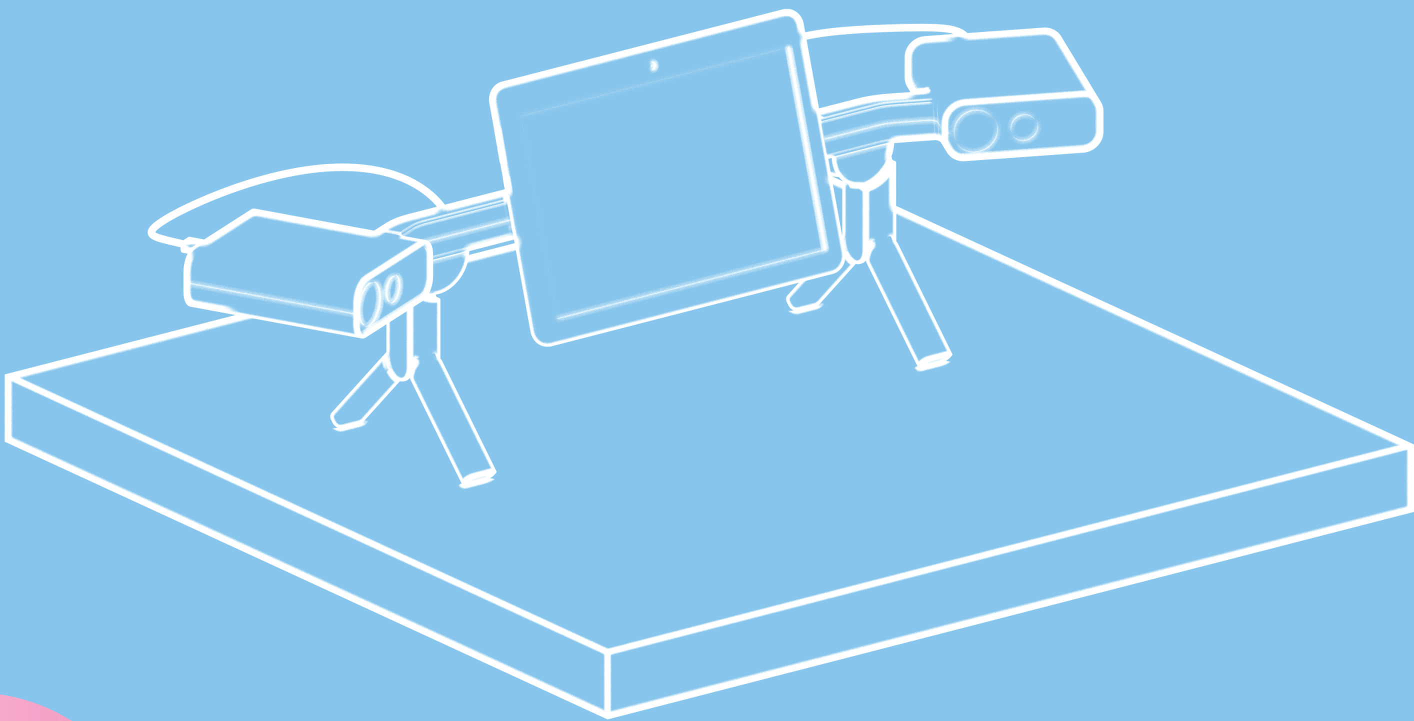


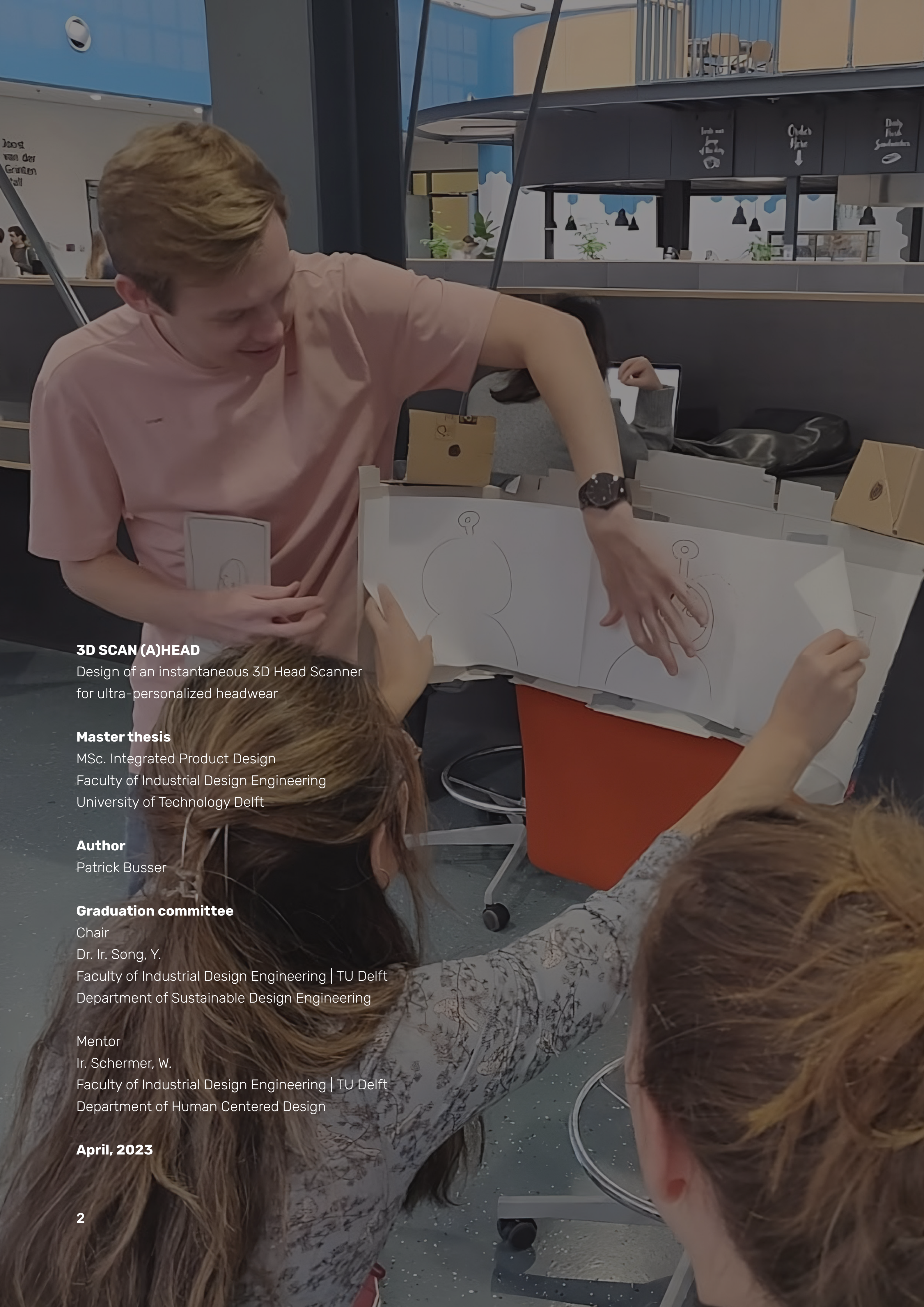
3D SCAN (A)HEAD

Design of an instantaneous 3D Head Scanner for ultra-personalized headwear

PATRICK BUSSER

MASTER THESIS

INTEGRATED PRODUCT DESIGN



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Design of an instantaneous 3D Head Scanner
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Master thesis

MSc. Integrated Product Design
Faculty of Industrial Design Engineering
University of Technology Delft

Author

Patrick Busser

Graduation committee

Chair
Dr. Ir. Song, Y.
Faculty of Industrial Design Engineering | TU Delft
Department of Sustainable Design Engineering

Mentor
Ir. Schermer, W.
Faculty of Industrial Design Engineering | TU Delft
Department of Human Centered Design

April, 2023

Preface

I would like to express my gratitude to the experts and partners who collaborated in this research by contributing their knowledge, facilities, and other resources towards its outcomes, and to all those who supported and accompanied me throughout the process of completing my master's thesis.

I want to take a moment to thank my chair and mentor, Wolf and Wim, for their valuable guidance and support throughout this project. Their help went beyond supervision as they either motivated me or encouraged me to slow down a bit whenever needed. They provided interesting discussions that helped me broaden my perspective and prioritize effectively. Their expertise and knowledge were crucial in this project and they also provided additional resources and support whenever needed. I am grateful for their contributions and couldn't have completed this project without them.

Thanks also to Jan Berend who originally was the main initiator of this project. Your passion to help these people inspires me. Next to your knowledge about everything related to the procedure and the target group, you gave me the necessary access to get into contact with clients which enabled me to obtain valuable insights from contextual research. Your ideas and input contributed a lot to the outcome of the project.

I would like to thank Piet, Mikael and Pashkin for their help in evaluating the 3D Head Scanner. Special thanks to Noud and his father who allowed me to make a very accurate 3D scan and use this data in my report and publications, this has helped me enormously. Also thanks to Bertus for his help in 3D scanning Noud, and for evaluating the results of this project and his recommendations.

Sarah, thank you for helping me to develop the digital prototype. I would not have been able to perform such realistic user tests without your help! Also thank you to everyone willing to participate in interviews, observations and tests, especially the people from Colpa Opticians and Kijk op Ogen.

A lovely thank you to my friends and family for the big support, help with tests, ideation and roleplaying, but also for the fun game nights! Thanks to my roommates who were always there to listen to my struggles, tolerated my 'special' working hours and reassure me in what I was doing.

joe,

Patrick

Contents

SUMMARY

Maatbril delivers personalized 3D-printed glasses by making a 3D scan of their client's head and modelling the glasses around this 3D model. This is especially handy for people with cranio-facial differences or other conditions that prevent them from wearing regular glasses.

A large proportion of Maatbril's clients are children and/or have a mental disability. Interviews and observations during scanning procedures showed that the 3D scanning procedure is often perceived as scary. Moreover, it is often challenging to get the client to sit still for about 20 to 30 seconds, which is the time it takes to capture the 3D scan.

The goal of this project is to design a non-invasive and versatile 3D scanning solution that produces high-accuracy 3D head scans near instantaneously, with simple controls for a single user. This 3D scanner will mainly be used by Maatbril employees, but it might occur as well 3D scanners will be located at healthcare institutions such Bartiméus and people that are no experts in 3D scanning will perform the 3D scan.

Experiments and roleplaying with different interaction concepts showed that not all participants have the mental capability to actively contribute in the scanning procedure, ruling out principles like gamification to get the client to sit still. Eventually, it was chosen to attract the client's attention with an integrated tablet which displays videographical content. This requires little mental effort, but still allows for the client to have something interesting to focus on, so he/she will sit (relatively) still. In the meantime, the 3D scan can be captured.

The final 3D Head Scanner makes use of 2 Azure Kinect DK sensors to capture the subject's face along with the requisite landmarks in about 25 milliseconds, with only the click of a button. These sensors work with Amplitude Modulated Continuous Wave (AMCW) Time-of-Flight technology, which was selected after evaluating all options and fit to this use case.

About 20 seconds after clicking the button, both scans have been aligned and the quality can be evaluated in the User Interface. The client probably didn't even notice any of this, as he/she was watching their favourite show on the digital tablet.

Repeatedly testing and optimizing the interaction of the final 3D Head Scanner resulted in a relaxed and non-invasive 3D scanning procedure, where no force or bribing of the client was required to obtain the 3D scans. After optimizing the alignment algorithm, 3D scans with an accuracy of 1.2 mm can be expected, which is in the range of accuracy Maatbril requires when designing their glasses.

CHAPTER **ONE**

INTRODUCTION

1

1.1 - Problem Introduction

Meet Noud. Noud was born with Treacher Collins syndrome, a genetic condition affecting the way the face develops. Treacher Collins is part of a larger group of cranio-facial differences[1]. The conditions under this umbrella have prevalence[2] between 1:3.200 for Goldenhar Syndrome to <1:1.000.000 for Miller Syndrome (MedlinePlus, 2022). However, the severity and occurrence of specific characteristics differs between the specific condition and between each individual. Moreover, about 75% of people with Down Syndrome also suffer from craniofacial differences.

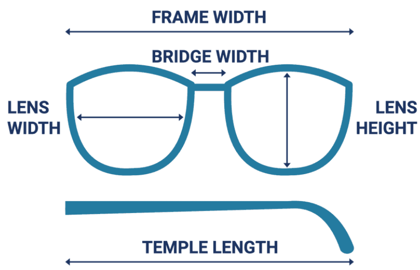
For people like Noud, it is (almost) impossible to wear regular glasses. Due to the irregular shape of the head, glasses can fall off more easily and/or they can cause extreme discomfort. Usually, glasses come in different sizes with three important main dimensions. The first dimension is the lens width [mm], the second dimension is the width of the nose bridge [mm] and the third tells about the length of the glasses' temples [mm]. For a good fit, the temples should start bending shortly after the triangular fossa[3].

[Figure 1]
3-year-old Noud, suffering from Treacher Collins Syndrome

(1)
Craniofacial differences are a deformity affecting a child's facial structure and skull. It is an umbrella term for several conditions and syndromes

(2)
Proportion of a population who have a specific characteristic in a given time period

(3)
Region on the ear that signifies the last point where the ear is connected to the skull



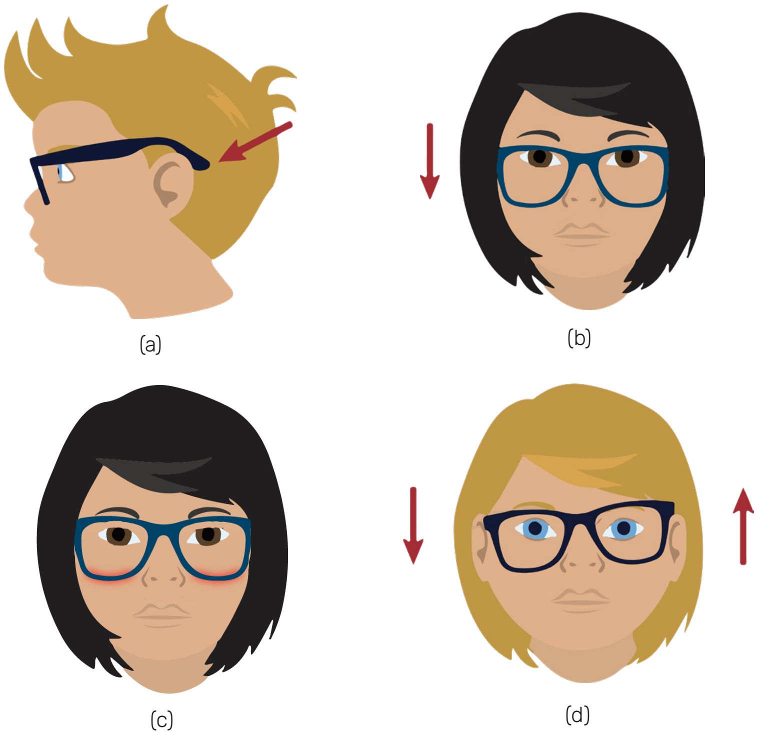
[Figure 2]
Important dimensions for glasses

[Figure 4] Noud with his Maatbril with integrated hearing aids.

When suffering from cranio-facial differences, the head is usually more asymmetric, leading to glasses that don't fit or cause discomfort. Examples of what might happen are temples touching the cartilage and causing discomfort (a), frames sliding down because of irregular nose shape (b), frames touching the cheeks and/or eyelashes (c) and glasses not sitting straight because of irregularly shape or absence of outer ears (d), as can be seen in Figure 3.

The vast majority of all glasses/eyewear is designed to be manufactured in large numbers, across a limited range of sizes. Opticians can usually secure the right fit by tweaking the bridge (nesting on the nose) and/or end pieces (on the ears) in a simple process that any wearer of glasses will be familiar with. For people like Noud, who have craniofacial features that are very different from those of you and me, this use of standard solutions is not applicable. Instead, they can use custom-made solutions such as Maatbril.

Currently, it takes about 30 seconds before the Maatbril employee has captured all required data. In these 30 seconds, the client is supposed to sit still while an employee walks around the client with an iPad with special depth sensor. Especially for children and people with intellectual disabilities this is often a challenge. When the client does move while a 3D scan is being made, this will lead to duplicate and/or missing geometry in the 3D model, meaning that the scan has to be retaken (Jan Berend Zweerts, personal communication, October 13, 2022).



[Figure 3] Potential issues with fit of glasses

1.2 - Project Introduction

This master's thesis was self-initiated, but eventually done in collaboration with Maatbril, a company that offers tailormade glasses for people with craniofacial differences.

Founder of Maatbril, Jan Berend Zweerts had already initiated a graduation project for the design of a 3D facial scanner last year. This graduation project was executed by Yaman Gupta, student in Integrated Product Design at the faculty of Industrial Design Engineering, TU Delft.

The results of this graduation project however, were not fully satisfying the needs of Maatbril. The average accuracy of the 3D scans was too low (~5 mm) and therefore unusable, while the interaction with the design was cumbersome and complicated. Inspired by the idea, this master's thesis was initiated with the goal of developing a 3D scanner that is able to capture 3D scans (near-)instantaneously with an accuracy of 2 mm, while it can be operated by a single person. The original Graduation Proposal can be found in Appendix L.

[Figure 5] 3D Scanner designed by Yaman Gupta as graduation project

[Figure 6]
Overview of relevant research areas for the project

1.3 - Design Goal

The goal of the graduation is to design and develop a 3D Head Scanner that is proven to be both effective in instantaneously capturing the client's head shape as well as a non-intrusive interaction for the person being scanned. The 3D Head Scanner should optimize the trade-off between cost and performance. Next to that, it should be able to adapt to different ambient light intensities, light directions and availability of furniture to cope with varying work environments.

1.3.1 - Research Questions

To find desired solutions for a 3D Head Scanner, it is important to gain knowledge and understanding about the current context, available technologies and their working principles and user needs. By uncovering how the design should interact with the user(s) and its surrounding environment, new insights can be gained for design possibilities.

RQ1: What does the current procedure look like and what bottlenecks can be observed?

RQ2: What stakeholders are involved, and what are they trying to achieve?

RQ3: How do 3D scanners work, and what technology should be implemented in this project?

RQ4: What contextual elements have influence on the product requirements?

1.3.2 - Scope

Figure 6 gives an overview of the relevant research areas of the 3D Head Scanner. There are three main levels that describe the project architecture; context (meta), product use (macro), and performance (micro).

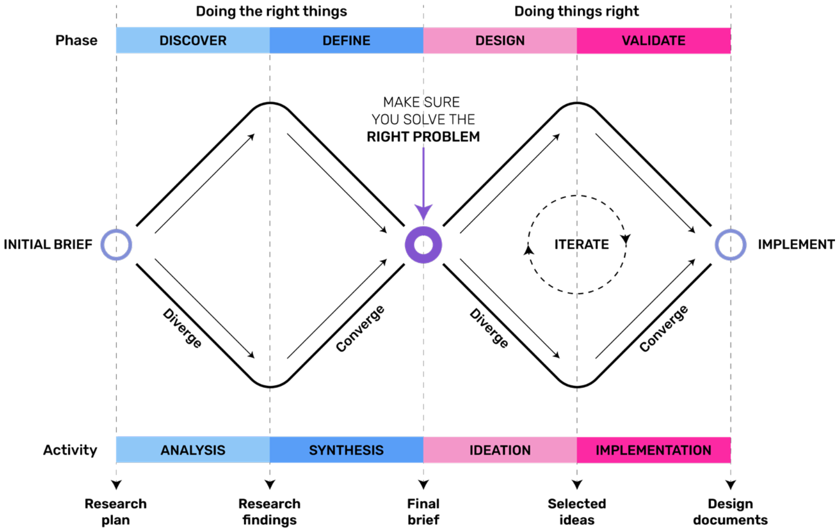
1.4 - Design Approach

The creation of a 3D Head Scanner involves a comprehensive approach that draws from various sources of knowledge, including desktop research, scientific research, expert knowledge, and design thinking. The design process is guided by the double diamond approach, which consists of four distinct stages: discover, define, design, and validate, as depicted in Figure 7. These stages entail different activities, such as analysis, synthesis, ideation, and implementation, with iterative cycles of ideation and implementation.

During the first phase, the focus is on researching and defining the scope of the project. This entails an analysis of the current 3D scanning procedure by means of observations and interviews, researching and testing available alternatives and 3D imaging technologies, and mapping out and getting in contact with stakeholders. The aim is to extract multiple design requirements and preferences that will serve as the foundation for the design statement and design drivers in the subsequent define phase.

As mentioned previously, the design and validation processes are closely intertwined. Validation is used to inform and improve the design, and the design is subsequently validated to ensure that it meets the specified requirements. During the design phase, there may be deviations to explore additional solutions, which are then implemented and tested against the design requirements. If the solutions do not meet the requirements, the design must be adjusted or discarded.

At the end of the graduation project, the 3D Head Scanner is likely to require additional iterations before implementation. Even after implementation, ongoing improvements based on patient experience will be necessary to refine the 3D Head Scanner.



[Figure 7]
Double diamond approach by David Artoumian

CHAPTER **TWO**

ANALYSIS

2


3D TAILORED EYEWEAR
Yuniku.
TAILORED EYEWEAR
powered by
materialise
KOLLECTIV
TOKYO

2.1 – Introduction

Instead of simply designing a 3D Head Scanner with more accurate sensors, it is important to understand the context in which it will be used as well since it might show opportunities for improvement that otherwise would have been overlooked. This was done by performing observations with Maatbril when making 3D scans of clients and interviews with Maatbril employees.

Next to that, Maatbril is not the only company making personalized 3D-printed glasses. Existing solutions should be tested to get a better understanding of what works and what not as to not get trapped in the same pitfalls. At the same time, good solutions can be used as inspiration for this project.

Although the two most important stakeholders, the person taking the scan and the person being scanned, are known, it is important to analyse their needs and wishes. Moreover, new stakeholders that are not (yet) part of the procedure will be introduced.

Finally, the current landscape of 3D imaging technologies is explored. Although there are many 3D scanners available depending on different established technologies, with the implementation of Machine Learning new solutions might be possible. Moreover, it is important to understand the factors influencing the quality of the 3D scan for the chosen 3D imaging technology.

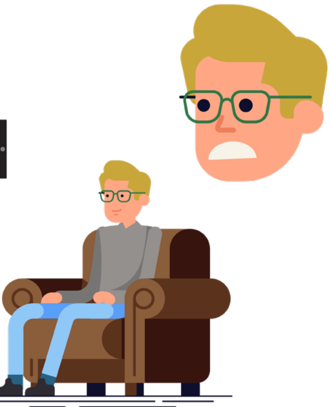
2.2 – Analysis of current procedure Maatbril

By mapping out the procedure that Maatbril is currently following, bottlenecks and inefficiencies were identified by means of interviews and observations with Maatbril employees, clients and/or their caretakers. Since this project aims at designing a new 3D Head Scanner, the main focus

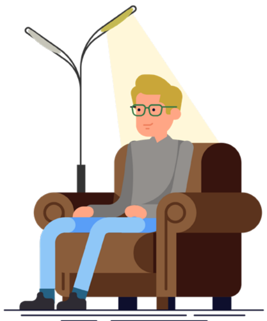
[Figure 8]
Current procedure Maatbril is following

is on the part of the procedure where the 3D scan is captured. Although bottlenecks were found in earlier and later phases of the procedure as well, they are considered out of scope. An analysis of the complete procedure and bottlenecks can be found in Appendix Z. An overview of how the glasses are produced subsequently can be found in Appendix C.

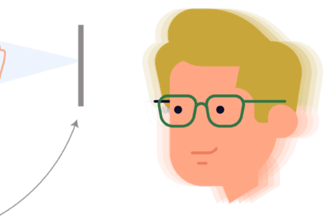
2.2.1 - Current 3D scanning procedure



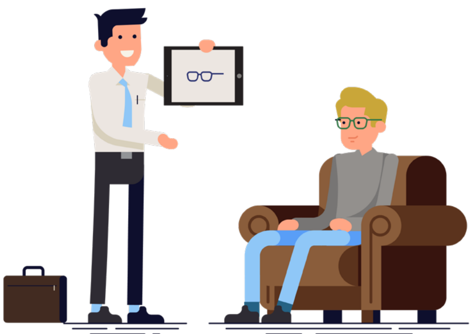
g the process by
previous scans



3. Finding a spot in the house
with appropriate lighting



geometry is captured,
customer cannot move



6. Choosing the preferred glasses
and writing down personal details

2.2.2 - Bottlenecks in current 3D scanning procedure

From observations and interviews with a Maatbril employee, it became clear that the fear factor can be quite high, especially when dealing with clients with mental disabilities. During observations, a client with Down Syndrome kept switching between hiding behind his caretaker because he was afraid and being very happy, running towards the Maatbril employee and hugging him. According to the Maatbril employee, this was about a 6/10 on the fear scale (Jan Berend Zweerts, personal communication, December 2nd, 2022).

A second bottleneck is the time that the client currently has to sit still. This is rather complicated if the client has uncontrollable spasms and/or moves his/her head to follow the iPad and/or is disturbed by the unfamiliarity with the situation and/or the caretaker/parent needs to help holding the client's head still. Also when working with (younger) children, these situations can occur as observed when making a 3D scan of Noud. According to Jan Berend, it is not uncommon for a parent to put his/her hand on top of the adolescent's head to hold it still for the required 20-30 seconds.

Even if the client sits still, it sometimes still happens that the quality of the 3D scan is (locally) compromised affecting the usability of the 3D scan. This can be caused e.g. by poor lighting conditions, specific skin types such a very dark skin, very reflective skin or semi-translucent skin, etc. If the scan is not sufficient, it needs to be retaken, meaning that the client has to sit still for another 20-30 seconds. During observations, it could happen that a scan needed to be retaken two or three times.

If it is not possible to capture the – often complex – geometry of the outer ears, the design of the glasses' temples is compromised in terms of length and temple tip design. If the ears don't show up correctly in the 3D head scan, often detail scans are made of just the ears to still capture this geometry correctly. These 'detail' scans will later be aligned with the complete 3D head scan manually, but this takes time and effort from the glasses designer.

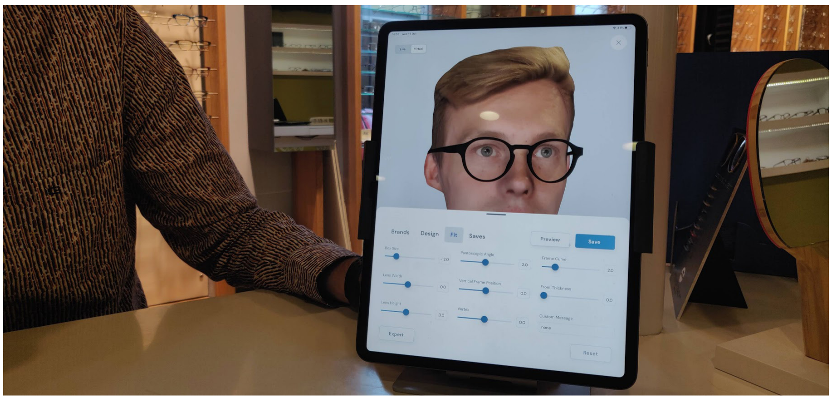
2.3 – Alternatives on the market

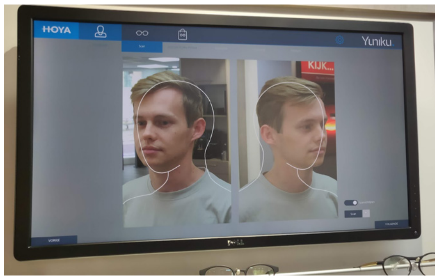
Since the majority of the market is focused on delivering cheap glasses to the mass, the amount of alternatives on the market is relatively low. In total, only two alternatives were found divided over several independent opticians that make use of 3D scanning for getting a good fit. Both Colpa Opticians and Kijk op Ogen were visited for observations and interviews. The results of these observations can be found in Appendix A. For a full analysis of the Dutch optics market, see Appendix B.

The solution used by Kijk op Ogen is the Hoya Yuniku 3D scanner (Hoya Vision, 2023). Although it provided an excellent image preview of how the glasses would look the client's face, it was quite a big, bulky system with electromotors that needs to be calibrated every two weeks, see Figure 9. In terms of usability, the person that is being scanned needs to stand at exactly the right place (marked on the floor), while the UI is complicated and glasses can barely be adjusted.

The second alternative, used by Colpa Optics, is the Sfered Platform (Sfered, 2021). It only uses an iPad and lets the user turn his/her face around to capture all geometry while being seated. Lots of parameters can be changed to get the ideal pair of glasses, while the preview was disappointing compared to the Yuniku system. The number of available glasses designs was also quite low.

Although both solutions wouldn't work for (a large part of) Maatbril's clients, the aforementioned do's and don'ts could be helpful. For a complete analysis of the different devices, see Appendix D.





[Figure 9]
Testing out Sfered platform (left) and Hoya Yuniku (right)

2.4 – Evaluation of previous prototype

During his graduation, Gupta made a first prototype of the 3D Head Scanner. In this project he mainly focused on the looks and embodiment of the device. In this chapter his design will be evaluated and learnings can be implemented in this graduation project.

First of all, it turns out that the participants of his evaluation session were afraid of the device. Gupta mentions: “She was visibly scared of the product when brought in close proximity to it and was unwilling to get near it.” and “... the scanner going around the head might invoke a sense of fear and claustrophobia in young kids”. In one instance, the participant was too scared to participate. The scanner was then placed vertically (upwards) as to not alarm the participant. “Once the child was distracted, the 3D Head Scanner would then be rotated into its scanning position around the participant’s and immediately captured the data” (Gupta, 2021).

To get hands-on experience and test out the effect of different shapes and movements on the experience, some quick tests with cardboard models were done. It became clear that something that doesn’t just block the view of the user is desired, and that some types of movement, especially those where the model was being lowered around the user, were preferred over others. The complete results of this test can be found in Appendix H.

[Figure 10]
Gupta's 3D Head Scanner on a Tripod

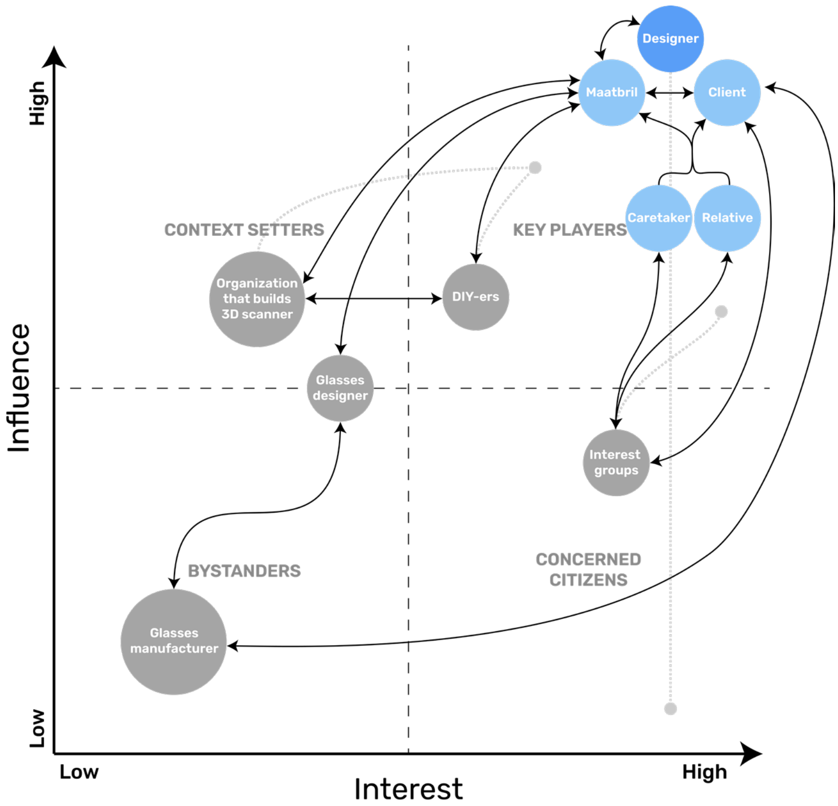
One of the other participants mentioned that the looks of the device made it feel like as if it was using radiation to make a scan, since there was quite some resemblance with a device that had been used at the dentist’s office.

Apart from the look-and-feel, it turned out that for participants it was hard to position their head in view of all three scanners - 3 out of 3 participants failed – because attention had to be paid to three camera preview simultaneously. This is something that needs to be tackled in the new design. The same applies to the stand that holds the 3D Head Scanner. Currently it is not possible for people in a wheelchair to be scanned in since the arms of the device are not long enough.

The fact that it didn’t take 20-30 seconds anymore to capture the data, made that it was less demanding for the participant than the original procedure, however the output quality was lower than expected, about 3 mm accuracy at the front of the face and alignment issues occurred due to incorrectly calculated transformation matrices.

2.5 – Stakeholders

Next to Maatbril and their clients, there are several other stakeholders involved in the process of designing and making tailor-made glasses. A brief overview of the most important stakeholders will be given in this chapter. The complete stakeholder analysis can be found in Appendix AA.



[Figure 11]
Stakeholder map

The diagram in figure 11 is divided into four sections called Key Players,[4] Context Setters,[5] Concerned Citizens[6] and Bystanders,[7] where each of the different quadrant requires a different way of interaction.

Person that takes the scan

Most likely a Maatbril employee will take the scan, but in rare cases it could happen that this will be done by a caretaker/relative or employees of an interest group. Next to helping clients get specialty glasses by 3D scanning their faces, their biggest concern is a quick and easy scanning procedure (Jan Berend Zweerts, personal communication, October 13, 2022). This means that

(4)
People or organisations that are essential to have as allies. They should be fully engaged in discussions and decision making

(5)
People or organisations that are influential, but initially uninterested. They should be kept satisfied

(6)
People or organisations that are affected but lack power. They should be consulted for their opinions and informed about decisions

(7)
People or organisations that have little interest or influence. They should be monitored and informed of decisions

the procedure should not take longer than currently is happening and that the procedure can be correctly executed by someone without experience. The way they are trying to reach this is by having a 3D scanner that is quick, outputs high-quality meshes, and is easy to set-up and use.

Client

The clients usually range from ~8-month-old babies to elderly people, both male and female, with mental and/or physical disabilities. Whereas the majority of the disabilities is of craniofacial nature, also people with e.g. Down Syndrome and photophobia are part of the 'target group' (Jan Berend Zweerts, personal communication, October 13, 2022). Especially for people with Down Syndrome the fear factor can play a big role in the scanning procedure.

To give an idea of the variance in head shape among Maatbril's clients, some examples are depicted in figure 12. From the figure it can be seen that among the clients, the reason why choosing a Maatbril might differ from oddly shaped noses, to atypical location of the eyes and/or deformation of the skull. A complete overview of the pathologies, characteristics and their prevalence can be found in Appendix E. It has to be noted that a significant part of the clients is making use of a wheelchair.

Caretaker / relative

In 90% of the cases, a caretaker, parent or other relative is present, since some of the clients simply need this (Jan Berend Zweerts, personal communication, October 13, 2022). Either they are a child or they suffer from mental disabilities. These caretakers usually have the best interest in the (mental) wellbeing of the person they are taking care of, and will usually try to keep them relaxed and/or stand up for the interests of the person being scanned. They can be used in the scanning procedure to make sure the client feels comfortable and sits still, so the person taking the scan can solely focus on acquiring a high-quality 3D scan, as is already currently done.

[Figure 12]
Variance in headshape among Maatbril clients

2.6 – State of the art

3D scanning is the process of turning real-world objects into digital models. It can be done with technologies like structured light, photogrammetry, and laser scanning. Recently, Lidar has become a popular 3D scanning technology, especially for autonomous vehicles, that uses lasers to measure distances to objects, and machine learning algorithms can be used to process and analyse the data. Together, Lidar and machine learning have greatly improved the accuracy and efficiency of 3D scanning.

In this chapter, available technologies will be compared and evaluated against relevant criteria for the 3D Head Scanner: working distance, accuracy, capturing time, cost, and invasiveness. The most appropriate method was selected, and factors that can influence the quality of the 3D scan will be highlighted.

2.6.1 - 3D imaging techniques

To make sure that the procedure is as inobtrusive as possible, it was decided that contact-based 3D scanning technologies were not part of the consideration. The same applies to methods using some sort of radiation other than Infra-Red or visible light. Although technologies like Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI) are capable of capturing very high resolution 3D scans, the costs are also very high and the client should not need to be exposed to radiation for this purpose (Mayo Clinic, 2021, 2022).

What remains are two types of active 3D imaging techniques and one passive 3D imaging technique. Laser-based 3D scanners, coming in three main variants[8] and structured light 3D scanners are deemed active 3D scanners because they emit some sort of (visible) light, while photogrammetry, the passive 3D imaging technology, solely makes use of the ambient lighting (Artec3D, 2022; Dai et al., 2010; Flynt, 2020).

Since each method has its own characteristics, benefits and disadvantages, an overview has been given in Table 1. A complete overview of the 3D imaging techniques and how they work can be found in Appendix F.

(8)
Time of Flight sensors | Calculate distance based on speed of emitted light

Phase Shift sensors | Calculate distance based on difference in phase of emitted light waves

Triangulation sensors | Calculate distance based on angle with which the reflected waves return

(9)
Accuracy is calculated by taking a percentage of the working distance.

Scanning technique	*Time of flight (Laser)*	*Phase shift (Laser)*	*Triangulation (Laser)*	***Structured light***	*Photogrammetry*
Typical working distance	*<300 m*	*2-80 m*	*0.5-2 m*	***0.2-2 m***	*1-300 m*
Typical accuracy	*<1 %[9]*	*1 mm*	*1 mm*	***<1 mm***	*5 mm*
Resolution	*Low*	*Low*	*Low*	***High***	*Medium*
Use environment	*Indoor, outdoor*	*Indoor, outdoor*	*Indoor, outdoor*	***Indoor***	*Depending on ambient lighting*
Hardware cost	*Medium*	*Medium*	*Medium*	***High***	*Low*
Software processing requirements	*Low*	*Low*	*Low*	***Medium***	*High*
Typical applications	*Autonomous vehicles, VR*	*LIDAR, Robot navigation*	*Robot navigation, road profiling*	***3D Face recognition***	*Aerial scanning*

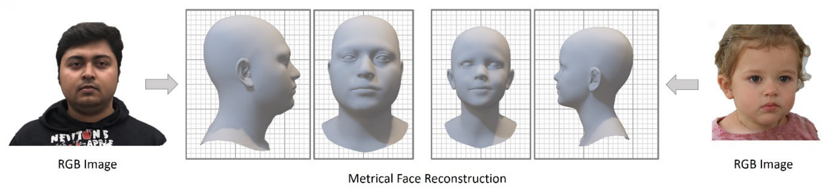
[Table 1]
Overview of traditional 3D imaging techniques and their characteristics. (Archaeology Data Service, 2022; Artec3D, 2022; Dai et al., 2010; Geospatial World, 2009; He et al., 2020; Revopoint3D, 2019; Wagner et al., 2014).

(10)
Resolution is the density of the points that can be measured simultaneously.

Accuracy is how close the measured points are to their true location.

Whereas the typical accuracy and resolution have a direct influence on the quality of the 3D scan[10], the same applies for hardware and software processing requirements' influence on the cost. Lastly, the typical working distance has a big influence on the use scenario of the 3D scanner. Based on these characteristics, structured light imaging was selected to be implemented in this project.

Whereas the technologies listed above have matured over time, several experimental or new techniques have emerged, especially in the field of computer vision and machine learning. With these new technologies, 3D sensors – which will likely contribute to at least 50% of the total cost - can be replaced by simple 'regular' camera's, saving hundreds of euros potentially. Therefore some of these techniques have been evaluated to see their fit for this use case.



[Figure 13]
MICA machine learning model for reconstructing 3D head shapes

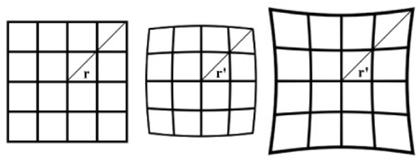
These models such as MICA - see Figure 13 - are trained with images and 3D scans of people with regular head shapes, and therefore it is questionable to what extent such machine learning algorithms can be helpful for people with atypical head shapes. Of course, a new model could be trained based on data of people with atypical head shapes for this purpose. The reality is however that the amount of data available to train this algorithm is very low, simply because the target group is relatively small, and the characteristics of the pathologies can differ largely from each other. For all try-outs with experimental techniques, see Appendix F.

2.6.2 - Influential factors on 3D scan quality

Ensuring that the 3D scans are of sufficient quality is essential. However, the quality of 3D scans can be affected by various factors, such as lighting conditions, object material, and the type of scanner used (Google, 2023). It's important to take these factors into account because they can impact the accuracy, resolution, and level of detail of the resulting 3D models. By considering these factors and adjusting scanning parameters accordingly, it's possible to optimize the quality of 3D scans and ensure that they meet the specific requirements. A complete overview can be found in Appendix G.

As for most optical systems, calibration is required for example to limit radial distortion[11]. This can usually be easily done with the help of a calibration artifact that contains 2D patterns of which the design is known. With these patterns, the calibration parameters can be calculated.

(11)
Distortion where straight lines are bended as general curves and points are moved in the radial direction from their correct position.



Various single- or multi colour patterns can be projected on an object, all having their benefits and limitations. Interestingly, many newly introduced scanners make use of blue light, with manufacturers claiming that it reduces interference with ambient lighting due to the short wavelength of blue light (Geng, 2011). Experiments seem to confirm that blue light scanners indeed outperform white light scanners for scanning biological tissue and teeth (Jeon et al., 2015; Wilm et al., 2015).

Voisin et al. showed that there are significant differences in accuracy under various illumination conditions (Voisin et al., 2007). Moreover, the differences between light and dark skin coloured patches accuracy are hugely in favour of light skin, under some conditions even being twice as accurate.[12] Light skin patches showed least deviation under night circumstances while dark skin patches gave best accuracy under daylight circumstances (Wilm et al., 2015).

(12)

Patch Color	Dark Night 1	Daylight	Cool White	UV	U30	Dark Night 2
Dark skin	1.21	0.96	1.19	1.11	1.06	0.98
Light skin	0.65	0.75	0.64	0.55	0.50	0.46

CHAPTER **THREE**

DESIGN GOAL

3

“The goal is to create a ***non-invasive*** *and* ***versatile*** *3D scanning solution that produces* ***high-accuracy*** *3D head scans* ***near instantaneously****, with* ***simple controls*** *for a single user.”*

3.1 – Introduction

During the analysis, an extensive understanding was gained regarding the current process, patient needs, available technologies and limitations, and the current market. This knowledge helped to shape a refined design statement and design drivers, which outline the essential functions or features the product must possess.

Finally, three envisioned future 3D scanning procedure scenarios are introduced in which the 3D Head Scanner should be able to function. These scenarios can be used to evaluate the ideas that will be generated in the Design and validation phase.

3.2 – Design goal and drivers

Through exploring the context surrounding the 3D Head Scanner, a reformed design goal and a set of design drivers were established. These will guide the design phase and support in decision making. It is important to note that this is an iterative process, which means that requirements may be modified, removed or added during the design process.

3.2.1 - Design goal

Based on the context analysis, the design goal for this project was re-written and can be seen on the previous page.

3.2.2 - Design drivers

Design drivers are the key factors that influence the design of a product or system, including its purpose, function, aesthetics, user needs, and constraints. The design drivers for this project were derived from a detailed examination of user needs, technological constraints, and other relevant factors that would impact the success of the product. By understanding the design drivers, informed decisions can be made to create a product that meets the critical requirements and delivers the desired outcomes. In this chapter, these design drivers will be discussed. A full overview of the requirements can be found in Appendix Q, where also the origin of the requirement is mentioned, as well as how the requirement was verified.

Performance

To get a 3D scan that can be used by Maatbril, the accuracy of the scan should be high enough to have a solid underlayer when designing the glasses. One of the main limitations of Gupta's design was that an accuracy of 5 mm could not be guaranteed, while a higher accuracy was required. For this graduation project, the **average accuracy of the 3D Head Scanner should be 2 mm or below**, as discussed with Maatbril (Zweerts, J.B. Personal Communication, October 14, 2022). Next to that, it's important that **all relevant geometry should be included in the 3D scan**. The eyes are needed to align the glasses to, the nose is needed to have a support for the frame and the triangular fossa - located in the outer ears - is needed to determine the length and design of the temple tips.

Comfort

Since the client usually requires quite a bit of attention already, the 3D Head Scanner should not require this. The 3D Head Scanner **should enable for quick setup, use and disassembly by a single person**. This means that a caretaker/relative can take care of the client, while the professional focuses on taking the 3D scan. To be as unobtrusive as possible to the client, the 3D scan **should be in a contactless manner** and the **capturing time of the 3D Head Scanner should be (near) instantaneous**, meaning that the client doesn't need to sit still for 20 to 30 seconds, as is the case now.

Versatility

Since about 80% of the 3D scans is made at home, the conditions under which the procedure happens are out of control (Zweerts, J.B., Personal Communication, October 14, 2022). Not only the amount of ambient lighting is out of control, but also the direction and diffuseness. This means that the 3D Head Scanner **should work in both well and poor illuminated rooms**. Next to that, the available furniture that can be used during the procedure is also out of control. Think of the height of tables and/or chairs available. This in combination with the wide variety of clients, makes that the 3D Head Scanner **should be capable of capturing a 5-year-old P5 African girl, as well as a 50-year-old P95 Caucasian male**. Lastly, people in wheelchairs should also be able to make use of the 3D Head Scanner.

Cost

In the current procedure Maatbril is using the Structure Sensor, mounted to an iPad. The sensor alone is currently being sold for $995 (Structure IO, 2022). Maatbril is – of course – looking for a solution that is as cheap as possible, without compromising the output quality (too much). The aim of this project is to develop a 3D Head scanner that is about the same price as the current solution, but the final 3D Head scanner definitiely **should cost less than €1500.**

3.3 – Future scenarios

Ideally, the 3D Head Scanner can be used in various scenarios by different users. After extensive discussion with Maatbril, three envisioned use scenario's were proposed. An overview of these scenarios and their characteristics will be described in this chapter.

Scenario 1: Maatbril visits the client the with 3D Head Scanner

This scenario is quite similar to the current procedure, where the main difference is the scanner that is being used. By decreasing the time that is needed to capture the 3D scan, the quality and success rate of the 3D scan will likely increase. In this scenario, an expert will take the scan, however, the environmental conditions will differ for every client.

Scenario 2: Maatbril leases the 3D Head Scanner to Healthcare institutions

Since a relatively large part of Maatbril's clients permanently live in Healthcare institutions, it might be beneficial to lease the 3D Head Scanner to Healthcare institutions such as Bartiméus or Baalderberg Groep. One or two people will be instructed to use the 3D Head Scanner and the scans will be automatically uploaded to Maatbril's database. In this scenario, people with a decent amount of knowledge will take the scan at the same location, meaning that a fixed spot for the 3D Head Scanner can be found.

Scenario 3: Maatbril sends the 3D Head Scanner to clients

It's not uncommon for Maatbril's experts to travel 1 to 1.5 hour to a client. To save time and cost of transport, the 3D Head Scanner could be sent to a client's home address, where the caretaker or parent can perform the scan. By means of an online meeting the Maatbril expert can help guide the person taking the scan through the scanning process. In this scenario, people with limited or no knowledge will take the scan, however, they are supported by an expert. The environmental conditions will differ for every client.

CHAPTER **FOUR**

DESIGN AND VALIDATION

4

4.1 - Introduction

During the Design and Validation phase, the 3D Head Scanner will be developed. In this chapter the results of this phase will be displayed, starting with a brief overview of the result.

This phase started with developing Proof of Concept (PoC) for the software: making sure that a 3D scan could be captured and processed. In chapter 4.2 the workings of the 3D Head Scanner will be elaborated on, guided by the most important functions of the software that was written for this project in Python. The considerations for implementing these functions and their added benefits will be discussed.

The interaction between both the person taking the scan and the 3D Head Scanner and between the person that is being scanned and the 3D Head Scanner will be discussed next. For the interaction between the Person taking the 3D scan and the 3D Head scanner an interactive User Interface will be developed in an iterative way. For the interaction between the person that is being scanned and the 3D Head Scanner, different interaction concepts with different levels of autonomy were developed and tested by means of roleplaying activities.

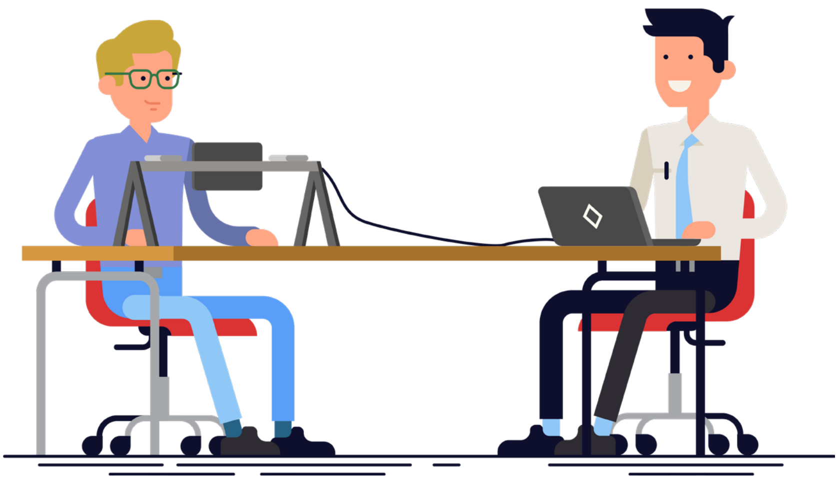
Effort has been put into developing a physical prototype that could function as a Proof of Concept (PoC)-prototype during this project. Aspects like sensor placement, adaptability and expected cost will be discussed.

Finally, the 3D Head Scanner will then be evaluated based on the design drivers that were mentioned in chapter 3.2.3. This will be done both by evaluating the performance in terms of accuracy and functionality with the PoC-prototype, as well as tests testing if the shaped interaction has the desired effect by means of tests with intended users. As a result of this evaluation, it can be concluded to what extent the design goals have been met and recommendations are made for further research and/or development.

4.2 - Proposed solution

The 3D Head Scanner is a compact 3D scanning solution with foldable legs, that can simply be placed on a table or kitchen counter. The scanner contains 2 depth sensors that will be able to capture the client's head shape in a fraction of a second. By quickly capturing multiple 3D point clouds after each other and combining this data, 3D head models can be reconstructed in high resolution and with high precision.

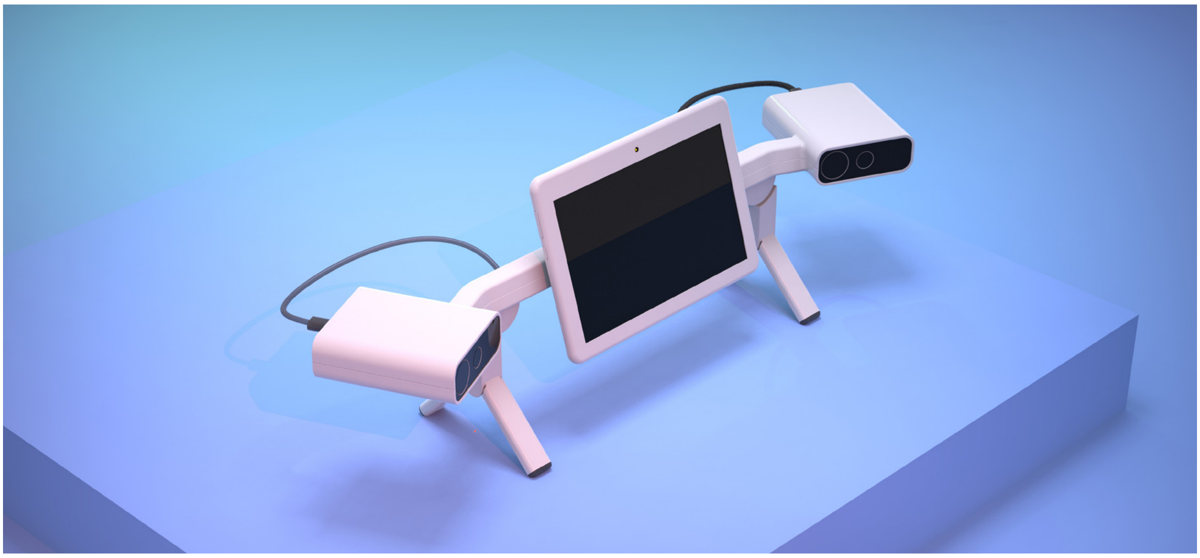
After folding out the legs of the 3D Head Scanner and connecting the USB-C cable to the laptop/tablet, you are ready to go. Align the scanner to the person that is being scanned by means of the integrated aligning support.



[Figure 14]
Proposed scanning setup

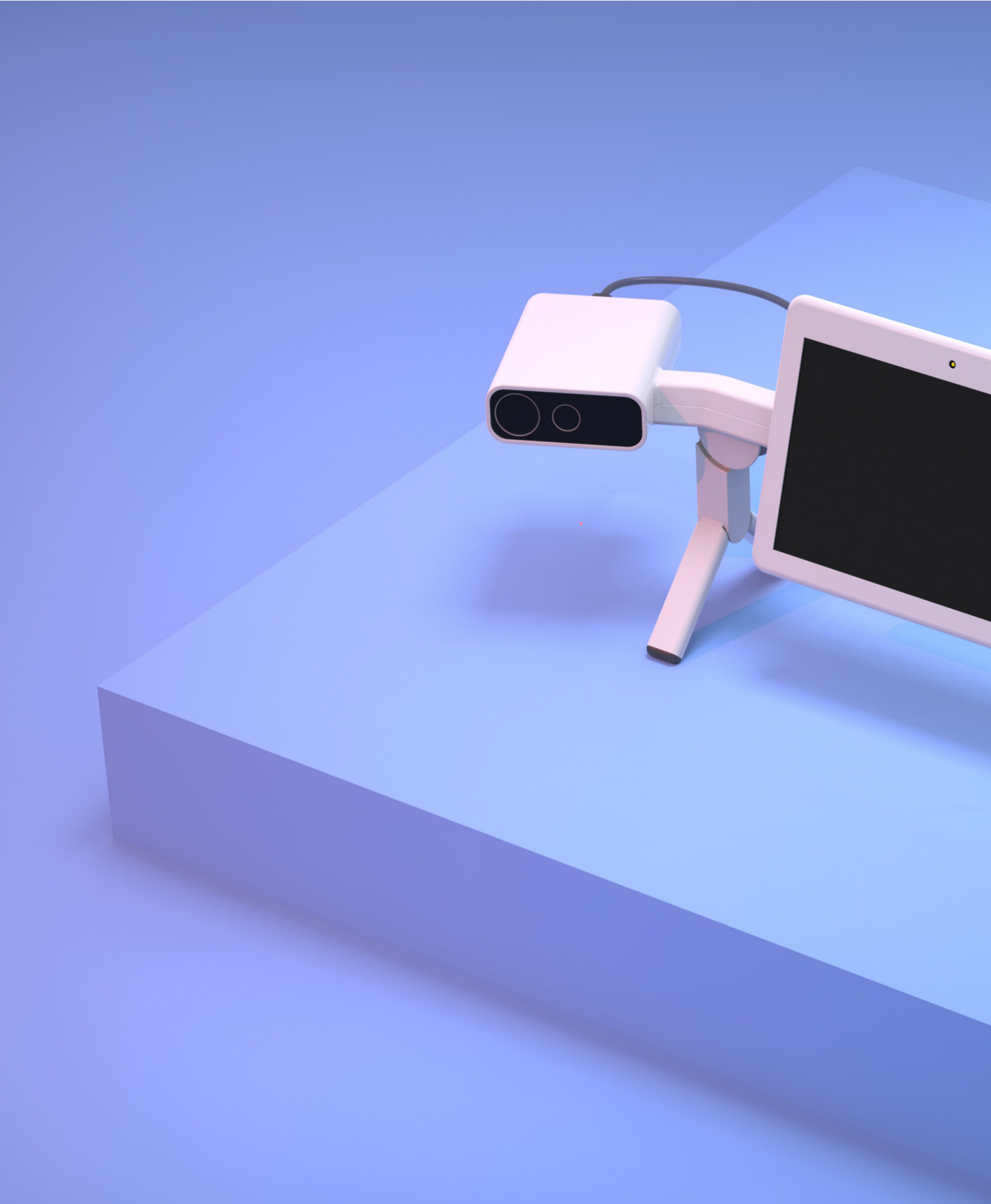
The 3D Head Scanner comes with an integrated tablet as can be seen in Figure 15. On this tablet some multimedia application such as YouTube or Netflix can be used to attract the attention of the person that is being scanned to make sure that he looks the right way and sits still.

Once the 3D scan is made, the person taking the scan can evaluate the quality of the 3D scan in a matter of seconds before entering all other required information and uploading the data to the Maatbril database.

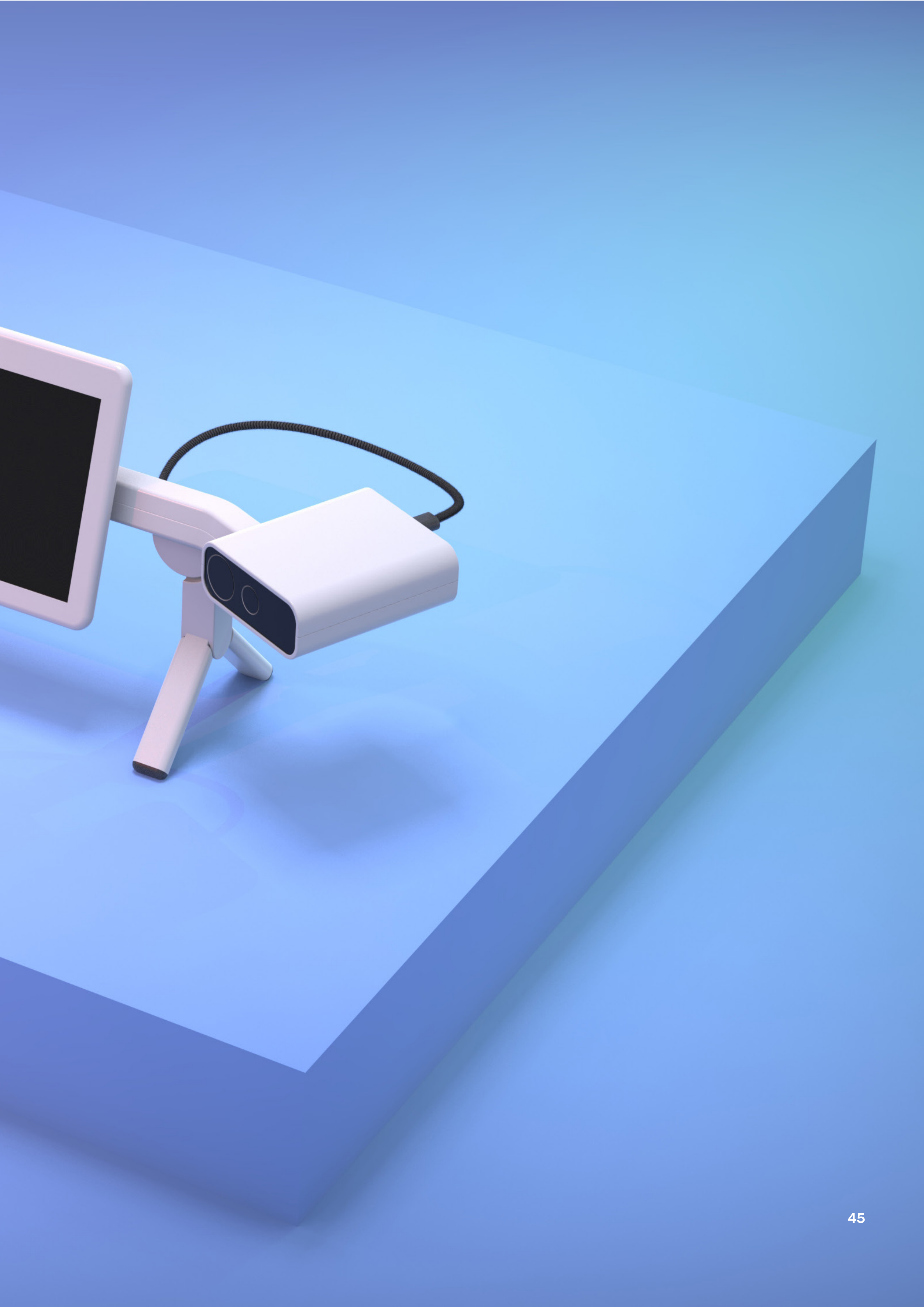


[Figure 15]
Concept render of the 3D Head Scanner

[Figure 16]
Concept render of the 3D Head Scanner in context



[Figure 17]
Concept render of the 3D Head Scanner



4.3 - Data acquisition and processing

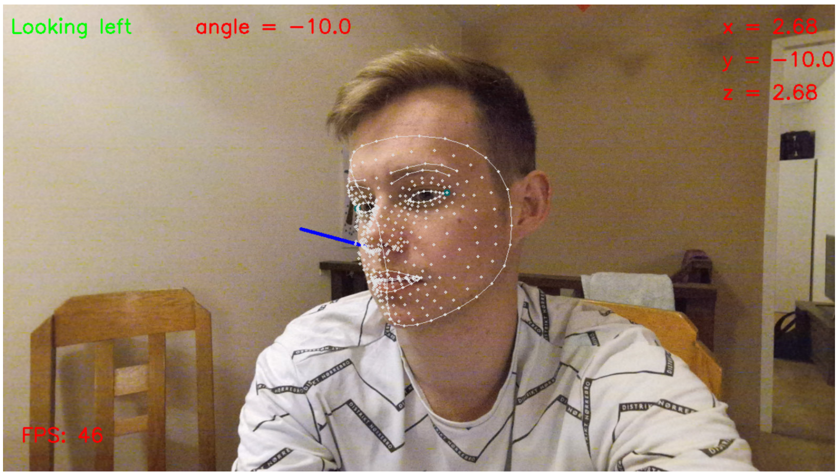
In the software of the 3D Head Scanner, small tricks have been implemented to increase the ease of use and comfort for the person taking the scan. In this chapter, the most important considerations and design choices are briefly explained.

User in focus

When starting the scanning procedure, first a window will pop up, showing the live camera feed of both camera's in RGB-values. An elliptical outline is being displayed over the video feed, as to give a reference of where the client's head should be. When the user's head is inside of this area for both camera's, the outline will turn green and the scan can be captured.

Automated capturing

One of the possibilities that this design offers, is to automatically capture the data without the user interfering. Once the system is activated, it will search for faces using Google's Media Pipe Face Mesh, which uses Machine Learning to estimate 468 3D face landmarks in real time. Based on these facial landmarks, it is possible to calculate the pose of the user's head and calculate the vector where the user is aiming at. At the same time, the tilt can be calculated picking points on both the left and right side of the client's head and comparing their height. When the client's aim is between certain values for a longer period of time, this means that he/she is sitting still and that the scan can be automatically captured. This period of time can be defined as a specific amount of frames, since the framerate of the sensors is known. The Python code for this can be found in Appendix X.



[Figure 18]
Output of code calculating the users pose

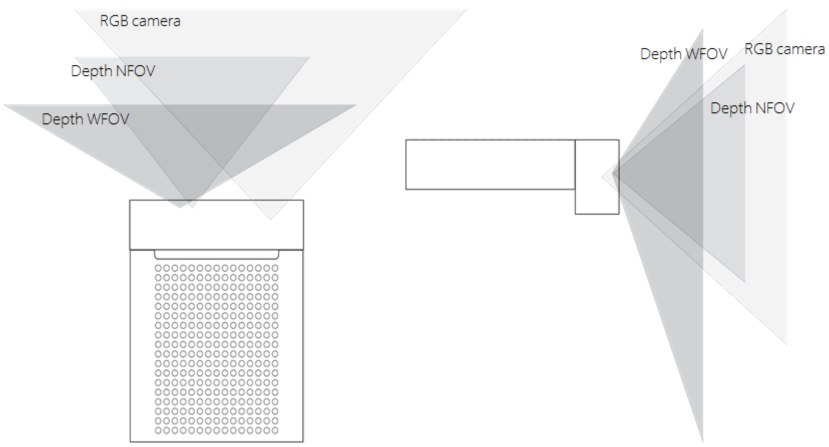
Data acquisition

The Azure Kinect DK sensor offers various operating modes for the depth sensor. There are options for using Narrow Field of View (NFOV) or Wide Field of View (WFOV) and for binning the data[13]. These settings have an influence on the framerate and operating range (Microsoft, 2022). Firstly, looking at the field of view, experiments showed that using the NFOV-setting suffices, since WFOV will only capture more background data that later needs to be filtered out.

(13)
A data pre-processing technique used to reduce the effects of minor observation errors. The original data values which fall into a given small interval, a bin, are replaced by a value representative of that interval

Mode	**FoV**	**FPS**	**Operating range**
NFOV | unbinned	75°x65°	0, 5, 15, 30	0.5 - 3.86 m
NFOV | binned	75°x65°	0, 5, 15, 30	0.5 - 5.46 m
WFOV | binned	120°x120°	0, 5, 15, 30	0.25 - 2.88 m
WFOV | unbinned	120°x120°	0, 5, 15	0.25 - 2.21 m

[Table 2]
Overview of different acquisition modes and characteristics

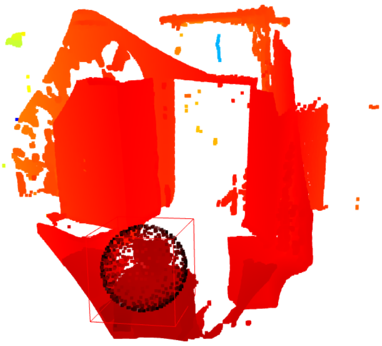


[Figure 19]
Graphical overview of viewing angles of different Field of View-modes

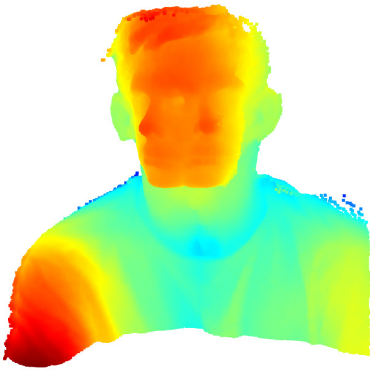
In terms of binning, Azure Kinect DK offers the possibility to use 2x2 binning, meaning that those four pixels will then be treated as a single pixel. Although this reduces the noise, it also significantly reduces the resolution of the (depth) image. Therefore it was chosen to use the "NFOV | unbinned"-setting for capturing data. A single scan has a data acquisition time of 12.8 ms in that case (Microsoft, 2022).

What could be a better way to reduce the noise is to make use of 'bursts': instead of collecting just one frame, collect multiple frames and combine this

[Figure 20]
All captured points



[Figure 20]
Inserted sphere to crop out region of interest



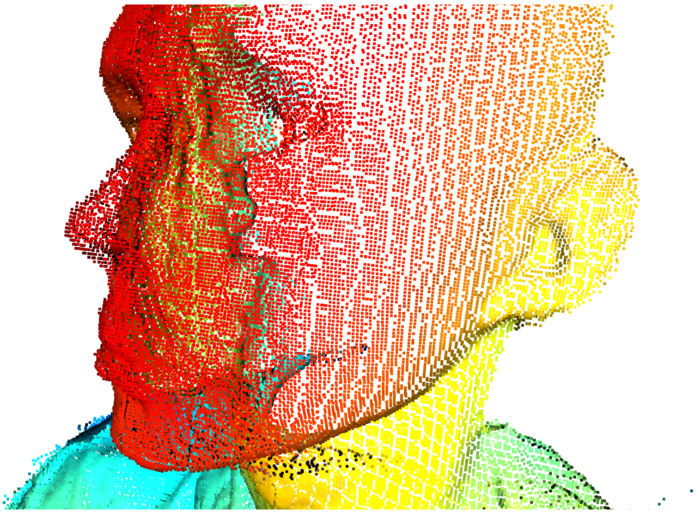
[Figure 20]
Result of crop

data. Although the data acquisition and processing time will increase, the resolution will be untouched.

RGBD to point cloud conversion

The captured data is saved as RGB-D data, meaning that it contains both the colour information and the depth map. This 2D depth map can easily be transformed into a 3D point cloud. When looking at the point cloud, it can be observed that a lot of (unwanted) background information was captured as well. To remove this data, we can draw a sphere in 3D around the place where we expect the client's head to appear. All points that do not fit this sphere will be filtered out, leaving only the points within the sphere, see Figure 20.

Although at first glance it might look like a watertight 3D-model, this is not the case as becomes visible when zooming in a bit further as can be seen in Figure 21.



[Figure 21]
Captured point cloud, consisting of about 370.000 points.

No calibration needed

When opening both scans (left and right) at the same time, it can be seen that they are not aligned as they should be. They should be both translated and rotated to make a good fit. Since the position and orientation of both sensors are known, it is possible to calculate the transformation matrix for one of the scans to seamlessly fit. However, to make sure that this transformation matrix is up to date, the system should be calibrated every once in a while, where the user needs to hold some sort of pattern in front of the device and based on this pattern, the transformation can be calculated. Since this can be quite annoying and/or time consuming to do, it is often not done frequently enough, meaning that errors can introduce.

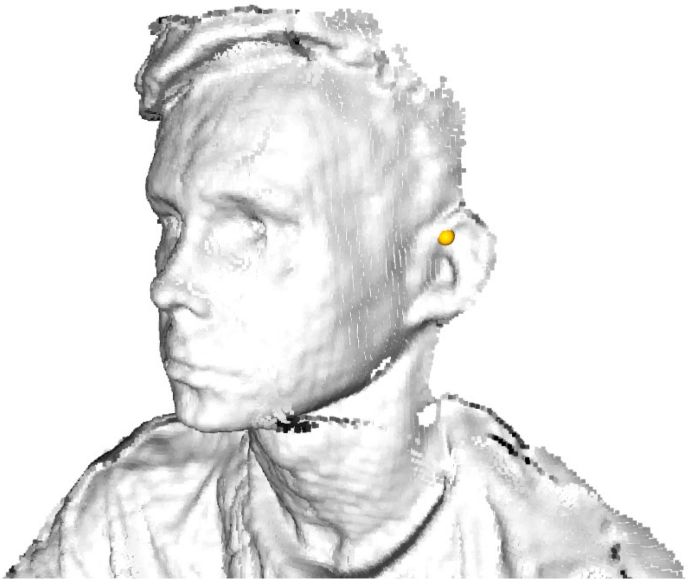
That is why this system has been designed in such a way that calibration is not needed. Global registration algorithms and Iterative Closest Point (ICP) algorithms will calculate an initial transformation that will roughly align the point clouds, before tightly aligning the two point clouds. It is important that the user checks that the alignment was successful (no double nose or other misalignments) before continuing the procedure. To do so, the person taking the scan has to approve the quality of the 3D scan and its alignment.

Voxel downsampling

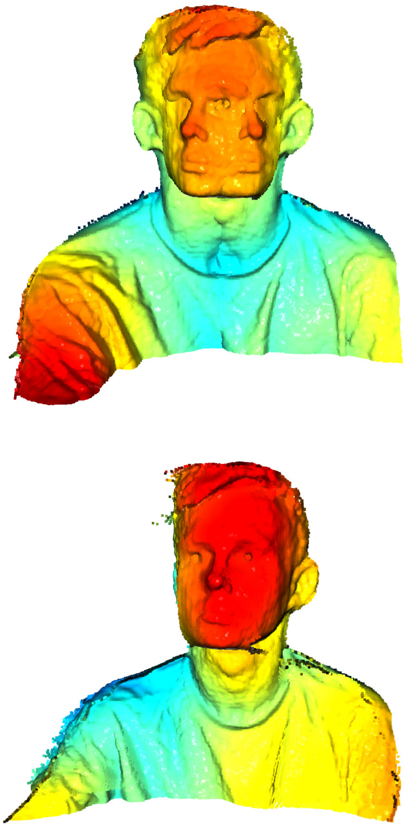
The amount of captured data points is quite high, especially when implementing bursts. This leads to higher processing times and slower interaction. Therefore it can be useful to implement downsampling methods such as voxel downsampling, to reduce the number of points in a scan. First of all, a grid of voxels[14] is created and the point clouds are bucketed into these voxels. Then, each occupied voxel generates exactly one point, which is averaging all points inside this voxel. Depending on the voxel size, the downsampling magnitude can be controlled.

Highlighting the triangular fossa[15]

For Maatbril, it is important to know the location of the triangular fossa, to be able to calculate the length and shape of the temples of the glasses. First the user is asked to select the triangular fossa for the left ear and after



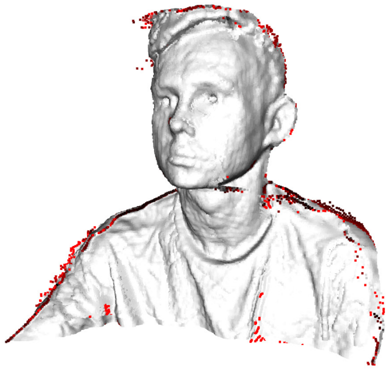
[Figure 23]
Highlighted Triangular Fossa of the left ear.



[Figure 22]
Scans from left and right sensor before alignment (top) and after alignment (bottom).

(*14*)
A voxel is a three-dimensional pixel or volumetric pixel, used to represent a value in a three-dimensional space

(*15*)
Region on the ear that signifies the last point where the ear is connected to the skull



[Figure 24]
Selection of statistical outliers (red).

that, the same for the right ear. To avoid confusion on which is the left ear and which is the right ear, the preview window will open with a zoomed-in view of the concerned ear. After marking the triangular fossa, the system will grab the coordinates of this point and save it in a .JSON file, along with other information about the client.

Noise removal

To remove noise, the system implements code that removes points that are statistical outliers and thus potential noise. The average distance between a point and it's 'neighbours' is calculated and if too high, the point is excluded from the scan. To tune this filter, the number of 'neighbour' points that are taken into account can be defined, as well as the aggressiveness of the filter, based on the standard deviation of distance between points.

Meshing

Whereas so far, only a point cloud of the client has been available, Maatbril requires a 3D mesh file, and thus does it need to be converted. There are various options for file formats such as Polygon File Format (.ply), Object Files (.obj), Object File Format (.off), GL Transmission Format (.gltf/.glb) and Stereolithography (.stl). The .obj and .stl file formats are most commonly used in 3D modelling at this moment and since the scan does not come with a texture mesh, a .stl file will suffice. There are different techniques for transforming the point cloud into a mesh, such as alpha shapes as defined by Edelsbrunner et al, the Ball Pivoting Algorithm by Bernardini et al. and the Poisson surface reconstruction algorithm by Khazdan et al. (Bernardini et al., 1999; Khazdan et al., 2006; Kirkpatrick et al., 1983). Poisson surface reconstruction was chosen to be implemented, based on accuracy and performance while reconstructing a sample pointcloud. A benefit of this method is that it does not leave any gaps in the mesh. Next to that, it gives the possibility to define the quality level, where output quality and waiting time can be optimized. A downside of this Poisson surface reconstruction algorithm is that it will extrapolate geometry as well. However, this geometry can be removed by a 'density mesh filter', which calculates the density of the mesh and deletes the mesh with a density

[Figure 25]
Result after meshing (top) and trimming with a density filter (bottom).

[Figure 26]
Result after applying an average filter (Left), a Taubin filter (Middle) and both average and Taubin filters (right).

below the set threshold as can be seen in Figure 25.

Smoothing

To filter out inefficiencies, smoothing filters can be used. Although various smoothing algorithms have been examined, such as Averaging filters, LaPlacian filters, Taubin filters, etc., a combination of Taubin and Averaging algorithms have been selected, based on quality of the output scan. The effect of these specific filters can be seen in Figure 26.

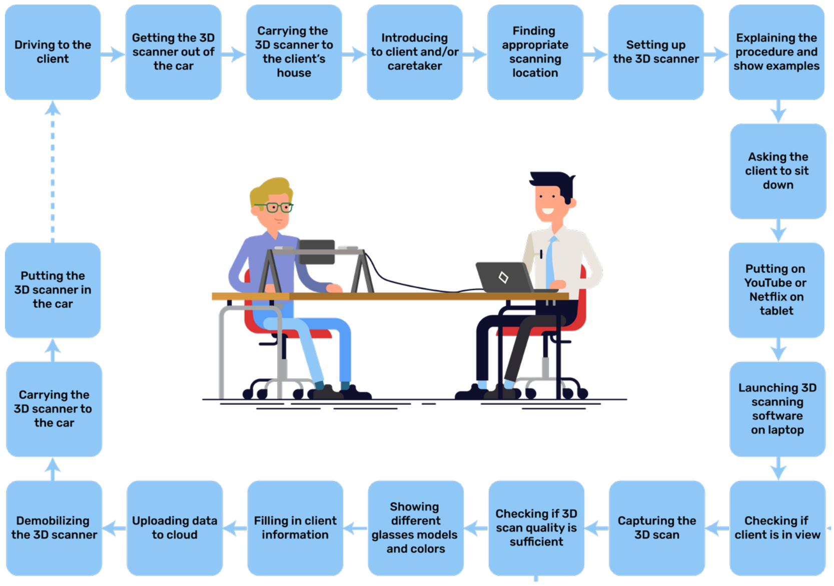
User data and output

To make sure all required data about the user is collected, and stored in an orderly fashion, a UI has been prototyped where the necessary details can be filled out, once completed, all important files are saved and packaged in a .ZIP file. This Zip file contains the raw scans in .ply format, the meshed .stl and the file with information about the user and the scan in .JSON format. The client's name is then used to name all files, e.g. John_Doe.JSON, John_Doe.STL and John_Doe.ply to avoid confusion. After zipping the files, the original files are automatically deleted from the device, saving Maatbril time and effort to find and or delete files, and next to that, it will save space in the internal storage of the device.

4.4 - Interaction

In this graduation project, a lot of focus has been put on the interaction between the 3D Head Scanner and the users. Especially when working with different use scenarios and potentially varying stakeholders, it is good to get an overview of who interacts with who or what. That is why for every user in every scenario, a step-by-step User Journey has been developed to find the key points in the interaction between the person taking the scan and the 3D Head Scanner and between the client and the person taking the scan. An overview of these User Journeys can be found in Appendix R.

In this chapter, the main moments of interaction for both the person being scanned and the person taking the scan will be discussed and design choices will be explained.



[Figure 27]
User Journey of a Maatbril employee when visiting a client at home

4.4.1 - Person being scanned

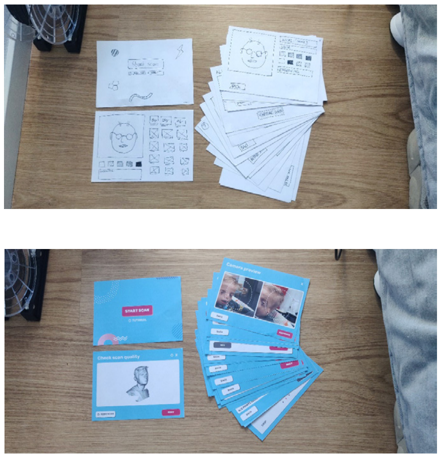
During observations of the current 3D scanning procedure, it became apparent that for some clients the fear factor was quite high, especially for clients with mental disabilities. The fact that an unknown man is walking closely around them while they needed to sit still for about 20 seconds did not help with that, as the caretakers often had to calm down or reassure the client. Kids at the same time often had to be bribed to sit still, and/or the caretaker or parent needed to hold the head of the client to make sure that they would sit still for the scan.

Whereas initial tests showed that it might be nice for the user to actively contribute to taking the scan, it became apparent that not all clients have the mental capacity to do so. For some of them, even simple actions like rotating their head at low speed would already be too much to ask.

To let the procedure be as inobtrusive as possible for the person being scanned, ideation was done to shape the interaction and different ideas were developed by means of 'How To?'s, brain drawing, and SCAMPER. Special attention was paid to see if and how it would be possible to integrate the scanning procedure in some everyday activity and how to make sure that the person being scanned would sit still, without having to force them. Moreover several ideas were generated where the client actively participates in the 3D scanning procedure. These ideas were tested by means of roleplaying to be able to detail and finetune the interactions. All initial ideation results and concepts can be found in Appendix T, while the findings of the roleplaying session can be found in Appendix U, followed by an evaluation of the different concepts in Appendix V.

Eventually, it was chosen to distract the client with (video graphical) content that is being displayed on a tablet or similar-sized screen. Simply said, the client is focused on the screen by watching something he/she finds interesting and while doing so, the 3D scan is quickly captured. The main reasons for selecting this concept being that it is the simplest interaction that can be performed also by people with limited mental capacity as initial tests have shown and it is easy to adjust the content to the user's interests. Moreover, there are no financial costs attached to the development of this, as existing solutions such as YouTube or Netflix can be used.

[Figure 28]
Roleplay activities with fellow students to test different interaction scenarios.



[Figure 29]
First paper prototype (top) and prototype after first iteration (bottom).

4.4.2 - Person taking the scan

To make life as easy as possible for the person making the 3D scan, a lot of time and effort has been put in the development of the User Interface (UI). The interaction should be quick, unambiguous and clear. After generating the first drafts of the User Task Flow (UTF) and a drawn paper prototype, these different ideas were quickly tested out with a small test panel of four participants. Feedback was collected, UTF's were refined and a higher fidelity paper prototype was developed and tested among a larger test panel. All screens of these prototypes can be found in Appendix I. Eventually, a digital prototype was developed and used for more realistic user testing.

[Figure 30]
Maatbril clients choosing the frame model


eer montuur
ste montuur
X
TWINS F
FACET M
FACET U
FACET F
EDGE U
EDGE F
FLAT M
FLAT U
NEXT

Quick start guide

Before being able to capture the 3D scan, the 3D Head Scanner has to be setup. To help people without prior experience to do this setup, the scanner comes with a one-page Quick Start Guide, as can be seen in Figure 31. The Quick Start Guide describes what steps to take before opening the software and contains the contact details of Maatbril in case contact needs to be made. A full scale version of the Quick Start Guide can be found in Appendix AD.

[Figure 31]
Someone studying the instructions on the 3D Head Scanner's Quick Start Guide.

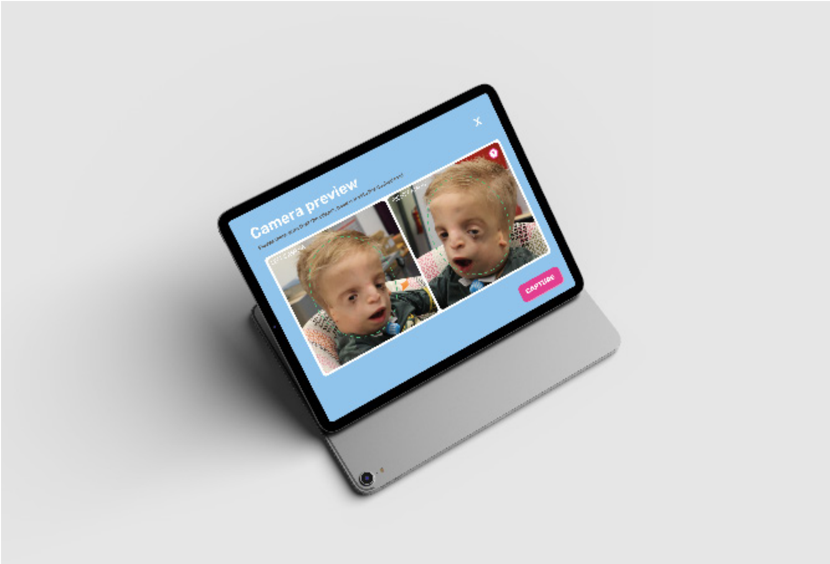
Opening the software

The User Interface is designed with the intent to get the 3D scan on the screen as quickly as possible, to be able to evaluate the quality as soon as possible and retake the scan if necessary. Only after confirmation of a successful 3D scan, the desired model and colour can be chosen and now is also the moment that additional user information is requested. To not keep the client and his/her caretaker waiting, at the very end the system will generate the 3D Mesh and upload it to the database.

[Figure 32]
Homescreen of the User Interface, the 3D scanning procedure can be started or a tutorial can be followed.

Aligning the 3D Head scanner

After clicking the ‘Start scan’-button, immediately a preview will open to check if the client is in view of both cameras as can be see in Figure 33. Various options were considered, including options where the camera of the tablet will be used for this purpose. Eventually, it was chosen to show the two RGB-previews of the two depth camera’s since this option was both easy to understand and it wasn’t as obtrusive for the client as the options that involved using the tablet. A complete setup and results of the experiment can be found in Appendix AF. The Python code can be found in Appendix W.



[Figure 33]
First screen that opens when starting the procedure, live preview of the 2 sensors to align the 3D Head Scanner.

Capturing the scan

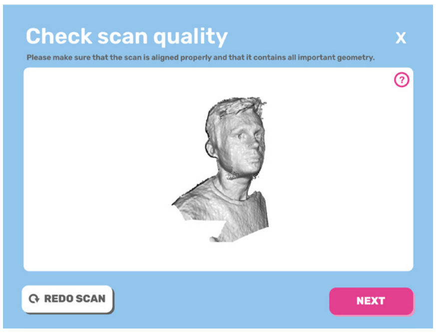
To capture the 3D scan, it was chosen to use a 'capture'-button on the User Interface, as can be seen in Figure 33. Tests with a physical button on the prototype showed that the user might get distracted when the person taking the scan pushes this button and accidentally turn their heads. Another option would be to implement a (wired) remote control, however, this only adds extra complexity and cost to the 3D Head Scanner, whereas the User Interface is already part of the design.

Checking the scan quality

To make sure that the quality of the 3D scan is good enough, a preview of the aligned 3D scans will be shown to the user. Here, he/she has to confirm that all important geometry is included (eyes, nose, frontal part of ears) and that the two scans have been aligned perfectly. Immediately after the algorithms have been aligned, an interactive window will appear with the results. To indicate that the screen is interactive, the point clouds will slowly rotate. If the results turn out to be not sufficient, the user can choose to retake the scan.

Selecting the desired model and colour

After confirming the scan quality was sufficient, the system will start converting the point clouds into a 3D model in the background. Meanwhile, the client (and caretaker) can choose the desired model and colour of the frame. Usually Maatbril will bring a physical case with different models to the

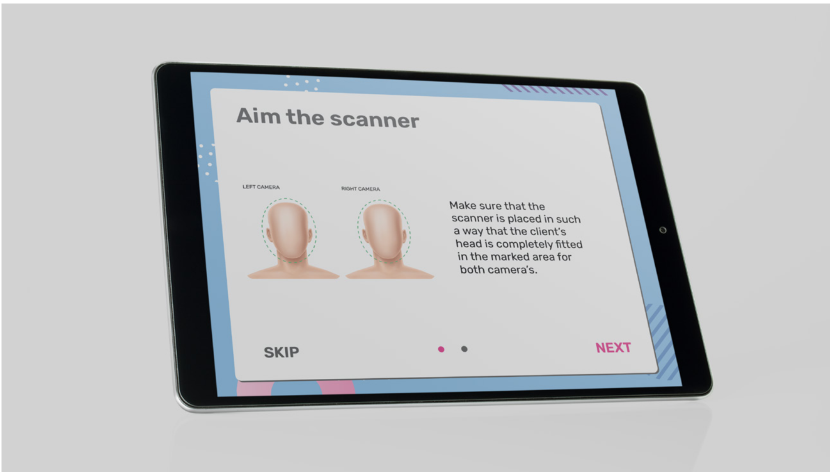


[Figure 34]
Preview of the two aligned 3D scans where the user can choose to continue or retake the scan.

scanning location, but the built-in preview in the UI let's the user evaluate the different models in different colors in 3D as well as can be seen in 36. In the following screen, the user can choose to have custom text engraved in one of the glasses' temples. A preview of this is shown in Figure 37.

Filling out all other details

Other details like contact information and special remarks can be added as a last step before clicking the 'upload'-button. Next to the glasses selection and engraving data, contact information will be inserted in case any questions or remarks arise when the glasses are being modelled. When all data is correctly inserted, the 'Upload'-button can be pressed which uploads the .ZIP with all captured and gathered data to the Maatbril database.



[Figure 35]
Integrated tutorial screen to explain alignment of the 3D Head Scanner

Integrated tutorial

Although a lot of focus has been put in designing a clear and unambiguous User Interface, some parts of the interaction could be a bit unclear. To make sure that the procedure runs as smoothly as possible, various tests were done to discover for what steps it might be beneficial to have some extra explanation available in the form of a so-called tutorial. The setup and all results of this test can be found in Appendix AC. Especially the alignment of the 3D Head Scanner with the user and the moment where the 3D scan needs to be checked in terms of quality were key points in the procedure where it might be nice to have such a tutorial card available. For new users, the tutorial can be started from the home screen so that he/she knows what to do before the procedure is started. Moreover, at these specific moments in the interaction, it is possible to revisit the explanation.

[Figure 36]
Interactive 3D preview of the selected frame model in the desired color

[Figure 37]
Interactive preview for specifying engraving in one of the glasses' temples


Check the scan quality
After
SKIP

[Figure 38]
Following the Integrated Tutorial

4.5 - Embodiment

Mainly for testing and evaluation purposes, a physical prototype has been developed by using off the shelf components combined with 3D printed mounts, as can be seen in Figures 39, 41 and 47. The prototype can be considered as a experimental prototype or even an alpha prototype as defined by the Loughborough iD cards (Loughborough University, 2014). The Python code for this prototype can be found in Appendix Y.

[Figure 39]
Physical prototype of the 3D Head Scanner

[Figure 40]
Azure Kinect DK (top) and internal sensor hub of Azure Kinect DK (bottom).

Sensor selection

The design contains two Azure Kinect DK sensor hubs utilizing the principle of Amplitude Modulated Continuous Wave (AMCW) Time-of-Flight (ToF). By emitting modulated illumination in the near-IR spectrum onto the scene and capturing an indirect measurement of the time taken for the light to travel from the camera to the scene and back, it records data. In simpler terms, it measures the time it takes for light to travel to and from the scene by casting modulated illumination and recording the result (Microsoft, 2022)

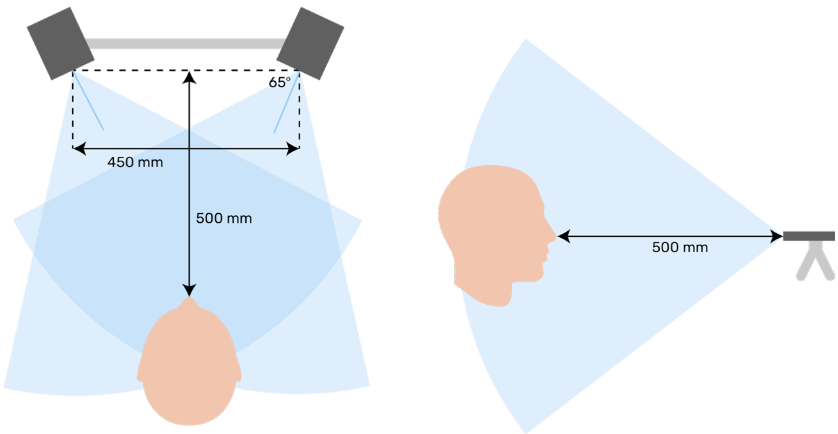
This technology was chosen after extensive analysis of different 3D imaging technologies such as photogrammetry, laser-based 3D imaging options and experiments with new types 3D reconstruction implementing Machine Learning techniques. In terms of typical working range, accuracy and cost of hardware and software it was deemed to be the best fit for this application. Initially, the idea was to implement Intel RealSense 435i 3D sensors, however the resolution and accuracy of this sensor was not sufficient (~5mm), that is why the more expensive and more accurate Azure Kinect DK has been selected. The analysis and results of the experiments can be found in Appendix F.

[Figure 41]
Azure Kinect DK sensor in prototype

Sensor placement

Instead of implementing three sensors, as was done in the previous prototype, for this prototype only two were used. The main reason was to save on costs, about €400. To make sure that a large enough part of the geometry is captured, ideally the sensors are placed as far away from each other and under a large angle. For the scan quality it would be beneficial to take the scan from as close as possible to have the highest resolution, and there should be enough overlap in the scans so that the algorithm can easily align the two scans. Gradient descent optimization[16] has been applied to find a good balance between the those parameters and the results can be found in Figure 42. The calculations can be found in Appendix J.

(16)
An iterative optimization algorithm used to find the minimum of a function by adjusting the parameters in the direction of steepest descent of the function



[Figure 42]
Sensor placement and field of view

Controlled via Windows

Currently, Azure Kinect DK sensors are not supported for MacOS, meaning that a Windows- or Linux-based device is required (Scatter, 2021). An ideal and cheap solution would be to use a Raspberry Pi, however the ARM-processor that it makes use of does not support the Azure Kinect DK sensors (yet). That is why it was chosen to make use of a Windows-based laptop or tablet for now.

Power and data through one cable

By implementing USB C, both power and data can be transferred through the same cable, without the need for an external power supply. This means that the 3D Head Scanner doesn't come with a power cord, but it will rather get it's power from the device it is connected to. By integrating a USB hub in the 3D Head scanner, only a single cable has to be connected to the device, allowing easy setup and professional appearance.

Foldable and compact

It was chosen to implement foldable legs in the 3D Head Scanner so that it can be put on a table or kitchen counter, since these are in any home and or Healthcare centre. Not only is it easier to carry the 3D Head Scanner around compared to bringing a tripod, it also allows for more flexibility when choosing an appropriate location to perform the 3D scan because of its relatively small footprint. Next to that should it help with the perceived appearance of the 3D Head Scanner: Gupta found that having the 3D Head Scanner on a tripod could make it look quite intimidating (Gupta, 2021).

A tripod mount is implemented in the 3D Head Scanner however, to be able to cope with complex situations such as people in wheelchairs, or the lack of appropriate available furniture.

[Figure 43]
3D Head Scanner placed in transporting case

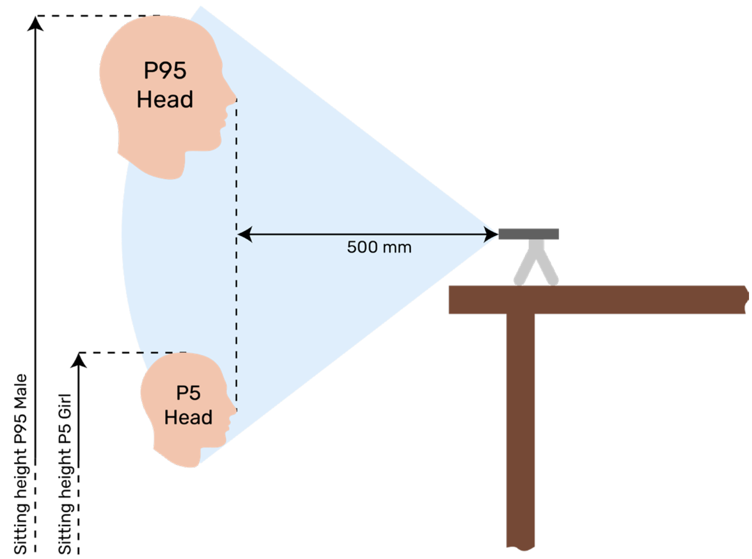
[Figure 44]
3D Head Scanner placed on a tripod

Works in every environment

The 3D Head Scanner will be used in different scenarios and thus also in different environments with different target groups. Because the system uses (near-)IR light, 3D scanning can be done even in the dark as preliminary tests have shown, although results might differ among different ambient light intensities.

There are many other variables however that could have influence on the system's functionality, especially looking at the dimensions. Next to the differences in height between different tables and chairs, there is also a large difference in size within the target group. The person that is being scanned could be a 5-year-old girl with a sitting height of 563 mm, but also a 60-year-old P95 male with a sitting height of 995 mm (Dinbelg, 2023). Since the placement of the 3D Head Scanner relative to the person being scanned is known, the field of view of the sensors is known as well. Calculations have been done, optimizing the height and angle of the sensors to make sure that the user's head will always completely fit within the sensor's field of view (with some margin).

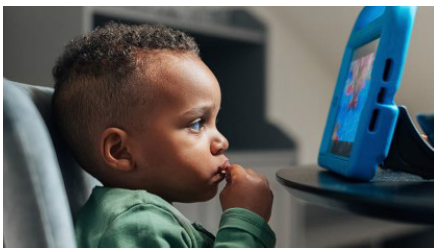
The calculations that have been done to assure that the system can be used in (almost) all situations can be found in Appendix K.



[Figure 45]
Overview of variance in sitting height and head size.

Integrated tablet

Although many families own an iPad or similar sized tablet nowadays, about 40% of the families doesn't have access to a tablet (Statista, 2020). Since many children -especially- already have the tendency to hold digital devices as close as possible to their eyes, the use of a smaller screen such as a smartphone should be avoided to make sure that the working distance of about 500 mm is maintained. That it why it was chosen to integrate a screen in the 3D Head Scanner despite the increase in cost.



[Figure 46]
Kid sitting at 'typical' viewing distance from iPad.

The decision to integrate a standalone tablet rather than for example a TFT screen[17] that could act as a second screen for the device controlling the 3D Head scanner was based on the following reasons:

Firstly, the tablet has an integrated battery, whereas a second screen either requires a power outlet or needs to be powered by another device. This would mean that an additional 2 ports (USB for power, HDMI for image) would need to be connected when choosing the second screen.

Moreover, having a standalone tablet would clearly split the functions of the different devices. The tablet should attract the client's attention, while the device controlling the 3D Head Scanner can use all it's resources for processing the 3D scans. This also means that if necessary, a relative or caretaker could take control over the tablet, making sure that the person taking the 3D scan can solely focus on acquiring an accurate 3D scan.

An added benefit of integrating the tablet is the fact that a tablet usually contains a front camera that can be used for aligning the 3D Head Scanner to the user, meaning that additional camera's are not needed to integrate in the 3D Head Scanner.

Production and cost

Although the design has not been worked out in such a way that it is (almost) ready for production, still production has been taken into consideration. Since the number of devices that will be produced will be less than 10 per year, investing in moulds for injection moulding is not profitable (Jan Berend Zweerts, personal communication, October 13, 2022). Moreover, to keep the barrier low for (new) parties to build and make use of the 3D Head Scanner, the percentage of 'of-the-shelve'-components should be as high as possible. To connect the various components, it is advised to use 3D printed mounts. These mounts can be printed on (small and) cheap FDM[18] 3D printers for e.g. Creality or Prusa whereas companies might be able to afford professionally looking SLS-printed[19] mounts.

The only tools that are required to build this 3D Head Scanner are a soldering iron or threaded insert tool, a M3 HEX key and a metal saw. And it can be done in less than 38 minutes on average as was tested in Appendix AG.

When assuming that the person that will build this 3D Head Scanner has access to a FDM 3D printer, the cost of the 3D scanner would be €823,44,[20] where the 3D sensors account for roughly 80% of the cost. A complete overview of components, where to buy them and their cost can be found in Appendix AB.

(*17*)
a thin-film-transistor liquid-crystal display (tft-lcd) is a type of liquid-crystal display (lcd) that makes use of thin-film transistor-technology (tft) to improve image quality

(*18*)
FDM (Fused Deposition Modeling) is a type of additive manufacturing technology that uses a heated nozzle to melt and extrude thermoplastic material layer by layer to create a three-dimensional object

(*19*)
SLS (Selective Laser Sintering) is a type of additive manufacturing technology that uses a high-powered laser to selectively fuse powdered materials, such as plastics or metals, into a three-dimensional object.

(*20*)
Calculated on March 22nd, 2023. Shipping included, travel bag and other accesories not included.

[Figure 47]
Physical prototype of the 3D Head Scanner

4.6 - Product validation

In this chapter the 3D Head Scanner will be evaluated both in terms of performance, functionality and interaction by means of experiments, user tests and consults with experts.

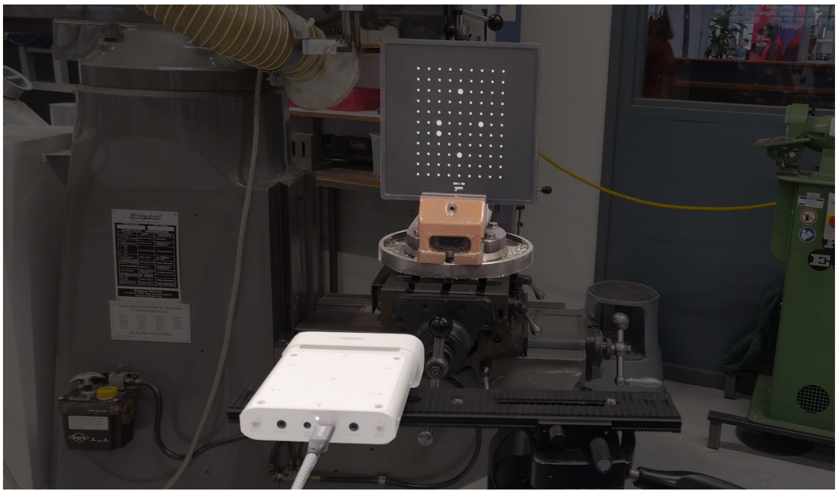
4.6.1 - Evaluation of performance

To evaluate the performance, both the 3D sensor individually and the complete 3D Head Scanner were subjected to experiments. Next to that, the system was presented to a 3D scanning expert.

Evaluation of Azure Kinect SDK sensor accuracy

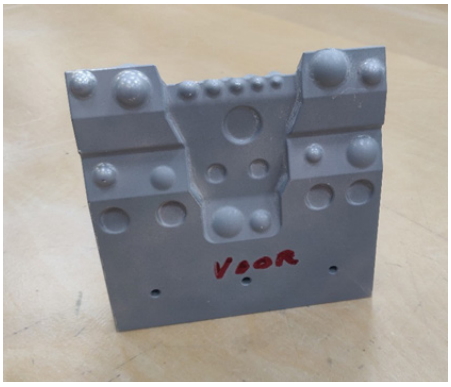
Whereas for various Intel RealSense depth sensors research is available evaluating the accuracy of the sensors, this is not the case for the Azure Kinect DK sensor. To be able to pinpoint the exact factors that need improvement in this project, it is important to understand if the 3D sensors are even capable of acquiring 3D scans with the required accuracy. To find this out, various experiments were performed. A calibration plate was used to evaluate the flatness error of the sensor, as can be seen in Figure 48. In this experiment, a virtual plane was fit to the captured point cloud and the average distance between the individual points and the plane were calculated, using the Root Mean Square error[21]. The Root Mean Square is equal to 1.1 mm for a distance between the calibration board and the sensor of 500 mm. This means that the desired accuracy of 1 mm will be hard to reach due to the sensor's limitations. For the complete results of this experiment, see Appendix AH.

(21)
See Chapter 4.2 for more inforation



[Figure 48]
Overview of test setup to measure Azure Kinect DK accuracy

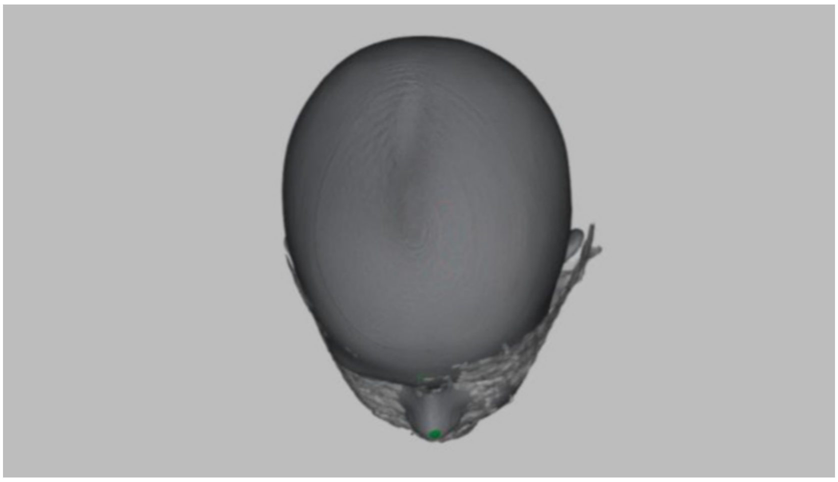
Next to that a calibration object was used to evaluate the accuracy of the 3D sensor at various distances. A similar setup was used as the setup shown in Figure 48, however, this time the calibration object shown in Figure 49, was used. This object had also been 3D scanned by the Artec Spider which could serve as ground truth for comparison. After aligning the scans from the 3D Head Scanner and the Artec Spider, again the Root Mean Square error has been calculated. At 500 mm distance, the Root Mean Square error was equal to 1.0 mm which increased up to almost 1.5 mm at a distance of 900 mm. It has to be noted that for the scans taken at 800 and 900 mm distance, the resolution became quite low, making it harder to accurately align both scans. This could also have had an effect on the measured Root Mean Square. The complete procedure and results can be found in Appendix AI. From these experiments it can be concluded that at 500 mm distance, the Azure Kinect DK sensor should be able to capture geometry with an accuracy of about 1.0 or 1.1 mm.



[Figure 49]
Calibration object

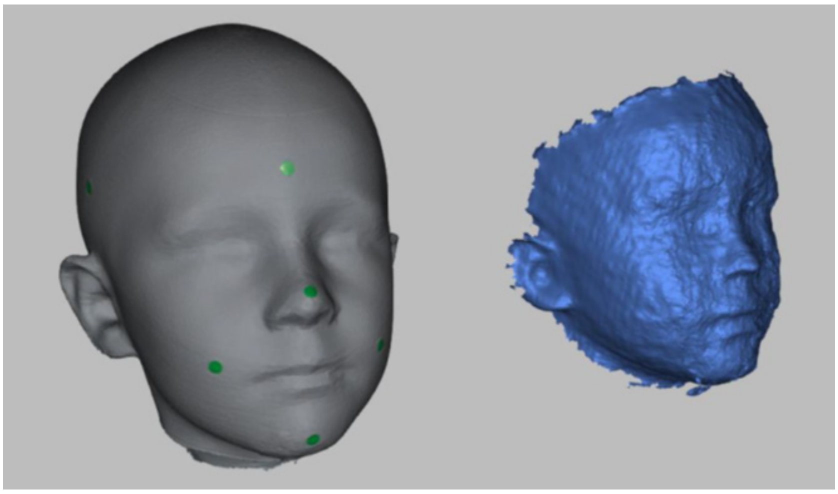
Evaluation of 3D Head Scanner accuracy

Now that it is known how accurately the Azure Kinect DK sensors are able to capture geometry, the performance of the 3D Head Scanner in terms of accuracy can be evaluated. To do so, a 3D printed head shape is scanned in with the 3D Head Scanner and again, it also has been 3D scanned by the Artec Spider which could serve as ground truth for comparison, as can be seen in Figure 51. What became apparent during this experiment was the Iterative Closest Point-algorithm[22] that is used to align the left and right 3D scan needs optimization. As can be seen in Figure 50, is the 3D Head shape captured by 3D Head Scanner too wide, meaning that the angle at which the scans have been aligned to one another is incorrect.



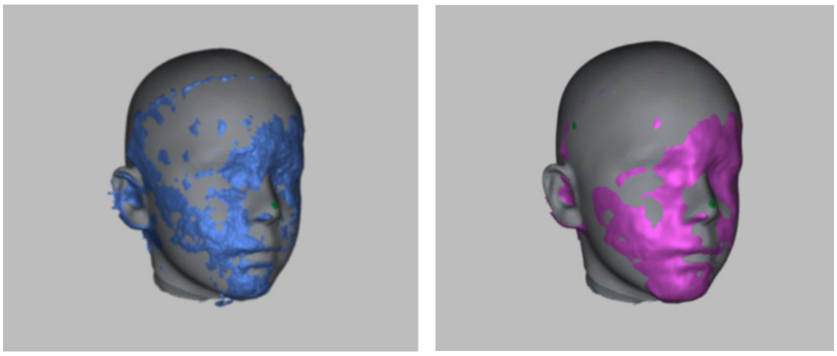
[Figure 50]
Difference in width of captured 3D scans

When calculating the error by means of the Root Mean Square, the value was equal to 2.3 mm. This is however giving a wrong image of the 3D Head Scanners potential: When making use of the ICP-algorithm implemented in the Artec Studio software, a (near) perfect alignment was made. This means that the amount of overlap, and thus the sensor location and orientation, were chosen correctly. When evaluating the accuracy of the 3D Head Scanner, using the Artec Studio ICP-algorithm, the Root Mean Square error was equal to 1.2 mm.



[Figure 51]
3D Head scans of Artec Spider (left) and 3D Head Scanner (right)

Experiments were done with smoothing of the 3D scan as well, since Maatbril desires smooth 3D models to work with, but it turned out to have a minimal positive effect on the accuracy of the system. It does make it however look a lot more clean and professional compared to the raw scan result, as can be seen in Figure 52. The complete setup and results can be found in Appendix AJ.



[Figure 52]
3D Head scans of Artec Spider and 3D Head Scanner shown over each other without smoothing (left) and with smoothing (right)

Lastly, experiments were performed to evaluate the effectiveness of implementing bursts, where multiple 3D scans are taken shortly after one another. These scans will then be averaged to reduce noise and increase accuracy. This goes however at cost of waiting time and to find out how much time this would cost exactly, the software was tested and processing times were recorded. The results of this experiment can be found in Table 3.

	1 frame	2 frames	3 frames	5 frames
Turn on, capture data, Turn off [s]	2.6	2.7	2.7	3.0
Transform data to point cloud [s]	1.6	3.2	4.8	6.5
Load point cloud and down sample [s]	20.9	38.6	63.2	114.4
Align left and right scans [s]	4.8	15.3	24.5	68.0
Time before seeing first result [s]	**29.9**	**59.8**	**95.2**	**191.9**
Combine scans into single scan [s]	20.5	38.5	63.2	94.7
Turning point cloud into mesh [s]	38.8	67.2	105.6	127.2
Smoothing and cleaning up mesh [s]	6.2	7.5	11.3	11.3
Total processing time [s]	**95.4**	**173.0**	**275.3**	**425.1**

[Table 3]
Capturing times for different burst settings

From the table it can be seen that the time between capturing the scan and displaying the first results is about 30 seconds for a single capture. When implementing bursts, this time increases in an almost linear way. The time before seeing the first results is important for the interaction, since it determines how long the person taking the scan has to wait before seeing if capturing the scan was successful. Unfortunately the comparison in terms of accuracy among the various bursts was unsuccessful. Double surfaces made it impossible to accurately measure the accuracy of the 3D scans. This means that the process of taking the average of the scans by means of voxelization was unsuccessful, or that potentially the voxel-size was too small. An increase in size also means a reduction in resolution for the resulting 3D scan.

Explorative valuation of performance by 3D scanning expert

The prototype and its´ output were evaluated by Bertus Naagen[23]. First of all, Naagen was positively surprised by the visual appearance of the device

(*23*)
Lab administrator Human-Centered Design and 3D scan expert at faculty of Industrial Design Engineering, TU Delft

– especially the size of it – and the setup- and capturing time. When showing the intermediary results, he was quite surprised by the accuracy and time needed for alignment of the 3D scans. Although the nose-bridge was a bit wider than one would expect, Naagen thought that this could be 'quite easily fixed' by some software optimization. Furthermore, he suggested to add the functionality to select feature points to do the initial global registration by hand when the software for some reason fails to achieve a good result.

Seeing the final result of the 3D scan, he noticed some double surfaces that did not get removed when downsampling the combined 3D scan. Moreover, there were quite a lot of artefacts in/on the 3D scan that had initially not been visible in the point clouds. Naagen expects that these artefacts have been introduced by the smoothing filters, that might have been "a bit too aggressive", but it could also have happened during the meshing procedure. Naagen predicted that optimizing of variables – by trial and error – might significantly reduce these problems. When introducing the 'burst'-concept, Naagen agreed that it could have a positive impact on the quality of the 3D scan, however, a balance needed to be found between improvement in quality and increase in processing time. "All in all, really good results for an individual, since usually entire departments are developing such software" Naagen concluded (Bertus Naagen, personal communication, March 23, 2023). For a complete overview of the feedback provided, see Appendix AE.

Evaluation of performance by Maatbril employee

The output 3D scan of the 3D Head Scanner was presented to Maatbril to evaluate to what extent the 3D scan would be useful for them and what improvements would need to be made. First of all, all required geometry was included in the scan and the achieved average accuracy should be good enough for Maatbril's procedure, assuming that the achieved average accuracy is representable for the local accuracy around the nose(bridge).[24]

(*24*)
Quick evaluation learned that this is actually the case, although a definitive number was not calculated.

Ideally, Maatbril would like to have a textured 3D model instead of the plain geometry. This texture is needed for the algorithm that is currently automatically detecting the location of the Triangular Fossa in the 3D scan. Lastly, unsmoothed 3D scans are too rough for Maatbril to work with, and moreover, a smooth scan could also be used to show to their clients and/or to virtually evaluate the fit of different models. More documentation about this evaluation can be found in Appendix AE.

4.6.2 - Evaluation of interaction and functionality

To evaluate if in practice the interaction between the client and person taking the scan and between the 3D Head Scanner and the person taking the scan are as designed for, user tests have been performed as well as an evaluation with Maatbril.

Evaluation by a Maatbril employee

A demonstration of the intended use scenario was given to the Maatbril employee who was pretending to be the client. The capturing and processing speed of the system were called "very impressive", since it delivered the first results more quickly than the current solution. Another point of improvement are the foldable legs of the 3D Head Scanner, due to the combination of loads and angles it could happen that the legs would fold themselves unannounced. For a complete overview of the feedback provided, see Appendix AE.

Evaluation of interaction and functionality

By means of user tests, the interaction with both the physical prototype and the User Interface was tested. Participants -that were not familiar with Maatbril's procedure- needed to go through the whole procedure up to the point where the order would be confirmed and the data would be uploaded to Maatbril's database. From these tests it was identified that in general, the 3D scanning procedure was straightforward and easy to understand. The main painpoints were -still- the alignment of the 3D Head Scanner to get the client in view and some smaller improvements for the User Interface, where e.g. the term "important geometry" was deemed too vague and the '?'-button[25] was not obvious enough. Documentation of this test can be found in Appendix AM.

(*25*)
Button in the UI that can be clicked to get more information about the specific step in the procedure

[Figure 53]
Participant setting up the 3D Head Scanner during user test

Evaluation of interaction with target group

With help of Maatbril, two meetings were arranged with actual Maatbril clients. The first meeting was with an adult, suffering from photophobia who could be visited at their home, while the second meeting involved two 5-year-old boys suffering from Coffin Siris Syndrome[26]. During the evaluation, the intended 3D scanning procedure was followed to see if inefficiencies and/or problems arose and to evaluate the wellbeing of the client during this scanning procedure.

(*26*)
a genetic condition that causes variable degrees of learning disability, developmental delays and distinct facial features. Approximately 200 cases have been reported in the medical literature

Something that could have been anticipated for was the fact that some of the tables are round, as was the case at the first evaluation meeting. Due to the relatively wide footprint of the 3D Head Scanner and the fact that the table was round, the 3D Head Scanner had to be placed a bit further than usually. This lead to the fact that part of the back of the 3D scan was cropped of by the cropping filter. The scanning procedure itself was quick and smoothly: The client was watching his favourite show on the integrated tablet and asked after a while when the scanning procedure would start. Only, at that moment, the 3D scan had already been captured and processed and the resulting 3D model could be shown immediately. This also made it quite easy to get the client's focus away from the tablet although the footage was not finished yet.

One remarkable bug in the system that occured was the fact that one of the Azure Kinect DK sensors was not recognized by the laptop. When plugging in the USB-C cable upside down - which should have no effect since it is USB-C - the sensor would be recognized. This bug had been noticed during development of the 3D Head Scanner as well.

The second evaluation was with two boys that suffered from Coffin Siris syndrome. This was the perfect case to evaluate how the integrated tablet and designed interaction would work out practice. When the participant arrived, the tablet was already displaying his favourite show. In both cases, the participant rushed to sit down and watch the show. Without any guidance or instruction from their caretaker - apart from removing their glasses - a 3D scan could be captured at first try.

As could be expected, at some point one of the participants tried to watch the tablet from closeby - about 10 cm. After about 20 seconds, the participant moved back a little and then the 3D Head Scanner captured the data. At no point did any of the participants express or look scared and/or bothered by the procedure. Most likely, they were clueless about the fact that a 3D scan had been made as well, although one of the participants was a bit curious about the whole setup. Within a matter of seconds however, the attention was reverted back to the tablet which was still displaying his favourite show. A complete overview of all observations can be found in Appendix AK.

[Figure 54]
Participant watching his favourite show during evaluation test

All in all, it can be concluded that the chosen interaction - distracting the client - works for the participants from the target group, even when dealing with kids and/or people with mental disabilities. Opposed to the current situation where force and/or bribing is often required, the 3D Head Scanner allows for a calm and non-invasive interaction, where capturing the 3D scan only seems a side-effect to the client. One of the two boys even asked: "When can we do it again?"

4.6.3 - Evaluation of other requirements

Looking at the design drivers mentioned in Chapter 3.2, most of them have been evaluated already in this chapter, however the cost has not been discussed yet. The final cost of the prototype was quite close to the set target - €823 vs €800 - while staying quite far under the upper limit of €1500.

Requirements about maintanence and operating lifetime have been set as well, however they have not been evaluated. Due to to the fact that budget for this project is limited, no (up to-) failure tests have been performed. The only requirement that was not satisfied - apart from the ones mentioned in Chapter 4.6.1 and Chapter 4.6.2 - is that the 3D Head Scanner should be able to act as a stand-alone device, however for the current version, a wired connection to a tablet or laptop is required. For a complete overview of all requirements and in what way they were evaluated, see Appendix Q.

CHAPTER **FIVE**

DISCUSSION

5

5.1 - Design benefits

When comparing the procedure Maatbril is currently following to the procedure that has been proposed and tested in this report, a few differences stand out. These differences will be discussed in this chapter.

First of all, the main difference is the time it takes to capture a 3D scan. Whereas currently this time is around 20 to 30 seconds, in the new procedure this will be a fraction of a second. Moreover, the time it takes before the first results can be seen in the new, are about 40 seconds quicker than is currently the case. This means that even if a scan needs to be retaken, it can be done a lot more quickly.

Next to that, it is not needed anymore to sit still on a chair while some 'strange' man is walking around you with a tablet. In the new situation, capturing the 3D scan is only a 'side-effect' for the client, that didn't even notice that the scan was being taken in most of the tests. The 3D Head Scanner allows for a calm and non-invasive interaction and 3D scanning procedure.

Evaluation of the 3D Head Scanner showed that an accuracy of about 1.2 mm should be possible, which is good enough for Maatbril's purpose, as long as the area around the nose also has this accuracy. Despite only using two 3D sensors, all important geometry is included in the captured scans.

The foldable legs make the 3D Head Scanner a versatile solution that can be used in any place. By means of trigonometry, the 3D Head Scanner was optimized in such a way that it is able to capure both small children and tall adults without having to adjust the 3D Head Scanner - despite their differences in size. The selected measuring technique is even capable of capturing 3D scans completely in the dark, as InfraRed light is used by the sensors.

Lastly, the newly designed 3D Head Scanner can be produced at a lower cost than the current solution.

5.2 - Design limitations

Although validation mainly showed positive outcomes, still there are some areas that can be focused on to improve the quality of this 3D Head Scanner.

Textured mesh

The main improvement that can be made is to combine the 3D triangle mesh with textured mesh. Not only will the scan look more realistic and will it be potentially easier to spot (misalignment) errors in the 3D scan, but it will also give the possibility to make use of Machine Learning (ML) to get the coordinates of the triangular fossa's. This is preferred by Maatbril since they are already using this in their current solution.

3D scan alignment
The Iterative Closest Point-algorithm (ICP) that is being used to align the left and right scans, does not always work properly, leading to (small) misalignment errors. This misalignment causes that the required accuracy cannot always be achieved and thus that the outputted 3D scan cannot always be used by Maatbril. In these cases, the 3D scan has to be retaken.

Footprint
For the current prototype of the 3D Head Scanner, the footprint is 750 x 150 mm. Especially when dealing with relatively small tables and/or round tables, this could lead to situations where the 3D Head Scanner does not fit on the table or needs to stand too far away meaning that part of the 3D scan will be cropped out. Moreover, the foldable legs that are currrently being used in the prototype sometimes fold back in under the load of the 3D Head Scanner.

Smoothing
The smoothing algorithms that are currently being used are too agressive. Although the 3D model is being smoothed quite well, it goes at cost of the accuracy of the 3D model - especially at the area around the nose - which is quite imporant for the fit of the glasses.

Wired control
Another limitation of the current 3D Head Scanner is the fact that a wired connection between the laptop or tablet and the 3D Head Scanner is required. Ideally, a headless system[27] would be implemented such as a Raspberry Pi to have more freedom and flexibility. Unfortunately, Raspberry Pi's don't possess a GPU that is powerfull enough to work with Azure Kinect DK sensors.

(*27*)
a computer that operates without a monitor, graphical user interface (GUI) or peripheral devices, such as keyboard and mouse

Aligning the 3D Head Scanner
During the user tests it became apparent that among participants, the level of spatial awareness differed significantly. This could be observed when participants tried to align the 3D Head Scanner to the client, but failed to get the client's head fully in view. Part of the problem could also be incomplete or unclear instructions in the User Interface.

Chapter 5.3 gives an overview of possible solutions for these limitations, as well as additional design recommendations.

5.3 - Design recommendations

Whereas in Chapter 5.2 some limitations of the 3D Head Scanner were discusses, this chapter aims at giving some directions on how to overcome these limitations. Moreover, some additional design recommendations will be given.

Textured mesh

Adding texture mesh to the 3D triangle mesh should be possible without introducing additional Python libraries. Instead of solely using the "*capture. depth*"-data to create the pointcloud, this depth-data will have to be combined with the "*capture.color*"-data that was captured simultaneously.
It might be needed to implement LED lights to guarantee high quality texture mesh, especially when lighting conditions are not optimal. This would prevent one side of the client's head being very bright and the other side very dark. The power for these LEDs can be drawn from the laptop or tablet that the 3D Head Scanner is connected to.

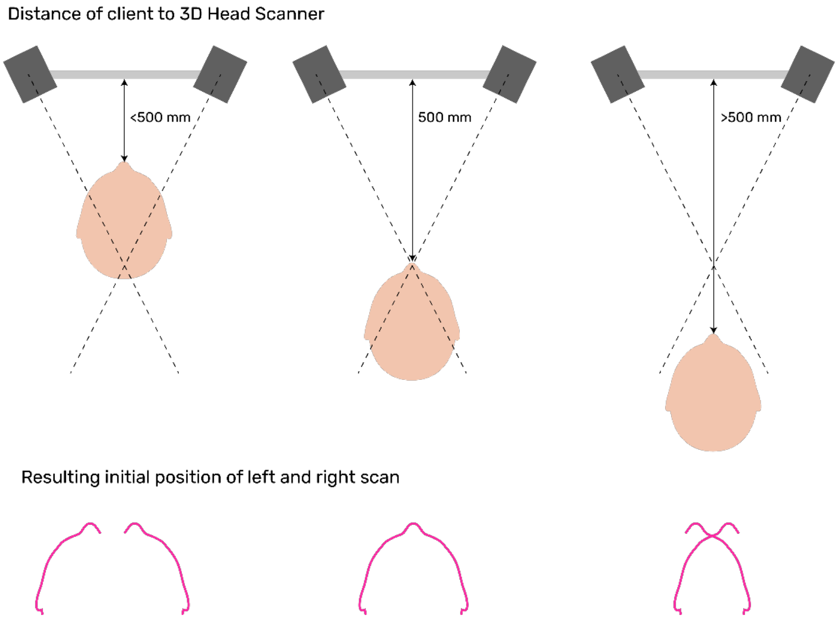
Virtual fit

Another improvement that could hugely benefit the experience is to implement a LIVE virtual fit of the different models. The used software packages already contain the functionality to load 3D models and augment them over the user's head, as can be seen in Figure 55.

[Figure 55]
Example of MediaPipe's capabilities of augmenting 3D models over the user's head in real time.

Calculate the scanning distance

To guarantee perfect alignment between the left and right 3D scans, a distance specific parameter should be implemented in this algorithm. The way the algorithm works now is that it uses a maximum correspondence distance between two points for the initial alignment. This distance differs however depending on the distance that the user maintains to the sensors, as can be seen in Figure 56. Using a value that is too low can lead to no alignment at all, or when the value is too high, wrong alignment can occur. To make a robust system, the distance to the user can be measured, and based on that, the Maximum correspondence distance can be adjusted.



[Figure 56]
Influence of distance to scanner on initial position of left and right scan.

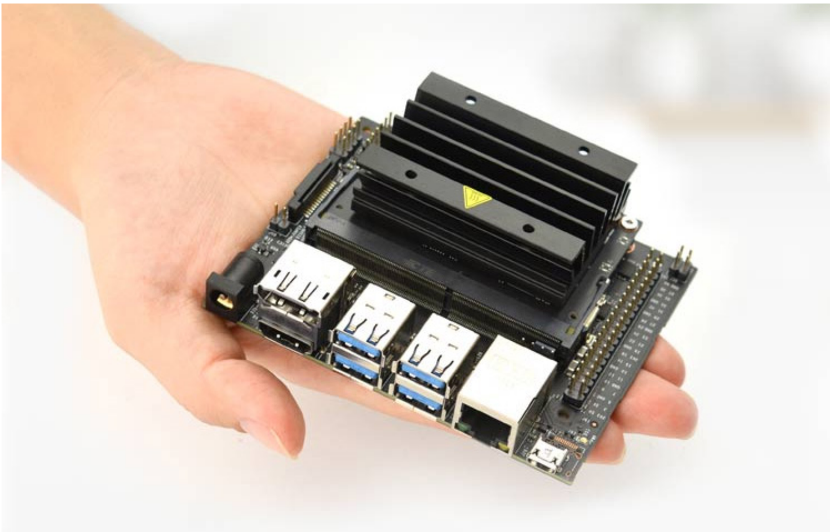
The calculated distance to the user should also be implemented for the cropping procedure, so that the software will never crop out part of the important geometry, such as the frontal part of the ears as happened during one of the evaluation tests.

Bursts

Further research should be done for the amount of shots to include in the bursts. A balance should be found between the increase in waiting time and the increase in accuracy. It seems a good idea to still use only 1 scan for evaluation of the quality and alignment, so that the person taking the scan can quickly see if the results are sufficient. Only later on in the process, when the client is looking at the preferred model and colour, the other scans are processed as well.
Moreover, a good method has to be found to combine the scans and calculate an average of the scans to reduce the needed computational power.

Code optimization
Optimizing the code will lead to an increase in the quality of the mesh, as well as a reduction in processing time. Currently, the resolution of the point clouds is decreased to make the model more lightweight and easier to work with, however, this step takes about 20 seconds of the 95 seconds in total and happens twice. The first time is when loading the point clouds, and the second time is after merging the two point clouds. Initial experiments showed that it is beneficial to remove this first reduction step since it saves about 15 seconds in total. The same applies to the meshing algorithm and smoothing filters, the quality of the output mesh influences the processing time and an optimum can be found.

Stand-alone
Whereas currently the 3D Head Scanner requires to be physically connected to a laptop or tablet, ideally the device can be used indepently, or at least wirelessly. Although Raspberry Pi is currently not an option to replace the laptop or tablet, libraries have been published for Jetson Nano, which sells currently for about €150.
This small device should be integrated somehwer in the 3D Head Scanner, potentially behind the tablet. This tablet could then also be used to controll the scanner, or a wireless connection could be made to a second tablet that could be used to control the 3D Head Scanner.



[Figure 57]
Jetson Nano computer

Quick Start Guide

The Quick Start Guide as it is now could use some improvement, e.g. by implementing written instructions instead of only visuals. Moreover, it could be beneficial to make these instructions available in the User Interface as well.

Alternative use cases

Lastly, in this project the main focus has been on capturing the 3D head shape to design customized glasses around them, however other use cases - requiring the same geometry - could benefit from this 3D Head Scanner as well. Use cases such as plastic surgery visualization and design of custom made (non-invasive) breathing masks show potential to be explored further.
The complete analysis of potential use cases and their fit for the 3D Head Scanner has been made and can be seen in Appendix S.

CHAPTER SIX

REFERENCES

6

Archaeology Data Service. (2022). Guides to Good Practice: LaserScan_1-2. https://guides.archaeologydataservice.ac.uk/g2gp/LaserScan_1-2#:~:-text=1.2.2%20Phase%20Shift&text=This%20limits%20the%20effective%20range,up%20to%20100%2C000%20points%2Fsecond.

Artec3D. (2022). What is laser 3D scanning? https://www.artec3d.com/learning-center/laser-3d-scanning

Bernardini, F., Mittleman, J., Rushmeier, H., Silva, C., & Taubin, G. (1999). The ball-pivoting algorithm for surface reconstruction. IEEE Transactions on Visualization and Computer Graphics, 5(4), 349–359.

Dai, F., Lu, M., & Asce, M. (2010). Assessing the Accuracy of Applying Photogrammetry to Take Geometric Measurements on Building Products. https://doi.org/10.1061/ASCECO.1943-7862.0000114

Dinbelg. (2023). Adult men body dimensions. http://www.dinbelg.be/adultsmen.htm

Flynt, J. (2020). Structured Light 3D Scanning: What Is It and How Does It Work? https://3dinsider.com/structured-light-3d-scanning/

Geng, J. (2011). Structured-light 3D surface imaging: a tutorial. Adv. Opt. Photon., 3(2), 128–160. https://doi.org/10.1364/AOP.3.000128

Geospatial World. (2009). Close-Range Photogrammetry. Geospatial Media and Communications. https://www.geospatialworld.net/article/close-range-photogrammetry/#:~:text=By%20definition%2C%20close%-2Drange%20photogrammetry,about%201%20to%20300%20meters).

Google. (2023). Face Mesh. https://google.github.io/mediapipe/solutions/face_mesh.html

Google Shopping. (2023). cheap laptop - Google Shopping. https://www.google.com/searchrlz=1C1VDKB_nlNL1047NL1047&tbm=shop&sxsrf=AJOqlzVDMAVSSbRoDIyjXMxnwzZk2hYPwg:1678713561972&q=cheap+laptop&tbs=mr:1,price:1,ppr_max:100&sa=X&ved=0ahUKEwi1tqis_9j9AhUnh_0HHWLzDJ4QvSsI8gooAA&biw=1536&bih=688&dpr=1.25

Gupta, Y. (2021). Design of a 3D Headscanner: Facilitating the design of ultra-personalized products for the differently-abled. https://repository.tudelft.nl/islandora/object/

uuid%3A295e10a0-22df-4a56-a4c4-351fac597fdd?collection=education

He, H., Sun, J., Lu, Z., Xu, M., Lao, C., Han, R., Cai, X., & Li, Y. (2020). Phase--shift laser range finder technique based on optical carrier phase modulation. Applied Optics, 59(17), 5079. https://doi.org/10.1364/AO.387196

Hoya Vision. (2023). Yuniku. https://www.hoyavision.com/vision-products/yuniku/

Jeon, J.-H., Choi, B.-Y., Kim, C.-M., Kim, J.-H., Kim, H.-Y., & Kim, W.-C. (2015). Three-dimensional evaluation of the repeatability of scanned conventional impressions of prepared teeth generated with white- and blue-light scanners. The Journal of Prosthetic Dentistry, 114, 549–553. https://doi.org/10.1016/j.prosdent.2015.04.019

Khazdan, M., Boliltho, M., & Hoppe, H. (2006). Poisson surface reconstruction. Eurographics.

Kirkpatrick, D. G., Edelsbrunner, H., & Seidel, R. (1983). On the shape of a set of points in the plane. IEEE Transactions on Information Theory, 29(4), 551–559.

Loughborough University. (2014). iD Cards | School of Design and Creative Arts | Loughborough University. https://www.lboro.ac.uk/schools/design--creative-arts/research-innovation/projects/id-cards/

Mayo Clinic. (2021). MRI | About.   https://www.mayoclinic.org/tests--procedures/mri/about/pac-20384768#:~:text=Most%20MRI%20machines%20are%20large,in%20a%20loaf%20of%20bread.

Mayo Clinic. (2022). CT scan | About.   https://www.mayoclinic.org/tests-procedures/ct-scan/about/pac-20393675#:~:text=A%20computerized%20tomography%20(CT)%20scan,than%20plain%20X%2Drays%20do.

MedlinePlus. (2022). Miller syndrome: MedlinePlus Genetics. https://medlineplus.gov/genetics/condition/miller-syndrome/#:~:text=Miller%20syndrome%20is%20a%20rare%20disorder%3B%20it%20is%20estimated%20to,reported%20in%20the%20medical%20literature.

Microsoft. (2022). Azure Kinect DK hardware specifications. https://learn.microsoft.com/en-us/azure/kinect-dk/hardware-specification

Revopoint3D. (2019). Comparing Three Prevalent 3D Imaging Technologies—ToF, Structured Light and Binocular Stereo Vision - Revopoint 3D Technologies Inc. https://www.revopoint3d.com/comparing-three-prevalent-3d-imaging-technologies-tof-structured-light-and-binocular-stereo-vision/

Scatter. (2021). Depth Kit and Azure Kinect running on Apple M1 Chip. https://forums.depthkit.tv/t/depth-kit-and-azure-kinect-running-on-apple-m-1-chip/999

Sfered. (2021). Frame & I | Sfered. https://sfered.nl/frameandi/

Statista. (2020). Tablet penetration 2020. Statista. https://www.statista.com/statistics/1107831/access-to-tablet-in-households-worldwide/

Structure IO. (2022). Structure - The World's Leading Healthcare 3D Scanning Platform. https://structure.io/structure-sensor-pro/specs

Voisin, S., Foufou, S., Truchetet, F., & Abidi, M. (2007). Study of ambient light influence for three-dimensional scanners based on structured light. Society of Photo-optical Instrumentation Engineers. https://www.researchgate.net/publication/229018982_Study_of_ambient_light_influence_for_three-dimensional_scanners_based_on_structured_light

Wagner, B., Stüber, P., Wissel, T., Bruder, R., Schweikard, A., & Ernst, F. (2014). Accuracy analysis for triangulation and tracking based on time--multiplexed structured light. Medical Physics, 41, 82701. https://doi.org/10.1118/1.4890093

Wilm, J., Jensen, S., Hoppe, N., & Aanaes, H. (2015). Structured Light Scanning of Skin, Muscle and Fat Structured Light Scanning of Skin, Muscle and Fat. https://backend.orbit.dtu.dk/ws/portalfiles/portal/119463589/tr15_07_Wilm_J.pdf

Zielonka, W., Bolkart, T., & Thies, J. (2022). Towards Metrical Reconstruction of Human Faces. https://www.ecva.net/papers/eccv_2022/papers_ECCV/papers/136730249.pdf