questions

9.4.1 Value of AR in Medical Training

RQ1: What is the value of augmented reality technology in training, especially in the medical field?

¹While the use of AR in medicine is still a novel approach to training, the effects of value of simulation for training skills is well established in learning research. Simulation has the potential to increase confidence, learning retention, while reducing time and cost (see section 2.2.3). AR is especially useful in this sense for its ability to provide 3D spatial visualisations, and is therefore able to provide additional depth to skills with a spatial component. As humans in a spatial world, most skills that involve manipulating objects around us naturally possess such a component is therefore arguably fully realized in AR. While the value of training simulations in medical field have been established [17], this project could not test the effect on learning under the current limitations with limited testing (section 9.6).

So visualizations in AR are valuable for understanding spatial relations, but also to increase interest. With the limited testing that was done for this project, it became immediately clear that even trained professionals were awestruck by relatively simple anatomical visualizations. This enforces e-learning theory's multimedia principle as a way to increase learning through interest, but must be sparingly implemented to only include relevant visualizations, so as to not cause distractions unnecessarily.

¹Section reworked from my project thesis [12]

When combined with procedures that require several considerations to consider and multiples steps, the cognitive load and the working memory can be at capacity, diminishing the effectiveness of learning according to e-learning theory [14]. This is where AR comes in as a simulation and guidance tool. One indication of this is the large investment by major technology companies such as Microsoft, that are marketing HoloLens 2 mainly towards industry, targeting mechanical step-by-step procedures with specialized guidance software [28]. Contrary to the procedure in this project, the mechanical procedures are much longer in duration and number of steps. However many procedures exist in medicine that involve many steps, such as during surgeries, so extending AR to training medical procedures with several steps may prove to be useful. I find that the lessons learned from this project point to AR being a well suited tool for the case that has been studied in this project.

The research that has gone into related work has not found any project that deals with the same scenario. Some projects use mannequins, as seen in [27], but considering the use haptics and procedure simulation for a novel injection technique, this project is one of a kind. It is also very different from other projects in that very little hardware was used. With more testing, this project could hopefully uncover more about its value, and thus serve as a basis for future medical research where AR is involved.

9.4.2 Anchoring Virtual and Real Space

RQ2: What solutions exist for alignment of real and virtual space (a.k.a. anchoring)

²Anchoring is an area of AR that still as huge potential to improve technologically. At the moment there are many different solutions, with varying levels of cost and complexity. The solution chosen for this project is one which only uses the sensors that are already present on the Magic Leap, and is therefore a relatively simple solution. This simplicity comes at a cost, as limitations arise when conditions are not ideal for the sensors to work effectively. While lighting conditions is a rather obvious optimization, less intuitive is perhaps the need for distinct surfaces with clutter, so that spatial perception functions properly. This makes results of anchoring vary depending on familiarity with the training equipment and application. There is however ways that combinations of image tracking and spatial perception can be better optimized, as synergy between the solutions can strengthen the result. In the case of a simpler medical training exercise, such as the one prototyped in this project, tolerances are somewhere under 5-10 mm, meaning that the chosen solutions are able to fulfil non-functional requirement 4 (table 3.4). The requirement for tolerances does make an interesting design decision for this and future engineering on similar topics, and

²Section reworked from my project thesis [12]

must be chosen according to requirements for tolerances and budget. Different solutions for anchoring can be seen in projects such as CTrue, Xvision (section 2.4.2), while the gold standard and boundary pushing technology of ExacTrac, shows the true potential of the technology.

9.4.3 AR Training App

RQ3: Is a training app using the Magic Leap and head mannequin for the Sphenoblock Procedure a viable solution?

The application was built with several uncertain elements that made it difficult to predict the value of the project, even if it would be able to achieve the technical requirements. The question is still difficult to answer at the end of the project, as discussed in section 9.4.1. If we ignore this question for a moment and assume that there is an inherent value in using AR in this context, how viable is the proposed solution? To answer this, we have to look at what worked out well, but more importantly what limitations are imposed by the current design and the Magic Leap.

The application works as a basic simulator, and integrates all the functionality that was envisioned at the start: haptic feedback, some anatomical visuals, SPG highlighting and surgical navigation. Based on comments by the medical professionals, the final result is good enough to be used as part of the introductory training for the procedure. As the real procedure is still being done with a different class of hardware, the app would not be able to replace training with that equipment. It could potentially serve as more than an introduction, as P2, the surgeon, suggested the possibility of using both types of hardware at the same time. Users would be able to train with the proper equipment, while receiving visual aid through AR. This could aid in improving users' spatial ability associated with using the 2D surgical navigation, as the 2D projection would have the 3D "solution" available.

In summary, the solution achieves a lot with very little, and this is an important factor in judging its viability. The Magic Leap headset may not be cheap, but the identified alternatives seem far more complex, less capable and more expensive.

Worthy of note is the use of the Magic Leap controller for tracking the MultiGuide. As experienced during this project, visual marker based tracking is not well suited for precise and fast movements. Alternatives would typically require an externally mounted base station, such as those used in VR pose tracking and the real MultiGuide and the Kick Surgical Navigation System (see figure 2.2).

The setup and configuration that would be required to begin a session with these tools integrated, would significantly raise the effort. Part of the envisioned use case for this project was practitioners running regular simulations to maintain their skill, and in such cases an increased effort can be the deciding factor in viability.

The integrated solution using controller tracking comes with its own downsides, and this became evident during the usability tests. Tracking the controller uses magnetic fields, which means that external fields can impact the accuracy of the controller tracking. It is an uncontrollable factor that varies by location, and can mean large inaccuracies in the tracking of the MultiGuide, which was revealed to be highly problematic for users. It could be possible to implement some sort of calibration method, and this is potentially a way to circumnavigate the problem.

9.5 Contributions

Following is a list of what I consider to be my contributions to the field of AR and medical training:

1. Develop a practical and useful medical AR application
2. Explore simultaneous tracking of multiple objects using different mechanisms, in a practical scenario constrained to one device
3. Explore usability fundamentals in AR
4. Explore interaction design using haptic feedback from objects that are present in both the virtual and physical space
5. Create an AR training simulator for the SphenoBlock procedure

9.6 Limitations

The project suffered from limited testing, and as a result, no quantitative data was collected about the real consequences of training with the system. There were a number of reasons for this, and were unfortunately difficult to avoid. The COVID-19 pandemic began during the first few months of this project. This resulted in restrictions placed by the government on socializing, as well as new challenges solving the problem of running tests without spreading disease. Dealing with medical personnel was even more restricting, leading to less meetings and therefore worse communication between the stakeholders.

Another fundamental problem with gathering quantitative data is the limited frequency in which surgeons perform this procedure. The researchers at St. Olav's University Hospital have only listed around 10 patients as part of their research, which has been running for more than half a decade. The number of surgeons who perform this procedure are few, and surgeons who train for it are non-existent at the moment.

Chapter 10

Conclusion

This project resulted in an AR application that integrates physical objects to provide haptic feedback. The medical procedure it simulates is enhanced visually, which may aid in spatial ability and understanding about the relevant anatomy. The surgeons tested were positive about its usefulness and potential in training, but the results of using this solution remain inconclusive. Data on potential performance improvements were not obtained due to few testers, a problem with the limited occurrence and trainees of the procedure, as well as problems with testing during an ongoing pandemic. The solution is low in complexity, cost and effort, compared to other visual guidance systems, thus being well suited for quick practice sessions and demonstrations.

The project has delved into a largely unexplored area of physical and virtual object alignment. Approaches to usability from other mediums are explored and tested in a new paradigm of augmented reality, pushing the boundary of known best practices in user experience design. Using a combination of virtual and real objects does not appear to subtract from the experience, but based on testing done in this project, provides a more rich experience that can aid in training when the combination is done right.

10.1 Future Work

As the project went on, it became clear that too many use cases started pulling the project in different directions. Further work needs to pick one direction out of the following three:

1. Aim to completely replace current navigation systems for the procedure
2. Become a demonstration tool where the user's perspective can be shared with observers not wearing the headset
3. Expand and improve the current practice simulation

The first option could explore the use of external tracking solutions to improve accuracy. This is likely best achieved with IR base stations and reflectors. External tracking would open for the use of HoloLens 2 as the AR headset, which may be a more user friendly headset Universal for all these directions is the need to explore better user experience design principles, in mainly two areas: visual design patterns and haptic feedback. AR can quickly overload the users visual sense, so figuring out what constitutes relevant information and how to best display it is an important next step.

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Appendix A

Usability Test Results

A.1 Usability Test 1

A.2 Participants

ID	Age	Occupation
P1	20s	IT Student
P2	20s	Business Student
P3	20s	Engineer Student
P4	20s	Social Student
P5	20s	Service Student

A.3 Results

A.3.1 Task UT1

Successful 1 *Lock the hologram in place. Move the head to a new location and make sure the hologram ends up locked in the new position.*

Person	Successful	Comment
1	Yes	Good
2	Yes	Good. Moves it, but is unhappy with where it locks, so unlocks and fixes a better position.
3	Yes	Wants to hold the trigger in at first, but quickly learns it's a toggle.

4	Yes	Communicates confusion when asked to move the head and have the head follow, asking how they can move the hologram when it is locked.
5	Yes	Takes some time to understand how to move the hologram along with the head.

Critical errors:	0
Non-critical errors:	0
Total errors:	0

A.3.2 Task UT2

Successful 2 Check if the entry point indicator is where the physical entry point is. If not, do step 1 again.

Person	Successful	Comment
1	Yes	Depends on the angle.
2	Yes	Says it's close.
3	Yes	Hole misses a little. Readjusts and fixes it.
4	Yes	Says the calibration is a bit off. Tries to recalibrate. Comments that when calibrating, the white square is jittery. Manages to recalibrate and align the entry point.
5	Yes	Good

Critical errors:	0
Non-critical errors:	1
Total errors:	1

A.3.3 Task UT3

Successful 3 Point out where the SPG is located on themselves.

Person	Successful	Comment
1	Yes	Good
2	Yes	Good
3	Yes	Good
4	Yes	Good
5	Yes	Good

Critical errors:	0
Non-critical errors:	0
Total errors:	0

A.3.4 Task UT4

Successful 4 *Attach the controller to the MultiGuide.*

Person	Successful	Comment
1	Yes	Good
2	Yes	Good
3	Yes	Comments the needle is offset by 1 cm.
4	Yes	Good
5	Yes	Good

Critical errors:	0
Non-critical errors:	0
Total errors:	0

A.3.5 Task UT5

Successful 5 *Perform injection procedure on SPG.*

Person	Successful	Comment
1	Yes	Struggles with offset needle. Can't make both indicators green. Offset problem.
2	Yes	Unsure about navigation. Should both points be green? Can't get both green. Has issue with offset problem.
3	Yes	Can't line up because of offset. Is a relatively short person, so does not sit down and tries to do the procedure standing. Pushes MultiGuide into mannequin and accidentally touches the trigger, activating marker tracking, because of angle from standing. Eventually gets inner indicator green, but is unsure if successful.
4	Yes	Somehow gets both indicators green. Holds the MultiGuide in an awkward angle, by rotating it sideways 90°. Says that the resistance is harder than they think is expected, suggesting it may be because of the offset on the needle.
5	Yes	Gets inner green, but not both.

Critical errors:	1
Non-critical errors:	5
Total errors:	6

A.3.6 Task UT6

Successful 6 *Change anatomical layers.*

Person	Successful	Comment
1	Yes	Good
2	Yes	Changes but can't get it back to how it was
3	Yes	Struggles a bit with the buttons
4	Yes	Tries to press both buttons at the same time at first. Eventually gets it.
5	Yes	Good

Critical errors:	0
Non-critical errors:	3
Total errors:	3

A.4 Likes, Dislikes and Recommendations

ID	Like
P1	<ul style="list-style-type: none"> •Not nauseating like VR •Anatomy visuals •Penetrating resistance
P2	<ul style="list-style-type: none"> •Anatomy visuals •Fast feedback from indicators
P3	<ul style="list-style-type: none"> •Skull visuals •Doing the procedure
P4	<ul style="list-style-type: none"> •Doing the procedure •Penetrating resistance •Anatomy visuals •Combination of real an virtual
P5	<ul style="list-style-type: none"> •Skull visuals •AR was fun

Table A.9: Likes from the usability test.

ID	Dislike
P1	<ul style="list-style-type: none"> •Needle offset
P2	<ul style="list-style-type: none"> •Complexity •Distinguish real from hologram •Problem with aligning entry point
P3	<ul style="list-style-type: none"> •Needle offset •Had a crash •Comfort: Heavy headset that did not fit head properly
P4	<ul style="list-style-type: none"> •Difficulty •Needle offset
P5	<ul style="list-style-type: none"> •Instability of the needle •Blinking indicator •Foam does not feel right

Table A.11: Dislikes from the usability test.

ID	Recommendation
P1	<ul style="list-style-type: none">• Attachment piece that is better calibrated so that there is no offset• MultiGuide handle with no holes if it is not intended to have the fingers through them
P2	<ul style="list-style-type: none">• An indicator showing angle from the correct angle
P3	<ul style="list-style-type: none">• Make alignment more accurate• Unbind trigger button
P4	<ul style="list-style-type: none">• More brain structures• A function to dissect the brain• Name labels for various brain parts
P5	<ul style="list-style-type: none">• A more stable needle and no offset• More realistic resistance feel

Table A.13: Recommendations from the usability test.

Appendix B

Consent Form

Following is the consent form signed by all participants i in interviews and testing. It gives right to use the data gathered from testing and feedback in accordance with EU regulations of data privacy, GDPR.

Taking part in the research project

” Immersive Technologies for Learning and Training ”

This is an inquiry about participation in a research project where the main purpose is to explore the potentials and limitations of Immersive Technologies (virtual/mixed/augmented reality, VR/MR/AR) for learning and training in different areas, as a part of master student projects at Innovative Technologies for Learning (IMTEL) VR lab. To conduct this research, we will need to investigate the development and use of immersive technologies for learning and training in various contexts, including learning of language and mathematics, visualization of climate change, immersive exploration of historical manuscripts, workplace training and visualization of medical procedures. In this form we will give you information about the purpose of the project and what your participation will involve.

Purpose of the project

To conduct this research, we will need to analyze the use immersive technologies for learning and training in various contexts, including learning of language and mathematics, visualization of climate change, immersive exploration of historical manuscripts, workplace training and visualization of medical procedures. The goal is to develop innovative learning methods and tools using immersive technologies.

Who is responsible for the research project?

NTNU, Department of Education and Lifelong learning is the institution responsible for the project.

Why are you being asked to participate?

You are asked to participate because you are a potential user of educational applications developed as a part of this project and have visited our lab/expressed interest in immersive technologies. Your feedback is important for develop innovative learning methods and tools.

What does participation involve for you?

You will be ask to test immersive applications for learning and training purposes and then give feedbacks in the form of questionnaires and interviews/group interviews.

Participation is voluntary

Participation in the project is voluntary. If you chose to participate, you can withdraw your consent at any time without giving a reason. All information about you will then be made anonymous. There will be no negative consequences for you if you chose not to participate or later decide to withdraw.

Your personal privacy – how we will store and use your personal data

We will only use your personal data for the purpose(s) specified in this information letter. We will process your personal data confidentially and in accordance with data protection legislation (the General Data Protection Regulation and Personal Data Act). Any data that can be traced to individual participants will be kept confidential and anonymized before being used for research purposes. Parts of the sound recordings will be transcribed (written down) and stored electronically. All source data will be handled and stored in accordance with the existing regulations by NTNU as the responsible institution and only persons associated with the project (IMTEL VR lab research personnel and master students) will have access to them.

What will happen to your personal data at the end of the research project?

The project is scheduled to end 31.12.2020. All data will be anonymized at the end of the project, e.g. audio and video will be deleted when transcripts and analysis of data are completed, except for selected video and photo material to be used for research purpose. These and anonymized recordings from the inside of the virtual environments may be used for demonstrations in research context in such a way that no information will be linked to individuals. Scientific reports and presentations from this study might contain recordings from the VR/MR/AR sessions, questionnaire results, anonymized photos/videos from the sessions and anonymized citations from the interviews.

Your rights

So long as you can be identified in the collected data, you have the right to:

- access the personal data that is being processed about you
- request that your personal data is deleted
- request that incorrect personal data about you is corrected/rectified
- receive a copy of your personal data (data portability), and
- send a complaint to the Data Protection Officer or The Norwegian Data Protection Authority regarding the processing of your personal data

What gives us the right to process your personal data?

We will process your personal data based on your consent.

Based on an agreement with NTNU, NSD – The Norwegian Centre for Research Data AS has assessed that the processing of personal data in this project is in accordance with data protection legislation.

Where can I find out more?

If you have questions about the project, or want to exercise your rights, contact:

- Ekaterina Prasolova-Førland (Department of Education and Lifelong Learning, NTNU)
- phone: +47 99 44 08 61, email: ekaterip@ntnu.no
- NSD – The Norwegian Centre for Research Data AS, by email: (personverntjenester@nsd.no) or by telephone: +47 55 58 21 17.

Consent form

I have received and understood information about the project **Immersive Technologies for Learning and Training** and have been given the opportunity to ask questions. I hereby declare my consent that my data in relation to Immersive Technologies for Learning and Training may be stored, documented and used for research and educational purposes as described above. I give consent for my personal data to be processed until the end date of the project, approx. 31.04.2021

(Signed by participant, date)

