Design of a 3D Head-scanner

Facilitating the design of ultra-personalized products for the differently-abled.

Yaman Kalyan Gupta
Integrated Product Design
M.Sc. Graduation Thesis

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PREFACE

When I was looking for a project to take up as my thesis, one of my many goals was to look for something that would place me outside of my comfort zone, yet let me exercise my skills to the maximum. That project came to me in the form of this Head-scanner, a great example of an industrial design project that also lies in a niche since it interacts with a very unique group of people. Although excited, there was a bit of hesitation since this was still quite a demanding project in terms of the required knowledge and skillset which included having to learn quite some things in the domain of coding, prototyping and engineering. Nonetheless, I took up the challenge and learned as I went eventually creating something that I am personally quite proud of. To see the Head-scanner built and working as intended was a huge moment of accomplishment for me and while there are things that might be lacking in terms of execution, I feel that this is the most important project I have had the honour of being able to do in my years of design so far and I would like to thank everyone that helped me through this tiring, yet rewarding journey.

I would like to thank Wolf, my supervisor for giving me the opportunity to work on this project, for guiding me technically and motivating me at every opportunity. In the same vein, I would like to thank Laura, my mentor for keeping me grounded and realistic about my planning and execution, for constant and accurate feedback on all aspects of the project and assisting me enthusiastically wherever possible. I would not be confident in pulling off this project if not for the both of you.

I would like to thank Jan Berend for being active and involved in the project despite being busy and for giving me feedback, customer access and company support throughout the project. I would also like to Pieter for the initial interview and the validation support without which this project would have remained incomplete. I would also thank Manfredi for explaining the Maatbril process to me and for being such a great person overall.

My friend, Varun deserves a huge thanks for all his support with the coding side of things and for aiding me at a moment's notice. I would also like to thank Aditya and Siddharth for their support and all those dinners which helped me get through my all-nighters. I would also like to thank Parshva for his engineering support and coaching me on certain embodiment aspects.

I would like to thank Kina for her support with collecting important research data and for supporting me during the project.

To conclude, I would like to thank my parents and my brother for their endless support that gave me the ability to work consistently on this project, especially during these tough time.

-Yaman Gupta, 2021

EXECUTIVE SUMMARY

The 3D Head-scanner is designed with the intent to scan a customer's head such that the client can design personalized glasses using the generated mesh. The uniqueness of this process is due to the fact that the customers are uniquely disabled and therefore unable to clearly announce their comfort levels.
The goal of this project is to design a new Head-scanner for Maat! since the process that they currently use involves interacting a lot of times with customers who move around a lot making scans invalid and operators having to put in extra effort. The client therefore wants a new and improved approach to scanning, one that is faster, accurate, portable and comfortable for their customers.
The initial brief was to replace their existing workflow through this new design, however, after some research and discussion, the approach was changed to suit Maat's future strategy of setting up stationary scanners all around the Netherlands in locations such as Down polis or Community centers where people could come for checkups and have themselves scanned as well resulting in a significant cut-down on the clients' travelling time.
The project starts with some contextual study where the clients are interviewed on their process, their observations and their expectations from the product. Further, clients are shadowed on a number of their customer visits for observation and gaining a first-hand understanding of a typical scanning process, customer behavior and interaction, involvement of parents, environment and noting down certain areas of interest that could motivate insights.
The observations lead to a deeper understanding of a child-customer's behaviour including points of distraction, various approach strategies employed by operators and how these aspects could be leveraged outside of a product's workflow. Certain important points to note are that children have to be distracted at a common point for some amount of time since the scanning process takes some time. This could either be a parent standing in front of them or their favourite show on a phone. Due to the motion of the scanner, kids often get distracted towards the operator leading to parents often having to hold their head straight.
Technological research is the next step and this involves looking at market competitors, their price ranges, techniques employed and feasibility with regards to the current context. Similarly, a number of scanning techniques are also considered before photogrammetry is eventually selected due to its speed, accuracy, ease of availability and pricing. Further tests are also carried out that involve comparing photogrammetry with structured light, scanning dummy heads for accuracy and working with the coding aspect and relevant softwares.

These steps directly inform certain design decisions which serve as constraints based on which concept ideas for the embodiment and possible look and feel are ideated upon. Factors such as area of capture, landmarks and available space influence the design of the product as it undergoes a number of iterations before settling on the current version.
The current Head-scanner makes use of 3 cameras to capture the subject's face along with the requisite landmarks in less than a second, with only the click of a button. As it is connected to a laptop, all the post-processing happens on the system where the different camera views are aligned creating a complete head. This head is then showed to the operator on a Viewer for them to check.
The final Prototype is repeatedly tested in a series of pilots and constantly optimized. Feedback is then collected and implemented as best as possible before finally being validated with 3 families having children of various ages and a variety of responses. The product performed quite well in terms of capture speed though the mesh representation left something to be desired.

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1. INTRODUCTION

3D scanning as technology has gained quite some traction in the past decade. It has found use in various industries, from medical organizations to design prosthetics and study human anatomy to archaeology to forensic studies. The ability to digitally capture the physical features with extremely high accuracy makes this technology versatile, to the point where future applications such as ultra-personalized products and the concept of digital twins for personalization do not seem too far. There are already several companies working towards adopting 3D scanning into their workflow to create tailor-made solutions
.
Maat! is a Dutch startup located in Amsterdam.
One such company is already in the ultra-personalized product industry designing specialized eyewear such as sunglasses and prescription spectacles for clients with unique visual needs and physical requirements such as Down Syndrome and Goldenhar. Their process uses 3D Scanning technology to scan clients' heads and then use the data to design their products. However, as part of their current workflow, they travel around the Netherlands to clients' homes to scan them, which is a very time-and effort-intensive approach but with a very personal touch.

As part of their plans, Maat! wishes to distribute the process of 3D scanning clients to care hotels and specialized centres around the Netherlands where the clients could come and get themselves scanned. As part of this plan, Maat! wishes to deploy specialized 3D Scanners to these centres that are easy to operate for non-specialized personnel and provide a comfortable experience. In addition, some of their projects focus on the speed of acquisition to avoid causing irritability and invalid scans, accuracy in capturing given landmarks for processing, and a non-intrusive design to improve the overall experience.

2. PROJECT BRIEF & STAKEHOLDERS

2.1. PROJECT BRIEF

It was gathered after initial meetings with the client Maat!, reading project documentation and some cursory studies that the project brief consisted of a number of factors to be addressed through literature review, technological research, testing, validation and embodiment design. The project brief was simplified into its core aspects and formulated as follows:

Design of a new 3D Headscanner to optimize the client's head-scanning experience by focusing on three aspects:
•**Increased speed of acquisition** to prevent unwanted distractions for the customer.
•**High accuracy of capture** to acquire workable mesh data that will later be designed upon.
•**Comfortable and stress-free experience** for the target customers considering their age, psychological status and the nature of the session.

This project brief and the three constituent statements clearly outline the research areas to be targeted and knowledge areas to be approached when designing a head-scanner.

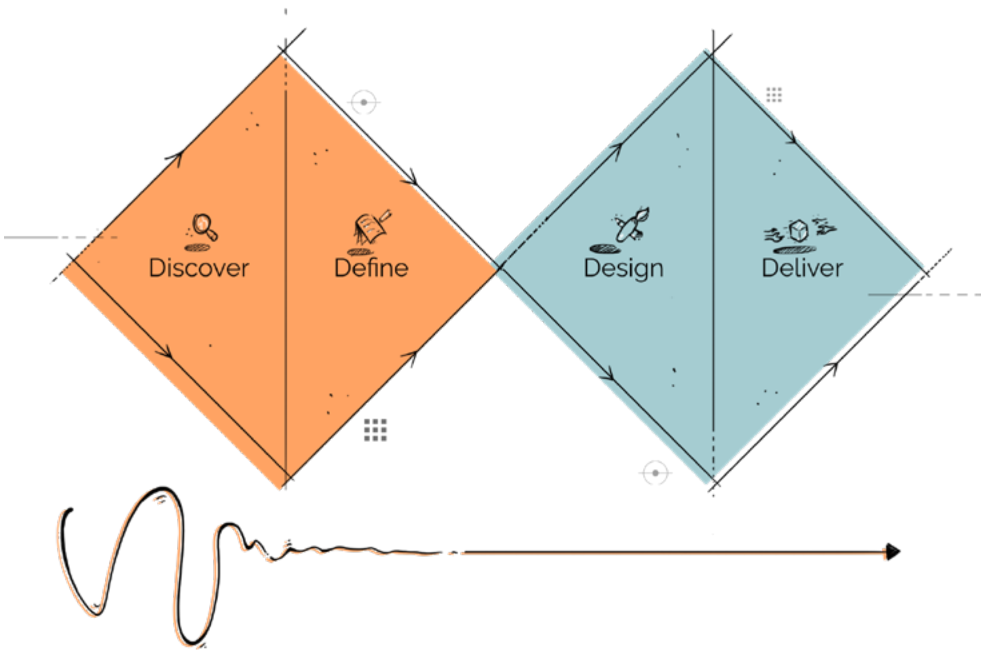
2.2. STAKEHOLDERS

As is the case with similar design projects, a number of stakeholders were identified for this particular project, two main stakeholders that stood out as being key influencers to the design of this product are the operator and the customer. As per the client's instructions, the customer experience is to be placed at the forefront when working on the solution. However, from an external observer's point of view such as the designers, both the parties bear equal importance since they are both immediate users of the product to some extent. The operator is responsible for the capture and handling of the product which needs to be optimized for maximum convenience since they might have to repeatedly scan a multitude of clients in a single day whereas the customer faces the front of the product and possibly experiences nervousness, anxiety and confusion, all aspects which need to be addressed through design and validation. While the users and their needs can be broken down into different points and considered individually, they also have to be considered as a single dual-facing product to create a holistic, integrated experience for the users.

3. DESIGN APPROACH

The Design Approach for this project follows the Double Diamond approach, which involves 4 phases, Discover, Define, Design and Deliver.
In the Discover phase, the intention is to gather information and understand the client's complete workflow. Relevant information for the Discover phase involves learning about 3D scanning, various scanning techniques, similar methods used in head-scanning, along with the pros and cons to finalize a feasible, quick and accurate scanning technique eventually.

A second aspect of the Discover phase is understanding the client's workflow by interviewing and shadowing them, their acquisition process, and observing their interactions with customers since customer behaviour and comfort are significant aspects of the project. All this data and knowledge eventually culminates into the Define phase in the List of Requirements. Here, the problem is broken up into separate parts such as accuracy, speed, operation, and customer experience and then further prioritized. Once outlined , the next step is to start testing, designing and prototyping, all of which lie in the Design phase. For this project, the comparative hardware and software testing phase must be extensive to finalize suitable scanner alternatives, ideal operating environment, accuracy, performance and speed. The conceptualization then involves considering the visual and interactive aspects of the products where the aesthetics, the operation and client interaction and behaviour are significant factors. The final step in this phase is prototyping and embodiment. There is much iterating and back and forth happening within this phase, making it a very active phase. The final phase is Deliver which involves validating the product with users and the client, possibly refining it further based on feedback and then finally handing over relevant project files such as the product specifications, CAD models, intended use style and software to the client, thereby closing the project.



4. ABOUT THE COMPANY

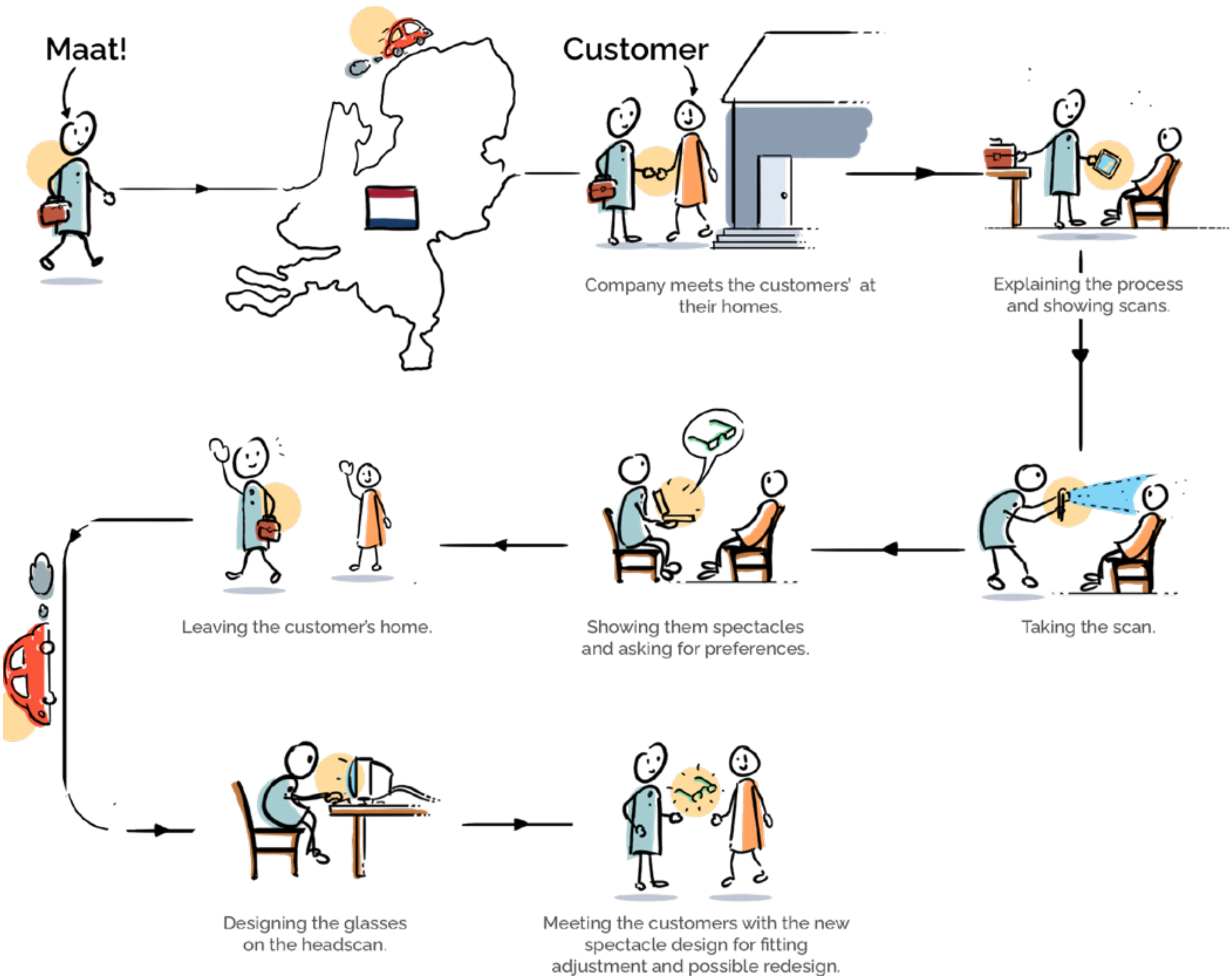
4.1. OVERVIEW

Maat! is a Dutch startup company that develops spectacle frames, especially for unique face shapes. These include clients with disabilities, such as adults and children with Down syndrome or clients with craniofacial abnormality. Maatbril also develops tailor-made spectacles for hearing aid wearers and people with a hearing implant. (Maat! website)
As a service provider with an ultra-personal focus, the company operates the pan Netherlands going to clients' homes and on-site services. However, soon, Maat! intend to set up scanning centres around the Netherlands in opticians' clinics and reduce their travelling time, optimizing workflow. According to this new model, customers would have to travel to these centres and get scanned with the data simply forwarded to Maat!. This aspect is a potential avenue for future product development, which is also a key motivator for many of the decisions made during this particular project, as described further ahead.

4.2. SERVICES & PROCESS

In order to deliver accurate spectacle designs each time according to the customer's needs and their unique physical measurements, Maat! carries out several processes. First, they travel to the customer's homes or occasionally to care homes for their senior customers and explain their process to onboard them and make them feel at ease.

They then carry out the scanning session to capture physical features and measurements. Next, they are shown a selection of sample spectacles along with fitting trials. This part allows the customer to pick their preferences once the customer selects a set that they prefer, Maat! then uses their 3D scanned data to design spectacles specifically for their head shape and facial structure. This product, once realized, is then tested with the customer (also by going to their homes). Additional adjustments are also handled by Maat! based on the client's further feedback.


Maat!
Customer
Company meets the customers' at their homes.
Explaining the process and showing scans.
Taking the scan.
Showing them spectacles and asking for preferences.
Leaving the customer's home.
Designing the glasses on the headscan.
Meeting the customers with the new spectacle design for fitting adjustment and possible redesign.

5. HEAD-SCANNING AT MAAT!

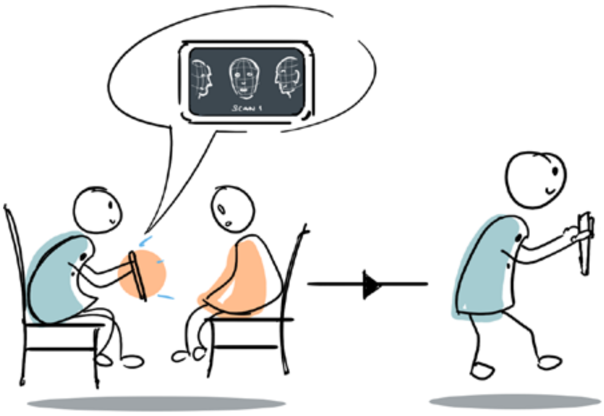
5.1. OVERVIEW

3D scanned images are essential factors that enable the design of ergonomic products. Other capture areas outside of body dimensions include length, width and circumference of the head. Other complex information is also captured, such as arcs, cross-sectional curvature, surface shape, area and volume, which are important for product design. (Lee et al., 2016)
There are several industries where head-scanning is an integral part of the workflow, some of the more medical, such as using 3D data to create personalized healthcare solutions such as orthotic helmets and facial implants, while others are more casual for 3D printing for record-keeping or more personal uses. (Artec website) In this case, however, it is more to help design products such as spectacles.

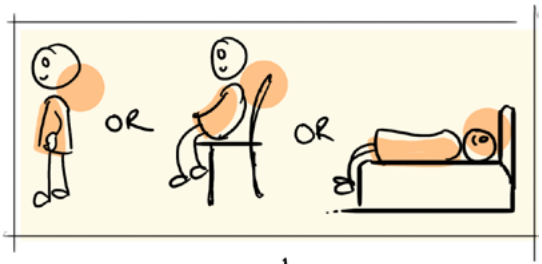
Maat! 's workflow consists of a number of steps, each of which is critical and highly dependent on the previous step to ensure that the final product is an accurate and comfortable fit. The most critical step is the 3D Headscan which involves an operator carrying out a head-scan of customers acquiring a series of landmarks to be designed upon later. The second step is designing the spectacles based on the head mesh acquired from the 3D scan, which involves the use of CAD software. The last step is to 3D print the spectacle frame, assemble it with the lenses and the product hand-over to the customer. Should any one of these steps be not executed properly, the workflow is delayed. These steps are further detailed in the below sections.

5.2. SCANNING PROCEDURE

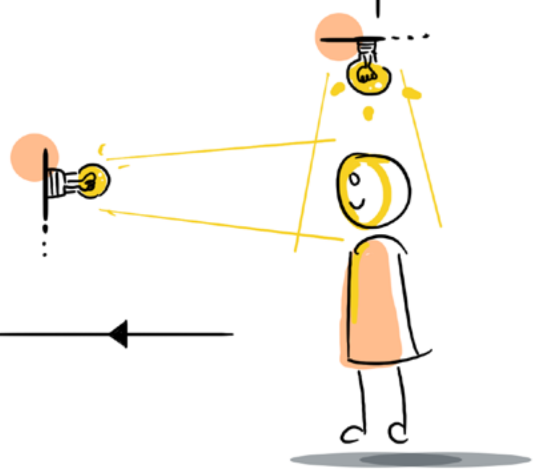
The process for head-scanning starts with the operator onboarding the customer by showing them some of the previous scans to give them an idea of the result. They further explain all the landmarks captured in the scan and that the customer would have to sit or stand still during the process.
Then the customer is asked to sit or stand at a location where adequate light evenly illuminates their face and the sides of the head to create a clean scan without artefacts. The operator then holds up the device and starts to scan, first covering the customer's nose properly from all angles since it is an important landmark. He then proceeds to scan both sides of the head in a uniform sweeping motion to cover the ears, ensuring that all the required landmarks are covered and that there are no gaps or artefacts in the mesh. Throughout this process which takes about 10 seconds on average, the customer must stay as still as possible while facing forward to help capture their pupils in a neutral position.
Once completed, the operator stops the scan and fills in the customer's details, marking the end of the scanning session. Often, the operator has to take multiple scans of the customer to cover different aspects of the head, which otherwise might not be possible in a single scan, primarily due to the customer's inability to stay still. The scanner captures data in 2 formats, the mesh and the texture data. The 3D mesh is necessary to design the spectacles, whereas the texture data helps align the lenses' focal point to the customer's eyes.



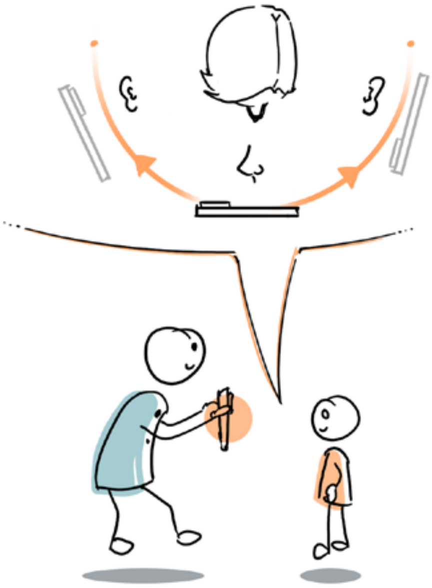
Showing the customer previous scans to make them feel at ease.



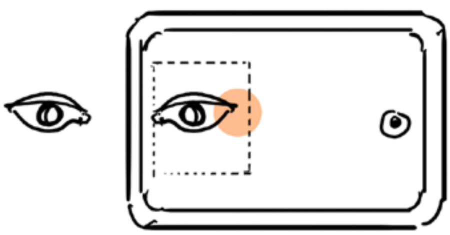
Taking scans of the customer in either standing, sitting or sleeping positions.



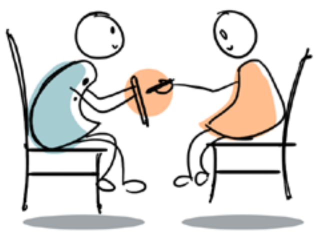
Ensuring that the customer has good side head and frontal illumination.



Scan starts at the center covering the nose first and then moves from side to side covering the ears.



Operator needs to ensure that the pupils are facing forward in the scans to ensure proper lens positioning.



Operator ends his session by getting the customer's name and details to assign to the scan.

Furthermore, the operator needs to ensure they cover all the necessary physical landmarks in the scan accurately so that the fit of the design is proper down to the last detail. These landmarks are as follows:

1. **The nose:** The operator needs to ensure that the nose of the subject is captured accurately. The bridge of the nose is the region where the spectacle pads rest, so those need to show clearly in the scan.

2. **The ears:** The front of the ears should be visible in the scan, especially in the texture map. The ears have a region known as the Triangular fossa, which signifies the last point where the ear is connected to the skull. Knowing the location of this region dictates where the tips of the spectacle arms would start to bend downwards.

3. **The pupils:** Knowing the position of the pupils in the texture map would help the designer to place the lenses accurately in front of the eyes, which would in turn influence how the frame is designed, so the customer needs to be looking directly ahead.

It is important to mention that none of these landmarks takes priority over the other as each of them influence the design of the frames in a significant way.

Fig. 5a: The facial landmarks to be covered in the scan. The image on the left shows the nose and pupils, while the one on the right shows the ear.

5.3. EQUIPMENT & POSTURES

To carry out a head-scan where speed and accuracy are essential while also keeping in mind portability since the equipment needs to be carried around, Maat! makes use of a device known as the Structure Sensor by Occipital.

Fig. 5a: The Occipital Structure Sensor Mark 1 shown with the attachment bracket and the iPad.

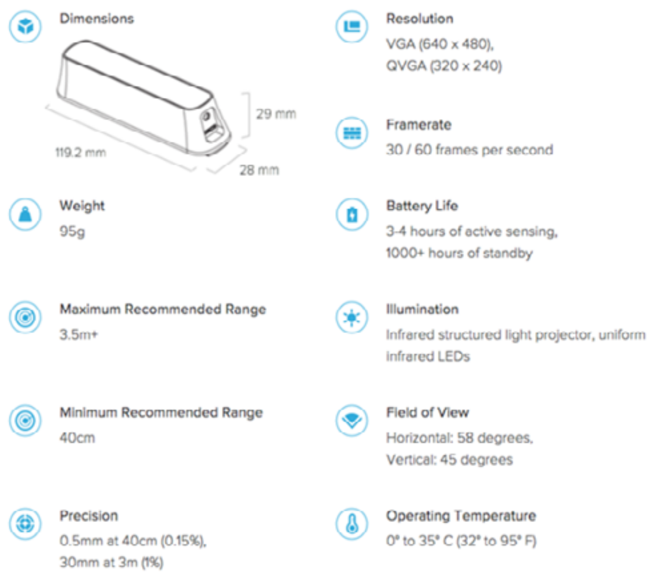


Fig. 5a: Specifications of the Structure sensor(Occipital, 2021)

The Structure sensor is a 3D scanning module operating on the structured light principle attached to an iPad through a USB cable and a bracket attachment. Further, using a native application that works in tandem with the Structure Sensor, the iPad essentially becomes a portable 3D scanner. (Occipital, 2021)

This whole setup can be deployed in 2 to 3 seconds and takes approximately 8-10 seconds to scan the head if it is kept still fully. (Zweerts, 2021)
The standard measuring distance for the Structure sensor lies in the range of 0.4 meters to 3.5 metres (Occipital,2021). However, it was observed that the client was scanning from an approximate distance of 1 meter each time though the scanner software allows for a manual adjusting of the scanning area, thereby reducing or increasing scanning distance.

From the observation sessions, it was ALSOfound that subjects can be positioned in 3 different body postures depending on their height, age and physical condition. These body postures are as follows:

1. **Standing**
2. **Sitting on a chair**
3. **Lying on a bed facing directly upwards**

Another critical factor here is the head position that should ideally face forwards, mainly to facilitate a good scan of the pupils; however, in scenarios where the customer cannot hold their head up stably, external assistance from family members is offered.

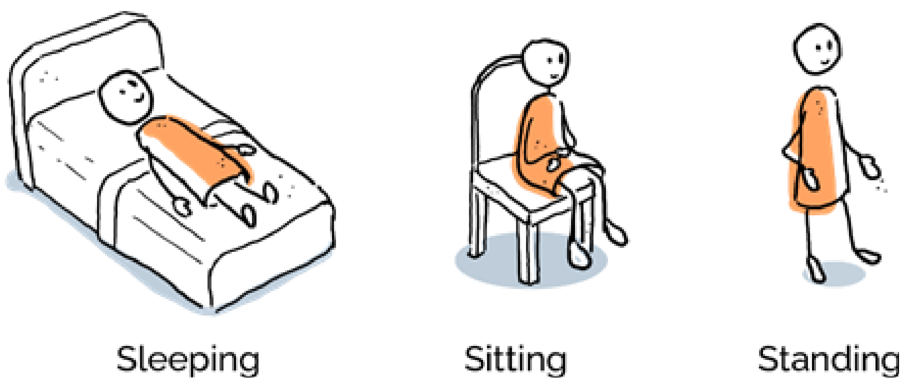


Fig. 5b: The various postures that subjects are observed in and covered by the device.

5.4. CONCLUSIONS

From seeing the various environmental conditions and subject postures, it is understood that some variables need to be considered when designing the final product, and while a few of these cannot be measured accurately, such as the dimensions of rooms, a rough estimation can be made which would inform the design decisions.
The current procedure of head-scanning, while quite flexible and versatile due to higher operator control and easy deployment-often requires the client to take multiple scans on account of a slower acquisition speed and customer distraction due to the nature of the hand-held scanning motion. It is clear from this observation that a quicker scanning method should involve a static setup, possibly with multiple devices, which relies less on human involvement and more on the scanner's capabilities. These aspects reduce the possibility of customer distraction due to movement and, by extension, invalid scans.

Other than just scanning the front and side of the head to obtain a mesh, it was understood that landmarks need to be captured in accurate detail, which is a primary objective of the scanning sessions. The final setup needs to consider these factors and acquire all the landmarks at high accuracy, including the ears positioned at the extremes. Additionally, to cover all sides of the head, especially the landmarks, external support might be required to turn the customer's head (if the customer is unable), thereby acquiring all the views. These landmarks are tested upon for accuracy of coverage in section 10.3. and also addressed in the list of requirements in section 11.0.

During the scanning sessions, three different subject postures were observed. While two of them involve the subjects facing forwards and being in a generally open environment, the last posture involves them lying on a bed, which involves an added obstruction of unknown dimensions to the context. The current hand-held scanner can cater to this just as quickly as it can with the other two postures, but the proposed setup would need to address this differently or not cater to this scenario. Something to consider here is that addressing this scenario might require the implementation of additional mechanisms or attachments in the design, raising the complexity of the product. These factors are further discussed in section 12.0 where each of the concept directions and their advantages and disadvantages is explained in detail.

6. MARKET STUDY OF 3D SCANNERS

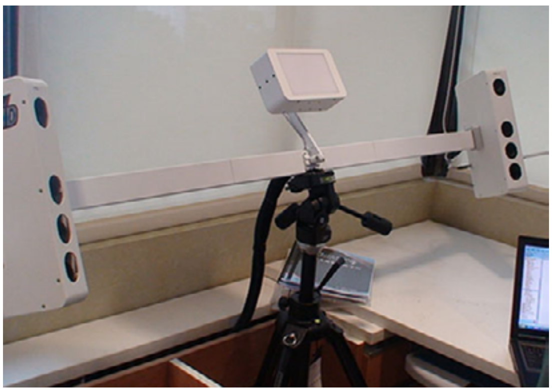
Literature shows that other researchers have established alternate methods to scan a person's head and relevant anatomical features using different 3D scanning techniques such as Photogrammetry, Structured Light, laser scanning and Passive Stereo. (Luchowski et al., 2005)
Some of these techniques are also implemented in 3D scanners, which are readily available in the market, as shown in Fig. 3a. Though not all of these scanners are specifically head-scanners, they are used for body-scanning, each having its advantages and disadvantages. Therefore, to compare the market competitors through a set of criteria, three different scanners are considered based on their pricing, scanning technique and level of complexity. These scanners are the Artec Eva, the VITUS 3D Body Scannerand the 3DmdFace(all pictured below in sequence), which is a smaller face-scanning variant of the larger 3Dmd Body scanner. Further, the comparative criteria for this section include reconstruction accuracy, speed of capture, pricing and product complexity within which lie the operation of the product, size and any involved mechanisms.

6.1. RECONSTRUCTION ACCURACY

Reconstruction accuracy refers to the scanners' ability to accurately construct a 3D mesh of the actual surface being scanned, in this case, the human head. Scanners' accuracy is determined by the quality of the projector, lens, and camera that captures the patterns. (Rocchini et al., 2001) Different scanning technologies offer different accuracy levels ranging from the Artec Eva, which has an accuracy of 0.1mm, which is a relatively high level of accuracy when combined with its ability to capture textures at 1.3 megapixels. The VITUS 3D Scanner and 3DmdFace have lower accuracies at 1mm and 0.2mm, respectively. (Maurer, n.d.) Both the scanners can acquire texture as well.

6.2. SPEED OF CAPTURE

Speed of capture refers involves the time taken by the scanner to acquire the target surface area. Hand-held scanners such as the Artec Eva do not have a set capture speed as it depends on the operator taking the scan. It has, however, been observed from tests performed using the scanner that an experienced operator could take around 10-12 seconds to acquire a full head. For fixed scanners such as the VITUS and the 3DmdFace, it depends on the layout of the scanner and the technology involved. For example, the VITUS scanner, a laser scanner, has a speed of 12 seconds due to its sliding mechanism where the scanners have to slide down on rails while projecting a laser line on the subject's body. Conversely, the 3DmdFace has a speed of 0.002 seconds due to its photogrammetry-centric approach to acquisition which involves multiple cameras taking photos simultaneously and then stitching them later to create the entire head.



6.3. PRICING

The prices of the concerned scanners hugely depend on the mechanisms and the structure involved in the construction of the scanner. Scanners with larger setups and more internal components such as the VITUS and the 3DmdFace are naturally priced higher, being two of the most expensive scanners available in the market. It is worth noting that laser-based scanners themselves are relatively cheap, as can be observed in smaller turntable models (Murobo, n.d.), but the VITUS scanner involves four such scanners, each with additional hardware working in tandem with the numerous mechanisms and physical structure that makes the complete body scanner. Photogrammetry set up such as the 3DmdFace uses multiple DSLRs along with separate dedicated light sources to extract the best possible scans from all angles. All this equipment, along with the metal mounting frame, incur high costs of prototyping and construction, which could translate further into production. The setup designed by Khalili in his study costs approximately 6000 dollars. (Zeraatkar & Khalili, 2020)

Scanner	Type	Cost	Time of Scanning
3D Systems Sense [1]	Optical subject or scanner must move	$419	Depends on subject/operator
Artec EVA [2]	Optical subject or scanner must move	$19,800	Depends on subject/operator
Geomagic Capture [3]	Optical with LED point emitter Subject or scanner must move	$14,900	Depends on subject/operator
Gotcha 3D Scanner [4]	Optical subject or scanner must move	$10,000	Depends on subject/operator
Head & Face Color 3D Scanner (Model 3030/RGB/PS)—(CyEdit+) [5]	Laser Fixed scanner/fixed subject	$63,200	Not specified
Head & Face Color 3D Scanner (Model 3030/sRGB/PS)-Hires Color—(CyEdit+) [6]	Laser Fixed scanner/fixed subject	$73,200	Not specified
Head & Face Color 3D Scanner (Model PX)—Single View—(PlyEdit) [7]	Laser Fixed scanner/fixed subject	$67,000	Not specified
Head & Face Color 3D Scanner (Model PX/2)—Dual View—(PlyEdit) [8]	Laser Fixed scanner/fixed subject	$77,000	Not specified
Vitronic-Vitus Smart XXL [9]	Laser-fixed subject	$65,000	12 s
KX-16 3D Body Scanner [10]	Infrared subject or scanner must move	$10,000	7 s
IIIDBody [11]	Optical fixed subject and scanner	$20,000–50,000	Not specified
SizeStream-3D Body Scanner [12]	Infrared	$15,000–20,000	6 s
SpaceVision-Cartesia [13]	Laser structured light-fixed subject and scanner	$20,000	2 s
INBODY	Photogrammetric full-body scanner	Not specified	0.05 s
3dMDbody-Flex8 [14]	Stereophotogrammetry	$190,000	0.002 s
Whole-Body 3D Scanner (Model WBX)—(DigiSize Pro) [15]	Laser line-fixed subject	$200,000	17 s
Whole-Body Color 3D Scanner (Model WBX/RGB)—(DigiSize Pro) [16]	Laser line-fixed subject	$240,000	17 s

Fig. 6a: 3D Scanners available in the market with their acquisition method, pricing and acquisition time.

6.4. COMPLEXITY

The complexity of a Headscanner depends on several factors such as how it is operated, the size of the product and the mechanisms involved in its functioning. The Artec Eva is the least complex scanner out of the three since it is just one hand-held scanner with a comparatively smaller form factor that can be freely moved around in a given space. While the multiple wires connected to the device, one for power and one to connect it to a computer, make the handling tricky since they limit the range of motion, it is still a highly versatile device suitable for several scanning scenarios. The 3DmdFace consists of a relatively simple, elongated metallic structure with camera modules on two ends and an LED in the middle to provide lighting, which still consumes some amount of space, but not quite as much as the VITUS scanner, which is essentially a 6-meter-tall open booth consisting entirely of metallic structures in addition to sliding mechanisms to move the scanner modules vertically.

6.5. CONCLUSIONS

From comparing the selected scanners, it was concluded that scanning techniques and the region to be scanned have a significant influence on the factors listed above, even though they are all interdependent. As an example, the Artec Eva can scan any region of the body, making it a flexible scanner, but by making it a flexible operating structure, the processing time increases, and the manner of operation becomes dependent on the user and not the product itself. The 3DmdFace remedies this by fixing the structure to target only the face and drastically reducing the capture time due to photogrammetry being a quick technique. On the other hand, the slowest and most complex structure belongs to the VITUS since it targets the whole body and further uses laser light scanning. The structural aspects are taken into account when finalizing a concept direction in section 11.0.
In the context of this project, it is possible to reduce scanning time and product complexity by selecting an appropriate scanning technique that is also suitable for the target group and does not cause anxiety or excitement as to disrupt the scan. As for the region to be scanned, that is already established to be the face from ear to ear. A possible consideration here is to adopt the direction taken by the 3Dmd-Face, which, although it is a fixed scanner, has a relatively straightforward structure that can be further optimized after some ideation and prototyping. It is also the fastest, which is a crucial requirement for this project, and it is possibly less distracting since there is no movement in the subject's FOV, though this statement remains to be tested.

7. TARGET USERS

7.1. OVERVIEW OF CONDITIONS

Maat's scanning sessions with customers naturally require the company to work with several conditions, a majority of which involve craniofacial anomalies and intellectual disabilities. Craniofacial anomalies are conditions involving congenital deformities of the cranium and face and, by extension, also affect a person's physical and mental well-being. (Singh & Moss, 2015)

Some of the more common conditions within the craniofacial spectrum include cleft lip/palate, Treacher-Collins syndrome, Goldenhar syndrome, and Down Syndrome. Standard features in all these conditions are unique shapes of the cranium and cranial structures, skull shapes and facial bones, including the nose, ears and eyes. (Singh & Moss, 2015). All these are critical structures to Maat's work area and are captured in detail during their scanning sessions. In addition, since Maat! 's area of expertise lies in designing spectacles specifically for the customers' heads, they consider all these physical features when designing elements of their spectacles. As an example, customers who lack an ear which is essential for spectacles to stay hooked on the head have a different frame design of the frame to grip a different part of the head, thereby adapting it for individual customers.

The following discussion outlines conditions and symptoms that Maat works with the most, such as Goldenhar Syndrome and Down Syndrome, affecting the craniofacial region and their mental development. Maat also faces the symptom of Photophobia, which is a sensitivity to light leading a photophobic person to wear specially designed lenses.

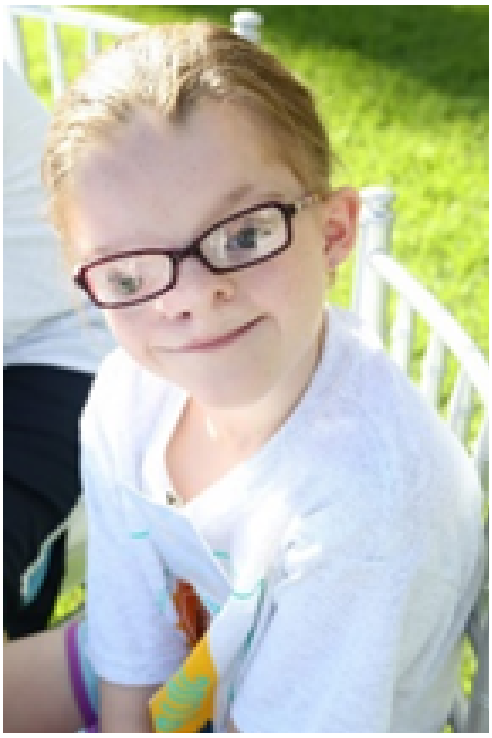


Fig. 7a: Shown from top to bottom are examples of people with Goldenhar, Treacher Collins Syndrome, and Down Syndrome.

7.2. DOWN SYNDROME

Down syndrome is a set of physical, mental and functional abnormalities resulting from three chromosomes rather than the usual two. The syndrome is characterized by an immediately recognizable craniofacial structure, partly a result of the developmental anomaly. (Shukla et al., 2014)

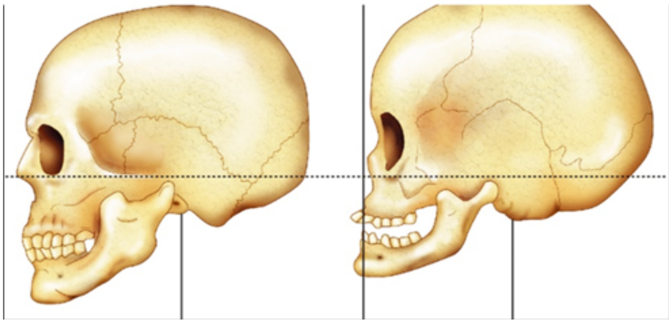


Fig. 7b: Shown on the left is an average human skull and on the right is a Down Syndrome affected skull.

Further observations revealed that people with Down Syndrome have rounder heads than curve inwards from the temples to the side of the head, smaller noses and longer eyelashes, all aspects that could affect the design of spectacles. Some highlighted features are visible in Fig. 7c.

Fig. 7c: Some notable physical characteristics of an infant affected by Down Syndrome. (Fergus & Garbi, n.d.)

Additionally, at least half of all children and adults with Down Syndrome face a primary mental health concern during their lifetime, including general anxiety, repetitive and obsessive-compulsive behaviour, impulsive and inattentive behaviour, and depression.

7.3. GOLDENHAR SYNDROME

Goldenhar syndrome or craniofacial microsomia is a rare condition characterized by several anomalies involving craniofacial structure, vertebrae and internal organs. The cause of this syndrome is unclear as it varies genetically and depends on various reasons.

Goldenhar typically affects various parts of the skull, face and jaw. If the skull bones are affected, the forehead and cheek on one side may appear flattened, and the eye socket may be smaller or displaced. Occasionally, the eye might even be absent. The ear canal may also be absent, causing total hearing loss. Sometimes there are also skin tags in front of the ear though these do not interfere with hearing. (Great Ormond Street Hospital website)

Fig. 7d: A girl with Goldenhar Syndrome. The asymmetric features of the face are visible here.

7.4. PHOTOPHOBIA

Photophobia is a common yet debilitating symptom seen in a number of ophthalmic and neurologic disorders, which is further defined as an abnormal sensitivity to light, especially of the eyes. It is poorly understood and challenging to treat. Photophobia patients usually wear spectacles with darker lenses and feel more relaxed in darkness. Light frequently triggers anxiety reactions in these patients. (Digre & Brennan, 2012)
Since 3D scanning technology depends on light as a primary enabler, it is vital to cover the possibility of any light sensitivities displayed by people with Photophobia. Many types of lights, including fluorescent, sunlight or blue light (computer or mobile screen), can adversely affect someone with Photophobia. Fluorescent lights have been shown to double incidences of headaches and migraine attacks. Similarly, 5 to 10 minutes of exposure to sunshine can lead to a painful experience. (Bullock, 2018)

Further, a few factors that aggravate pain caused by Photophobia are as follows:

1. **The brightness of light:** Brightness is also cited as a critical trigger other than the luminance of a particular light source. Though what may seem bright to an average person could be painful for someone with the condition.
2. **Flickering or flashing light:** High visual contrast, such as flashing lights that go quickly from bright to dark, are also significant concerns. Striped patterns are known to be triggers as well. Additionally, fluorescent light has an invisible flicker not visible to the naked eye but can be picked up by the brain.
3. **Colour or wavelength of light:** Blue-colored light is proven to be a significant health problem especially considering its presence everywhere.

Fig. 7e: A person with Photophobia wearing unique spectacles with different lenses and side-guards to avoid light leaking in from any

8. PROXEMICS

8.1. OVERVIEW

Proxemics is the study of measurable distances between people as they interact. It is a theory of non-verbal communication that explains how people perceive and use space to achieve communication goals. As per the principle of proxemics, there are four types of distances people keep: intimate (0 to 0.457 meters), personal (0.457 meters to 1.21 meters), social (1.21 meters to 3.048 meters), and public (over 3.048 meters). Additionally, proxemic behaviour is learned chiefly from observing others rather than explicit instruction, which is why the concept of physical contact varies from culture to culture. Aspects such as body angles, touch and eye contact are significant indicators of familiarity.

8.2. ANXIETY-INDUCING FACTORS

Encountering proxemic behaviour separate from one's own is known to trigger anxiety. Additionally, research has been carried out to prove that whenever a human experiences violation of their personal territory, the usual responses are either aggression, discomfort or moving away. However, there are also exceptions, such as people voluntarily giving up their personal space in order to ride a crowded train or elevator.

Due to the well-known anxiety-inducing nature of specific medical instruments such as an MRI machine which is attributed mainly due to its tunnel-like claustrophobic structure, 3D Scanners need to be at a set distance from the subject in order to acquire accurate scans of the surface mesh while ensuring that the subject is comfortable. While the minimum range for each type of scanner varies, it is also vital to ensure that the device is not within the subject's personal space, thereby making them feel uncomfortable or intimidating. The reason this needs to be considered is that a substantial number of the client's customers lie under the ages of 15, and further considering their intellectual condition, likely, seeing such a product or group of products located so close to them could scare them making them unwilling to comply with the scan session requirements. This assumption can be drawn from the research study being done by Philips on redesigning MRI machine exteriors and the overall medical experience of kids when coming to a hospital for the first time for their check-ups.

Therefore, keeping in mind these aspects, it is crucial to find a balance between the scanner's optimum distance so as to generate an accurate mesh and the ideal distance not to invade the subject's space or make them feel uncomfortable. These aspects are investigated from section 10.4, where a head is scanned for accuracy from different distances and the accuracy of acquisition verified.

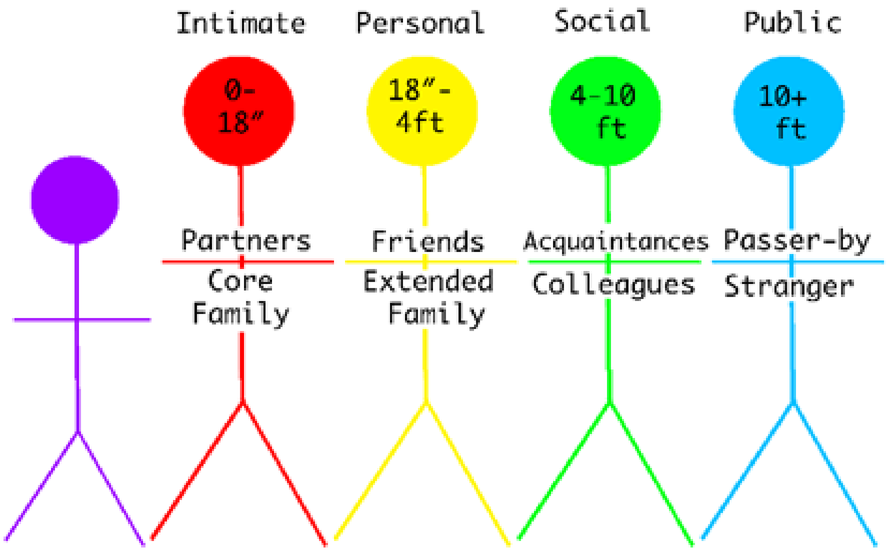


Fig. 8a: A diagram depicting the various distances and how they relate to the person's relationship with other people and how they might be perceived. (Dutch Review website)

9. FIELD STUDY

9.1. OVERVIEW

Maat! operates out of a number of places across the Netherlands, most of which are customers' homes but also include care homes and sometimes healthcare facilities as well. Different environments have different conditions of lighting, space and obstructive elements, which can have an effect on the quality of the scan, distance from the subject and the amount of space the client has to within.
Generally, the scanning environments are well-lit with plenty of sunlight to facilitate a clean scan with well-lit texture data as well. In situations where adequate light is unavailable in the area, it was observed that customers were brought to a location where such an environment can be created, and the scan can be carried out. (Zweerts, observation, May 3, 2021) It is known from the first observation session that in the situation of the first customer, the scanning session was being conducted in the kitchen/living room space with big glass doors to let the light inside. Further, the scan was being conducted at 1400 hours when environmental light is quite bright. In addition to that, the ceiling lamps were also turned on to create a uniform light on the subject's face and ears and to avoid harsh shadows in the texture map.
A similar setup was observed in the second observation, where the location was a care home. For an optimal scan, a chair was placed in the centre of the room with adequate external light, and then the customer was asked to sit on the chair facing the outside.
It should be mentioned that the client has to work within a number of different environments, and while more spacious rooms such as the ones in clinics might not have quite as many obstructions, other spaces such as care homes and clinics have very different and often congested layouts. Therefore, adaptability to different environments is an important aspect to consider when coming up with a solution.

9.2. DIMENSIONS

It is essential to have an idea of the dimensions within a given space to ensure that the scanning setup or product fits within that space. In this case, however, space keeps changing depending on the room, the direction of light and the customer's furniture arrangement; therefore, an approximation is the only possible method to determine the maximum available space for each scenario. To further motivate, anything much bigger or too distributed from the current setup would be inflexible and challenging for the client to carry to people's homes or deploy there. The design of the scanning solution is primarily found to depend on one crucial question depending on the factors discussed, how should the scanner be designed in order to have sufficient facial overlap and optimal space occupation?
For the most part, this point can be resolved by means of prior testing and do not necessarily relate to the environmental constraints; however, a secondary element of this question depends on the design of the outer casing and the eventual layout of the product.

9.3. CONCLUSION

A number of medical conditions were researched and understood to understand if any of them could have any direct impact on the design decisions later on in the process. Some of the customers, while not physically affected by the planned setup or product, might experience psychological distress if the setup results in being too intrusive or visually intimidating. Additionally, certain aspects of the design might trigger specific reactions in the customers, possibly due to the look and feel or a particular functional aspect. Therefore, the product needs to have a very neutral and friendly physical appearance so as not to agitate first-time users. These form aspects were explored further while ideating and outlined in section 12.3. where the enclosure design is explained.
Maat! works with customers who are photophobic and are sensitive to visible light, which is a crucial aspect to consider when deciding on the type of technology. In this case, scanning technologies that work only by projecting visible light towards the subject could have severe consequences on the customers. Also, customers with epilepsy who are prone to seizures might react adversely to flashing lights, such as Artec Eva's case. Therefore, the product needs to be capable of giving accurate results either in ambient light or make use of alternate sources of illumination-possibly non-visible-such as IR.

The environment in which the product will operate varies depending on the household or the care hotel. However, if a maximum viable area of operation is outlined based on the available data, then it should already be easier to assume the approximate dimensions of the product. As far as environmental obstructions are concerned, some flexibility can be implemented in the design phase itself; however, overly considering every scenario could raise the complexity of the product. Therefore, a good approach is to consider some very standard scenarios outside of which it is recommended to change the scanning location to something more acceptable. This is tested and explained with mockups and prototypes in section 12.1.
Researching proxemics helped to provide an idea of personal space and what could be considered acceptable and comfortable in terms of proximity to the customer. It is important to consider the nature of the customers that Maat! works with, which makes it essential that the final product interacts with them from a distance that does not agitate them or overly excite them as to hinder the scan. An appropriate distance needs to be set where the product is not considered as intruding into personal space but at the same time also acquiring scans with optimum accuracy. This aspect also depends on the concept of disparity shift in section 9.3 and also tested in section 12.1.

10. CHOICE OF TECHNOLOGY

10.1. OVERVIEW

To design the product embodiment meant selecting suitable hardware to accomplish the accuracy and acquisition requirements. For this purpose, two different scanners were narrowed down, both of which follow the active stereo principle of scan acquisition, and these are the Realsense D415 and D435i. These scanners were selected based on prior head-scanning research at the TU Delft, where an infant's head was scanned using a multi-scanner setup for the purpose of head size measurement. In that research, after exhaustive testing using three different scanners, each of which was a Realsense, the final candidates were the above-mentioned cameras (Zevenberg, 2020). A third contender for this stage was the Structure Sensor Mark 2 by Occipital, which was considered for its high-resolution capture and accuracy, ability to capture both depth and RGB data as well as high flexibility in terms of usage and freedom of movement. Conversely, a few issues were immediately visible before and during experimentation with the device, the first of which is pricing. The Structure Sensor Mark 2 costs 527/- which is the equivalent of three active stereo scanners (Realsense website, 2020). Additionally, keeping in mind its acquisition technique, it is notably slower than active stereo cameras in capturing the required area of the face, which is from ear to ear. To use this scanner, the operator would manually have to move around the subject to carry out the scan, which makes it the same as the existing method of scanning employed by the client, therefore making it not desirable. Keeping in mind these factors, the Structure Sensor Mark 2 was not considered to be a final choice for comparison. The following section discusses the relevant specifications of the D415, the D435i, the tests carried out using both the scanners, and the results obtained.

10.2. HARDWARE COMPARISON

Designing the final product meant selecting suitable hardware to accomplish the accuracy and acquisition requirements of the client, and for this purpose, both the selected scanners are compared on several criteria which could determine at a glance which product is more suitable for further process.

	 D435I	 D415
Best Resolution	848 x 480	1280 x 720
Field of View	86 x 57	64 x 41
Depth Accuracy	<2% at $2m^2$	<2% at $2m^2$
Ideal Depth Range	0.3 to 3 m	0.5 to 3
Pricing	199/-	149/-

Fig. 10a: Comparison between a D435i and D415.

10.3. PLANE FIT

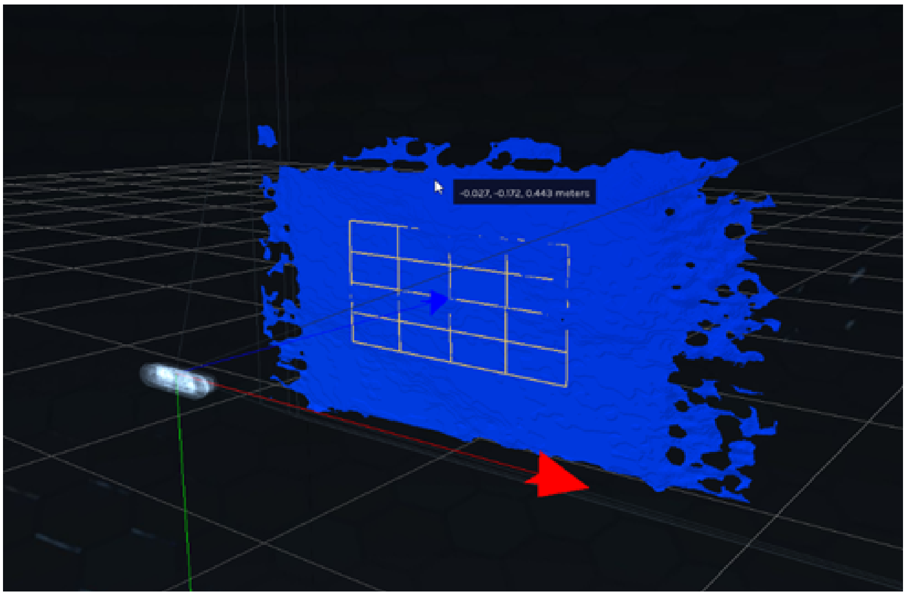
As an initial test to map out the scanners' calibration status and measuring error, both the scanners were first pointed towards a plain white wall to test their respective errors, known as RMSE errors. It is at this stage that exposure and laser power can be adjusted for varying results. Once an optimum result is obtained at this stage, both cameras are then pointed towards a printed grayscale pattern available for download on Intel's website- which in this case, was stuck to the same wall. At this point, the cameras start to show depth error readings. Intel has a specific software known as the Depth Quality Tool, which was used for this test.

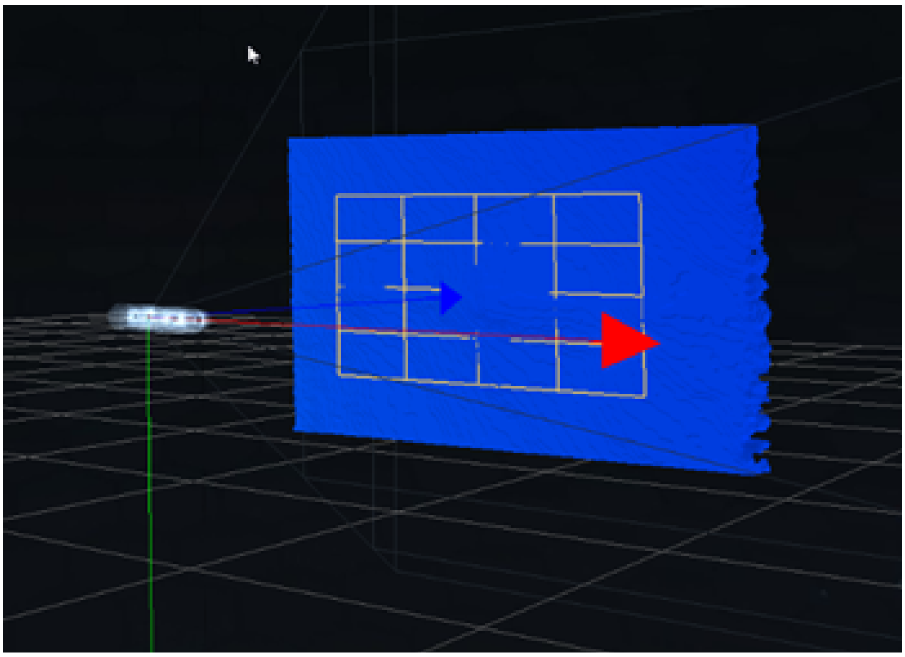
D435i

As is visible from this test that was done using the D435i, there is a visible loss of quality towards the edge of the plane, which is acceptable since the ROI is already predefined by placing the scanner in front of a dummy head at the estimated operating distance. That ROI is depicted in these images by the yellow grid.
When tested on the fitted plane, the RMS error provided by the scanner was in the range of 0.18% to 0.21% at a distance of 450mm. A set of calibration sequences were run on Intel's Dynamic Calibrator to ensure that this was not a calibration issue; however, post-calibration, the results remained the same.

D415

The next step was to carry out the same test using the D415 to compare both scanners. In this case, the FOV is noticed to be lesser and with much cleaner scans at the edge, as is visible from the figures below..
Upon testing it on a fitted plane for depth accuracy, the RMS result obtained was 0.3% at a distance of 450mm. Similar to the previous test, a series of calibration sequences were carried out, but the end result stayed the same.





10.4. HEAD RECONSTRUCTION

The next step to compare the relative accuracies was to compare both the scanners by means of testing them in a realistic scenario by scanning a dummy head. For this test, a dummy head, as shown in Fig. 10b, was arranged on which landmarks were applied in the form of black spots for ease of alignment after the acquisition stage.

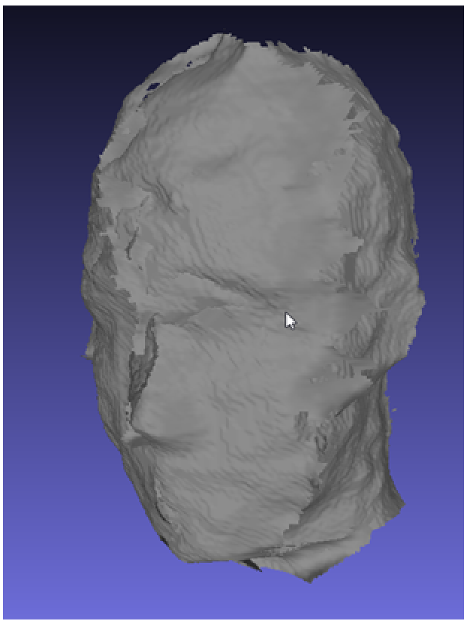
Before the comparison, an acquisition was made using the Artec Eva scanner to obtain a ground truth and also to set a quality benchmark to approach. Both the D435i and D415 cameras were mounted on tripods and placed at a distance of 450mm from the head, which was placed on a revolving stool to match the scanner level and to act as a turntable since multiple scanners were unavailable for this test. The head was positioned away from direct ambient light due to its slightly reflective nature but which did not affect the scan results too much. Further, the stool was marked with angle markers in the form of tape to understand the angles at which the relevant landmarks were visible to the scanner, which would further help in the later stages of the project. The software used to extract meshes was the stock Intel software called *Realsense Viewer.*

Fig. 10b: The dummy head used for the numerous experiments with the taping, landmarking and scanner setup.

D435i

As is visible from the mesh shown in Fig. 7d, only a general shape of the face is acquired with no details visible in the scan. Additionally, the scan presents with rough unprocessed edges on account of the acquisition method, which is by taking frames of the head from different sides. This mesh has been recreated by means of the MeshLab software, which is point-cloud processing, registration and alignment software.
Considering the landmarks that needed to be captured, the nose appears relatively clearly; however, the ear region shows up only in some elevation. Additionally, the ridged lines affect present difficulties in understanding the exact surface placement, which might cause issues in designing something to fit.

Due to the use of dot markers on various parts of the dummy head, alignment was relatively easy using a point-based glueing system in the software. Point-based gluing is a method that lets one manually select corresponding points on two different scanned-but partially overlapping-meshes. Once the point pairs are picked, the algorithm then aligns the two meshes roughly. This is where using the tape markers made the process convenient. Additionally, the markers served the purpose of acting like pupils on the eyes since the visibility of the pupils in the texture map is a key factor in deciding the scanner's performance.



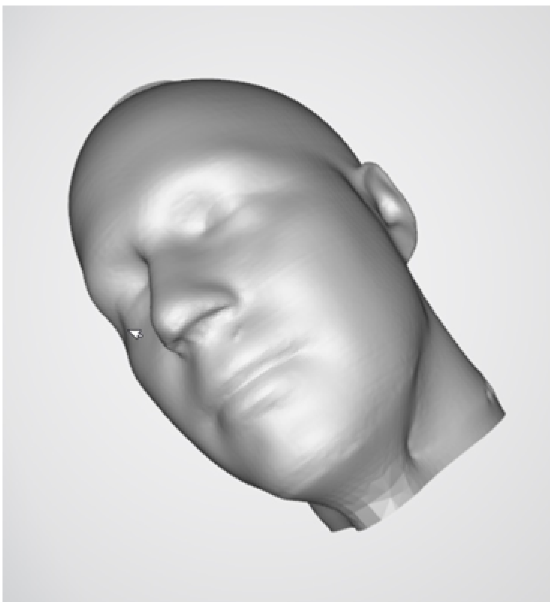


Fig. 10c: A comparison of the meshes between the D435I(left) and the Artec Eva(right).

A 3D printed ear was used to ensure that the low capture accuracy was not due to the generic design of the dummy. This ear was obtained from the 3D scan of an actual human ear and therefore represented an actual human ear both in size and in its features as is visible in Fig. 7e; the ear was further taped up using masking tape to reduce the reflectivity of the PLA material used to 3D print it thereby simulating the natural properties of the skin. However, the results obtained even from this model were not ideal, leading to the conclusion that the scanner was unable to capture features accurately enough even though it captured the texture map clearly, as can be seen from Fig. 10d.

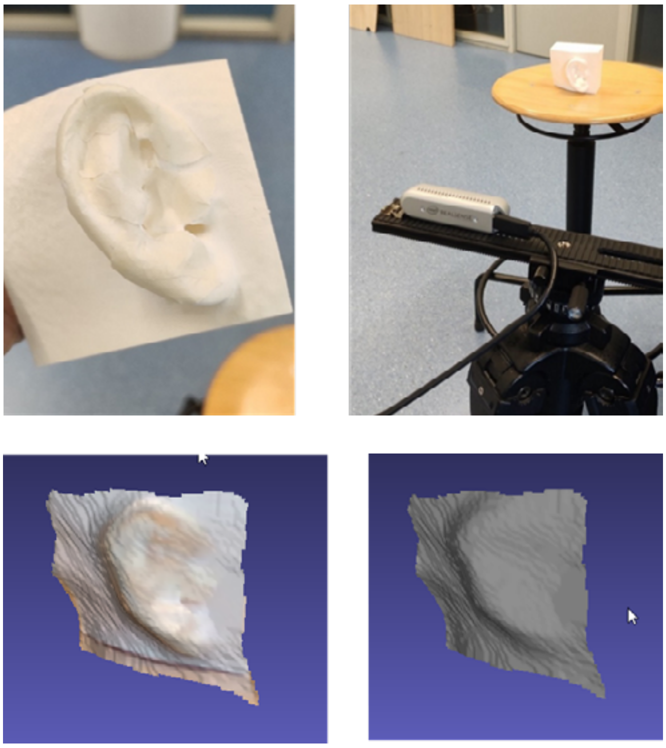


Fig. 10d: The taped ear used for the accuracy test.

D415

A similar procedure as before was carried out using the D415 scanner, where the head was again placed on the rotating stool and captured at various angles. Shown below in Fig. 10e is a mesh obtained from the D415 alongside the D435i acquisition. It is noticed that immediately the results obtained are of a higher quality with the D415 acquiring more details, especially in the ear region, around the nose, eyes and even the crease of the mouth. Although, the contour-line like effect is still noticeable similar to the D435i.

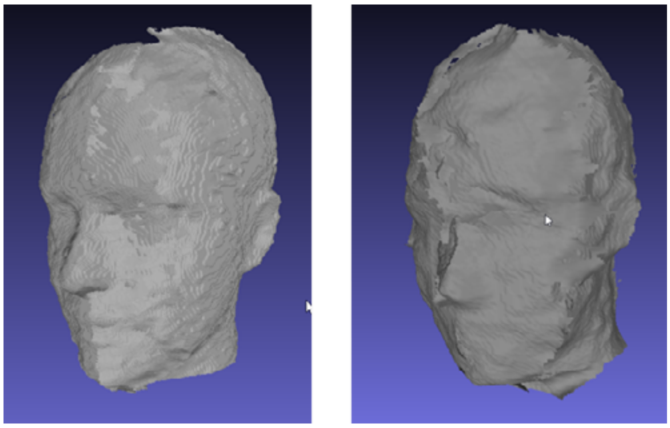


Fig. 10e: Comparison of the D415 and the D435i scans.

In order to acquire cleaner scans in the Realsense Viewer, specific actions such as changing the disparity shift value of the scanner were performed. (Zevenberg, 2020) It was found that a disparity range of 80-120 provided the best performance from the scanners. The benefits of changing this value further involved the capture of only the face and not the unnecessary surrounding data, along with much cleaner acquisitions and more precise details. The results are visible in Fig. 10f. The face acquisition on the left is after applying the disparity setting, while the right is before tuning.

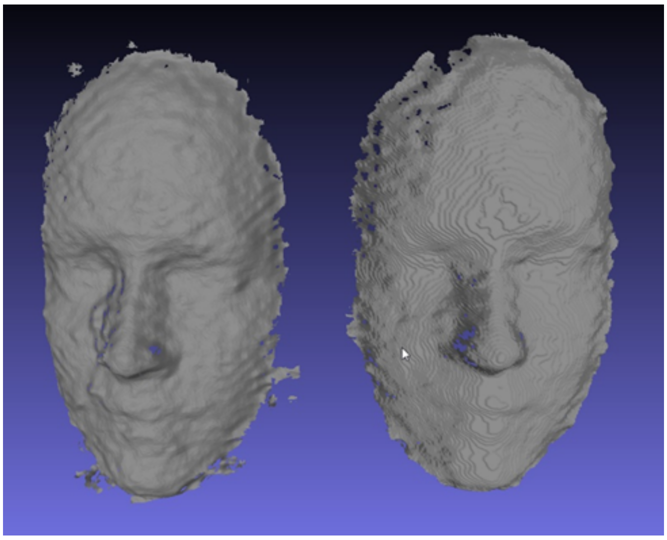


Fig. 10f: Difference in acquisition quality after changing the Disparity Shift settings. The post-disparity scan is on the right.

10.5. TESTING WITH HUMAN FACE

Since the dummy head had surface properties that are not representative of how a human head reacts to light, it was important to test the scanner with an actual human head to see whether there are any differences in detail capture and whether the overall noise in the acquisition visible from the previous images can be avoided.
For this test, the primary researcher volunteered as the subject and captured their face from different angles to be aligned later on.

From the images, it was noticed that there is noticeably lesser surface noise than the white dummy head, and the important landmarks to be covered, such as the nose and ears, show up quite clearly in the scans. The nose bridge area, which is crucial to design spectacles around, is relatively free of noise, and the ears show in good detail.
Next, the texture map was studied to understand whether the pupils and triangular fossa in the ear region are visible in the scan. The result is shown in Fig. 10h and shows quite clearly that the position of the pupils is visible, as well as the ear region.

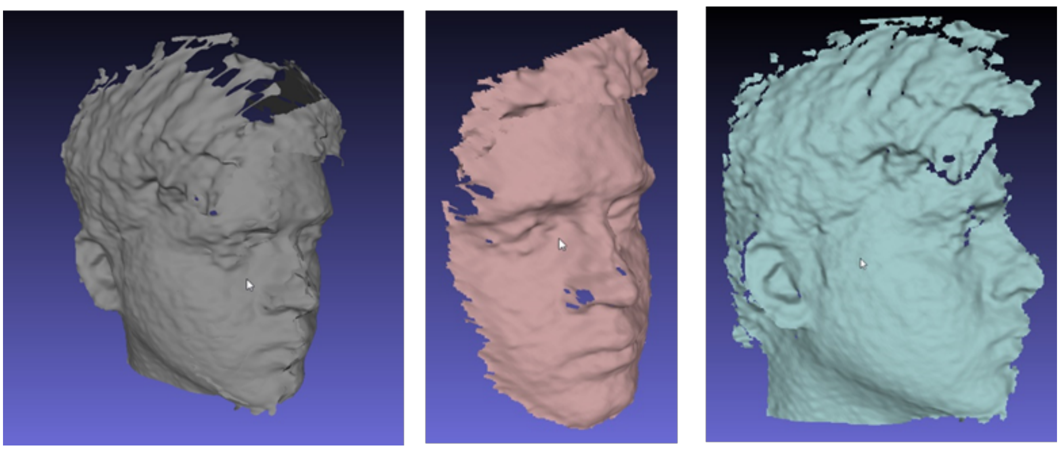


Fig. 10g: Acquisition of a human subject showing the detailed capture of human skin and individual views.

Fig. 10h: Texture detail of the same subject with pupils and triangular fossa region of the ear clearly visible.

The final step to ensure the accuracy of facial reconstruction was superimposing point clouds obtained from the Artec Eva and Realsense. This test aimed to understand the closeness of the stitched Realsense point cloud to the single-mesh Artec Eva acquisition. The software employed for this test was CloudCompare, chosen for its ability to perform mesh comparisons and show an estimate of the distances and deviation between the 2 meshes. The results of the comparison are visible in Fig. 10i For this particular analysis, the distance was set at 1mm which is further visible from the color scale on the left where solid red means a distance of more than 1mm while solid blue means less 1mm deviation. It is visible that very little area of the Realsense mesh is closer than 1mm to the reference Artec Eva mesh.

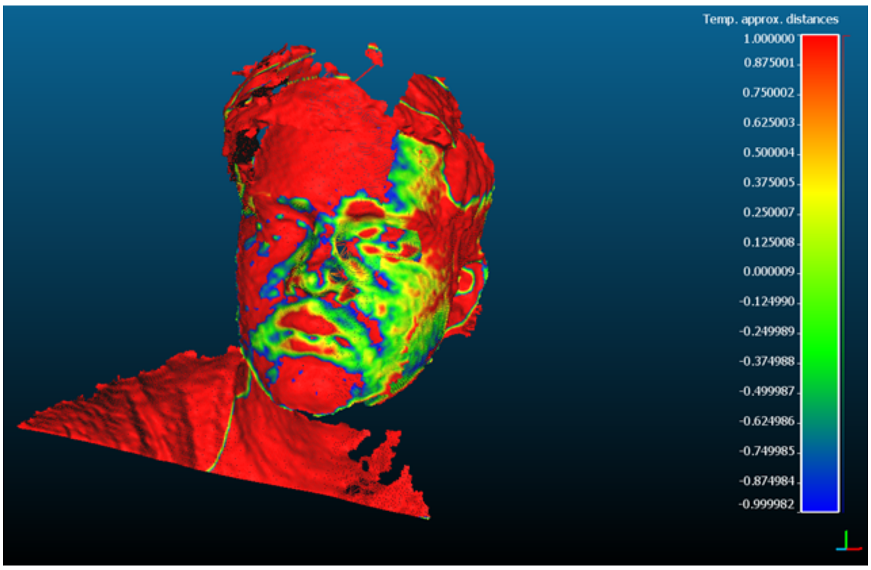


Fig. 10i: Color map showing corresponding matching areas between two meshes of the same face but acquired through different scanners.

10.6. CONCLUSION

The D435i performed better in the plane fit test with an RMS of 0.20%, which was better than that of the D415. However, the D415 was noticed to have a lesser distortion in the ROI and near the edges providing an overall cleaner acquisition. As for the reconstruction tests, the D435, while capturing a significantly larger area, was only able to operate at a lower resolution of 848*480 which led to low-quality acquisitions. Additionally, its larger FoV made it so the facial aspects captured were not as highly detailed as the D415. The competitor, while having a lower FoV, also had more pixels within the given coverage area leading to greater detail. Additionally, it was able to work natively at a higher resolution of 1280*720, higher than the D435I leading to better acquisitions. Once the disparity shift values were changed a bit to reduce minimum Z, it further increased the quality of the scans, making them cleaner, although it was noticed to reduce the FOV further as well.
This shows the D415 to clearly be a better choice than the D435I in multiple aspects, not to mention that it is also priced lower than the D435i.

11. LIST OF REQUIREMENTS

11.1. REQUIREMENTS

After collecting all the relevant information regarding the topics and forming conclusions, the next step was to make them concrete in a list where they were further broken down into categories and prioritized. Additionally, the list also included the clients' wishes as additions which could also be considered within the design. The list is as follows:

1. The product needs to make a contactless scan of the person's head to avoid intruding in their personal space and agitating them. As per proxemic research, the finalized distance is 300mm.
2. The product must make an acquisition from ear-to-ear.
3. Mesh capture must have a maximum accuracy of 3mm.
4. The product must capture both mesh and texture data for design and visual representation purposes.
5. The product must make an acquisition in a timeframe spanning no more than 20 seconds to avoid causing a distraction for the subjects, thereby reducing any possibility for repeat scans.
6. The product must capture mesh data for the bridge of the nose, position of triangular fossa region in the ears and the position of the pupils in high accuracy with a maximum allowable deviation of 3mm.
7. The product must cater to the sitting posture of the customers to ensure a standard height limit that is within the scanner's vertical reach.
8. The product must accurately capture heads of various sizes and shapes.
9. The product production costs should lie in the range of 500 to 1000 euros as this a budget requirement set by the client company.
10. The product must function with non-visible projector light to avoid agitating customers or causing visual irritation when being scanned.
11. The product must have a minimum size of 900mm, keeping in mind the 300mm distance constraint from the customer's head.
12. The product must be able to ignore environmental obstructions such as nearby furniture, items in its field of view such as the chair backing or wall behind the customer or even people standing close by both in its placement and during a scan.
13. The product must acquire a consistently accurate mesh-of accuracy as previously mentioned in variable lighting conditions keeping in mind the time of day and the direction of light on the customer's face.
14. The product must be low-maintenance and avoid having complex surfaces or finishes that attract dust and residue. This could lower the product's efficiency, slow down the overall duration of the scanning process and warrant unnecessary attention from operators.
15. The product must be comfortable to operate by one person since only one operator will be moving the product, performing the scan and verifying the final result.

11.2. WISHES

The wishes are different from the requirements since this section talks about the aspects which are not necessary for the intended functioning of the product but would affect its functionality, desirability and user experience positively. Therefore, implementing these in the product is of secondary importance as compared to the list of requirements.

1. The product must have a neutral and friendly appearance to avoid causing intimidation or anxiety in subjects.
2. The product must have as few mechanisms as possible to avoid unwanted failures on the field, reduce weight and reduce complexity.
3. The product should account for all the subject postures.
4. The product must be engaging and create a fun experience for the subject.
5. The product must be easy to operate for secondary parties such as technicians after instructions.

12. CONCEPTS

12.1. OVERVIEW

The List of Requirements was realized in the form of a number of different concept ideas. The ideas targeted a number of different design areas ranging from the functions to the user experience and also the aesthetics, which at this point was identified as a significant factor contributing to the customer's perception of the product. These factors have been further discussed below through the scope of three different potential directions that could be taken with the product. As per the agreement with Maat and the timeframe of the project, it was decided to leave the stand design out of scope; instead, an interface between the scanner and a tripod could be a viable approach.

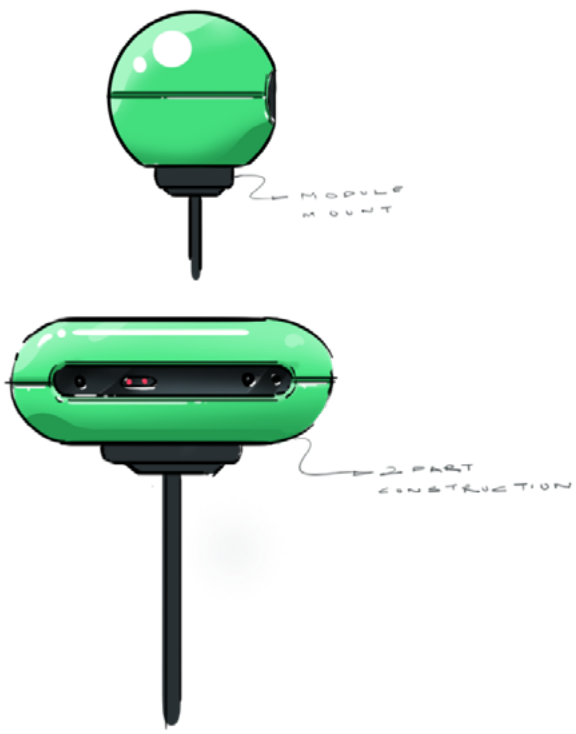
12.2. DIRECTION 1

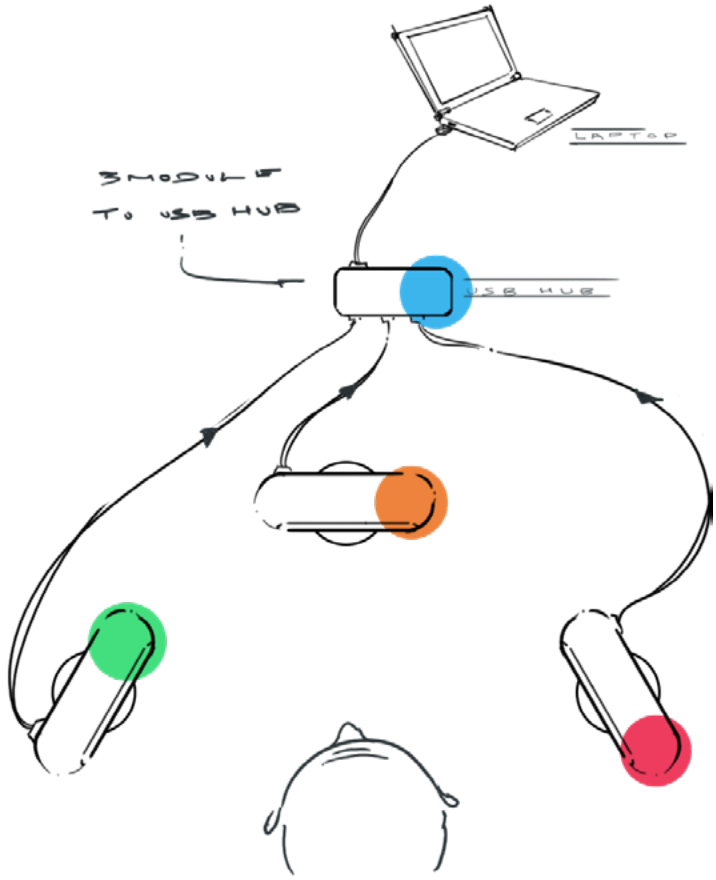
The 1st concept direction, as pictured in Fig. 8a, is a set of 3 free-standing scanner modules placed in front of a subject at stipulated places for maximum coverage of landmarks. The idea behind this concept was to avoid the feeling of claustrophobia when facing something so close to them. Multiple free-standing structures also help to adapt to not as spacious environments by being placed on desks and tables. There are certain advantages and disadvantages of this concept as well. The advantages are as follows:

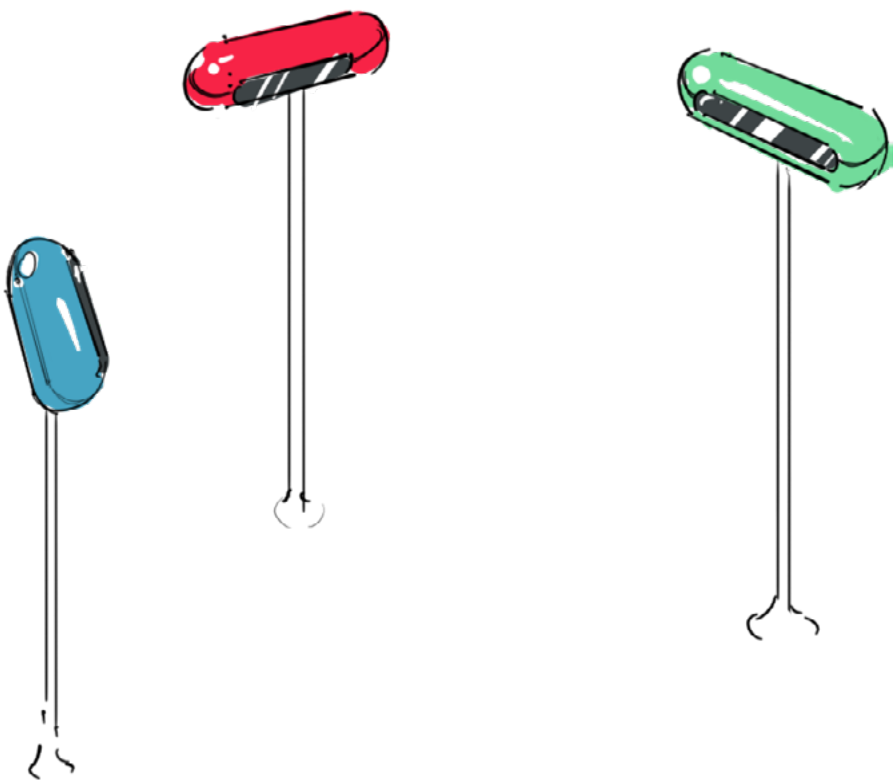
- Lots of storage options as the modules are compact and free-standing.
- An open structure that would prevent the feeling of claustrophobia and fear of standard medical equipment.
- Adaptive to congested or cluttered environments as individual modules can be placed on different heights.
- Individual modules create isolated points of interest for the subject.
- Modules are easy to access separately in case repairs need to be done.

The disadvantages of this concept are as follows:

- Individual modules are challenging to place in the correct places to cover landmarks uniformly.
- Due to the possibility of different modules being placed at different distances, accuracy will always fluctuate, which is not desirable.
- Different modules need different connectors, increasing the open wires in the environment. This makes wire management very difficult.


MODULE
MOUNT
2 PART
CONSTRUCTION


LAPTOP
3 MODULE
TO USB HUB
USB HUB



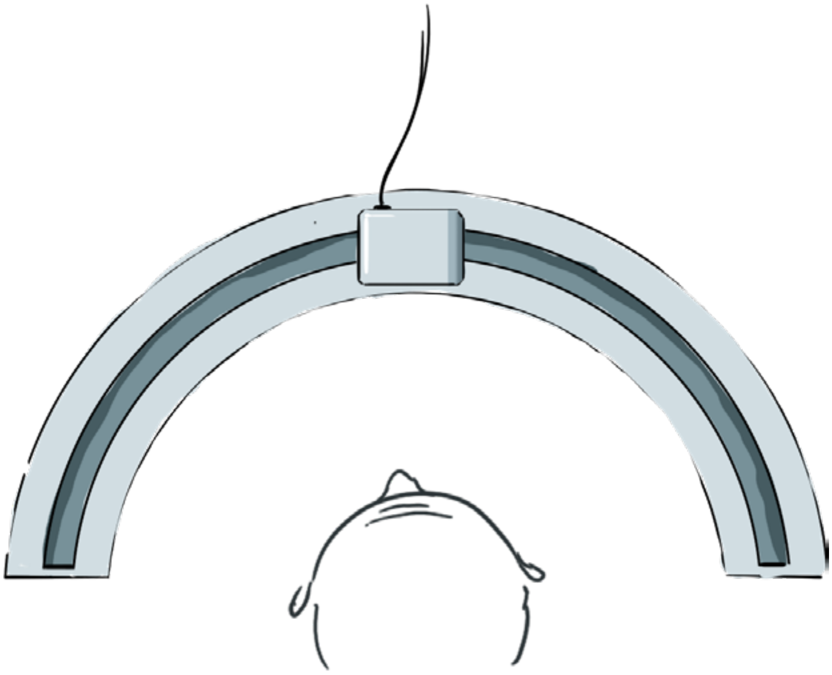
12.3. DIRECTION 2

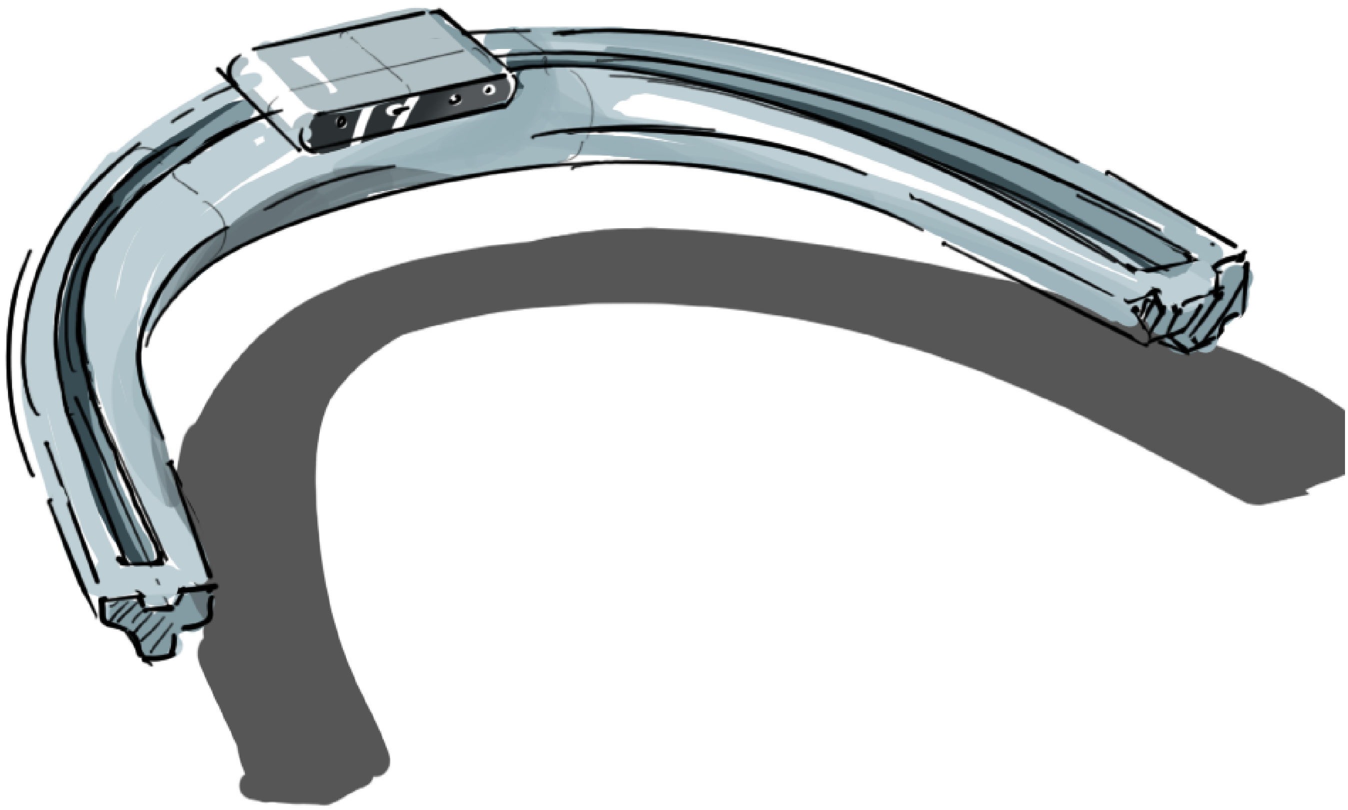
The 2nd concept direction pictured in Fig. 8b makes use of three D415 scanner modules arranged statically in a semi-circular fashion to cover multiple places of the face with overlap as well. The scanner is meant to work with a USB Hub connecting the three scanner modules to a shared system. The envisioned operation was for there to be a screen and button on the device itself for the operator to view, but the feasibility for those remains to be tested. The user would be required to move his head in the range of the three scanners such that the operator could view the required landmarks and then capture them. The advantages of this concept as cross-checked with the list of requirements is as follows:

- Static placement of cameras relative to each other and the overall setup ensure that frequent calibration is not required as transformation can simply be coded into the scanners.
- Multiple camera setup ensures that no moving mechanisms are required to cover the required landmarks of the face.
- Acquisition speed is increased due to multiple cameras operating simultaneously.
- The acquisition can happen on the device, and processing can happen on the connected system.

There are further some disadvantages of a concept such as this which are as follows:

- A setup such as this can be a hindrance in a smaller room since it is not designed to be portable.
- Using three scanners and a USB hub to connect them raises the overall cost of the product.





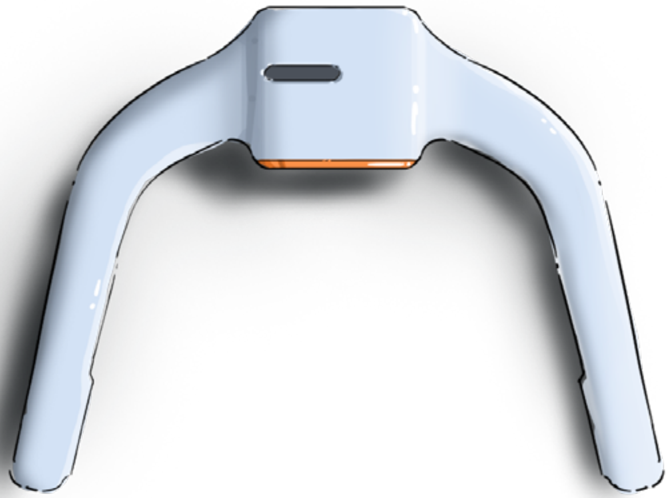
12.4. DIRECTION 3

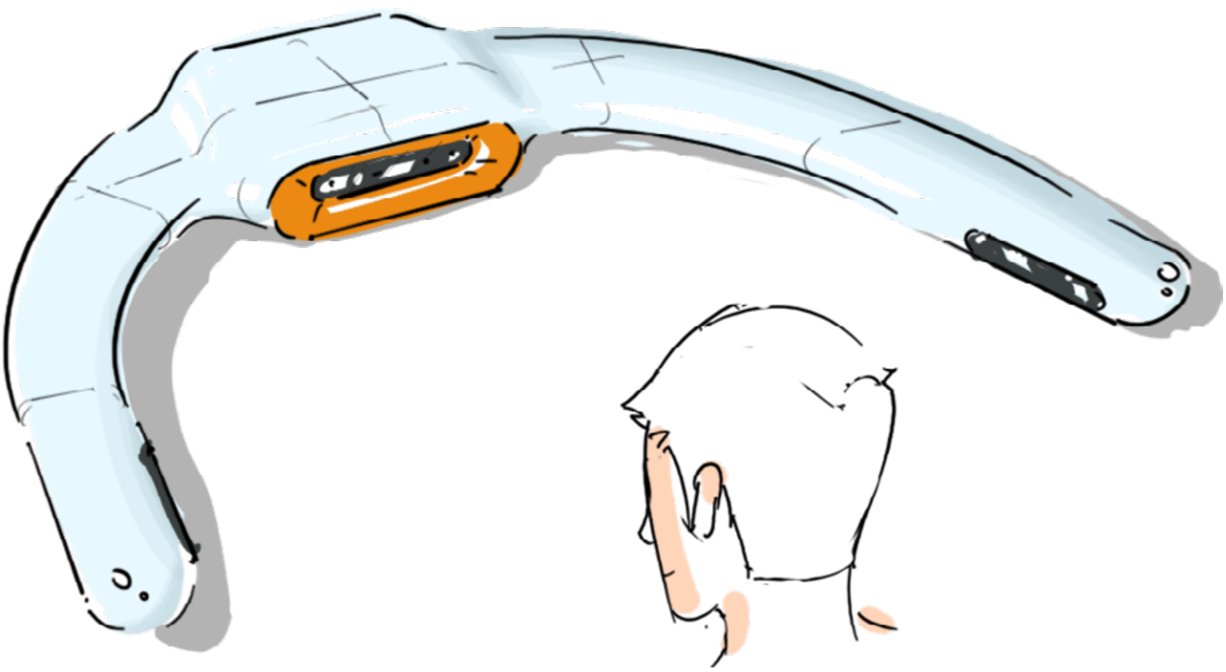
The 3rd and final concept direction, as shown in Fig. 8c, makes use of a single scanner mounted on a rail-based system. The intention with this concept direction is to limit the use of scanners while changing the structure of the frame to create a dynamic system. Depending on how much overlap it needs for different head sizes, the camera can slide and make acquisitions at stipulated points along with the rail system. The user, in this case, would only be required to look straight ahead while the single-camera moves along the rails and makes acquisitions. This concept, too, has some advantages and disadvantages. The advantages are as follows:

- Only a single camera is required in this setup.
- Fewer cables inside the product mean managing fewer cables.
- The setup could potentially be disassembled and reassembled fairly quickly.

The disadvantages of this concept are as follows:

- Making a custom rail system would raise the costs of the product.
- Moving the camera module would draw attention, causing the subject to look towards it rather than straight ahead, making scans invalid.
- Having a sliding system means having a solid cable management system built into the frame as the camera would be moving to various degrees, thereby extending and retracting its USB cable.
- Since this concept makes use of slide-based operation, it will create noise when it is working, which is not acceptable considering the target users.
- Having multiple mechanisms in the system increases failure points and opportunities for breakdowns which is not desirable.
- Complicated software and hardware development to connect scanner positioning with the slide mechanism.





12.5. CHOICE OF CONCEPT

At this point, the pros and cons of all three concepts were well-known, so the next step was to select which of these concept directions will be selected to go forward for further development and refinement. For the purpose of selecting a concept, a Harris Profile was used. This would help to rate the concepts in various design-defining criteria. The concept at the end with the most balanced criteria rating structure would be the one to go forward. The Harris profile criteria, as can be seen below, are derived from the list of requirements, albeit in a combined manner to help grade them with ease on a table such as this. The speed of acquisition criteria involves the overall speed of the product from initiation to capture. The accuracy criteria include the factors of actual mesh accuracy and post-processing accuracy, and facial plane overlap performance, which are also dependent on the positioning of the scanners within the product. User comfort encompasses both the front-facing users, such as the customer being scanned and the back-end user, such as the operator. Aesthetics involve the looks of the concept with relation to the customer perception. Design complexity includes using mechanisms, construction complexity, wire management and looking at the product as an overall integrated system, not just the physical product. Lastly, adaptability involves how suitable each of the concepts is to a variety of different environments. This includes size, modularity and the ability to retract.

Based on the Harris Profile, it was clear that the most balanced concept here was Concept 2, which was the Static Scanner Modules.
While the Harris Profile gives a concrete look at all the involved criteria and helps to condense them into more understandable and grade-able points, the decision to finalize concepts had started during the testing phase itself when vital processes such as calibration, construction complexity, scanner constraints were slowly being discovered and tested leading to some apparent conclusions being made in favour of the original goals set by the client, acquisition speed due to customer distraction, the accuracy of the final scan to make designing the spectacles easier, and user comfort which would include aesthetics and overall scanning experience. These have always been the guidelines to judge the validity of all ideas and concepts, even more so than aesthetics.

Concept 1 - Individual Free-standing Scanner Modules

Criteria	- -	-	+	++
Speed of Acquisition				X
Accuracy		X		
User Comfort			X	
Aesthetics			X	
Design Complexity	X			
Adaptability				X

Concept 2 - Static Scanner Modules

Criteria	- -	-	+	++
Speed of Acquisition				X
Accuracy			X	
User Comfort				X
Aesthetics			X	
Design Complexity				X
Adaptability		X		

Concept 3 - Single Camera Rail System

Criteria	- -	-	+	++
Speed of Acquisition	X			
Accuracy			X	
User Comfort		X		
Aesthetics		X		
Design Complexity	X			
Adaptability	X			

13. EMBODIMENTS

13.1. OVERVIEW

Once a concept was ideated on and finalized on paper, it was necessary to consider its feasibility in a real-world scenario which would be possible only by taking into consideration factors such as the layout of the modules, the parts involved in the construction of the scanner along with their integration with the internal components, additional hardware and integration between the scanner and the stand, in our case a tripod.

13.2. SCANNER MODULE LAYOUT

It was vital to fix the position of the various scanner modules in a given space for reasons already discussed in the previous section. The other processes involved in establishing the position of the scanner modules involved three different but connected approaches, namely the virtual method, the test acquisition method and the mockup method.

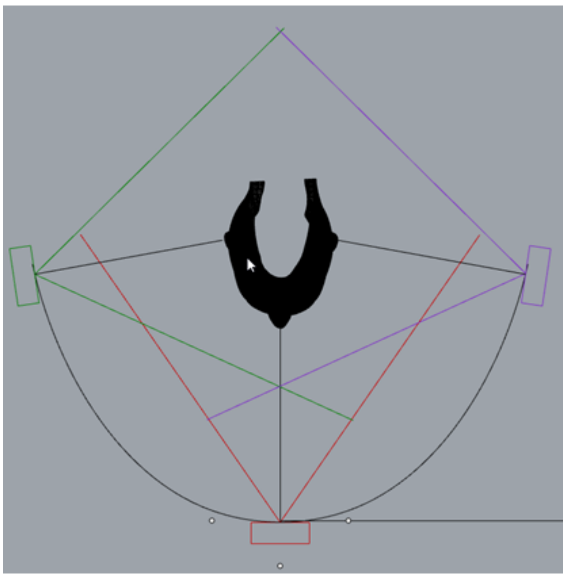


Fig. 13a: Initial Scanner layout testing.

The virtual method involved using Grasshopper, a parametric software, to simulate the positions of cameras relative to each other and to the subject, as shown in Fig. 9a. Grasshopper allows one to change the positions of elements relative to other objects really intuitively. This aspect would help determine the optimum position of three scanners such that they are at a comfortable distance from the subject with enough field of view and that they have enough coverage between scanner FOVs so post-processing software could find ample features to help with the alignment of various meshes.
The second method made use of a testing setup where a dummy head was placed on a turntable at a certain distance from the scanner and then turned to capture acquisitions of different sides of the head. This is already discussed in previous sections.
Lastly, the mockup test made use of a cardboard mockup roughly following the same shape as the final concept to ensure that the recommended distance was followed between scanners and the subject's head.
While all these steps were carried out in the presence of only a single scanner, the final setup makes use of multiple scanners. Three free-moving 3D printed mounts were created to simulate the setup of multiple scanners, as shown in Fig. 13a, which were then placed in accordance with all the layout information gathered from the previous steps.

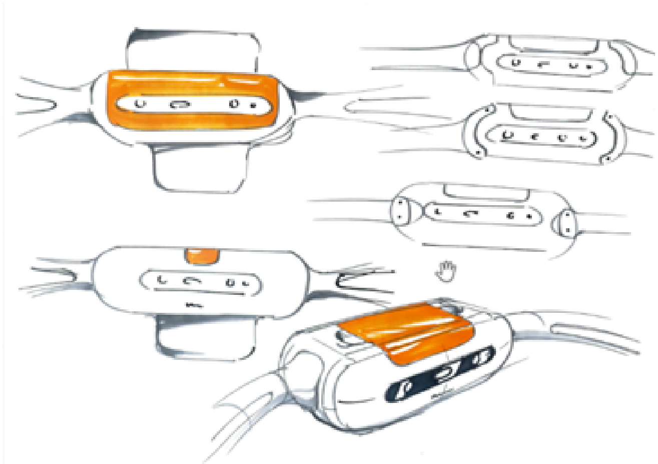
13.3. SCANNER CONSTRUCTION

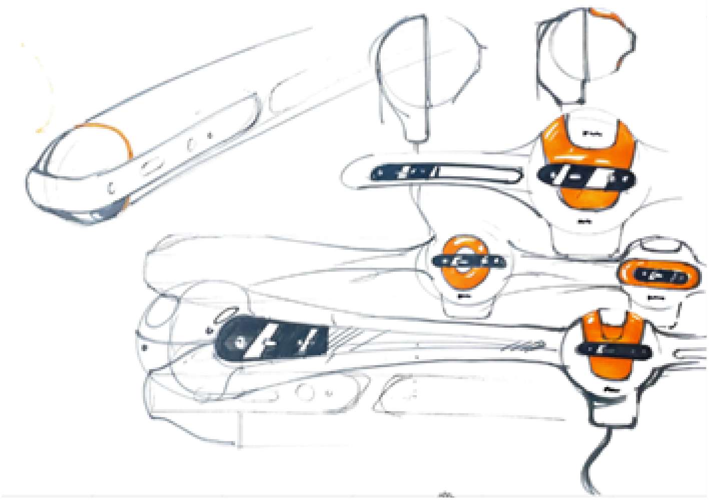
It was important to set a basic wireframe of the product before considerations can be given to the construction of the body such that the scanners are fixed in space. Mentioned below are some factors that would influence the scanner design from a construction point of view.

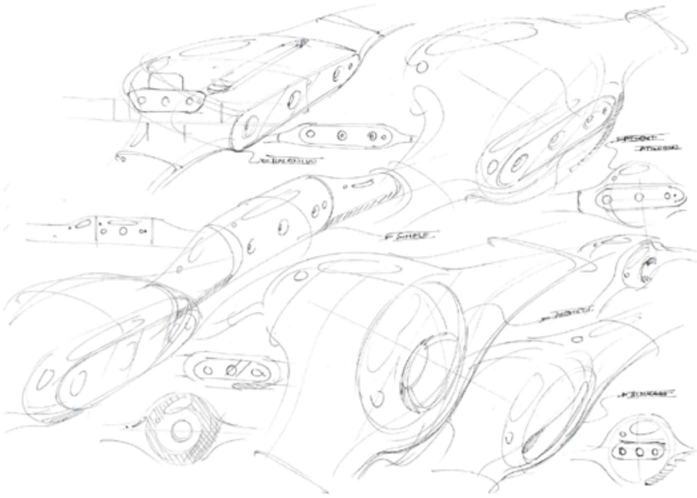
1. The position of the camera modules needs to be fixed inside the body as that would influence how correctly the mesh acquisitions from the different modules are aligned in post-processing.
2. The weight of the scanner is an important factor as it will be mounted on top of a stand with support only at some points at the bottom. Additionally, considering that it is a cantilevered design, uneven weight distribution could lead to the extreme ends of the scanner body droop over time, affecting the accuracy of acquisitions.
3. Easy accessibility to the internals for the purpose of inspection, repair and part replacement was also a factor to be considered. At the same time, it might be easy to access the scanner module in the middle, the ones at the extremes needed to be accessed separately for the ease of repairing.
4. The manufacturing volume for these products is relatively low, considering this is not a consumer product. This means that tooling costs are a concern leading to the conclusion that the construction needs to be simplified for ease of manufacturing.

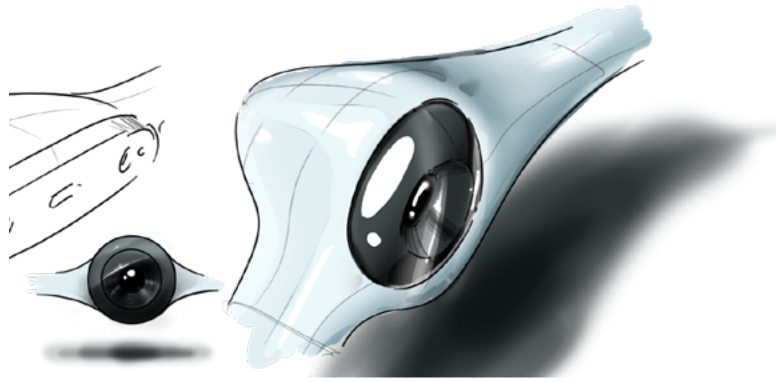
13.4. ENCLOSURE DESIGN

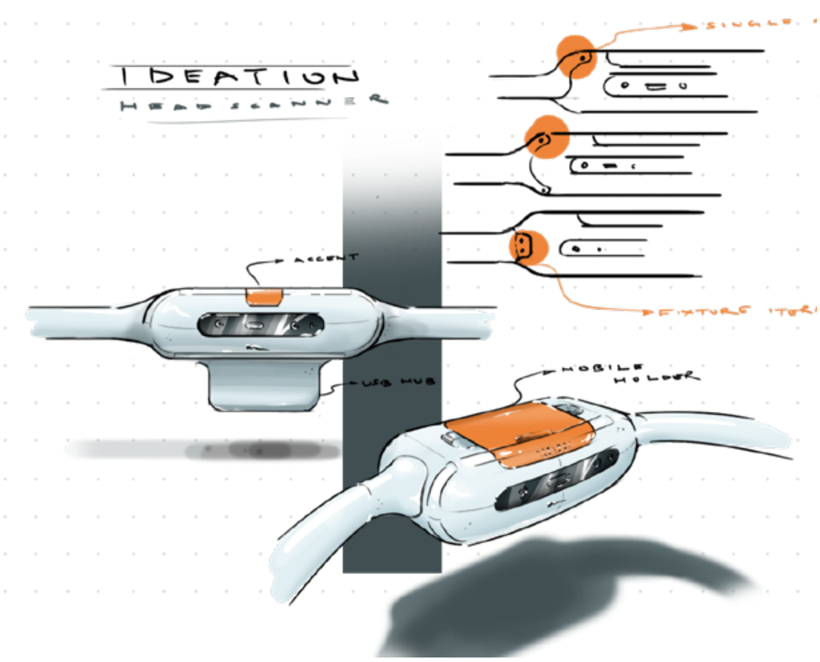
The form of the enclosure had already been ideated early on, as can be seen in the concept phase, but it was later adjusted in several iterations to accentuate and modify certain elements keeping in mind the design intent, available resources and feasibility. One of the prime examples of this is the design of the side cameras.

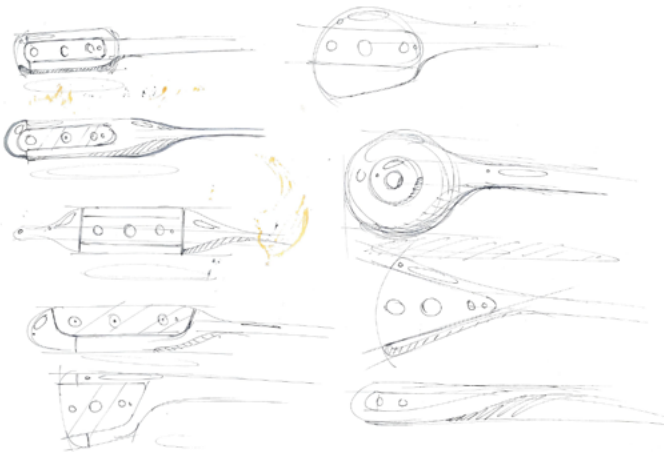


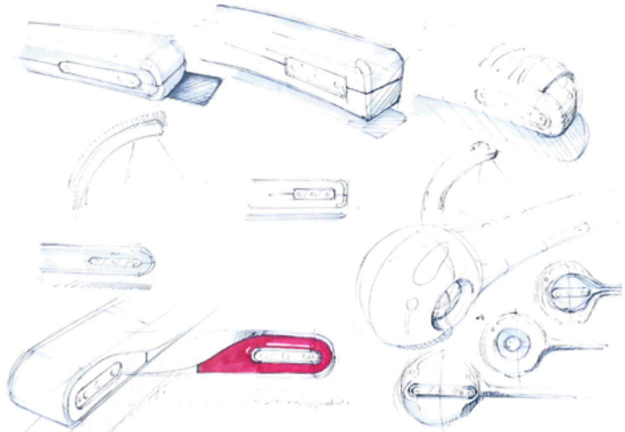


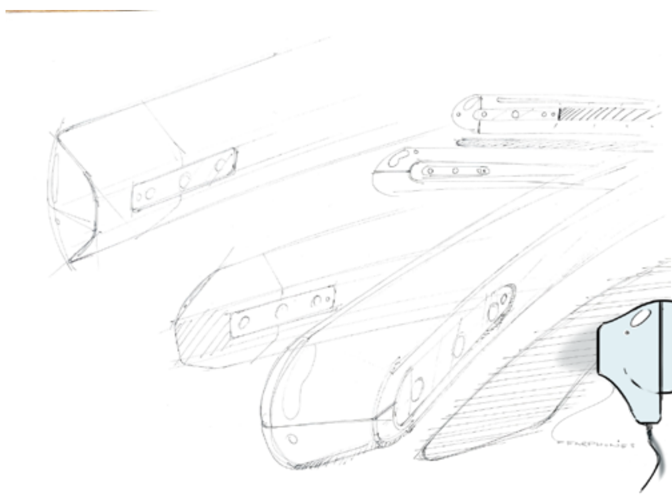


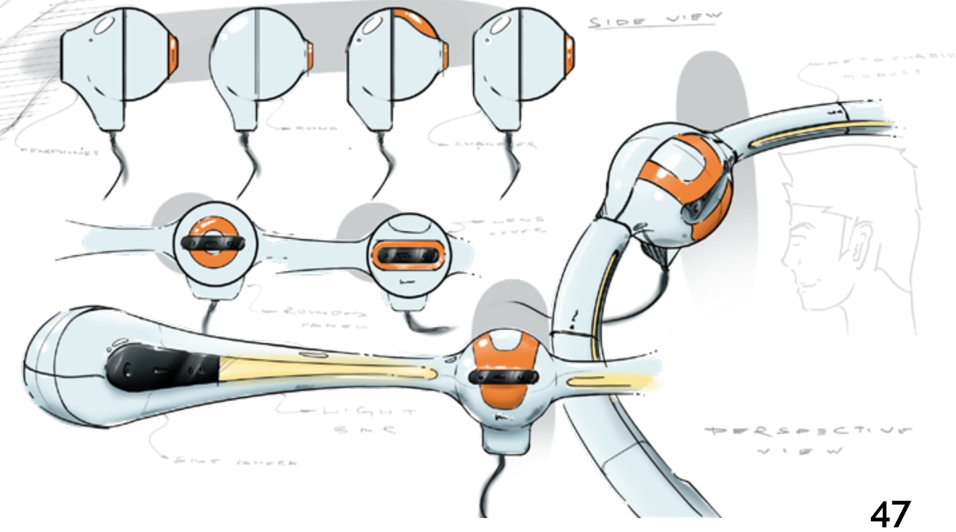



IDEATION
HEAD SCANNER
ACCENT
MOBILE HOLDER








SIDE VIEW
PERSPECTIVE VIEW

For the purpose of prototyping, 3D printing as a process was used, which is a more versatile process even if the build volume is limited to smaller sizes and the build times are highly dependent on the part design. Additionally, while the process is expensive, it gives much freedom in terms of design that some other processes do not have. As far as print quality is concerned, due to the layered structure of prints, these tend to be quite brittle depending on the layer direction, and thinner parts such as ribs could break off very quickly.

Figure 13b. shows an exploded view of the product. The internal components are not portrayed here but discussed in the next section that is discussed in further detail in the next section. Also mentioned below are the overall dimensions of the product, the number and types of screws used in this assembly and the total number of parts.

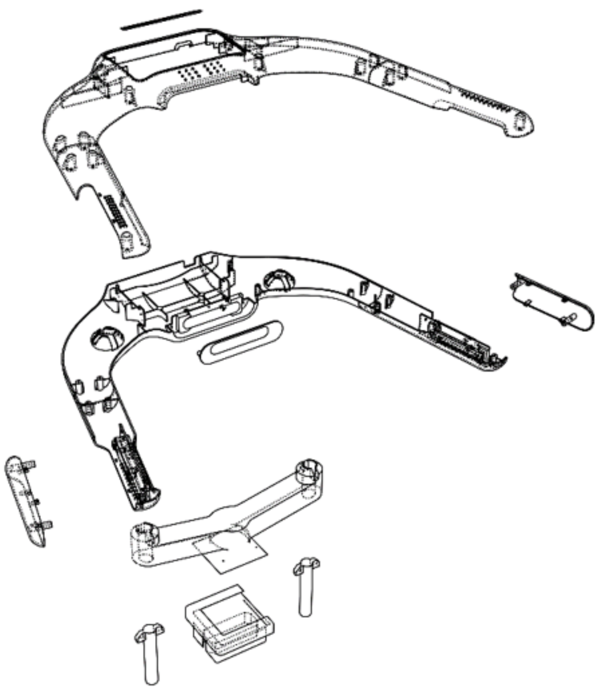


Fig. 13b: Exploded View of the Scanner.

13.5. STAND INTERFACE

A significant part of the whole design was the stand interface. Since the design of a complete stand was considered out of scope, keeping in mind the time constraints and the project focus area, it was decided to go ahead with a stock tripod seeing as they are designed to be quite robust with a well-designed locking system and adjustable height.

It was, however, important to design the interface between the scanner and the tripod, seeing as they are not designed to attach to each other.

The interface was designed to be robust and highly functional such that it would support the weight of the scanner. Extra care had to be taken to design the part that would support the scanner since the design is partially semi-circular and also cantilever-ed and ensure that it does not topple off the tripod. The elements making up the stand interface were designed to make the mounting and dismounting of the product as quickly as possible, especially since the interface-product touch-point is present in a challenging area to access and are therefore not accessible to lock-in.

As shown in Fig. 13c, the stand interface makes use of two keys, both of which have flanges at one end. Upon setting

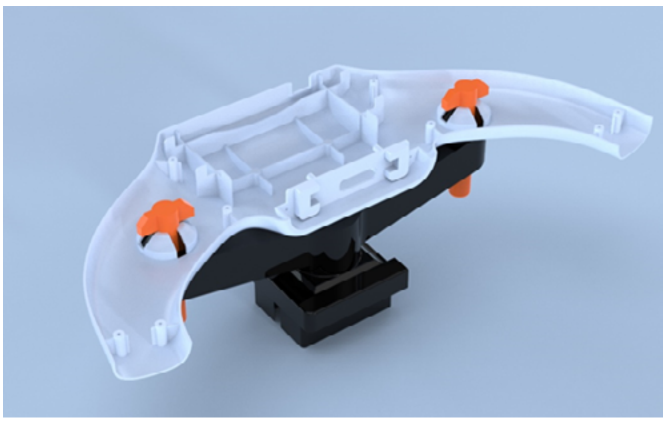


Fig. 13c: Interface Locking mechanism

the printer down, they need to be pushed into the product through a couple of slits and then turned and released such that the prongs land in two dead-end slits perpendicular to the existing two. This locks the product in place, preventing it from toppling in any direction.

13.6. INTERNAL COMPONENTS

The Head-scanner is designed mainly to be used in well-lit indoor situations where it will be completely stationary. This gives some amount of freedom in terms of the hardware that can be used in the device since the scanner can work in tandem with more powerful systems such as a laptop rather than onboarding everything into one device for the processing, which might take longer than acceptable.

The components being used inside the device consist of a USB Hub consisting of 4 ports which are further connected to the three different scanner modules by means of three 1-meter USB 3.1 cables. The scanner module set further consists of the Intel D415 camera module and the D4 Vision processor board, which does the depth processing and generates the depth map. These two components are connected by flex interposers which are a specially-designed flexible version of the rigid interposers that generally come with the scanner modules. Using these for the internals gives considerable design freedom as the connected components can be placed at a distance from each in any position.

The scanner is intended to work with a laptop to display the Viewer and so is connected to it via a micro-B to USB3.0 cable. It is worth mentioning that the USB hub being used is of a powered variety, but for the given use case, it was noticed that powering it is not required. This is pictured in Fig. 9e

13.7. SOFTWARE

Meshlab was the primary software used for the test part of this project; however, using it for the final product and is not recommended as the future scanner operators are not envisioned to be experts at using 3D software. Additionally, Meshlab has a learning curve wherein many cleaning algorithms have to be run in a specific sequence before one can start to align different meshes. Therefore, the final vision from the software point of view is that operators do not use any stock software.

It is also not intended that Maat! use any other software once the meshes are sent to them as it would count as an unnecessary and additional effort on their part, which is something that they do not have to do with the meshes acquired from the Structure Sensor.

The envisioned workflow for the operator is simply using an executable file consisting of Python code with all the processing and alignment algorithms built into it, as pictured in Fig. 13c. These aspects are discussed more in detail in section 10.2.

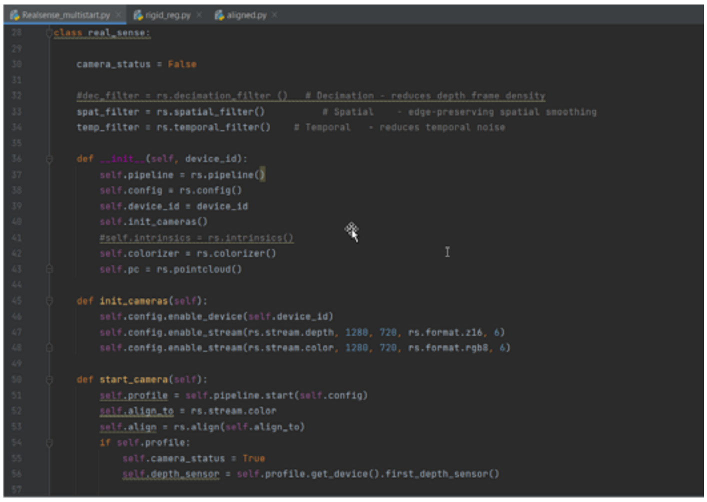


Fig. 13c: Python interface showing the code

14. PROTOTYPE

14.1. OVERVIEW

The final step of the design process was to prototype the concept and test it with all the internal components and the software working together. This section is divided into two different sections describing the approaches to both aspects of the prototype.

14.2. ENCLOSURE

As part of the iterative process, a number of prototypes were made for parts of the enclosure, some of an aesthetic nature and others of a more functional nature.

The aesthetic prototypes, as pictured in Fig. 14b, were 3D printed out of PLA using FDM (Ender3 Pro) for the purposes of verifying the real-life scale of the product and the initial fitment of parts, also to see whether the internals would fit inside them.

14.3. SOFTWARE

The software aspect of the product was prototyped using Python 3.9 and 3.7 in tandem with some libraries such as Open3D and Numpy to make the final version of the code automate all the processing.

The code is made easier to access in the form of an Executable file, keeping in mind the software knowledge of different operators. Then the operator would simply have to click on it prior to the customer sitting in front of the scanner.

The program runs a number of step-by-step sequences in order to carry out a successful acquisition. Since the program runs on a laptop, it starts by sensing whether three camera modules are connected to the system and further initializing them. Once it has completed that segment, a Viewer pops up on the screen containing three views showing each mesh representation in real time. The meshes are represented in a bright green colour, clearly signifying the elements being visualized by the camera.

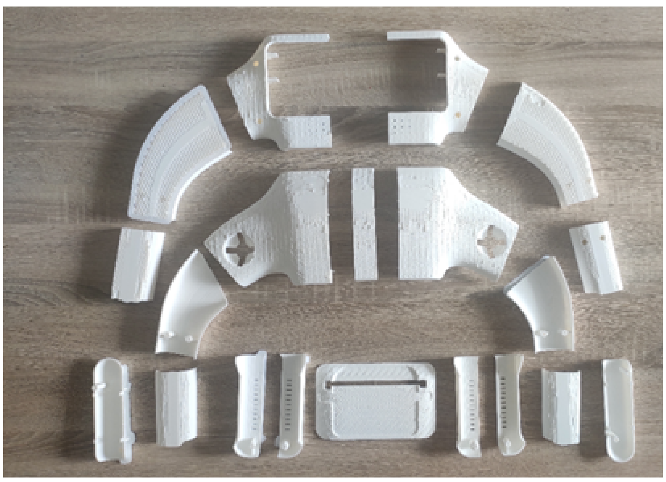


Fig. 14a: Flatlay of the top half of the scanner.

Fig. 14b: Aesthetic Prototypes of the scanner ends.

Once the operator has confirmed that the required landmarks are in the range of the scanners, they can close the Viewer, which automatically triggers the capture segment. This process has been repeatedly tested to note the acquisition time and any significant difference corresponding to the number of points appearing in the scanner range. From this experiment, it has been noted that the acquisition time of the three scanners working together ranges from 50-60ms which is a factor that immediately satisfies a significant time requirement of the project.

The program then runs the alignment segment (which could take some time) using rigid registration and ends the program by showing each of the individual point clouds and the aligned head point cloud for inspection. Closing these views saves the files on the system for transfer.

Fig. 14c: A working prototype of the Head-scanner complete with the mount and color scheme.

15. VALIDATION

15.1. OVERVIEW

The final step in the project was to validate the embodiment with the customers, namely the children and parents. For this study, the full working prototype was prepared along with the working code. Additionally, the complete study procedure along with research questions, points of observation and interview questions were also outlined with the intention of a semi-structured interview though flexibility was anticipated in unique situations. Before the final study with real-world customers, pilot tests were conducted with known participants to further optimize the study and adapt to certain unexpected responses should they occur.. The reasoning behind doing a validation study was to help understand a number of product-related aspects. which are as follows:

1. Realization of the envisioned experience. Whether the initial experience that was envisioned with the design of this prototype was realized in a real-world context and to what degree.

2. User Perception of the product and subsequent interactions. How did the users perceive the physical product for the first time and what their interactions would be?

3. Potential failure points in the product or experience. When testing a product in a real-world scenario with intended users, one of the aims is also to see what are the various failure points that a product could face which would then be refined and re-validated with clients.

15.2. VALIDATION PLAN

The target group for this validation study were children since their reaction to the product was considered of critical importance and would affect the quality of the scan to a higher degree. An objective for the test and research questions were further devised for the validation study to extract relevant and applicable results.

Research Objective

To evaluate the design of the 3D Headscanner and the experience that little children have when interacting with this product. The aim and intention are for them to have a comfortable, relaxing scanning session where they are not feeling agitated or feeling uncomfortable due to the Headscanner.

Main Research Questions:

1. How do children/parents perceive the product?

2. Does the 3D Headscanner make the children feel comfortable when they are in close proximity to it?

3. Does the 3D Headscanner and its elements have their attention during the duration of the scan so they are not distracted?

4. What is the anxiety-inducing element (as observed in medical products) when they are in close proximity to it/standing “inside” it?

15.3. VALIDATION RESULTS

The product was validated with 3 families with the customers lying in different age categories. The responses obtained from the three tests were found to lie in different spectrums. While some of them were to be expected from pilot tests, certain emotional transitions came as a surprise. It is also important to mention that the validation test was in a comparative situation where the client used their Structure Sensor before the Head-scanner. The full interviews can be found in Appendix whereas the summarized versions are as follows.

First-time Interactions with the Head-scanner

From two of the three studies, it was observed that the participants, one of whom had Down Syndrome, were fairly calm when interacting with the Head-scanner, which was an unexpected result. The participants were highly cooperative and responding to adjustments as best they could. With them, it was quite easy to acquire scans, even multiple ones. As for the third participant who was also the youngest, an anticipated response was observed. She was visibly scared of the product when brought in close proximity to it and was unwilling to get near it. The reason for this was identified to be the semi-circular shape of the product going around the head that might invoke a sense of fear and claustrophobia in young kids. Participants faced some difficulty when attempting to self-position their head in view of all three scanners and in 2 different instances, their heads had to be adjusted by their parents.

Alternate approach strategy

In the event that it was not possible to scan the participant, an alternate approach strategy was employed, one that involved a parent holding a phone under the scanner to draw the child's attention there and in the meantime, the Head-scanner itself would be held facing vertically upwards as to not alarm the participant. Once the child was engaged in the phone, the Head-scanner would then be rotated into its scanning position around the participant and immediately captured. Surprisingly, this approach worked with the youngest participant and was in fact employed up to 4 times with recurring success.

Head-scanner capture speed

In all the instances when a scan was captured, the speed was noticed by the parents' to be a significant aspect of the product. It was observed to be less demanding for the participant than the Structure Sensor since the capture did not require one to hold a position for the duration of a scan and was especially effective for participants who were not in a position to cooperate. One of the participants remarked that it was easier to use the Head-scanner since she did not have to hold her breath and posture.

Scan Quality

While the scanning speed was considered remarkable, the scan quality was noticed by two participants to be of a lesser quality than the Structure sensor, both in alignment and mesh quality. This was due to the fact that the transformation matrix is incorrect and needs to be adjusted to obtain better results. Secondly, since the Structure sensor offers a decimated mesh as the end-result, it simply looks cleaner than the mesh shown by the Head-scanner.

Safety of the Head-scanner

The Head-scanner was observed to be safe for children in all three aspects, but in 2 instances, it was conditional. One of the participants' parents noted that the device was considered safe due to its non-contact nature but the effect that it has on the child's mental well-being is a cause for concern. One of the other participants mentioned feeling as if the device was using radiation when scanning since it reminded her of a similar instrument used at the dentist's office.

16. RECOMMENDATIONS

16.1. OVERVIEW

The validation study resulted in certain recommendations which are discussed below in the form of design areas which can be improved as next steps. These are as follows:

16.2. HEAD-SCANNER STAND

During the validation study, product shortcomings were noticed in terms of horizontal distance between the customer and the scanner. Having to readjust their head constantly before they can be in correct horizontal range of the scanner is a challenge for the concerned target group, a factor which was observed a number of times. To make this step easy, the next step could be to design the stand of the product thereby replacing the current stock tripod which was implemented in the design to enable the designer to focus on the scanning aspect of the design and not too much on the stand and platform mechanisms. This element can be newly designed in the next step as a rolling platform to move the device closer to the subjects.

16.3. VISUAL EXPERIENCE

It was gathered from client discussions that a big part of the experience is the virtual viewer that the client uses on their iPad to show customers how they would look in certain spectacle designs immediately after a scan has been taken. This, however, was considered out of scope for this project since this would involve considering aspects not directly involved with the physical design of the product or not part of the immediate product experience. For the future, a possible direction could be to simply integrate the Head-scanner system to the iPad such that the UI remains unchanged and Point clouds can be transferred.

16.4. REMOTE DEVICE INTEGRATION

One of the many challenges in the early stages of the design was operating the Head-scanner remotely from a mobile device, this includes functionality such as triggering acquisition, viewing the scanner views, post-scan mesh check. Additional aspects to consider in such a system would be on-device processing on an iPad as opposed to processing on a laptop right now, wireless communication between the head-scanner and device to trigger scans, transfer meshes and show the live scanner views with minimum latency. After discussions with the clients and considering all the aspects of such an undertaking in the designer's capabilities, the direction was eventually changed to a more connected, stand-alone system also to stay in line with the company's future strategy where the product will be used indoors in certain set locations. Another major reason for not following such a direction was the amount of non-scanning code that would have to be written, possibly to set-up a server to be displayed on the iPad for off-device processing and just to create connections between the Raspberry Pi and the device would undermine the time that is required to carry out the project itself. For the future, it could be an option to investigate this aspect further as doing so would optimize the operation of the device under difficult conditions.

16.5. PORTABILITY

In the initial stages of the project, the brief was essentially to replace the existing Structure Sensor and design a head-scanner with all the capabilities of the current-scanner with the added benefit of portability. This was, however, changed in light of the new direction as mentioned in the remote device integration section. The reasons for this were the tight engineering constraints that would have to be addressed when designing a modular or retractable system would take up considerable amount of time and even then, might not be perfect enough to create such a system where side scanners are perfectly positioned. This would eventually reflect on the point cloud causing invalid scans. This can, however be addressed in the future with given time and to make use of the quickness of the existing scanner on the field as well.

16.6. ALTERNATE SCANNERS

During the choice of technology phase, it was identified that the Realsense D415 cameras are accurate only upto 3mm at the front of the face near the nose bridge which could be further optimized and made more accurate with higher quality(and more expensive) scanners, possibly ones that make use of a different scanning technology altogether. It is worth mentioning that since speed is a crucial element in the scanning process, the newer technique needs to be as fast if not faster than Stereophotogrammetry.

17. REFLECTION

Initially, the project itself was observed to be a challenging proposition, however, establishing a detailed plan for each phase in the form of a linear Gantt chart helped to visualize an idea of the various steps to take thereby shifting focus from the whole project and instead trusting the process phases. This helped to take away some performance stress and in turn work in much more detail per phase. In the same vein, it is important to mention that the execution of the plan had started to lag behind despite the plan still being very realistic, a factor which was taken into account at the later project stages and attempted to correct constantly since it had essentially triggered a domino effect influencing all the future stages and also the timeline of the project.

The observation and interview phases were largely facilitated by the client which helped to gain a holistic idea of the client process and other relevant factors such as child-customer behaviour and the environment that the client works in. The validation phase was made especially difficult due to the vacation period starting which made a lot of contacts not possible and secondly, the prevalence of the COVID-19 pandemic which made willing participants not want to facilitate a validation session. Nonetheless, a few sessions were eventually organized and performed smoothly. However, it would have been optimal to stay prepared for earlier validation session which were prepared by the client but which could not be met due to the prototype not being complete.

Quite a few learning goals were set before the start of the project most of which were achieved to a greater degree than others. One of the more successful learning goals involve designing for a working prototype rather than just an aesthetic one. This undertaking led to certain considerations such as the fixtures, internal engineering, space-claim, part fitment and wire management to an extensive degree. Certain parts were engineered differently from standards due to a lack of part engineering knowledge but which was developed later through working on the product and figuring out shortcomings. Wire management was constantly optimized throughout the prototyping phase till the final result had a good internal structure. In terms of part-to-part fitment, still better execution can be achieved making it a more well-constrained product.

In terms of software, Grasshopper was initially used for virtual prototyping which led to achieving a basic understanding of a multi-camera layout with respect to a head and which was further taken forward using a cardboard mock-up roughly simulating the layout and to test claustrophobic effects. It was the assumption that more Grasshopper would be involved in the project but it was not. Rather, a number of different software came into play such as Meshlab, Realsense Viewer and CloudCompare all of which helped to learn an ideal 3D scanning and post-processing workflow.

As for the knowledge side of things, a lot was learnt from reading past processes, talking to the project supervisor and testing with the hardware itself. This is perhaps the greatest accomplishment that so much was learnt about 3D scanning as a technology, market competitors and other more integral elements such as alignment, disparity shift and connectivity and also put to use in the given time.

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