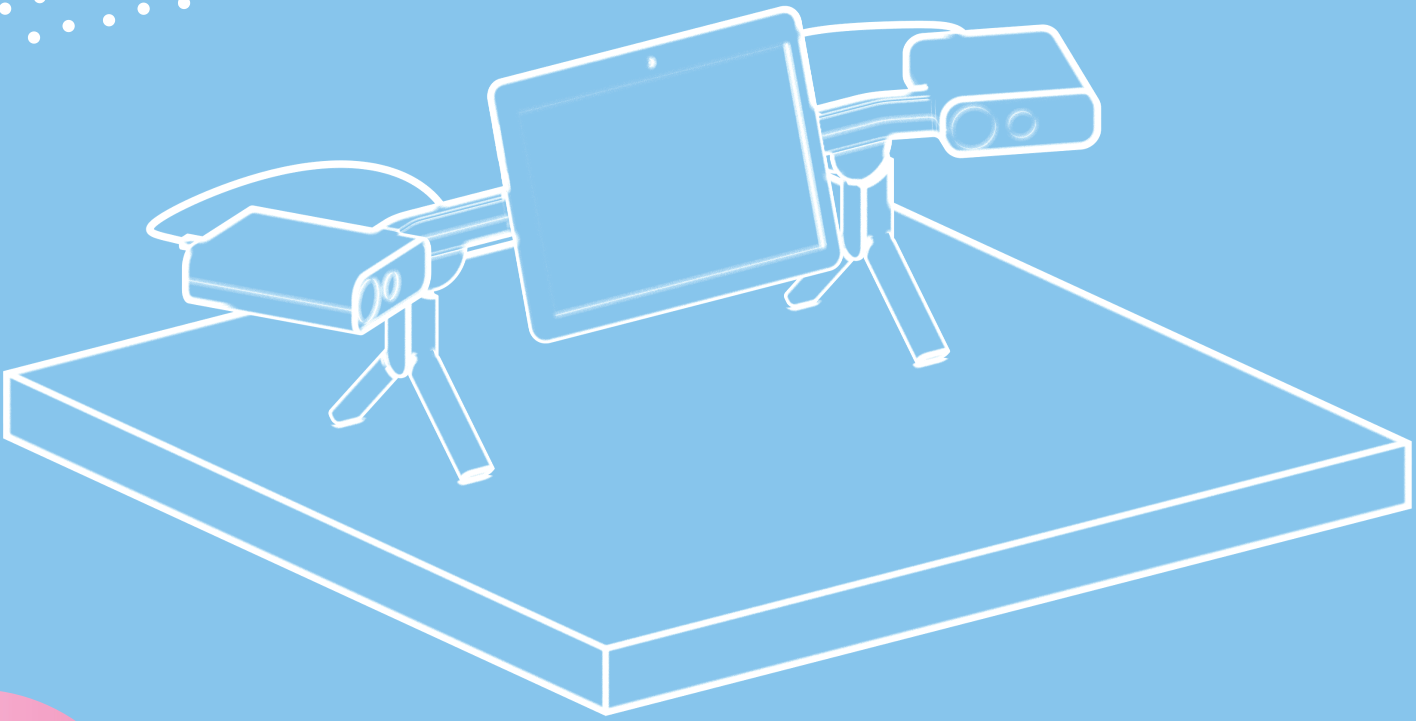

APPENDIX

PATRICK BUSSER

MASTER THESIS

INTEGRATED PRODUCT DESIGN

Table of contents

Appendix A: Observations Opticians visits

Observations Colpa

- It goes faster than expected, max 15 seconds are needed
- Spoken instructions are quite clear
- Uploading takes quite a while
- They sometimes have people with down syndrome, they can usually do it themselves
- Many options available for advanced customization, many variables can be changed
- Result looks a bit wonky, temples going through ears
- Both glasses in acetate and PA available
- iPad is placed in a stand on the table, user doesn't need to hold the iPad

Observations Kijk op Ogen

- Massive device that has a moveable arm with scanners
- Everything is ran on a windows PC, keyboard and mouse needed
- System never turns off, sometimes one of the sensors doesn't work
- Only a few parameters can be adjusted to 'honour the design'
- There is not one spot where to stand, depends on the user
- Getting the head in the frame is quite hard since the screen is next to the device
- Didn't expect a bright flash while taking the scan
- Processing of 3D scan was fast, several seconds, also updating goes quickly
- Many many different designs, over 100
- Scan is made almost instantly
- Software is not so handy to use or optician just doesn't know how to use it
- Scan looks good, nice that they put the temple behind the ear
- Only changes up to 3 mm can be made
- Only 3D printed glasses available
- Calibration is horrendous, having to align a plate in 4 cameras in several positions
- It takes about 3 weeks to produce the glasses

Appendix B: Opticians in the Netherlands

In the previous chapter, an overview of potential use cases has been displayed, but from now on the main focus will be on the *fitting of glasses*-use case to make things more concrete and because it is relatively easy to get in contact with stakeholders since Maatbril is quite interested in this graduation project as well.

Looking at the Dutch optics market, it seems to be quite saturated already. Over the last five years the number of companies in this market has remained almost equal (-0.4%)[1] while the amount of physical stores (+0.9%) slightly increased[2]. The size of these physical shops is also slowly increasing with about 1m^2/year[3]. In 2022 there were 2293 physical optician stores in the Netherlands, of which about 46% was owned by independent opticians.

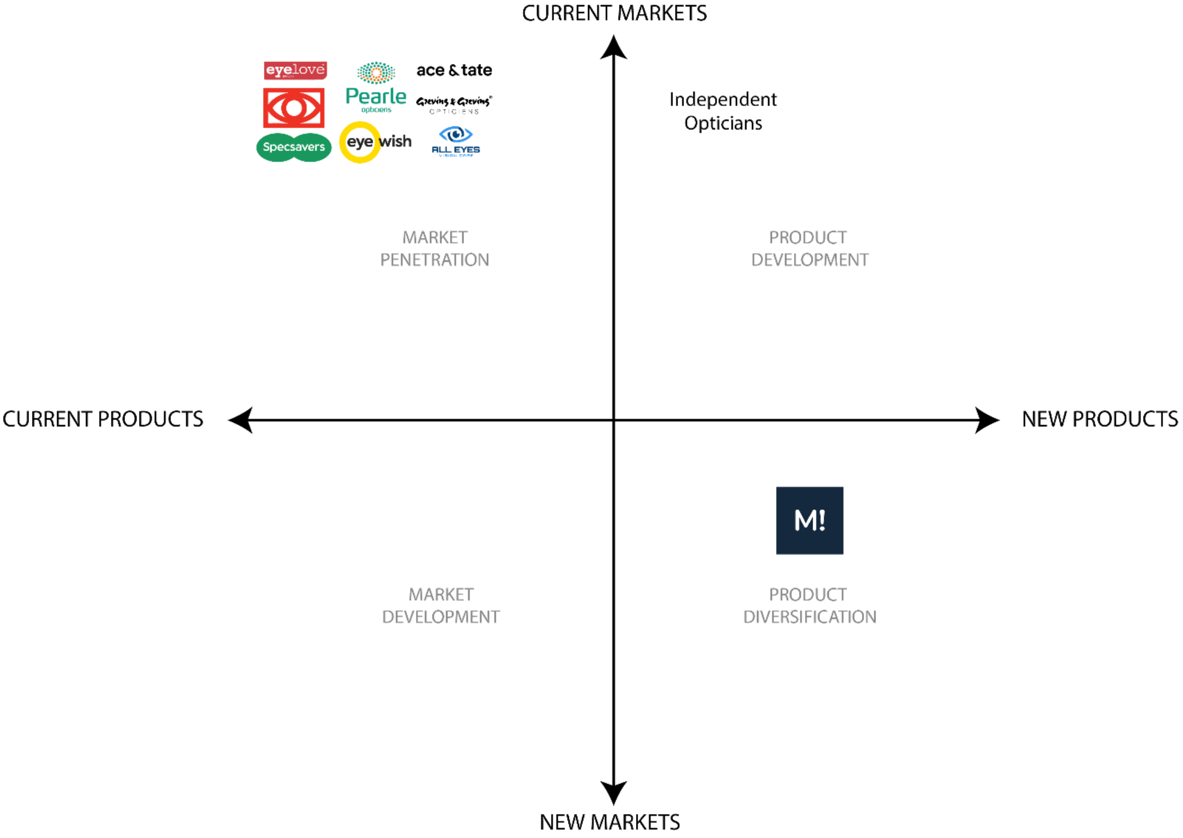

Figure 1: Overview of Dutch optics market

If we look at the current situation in the Netherlands, we can divide the market into four main segments. The market leaders such as Pearle, EyeWish, Hans Anders, Specsavers and Eyelove all have more than 100 locations throughout the Netherlands[4]. Secondly there are the smaller chains such as Ace and Tate, Greving&Greving, EyeCare and Oogwereld with up to 50 locations each. Both the market leaders and these shops focus on selling regular glasses to the mass for low prices, with limited to no options for personalization (Hans Anders employee, personal communication, September 28, 2022)(Pearle employee, personal communication, September 28, 2022)(Specsavers employee, personal

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[1] 2018: 1290 | 2019: 1305 | 2020: 1300 | 2021: 1305 | 2022: 1285

[2] 2018: 2277 | 2019: 2309 | 2020: 2296 | 2021: 2290 | 2022: 2293

[3] Retail Insiders. (2015). Optiekzaken. https://www.retailinsiders.nl/branches/persoonlijke-verzorging/optiekzaken/

[4] Pearle 340, EyeWish 142, Hans Anders 250, Specsavers 141, Eyelove 113

communication, September 28, 2022)(Unique optiek employee, personal communication, September 28, 2022).

Looking at the Ansoff Growth Matrix in figure 1, they can be classified as Market Penetrators. At the same time there are independent opticians, which make up for the third segment. In general, they sell the same products as the previous groups, but there is more room for personal care and attention. Next to that, some of those independent opticians are selling 3D printed -tailor-made- glasses as well, placing them somewhere between Market Penetration and Product Development. Lastly there are the specialty opticians such as Maatbril who focuses on a different target group, namely people with special pathologies, even though it’s quite a niche area. Since they are selling a new type of product -3D printed glasses- to a new market, they are doing so-called Product Diversification.

Appendix C: Glasses production process

Looking at the production processes for tailor-made glasses, the two main directions to look into are either additive manufacturing or subtractive manufacturing methods. In this chapter a brief look will be given into the possibilities and limitations of both methods.

Additive manufacturing

Most of the tailor-made glasses are being produced by means of Selective Laser Sintering, an additive manufacturing method where a laser solidifies and fuses plastic – often Nylon – powder particles. New powder will be added to the build plate after every layer. This makes that no support needs to be printed since the 3D print will always be supported by unfused powder.

The temples of the glasses will not always be 3D printed as well, often a 3D printed front is combined with carbon or titanium temples. Next to that, in unique cases, not the glasses, but rather a mould for glasses is 3D printed. In this mould, titanium frames can be bent to the correct shape[1], as can be seen in figure 2. However, the costs per model will increase quite a lot using this method.

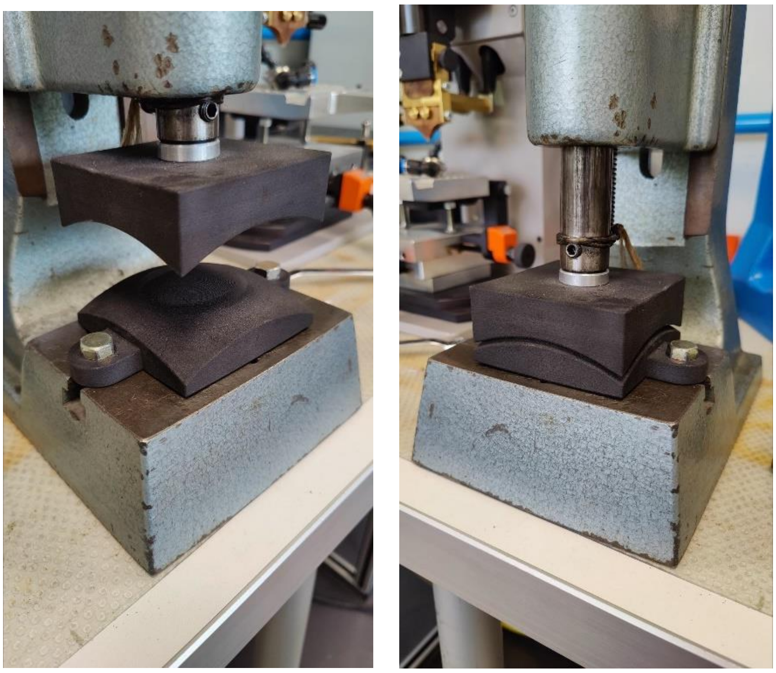

Figure 1: 3D printed moulds for bending of personalized titanium glasses

The benefit of 3D printed glasses are that they are lightweight, one of the downsides though is that only matte finishes are possible and translucent options are not possible. Although it takes a while to print the frames, up to 80 frames can be printed on the print bed (figure 2) of a regular-sized[2] SLS-printer in about 1.5 days. This is mainly because models can be stacked on each other since the complete print bed will be filled with powder. When a print is done, the glasses need to be removed from the build plate (figure 2) and cleaned a bit. Optional post-processing can be done to change the colour and/or finishing of the material. After the glasses are inserted and the temples are connected, the glasses are ready to be delivered to the client.

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[1] FormLabs. (2022). *How a Swiss Eyewear Manufacturer Uses SLS 3D Printing to Produce High-Quality Eyewear*. https://formlabs.com/blog/swiss-eyewear-manufacturer-uses-sls-3d-printing/

[2] Formlabs Fuse 1 SLS printer, print bed size is 165x165x300 mm

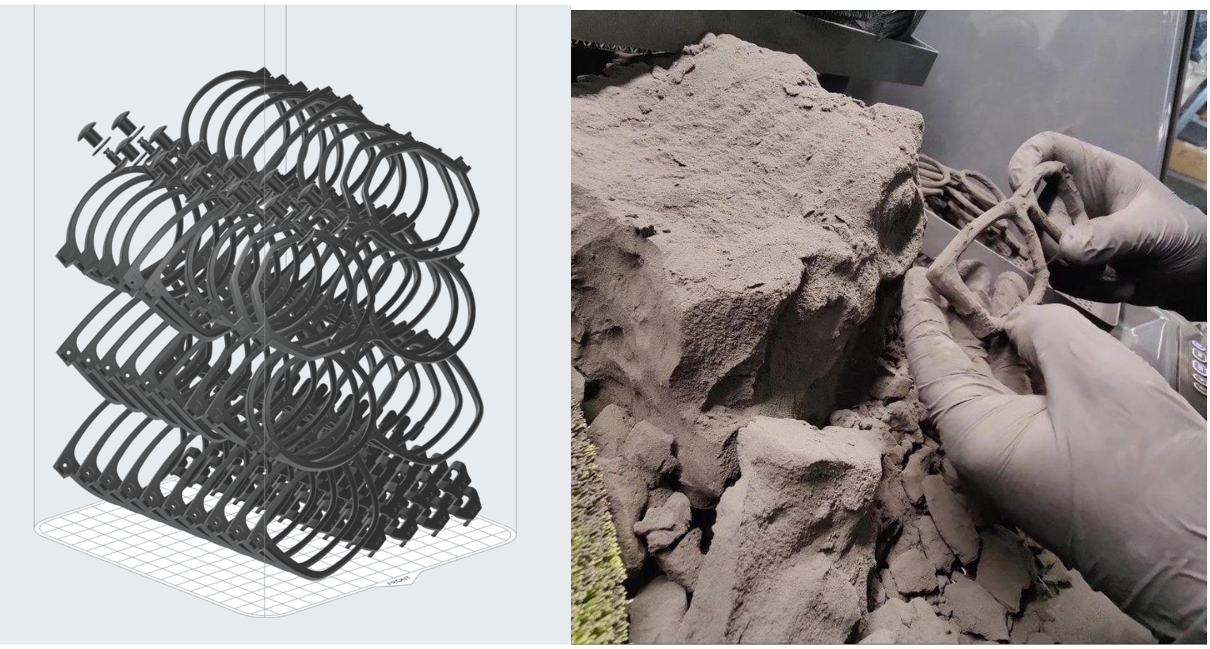

Figure 2: 3D printing process of glasses

Subtractive manufacturing

Subtractive manufacturing methods require significantly more steps to get to the final result than additive manufacturing. Whereas this manufacturing method is mainly used for mainstream models, for about one year it is now possible to also make tailor-made acetate glasses using this method (Colpa employee, personal communication, October 18, 2022).

Big acetate sheets are cut into small slabs before milling out the nose bridge. Extra material is then added to serve as the support geometry for the nose bridge. After cutting out the holes for the lenses, the exterior is milled out. The flat sheet is then heated and bended over a mould. Next, the metal hinges are placed in the frame. After polishing the frame to give it the shiny look it is known for, first the temples are connected and as a last step, the lenses are added to the glasses[3].

Figure 3: Milling process of acetate glasses

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[3] Dandan. (2017). *How Acetate Eyewear Frames Are Made*. https://www.youtube.com/watch?v=RgcC5hjUVmI&ab_channel=DANDAN

Acetate glasses are very popular because of the unique look that the speckles give, combined with the semi-translucent look. Another benefit is that because of the plasticizer[4] in the product, the temples can easily be adjusted to fit well behind the ears, whereas for SLS 3D printed glasses, this is a lot harder. At the same time, this plasticity also comes with a downside, over time the glasses are going to creep a bit, causing slight changes in the size of the glasses. Another downside is that over time, the material becomes more brittle since the plasticizer are slowly disappearing.

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[4] A substance that is added to a material to make it softer and more flexible, to increase its plasticity

Appendix D: Alternatives on the market

The wide variety of use cases for 3D scanning gives that there are many 3D scanners on the market, varying in quality, range and scanning speed. Looking at the 3D scanners that are currently being used by opticians, only four remain, including Yaman's prototype. All of these scanners have been tested during this Master's graduation project. In this chapter a brief overview of the characteristics and experiences will be given.

D.1 Occipital Structure Sensor Pro

This add-on module can easily be mounted to an iPad and is connected via lightning-cable. It uses the processor of the iPad to process the depth images[1]. Scanning can easily start by opening the app and tapping the 'Scan' button. The person taking the scan will need to walk around the client, to capture the required information. This solution is currently used by Maatbril who then uses the 3D scan as an underlay to design the glasses around the client's head.

Figure 1: Occipital 3D scanner for iPad

D.2 TrueDepth (by Apple)

From 2017 onwards iPhones implement TrueDepth cameras[2] and since 2020 the iPads also have them. This TrueDepth contains a dot-projector, IR light, and IR camera and works with structured light technology[3]. This TrueDepth technology forms the basis of the Sfered platform, which is used by eight independent opticians in the Netherlands[4]. An app will guide you through the whole scanning process, giving auditorial commands. After moving the head left and right, the scan is processed and uploaded, before applying an augmented model of which specific dimensions can be altered. Next to the general frame size, the frame width, frame height, pantoscopic angle[5], frame curvature[6], vertical frame position and frame thickness can be changed independently. Moreover, not only the width of the nose bridge can be adjusted, also the angle and depth of the geometry that rests on the nose can be adjusted (Colpa employee, personal communication, October 19, 2022). In total there are 10 designs that can be chosen from. They are mainly focused on people with regular head shapes that want 3D-printed glasses because they are light-weight, they fit perfectly, and/or because it's something new (Colpa employee, personal communication, October 19, 2022).

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

[2] A sensor array located at the front side of iPhones and iPads capable of seeing depth

[3] iCulture. (2021). *TrueDepth: complete uitleg over de 3D-camera op iPhone en iPad*. iCulture.nl. https://www.iculture.nl/uitleg/truedepth/

[4] Sfered. (2021). *Frame & I | Sfered*. https://sfered.nl/frameandi/

[5] The angle of the frame front relative to the temple

[6] The straightness of the glasses, how closely the frame will follow the curvature of the head

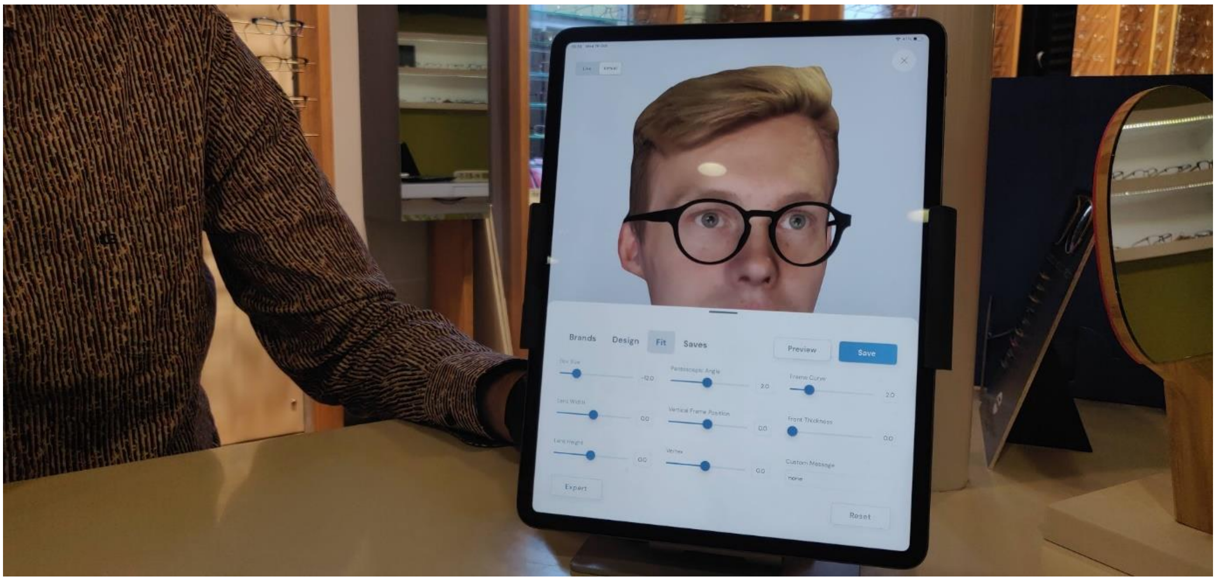

Figure 2: Testing out the Sfered-based 3D scanner

D.3 Hoya Yuniku

The other options used by several independent opticians is the Yuniku by Hoya. The glasses manufacturer focuses on perfect alignment of the lenses for the client's eyes and to do so, they developed the Yuniku, a 3D scanner that can be found at several independent opticians in the Netherlands. The height of the scanner can be adjusted by means of an electromotor and the user has to stand in front of the device to get the head fitted into the frame, see figure 3. The system uses two structured light scanners to capture the users data in an instant. A downside is the fact that it is hard to align the user in the right spot and that the system should be calibrated every other week, which is quite a complex process where the optician has to hold patterned plates in front of the scanner in several orientations. In total they offer over 100 different designs, however, only four parameters of the glasses can be slightly – changes up to 3 mm or 3 degrees – altered (Personal communication, October 28, 2022).

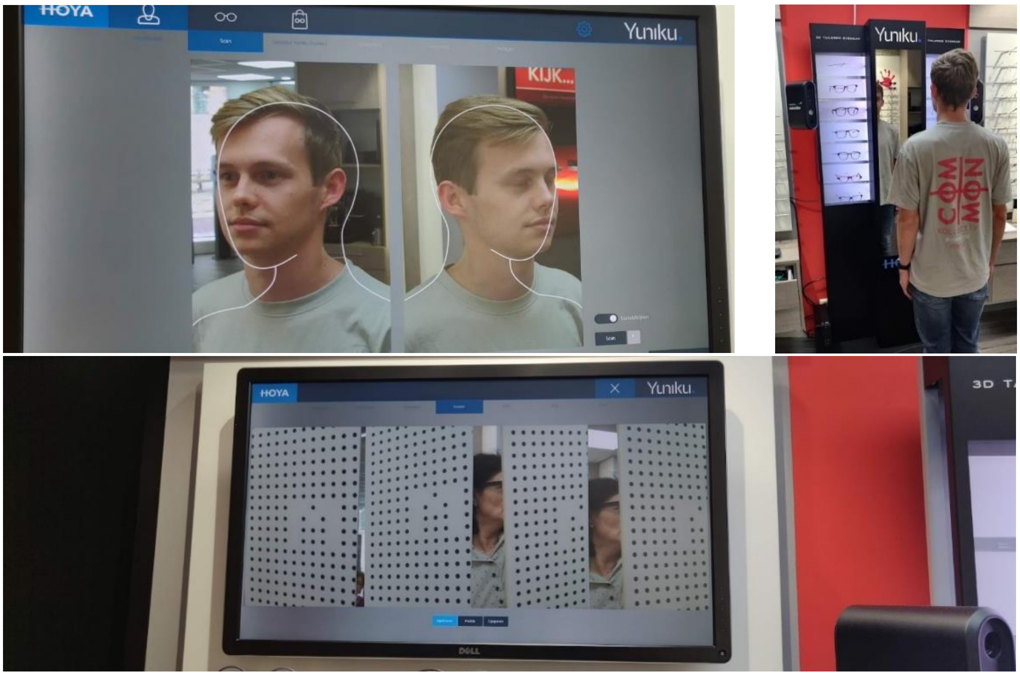

Figure 3: Testing out the Hoya Yuniku 3D scanner

D.4 3D Scanning behind the ear

However, for many people with craniofacial differences, not only specific dimensions would need to be changed, but rather the geometry as a whole. People with microtia for example usually have a hard time wearing glasses, because they often simply fall off because there is no external geometry that can be used to let the temples rest on. That is why Maatbril goes even one step further for their clients. They also make use of a template, but they adjust the geometry of the glasses themselves by modelling a unique geometry for every client. For some designs this means that the temples have an extra protrusion, as can be seen in figure 8. Another example is where hearing aids are integrated in the temples.

Figure 4: Custom-made glasses designed by Maatbril

It is hard however to accurately capture the geomtetry behind the ear(s). Romano found that even 3D scanning with a high quality 3D scanner such as the Artec Spider would not really suffice. Therefore, a model was prototyped that could be easily bent around the client's ear and would keep that shape so it could be scanned in afterwards[7].

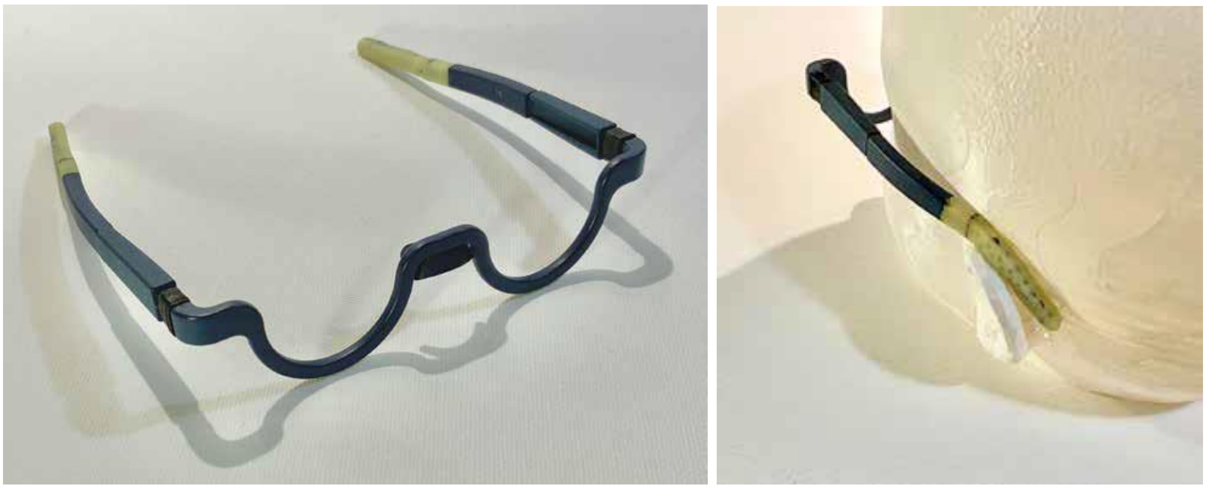

Figure 5: Special tool designed to measure the geometry behind the ears

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[7] Romano, C. (2022). *Design of adjustable measuring tool for posterior auricular area*. https://repository.tudelft.nl/islandora/object/uuid:b0ee985d-01a0-450c-b361-b77b1a9349a6?collection=education

D.5 Yaman’s prototype

Lastly there is the prototype that was made by Yaman Gupta for Maatbril[8]. This U-shaped 3D scanner contains three structured light sensors to instantly capture the frontal part of the face and both sides of the head at the same time. Unfortunately, several problems concerning usability and accuracy made the product not suitable to use for Maatbril (Jan Berend Zweerts, personal communication, October 13, 2022).

Figure 6: Gupta before 'entering' the 3D Head Scanner

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[8] Gupta, Y. (2021). *Design of a 3D Headscanner: Facilitating the design of ultra-personalized products for the differently-abled.* https://repository.tudelft.nl/islandora/object/uuid%3A295e10a0-22df-4a56-a4c4-351fac597fdd?collection=education

Appendix E: Target users

Looking at Maatbril's clients, there is not a very specific target group. The clients usually range from 8-month-old babies to elderly people, both male and female, with mental and/or physical disabilities. Whereas the majority of the disabilities is of craniofacial nature, also people with e.g. Down Syndrome and photophobia (Jan Berend Zweerts, personal communication, October 13, 2022). In this chapter, a short overview of the most common pathologies and their occurrence will be given.

Goldenhar Syndrome

Goldenhar Syndrome is a congenital defect[1] characterized by incomplete development of the ear, nose, soft palate, lip or mandible. Usually it occurs on just one side of the body. Next to these external issues, some patients can have growing issues with internal organs such as the heart, kidneys and lungs. Treatment usually consists of surgical intervention to help the child develop. The prevalence of Goldenhar Syndrome is about 1:3.200 to 1:5.600 with a male-female ratio of 3:2[2].

Treacher Collins Syndrome

Treacher Collins Syndrome (TCS) is a genetic disorder[3] characterized by deformities of the eyes, ears, cheekbone and chin. The most common characteristic is the underdeveloped lower jaw, while the external ear can be small, rotated, malformed or entirely absent[4] [5]. About 5% of people with also suffers from mental disabilities. Treacher Collins is not curable but symptoms may be managed with reconstructive surgery. Severity of Treacher Collins is measured in on a scale from 0 – meaning no deviation – to 3, which is the most severe option. M0 stands for a 'regular'-shaped mandible[6], while E2 stands for the absence of the external auditory canal. Treacher Collins Syndrome has a prevalence of about 1:50.000[7]. Moreover, there are quite a few syndromes that are very similar to Treacher Collins Syndrome, such as Nager syndrome (75 cases known worldwide), Miller syndrome (1:1.000.000) and Pierre Robin Sequence (1:8.000 – 1.14.000). For the latter, the child can already look 'normal' at the age of four again without any surgical interference[8] [9] [10].

---

[1] Abnormal condition that is present at birth regardless of its cause

[2] Gaurkar, S., Gupta, K., Parmar, K., & Shah, B. (2013). Goldenhar syndrome: A report of 3 cases. *Indian Journal of Dermatology*, *58*, 244. https://doi.org/10.4103/0019-5154.110876

[3] Mutation (a harmful change to a gene) that affects your genes or when you have the wrong amount of genetic material

[4] MedlinePlus. (2020). *Treacher Collins syndrome: MedlinePlus Genetics*. https://medlineplus.gov/genetics/condition/treacher-collins-syndrome/

[5] NORD. (2019). *Treacher Collins Syndrome - NORD (National Organization for Rare Disorders)*. NORD. https://rarediseases.org/rare-diseases/treacher-collins-syndrome/

[6] in a person or animal, the lower jaw bone

[7] GARD. (2021). *Treacher Collins syndrome - About the Disease - Genetic and Rare Diseases Information Center*. https://rarediseases.info.nih.gov/diseases/9124/treacher-collins-syndrome/

[8] MedlinePlus. (2013). *Isolated Pierre Robin sequence: MedlinePlus Genetics*. https://medlineplus.gov/genetics/condition/isolated-pierre-robin-sequence/#:~:text=Isolated%20Pierre%20Robin%20sequence%20affects,in%208%2C500%20to%2014%2C000%20people.

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

[10] NORD. (2018). *Nager Syndrome - NORD (National Organization for Rare Disorders)*. NORD. https://rarediseases.org/rare-diseases/nager-syndrome/

CHARGE syndrome

Charge Syndrome is a genetic disorder, where the name is an abbreviation of the characteristics: Coloboma[11], Heart defects, Atresia choanae[12], growth Retardation, Genital abnormalities and Ear abnormalities. However, not all of these characteristics will always be present, usually one or a few are present[13]. The prevalence of CHARGE syndrome is 1:8.500 to 1:10.000, however not all characteristics of CHARGE syndrome are relevant for this use case.

Saddle nose

Saddle nose is not a disorder or a disease itself, but it's a characteristic where the top part of the nose is sunken or barely present at all. The reason for the occurrence can trauma related, it can be caused by Septal Hematoma[14] or tumour or the use of cocaine for a longer period of time[15]. The exact prevalence is not known.

Apert syndrome

Apert syndrome is a genetic disorder, with a lot of similarities to Treacher Collins Syndrome. One of the major differences is that fingers and/or toes may be fused as well in Apert syndrome[16]. The prevalence of Apert syndrome is 1:65.000 to 1:88.000.

Down syndrome

Down syndrome is a genetic disorder caused by the presence of (part of) a third copy of chromosome 21. Some of the characteristics are physical growth delays, mild to moderate intellectual disabilities and characteristic facial features. The average IQ of a young adult with Down Syndrome is about 50, the equivalent of a 8 or 9-year-old child. The probability of getting a child with Down Syndrome increases with the age of the mother[17]. The prevalence of Down Syndrome is about 1:1.000, and from the

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[11] Ocular defects of the eyelids, iris, lens, retina or optic nerve

[12] Disorder where the back of the nasal passage (choana) is blocked, usually by abnormal soft tissue

[13] MedlinePlus. (2016). *CHARGE syndrome: MedlinePlus Genetics*. https://medlineplus.gov/genetics/condition/charge-syndrome/#causes

[14] when blood collects in the area of your nose between your nostrils

[15] NYC Mourad. (2022). *Saddle Nose Deformity*. Facial Plastic Surgeon. https://www.nycfacedoc.com/conditions/saddle-nose-deformity/#:~:text=What%20is%20a%20Saddle%20Nose,vault%20region)%20of%20the%20nose.

[16] Boston Children's Hospital. (2022). *Apert Syndrome | Boston Children's Hospital*. https://www.childrenshospital.org/conditions/apert-syndrome#:~:text=Apert%20syndrome%2C%20also%20known%20as,every%2065%2C000%20to%2088%2C000%20births.

[17] Patterson, D. (2009). Molecular genetic analysis of Down syndrome. *Human Genetics*, *126*, 195–214. https://doi.org/10.1007/s00439-009-0696-8

people with Down Syndrome, about 75% has a flat head, 70% has abnormal outer ears, 68% has a flattened nose[18] [19].

Photophobia

Photophobia is a symptom of a variety of diseases and disorders, causing an abnormal sensitivity of light, often leading to pain. 5 to 10 minutes of sunlight can already be painful for a person with photophobia[20]. It can be caused by anterior segment diseases[21], posterior segment diseases[22], dry eye syndrome intracranial conditions[23], migraine, Traumatic Brain Injury, Blepharospasms[24], and Agoraphobia. Not only is the luminance of the emitted light an issue, also brightness[25], flickering (of LEDs) and wavelength have an influence on the severity[26]. The prevalence of Photophobia is not known.

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[18] Hickey, F., Hickey, E., & Summar, K. L. (2012). Medical Update for Children With Down Syndrome for the Pediatrician and Family Practitioner. *Advances in Pediatrics*, *59*, 137–157. https://doi.org/10.1016/j.yapd.2012.04.006

[19] Weijerman, M. E., & de Winter, J. P. (2010). Clinical practice. *European Journal of Pediatrics*, *169*, 1445–1452. https://doi.org/10.1007/s00431-010-1253-0

[20] Wu, Y., & Hallett, M. (2017). Photophobia in neurologic disorders. *Translational Neurodegeneration*, *6*. https://doi.org/10.1186/s40035-017-0095-3

[21] Diseases in the front part of the eye (Iris, eyelid)

[22] Diseases in the back part of the eye (retina, cones)

[23] Conditions within the skull

[24] Spasms of the eyelid

[25] Luminance is the intensity of the emitted light, while brightness is the intensity of the perceived light

[26] Digre, K. B., & Brennan, K. C. (2012). Shedding Light on Photophobia. *Journal of Neuro-Ophthalmology*, *32*, 68–81. https://doi.org/10.1097/wno.0b013e3182474548

Appendix F: 3D imaging techniques and experiments

F.1 3D Imaging techniques

To get a better understanding of the technological possibilities an overview of current 3D imaging techniques has been made, where characteristics, advantages and disadvantages are being discussed. Only non-contact techniques are being evaluated as contact-based digitizing techniques are too invasive and therefore not desired from a usability standpoint.

Computerized Tomography

Computerized Tomography is also known as CT or CAT scan. In a CT scan, a special x-ray device moves around the patient. The technique is mainly focused on getting a clear 3D image of the internals of a patient. Sometimes the patient is asked to swallow a specific contrast material to achieve a clearer image[1]. Within computerized tomography there are various variants, ranging from Cone Beam Computerized Tomography scanners – designed to take scans of the head – to Micro Computer Tomography scanners, that are being used in product scanning mostly. Although a high accuracy 3D scan can be achieved, the price of such a scanner is can easily be around one hundred thousand euros. Another downside is that the patient is being exposed to radiation, which is one of the reasons that this imaging technique will not be considered further.

Magnetic Resonance Imaging

The process of Magnetic Resonance Imaging, or MRI, is imaging the water in tissue. A big improvement over CT scans, is that there is that it is a radiation-free process. Moreover, contrast material is not needed to get a clear image. MRI too is mainly used to get a clear image of organs, tissue or the skeletal system[2]. The downsides of this technique are again that the scanner is expensive and that it takes about 15-90 minutes to capture a scan, in which the patient cannot move, which makes this this imaging technique not feasible for the scanner that is being designed in this Master's graduation project. For some of the clients, not moving for a mere ten seconds already is a problem.

3D laser scanning

Within 3D laser scanning, the characteristics of light are used to determine the distance to an object. *Time of flight (ToF) laser scanners* look at the time it takes until the light pulse is being reflected and based on that measured time, the distance can be calculated. (figure 1)

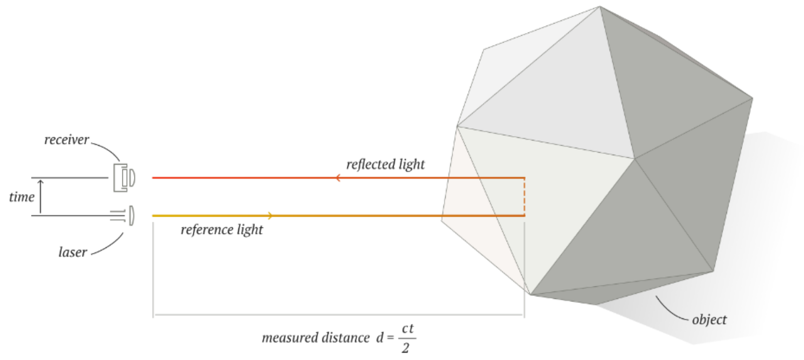

Figure 1: Working principle of Time of Flight 3D laser-scanning

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

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

This technique is mainly used to scan large objects such as airplanes and buildings. The exact characteristics can be found in table 1. Moreover, there are possibilities to caption RGB data as well, either through an internal camera or an external camera set[3]. The same applies to *Phase shift laser scanners*, a type of 3D scanner that is known for its fast scanning, up to a million points per second. By emitting laser light at alternating frequencies, the difference in phase between the emitted and reflected signal tells something about the distance to the object. (figure 2)

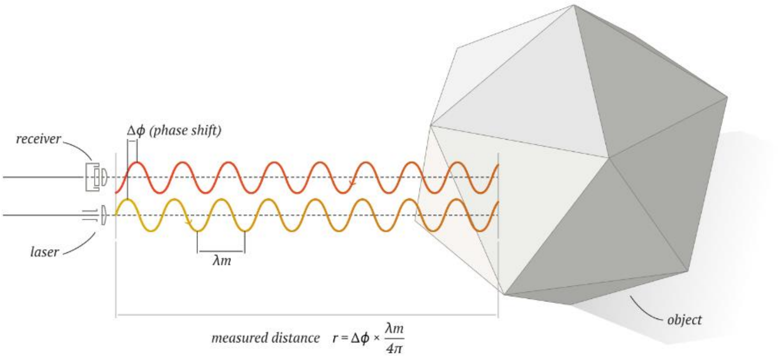

Figure 2: Working principle of phase shift 3D laser-scanning

This technique is more accurate than the ToF-scanners. Lastly, there are *Triangulation laser scanners.* They work on at much smaller distances than the two previous techniques due to the decreased accuracy with range. This is because it uses the principle of triangulation, where the emitted laser pulses are return on a specific location on an image sensor. The distance between the object and the 3D scanner is calculated using trigonometry. (figure 3).

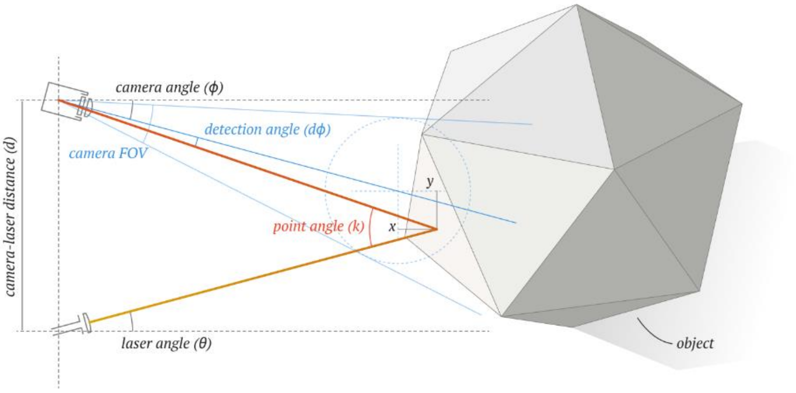

Figure 3: Working principle of triangulation-based 3D laser-scanning

A downside of the laser-based scanners is that they emit laser beams that could potentially be dangerous for the eyes. A benefit of these so-called active 3D imaging techniques[4] is that they are not dependent on ambient lighting, and therefore they will also work in dark(er) environments.

Structured light scanning

Another active 3D imaging technique is structured light scanning. A camera projects modulated light patterns on the surface and calculates the disparity between the observed pattern and projected pattern. Structured light scanners are usually used indoors, since

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

[4] 3D imaging technique that emits some kind of light or radiation and detects its reflections.

sunlight can interfere with the projected patterns[5]. The technology works with both visible and invisible light[6]. Structured light scanners are useful in cases where high accuracies and short ranges are required.

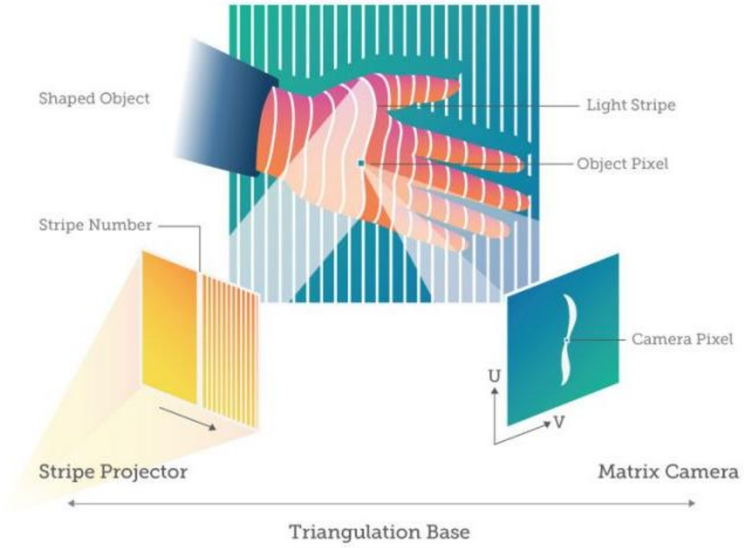

Figure 4: Working principle of structured light 3D scanning

If possible, visible structured light scanners should be avoided because of the experience for the user. During this Master's graduation project I got my head scanned with an Artec Eva scanner, which is a visible structured light scanner and it was quite intense to get those light patterns projected on your face, even with your eyes closed. For kids and people with special pathologies, this could be even worse. Next to that, preferably the client should keep its eyes open during the scanning process, so that later on, the pupils will be visible in the 3D texture mesh. This helps in aligning the lenses of the glasses[7].

Photogrammetry

The most well-known passive imaging technique[8] is photogrammetry, where imagery from a single camera or from a camera array is combined into a 3D model. When taking multiple images from the same object from different positions, the 3D model can be reconstructed[9]. When the 3D orientation of the cameras is not automatically determined, manual interaction may be required. A big benefit though is that the equipment that can be used is relatively cheap (regular cameras), but they are dependent on the ambient lighting conditions and require intense software processing[10]. If light conditions turn out to be generally sufficient or if they can easily be improved, photogrammetry can be a valid option.

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

[6] The visible light spectrum is defined as light with a wavelength between 380 and 625 nm. Invisible light is either above (infrared) or below (ultraviolet) this range

[7] Gupta, Y. (2021). *Design of a 3D Headscanner: Facilitating the design of ultra-personalized products for the differently-abled.* https://repository.tudelft.nl/islandora/object/uuid%3A295e10a0-22df-4a56-a4c4-351fac597fdd?collection=education

[8] 3D imaging technique that recovers information from scenes that are only illuminated with ambient lighting.

[9] Mikeroyal. (2022). *GitHub - mikeroyal/Photogrammetry-Guide: Photogrammetry Guide. Learn all about the process of obtaining measurements and 3D models from photos. Creating topographic maps, meshes, or point clouds based on the real-world.* https://github.com/mikeroyal/Photogrammetry-Guide

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

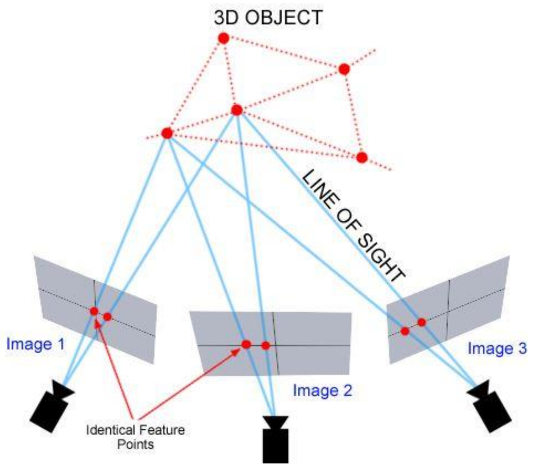

Figure 5: Working principle of photogrammetry

Scanning technique	*Time of flight*	*Phase shift*	*Triangulation*	*Structured light*	*Photogrammetry*
Typical working distance	*<300 m*	*2-80 m*	*0.5-2 m*	*0.2-2 m*	*1-300 m*
Typical accuracy	*<1 %*[11]	*1 mm*	*1 mm*	*<1 mm*	*2 mm*
Resolution	*Low*	*Low*	*Low*	*High*	*Medium*
Use environment	*Indoor, outdoor*	*Indoor, outdoor*	*Indoor, outdoor*	*Indoor*	*Depending on ambient lighting*
Hardware cost	*Medium*	*Medium*	*Medium*	*High*	*Low*
Software processing requirements	*Low*	*Low*	*Low*	*Medium*	*High*
Applications	*Autonomous vehicles, VR*	*LIDAR, Robot navigation*	*Robot navigation, road profiling*	*Face recognition*	*Aerial scanning*

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

Looking at the techniques mentioned above, structured light 3D imaging seems to show most potential: It is a high accuracy, high resolution solution that works for relatively close distances. The only downside is the relatively high costs of the hardware.

3D Facial Morphometry

Instead of making a 3D scan of the client's head, a 3D model can also be made using the process of reconstruction, this forms the basis of 3D facial morphometry[12]. In 3D facial morphometry, tracking points – so-called facial landmarks – are placed at a range of tracking points as can be seen in figure 6. With these points (Figure 7: green), a template 3D model of the human head can be adjusted according to the measured dimensions (Figure 7: blue).

---

[11] Accuracy is calculated by taking a percentage of the working distance

[12] Any measurable or observable characteristic related to the shape, structure, color or pattern of the region of the body that includes the front part of the head from the chin to the top of the forehead, where the mouth, eyes, nose, and other features are located.

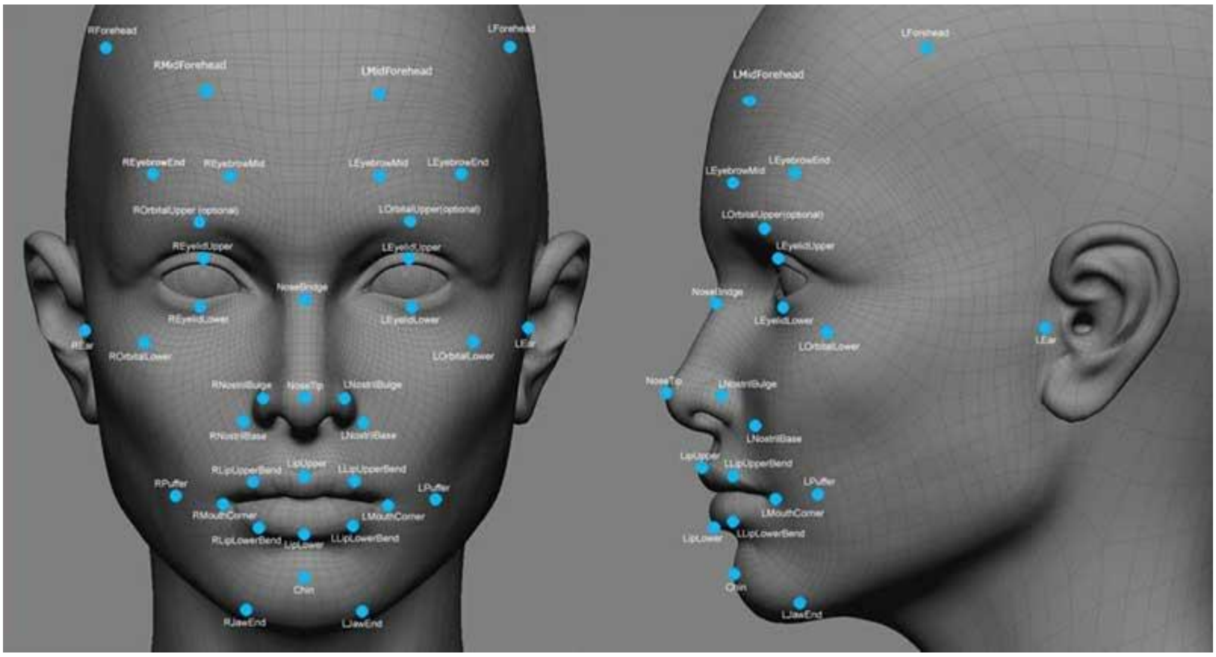

Figure 6: Overview of important facial landmarks within facial morphometry

Figure 7: Overview of capabilities with 3D facial morphometry

Researchers from the University of North Carolina have shown that it is relatively easy to recreate textured facial 3D models from just a few social media images. These 3D models were good enough to fool facial recognition software in up to 85% of the time, even though the photos were often low in resolution or only revealed part of the face[13]. When using photos with a higher resolution, more facial landmarks can be placed, improving the accuracy of the 3D model[14]. This method is also used in hospitals to check babies for syndromes[15].

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[13] Newman, L. H. (2016). *Hackers Trick Facial-Recognition Logins With Photos From Facebook (What Else?)*. WIRED. https://www.wired.com/2016/08/hackers-trick-facial-recognition-logins-photos-facebook-thanks-zuck/

[14] Datagen. (2022). *Facial Landmarks and Face Reconstruction: An Intro*. https://datagen.tech/blog/facial-landmarks-and-face-reconstruction-intro/

[15] National Centre for Biotechnology Information. (2007). The use of 3D face shape modelling in dysmorphology. *Archives of Disease in Childhood*, *92*, 1120–1126. https://doi.org/10.1136/adc.2006.103507

Currently, there are many developments in this field[16], and although the exact methodology differs, most of them implement deep neural networks[17]. Koizumi et al. managed to get to an accuracy of 1.5 mm without using facial landmarks, Grassal et al. came up with a model that converts a short video to an animatable 3D model with an accuracy of 1.2 mm, while Zielonka et al. were the first to get a sub-millimetre accuracy of 0.9 mm with just a single input image[18] [19] [20]. A more complete overview can be found on PapersWithCode website[21].

The question remains though to what extent this technique also works for people with craniofacial differences and/or strong asymmetrical head shapes. This is something that has to be tested with photos from the target group as input.

Photogrammetry using Neural networks

One of the bigger downsides of photogrammetry is the large processing times, from a couple of minutes up to several hours for large and complex scans. The use of neural networks could drastically decrease this processing time, as NVIDIA shows with their Instant NeRF-model. After inputting a few high-resolution photo's, it will nearly instantly recreate a 3D scene[22].

Moreover, Matuzevicius et al. have shown that Neural networks can also be used in photogrammetry to optimize the process and limit the number of interactions that the user has to have with the scanner. In their proposal, a video stream was used as input and split into separate frames. A neural network would then detect if a head would be present in the picture, and select the most suitable frames, also based on image quality. Next to that, it performs initial feature point selection, to mask the user's head and remove the background[23]. A result of this setup has been displayed in figure 8.

---

[16] A list of publications since 2020 with their achieved accuracy:
2020 | UMDFA | 1.52 mm
2020 | MGCNET | 1.31 mm
2020 | 3DFFA_V2 | 1.23 mm
2020 | DECA | 1.09 mm
2021 | SynergyNet | 1.27 mm
2021 | Dib et al. | 1.27 mm
2021 | Pixie | 1.18 mm
2021 | Focus | 1.09 mm
2022 | MICA | 0.90 mm

[17] A neural network with a certain level of complexity (more than two layers). Deep neural networks use sophisticated mathematical modeling to process data in complex ways.

[18] Grassal, P.-W., Prinzler, M., Leistner, T., Rother, C., Nießner, M., & Thies, J. (2022). *Neural Head Avatars from Monocular RGB Videos Monocular RGB Video Neural Head Avatar with Articulated Geometry & Photorealistic Texture*. https://arxiv.org/pdf/2112.01554.pdf

[19] Koisumi, T., & Smith, W. A. P. (2020). *"Look Ma, no landmarks!" – Unsupervised, model-based dense face alignment*. https://www.ecva.net/papers/eccv_2020/papers_ECCV/papers/123470681.pdf

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

[21] PapersWithCode. (2022). *Papers with Code - NoW Benchmark Benchmark (3D Face Reconstruction)*. https://paperswithcode.com/sota/3d-face-reconstruction-on-now-benchmark-1

[22] Stephens, J. (2022). *Getting Started with NVIDIA Instant NeRFs | NVIDIA Technical Blog*. https://developer.nvidia.com/blog/getting-started-with-nvidia-instant-nerfs/

[23] Matuzevičius, D., & Serackis, A. (2021). Three-Dimensional Human Head Reconstruction Using Smartphone-Based Close-Range Video Photogrammetry. *Applied Sciences*, *12*, 229. https://doi.org/10.3390/app12010229

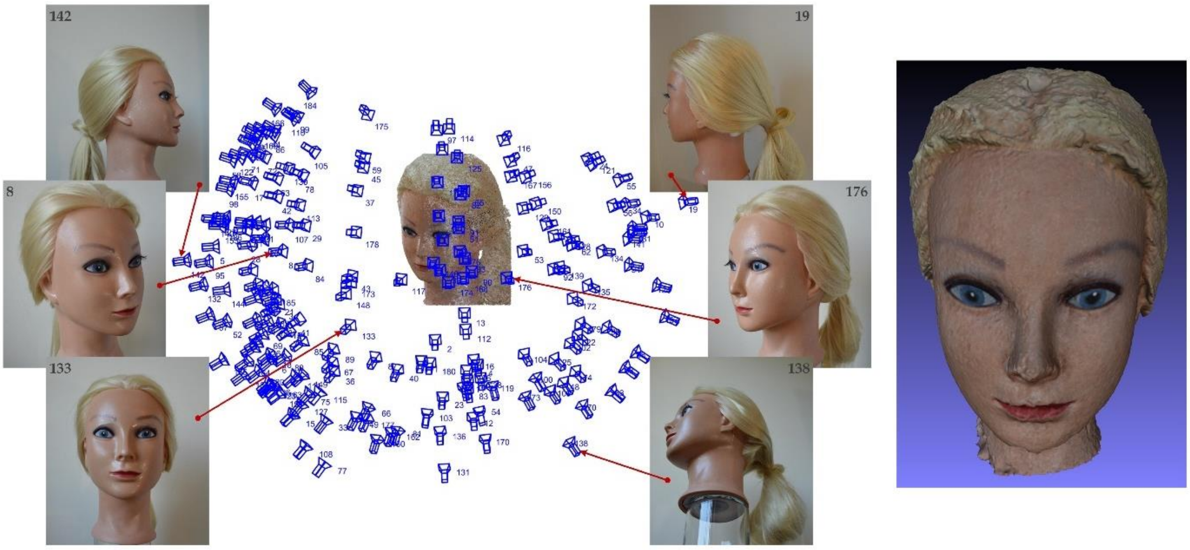

Figure 8: Results of video stream as input for photogrammetry by Matuzevicius and Serackis

F.2. Experiments

NVIDIA's Instant-neRF

NVIDIA's Instant-neRF software is capable of generating a 3D model of an object or scene in a matter of seconds, based on a few images or short video as input. Although the results look quite promising visually, it is not known to what extent the results are also useful when exporting the data as 3D models.

Therefore, it was attempted to install the software and test it on an object of which the geometry was known. To do so, the object would be 3D scanned with a high accuracy 3D scanner – e.g. Artec Eva, accuracy of 0.2 mm – before it would be photographed and inputted in Instant-neRF. The results of both resulting geometries would be overlaid and the differences in geometry could be evaluated.

Installation of this software on a Windows-based device lead to many errors and while resolving these errors, results of other people were found. Next to many other people that faced difficulties installing the software, the people that were able to get the software running were not impressed with the quality of the output, especially looking at the time that it took. Even with a ~€500 GPU, the results after 10 minutes of 'rendering' were very low resolution, as can be seen in image 9[24]. Looking at the quality and cost, this technology is not (yet) useful to implement in the 3D scanner. The results that NVIDIA posted on their own website were rendered with a €1000 GPU[25].

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[24] NVlabs. (2022). *CMake error • Discussion #233 • NVlabs/instant-ngp*. https://github.com/NVlabs/instant-ngp/discussions/233

[25] PassMarkSoftware. (2017). *GeForce GTX 1080 Ti vs Quadro P1000 vs GeForce RTX 3090 [videocardbenchmark.net] by PassMark Software*. https://www.videocardbenchmark.net/compare/3699vs3727vs4284/GeForce-GTX-1080-Ti-vs-Quadro-P1000-vs-GeForce-RTX-3090

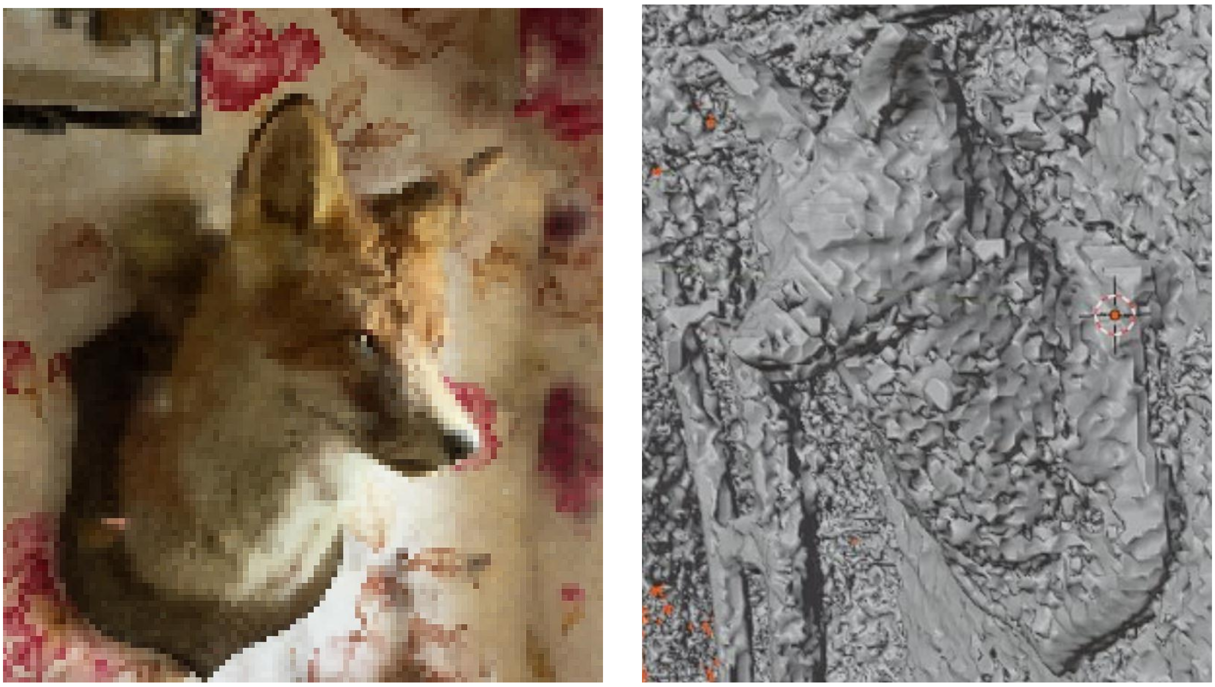


Figure 9: Object (Left) and reconstruction of object with Instant NeRF after 10 minutes (Right)

Facebuilder for Blender

Another software package that was tested was the Facebuilder for Blender. This package reconstructed the shape of the head based on a couple of photos from different sides that needed to be imported. The user then had to drag specific points to their corresponding location on the photo. Based on these location on the photos, a 3D model of the head was reconstructed. However, not only was the procedure quite time-consuming, the result was also not as good as needed. Although a built-in AI can help with aligning the points, to get the best results, all points should be precisely aligned by the user. After about 20 minutes, the points had been aligned for 3 photos, leading to the result depicted in figure 10.

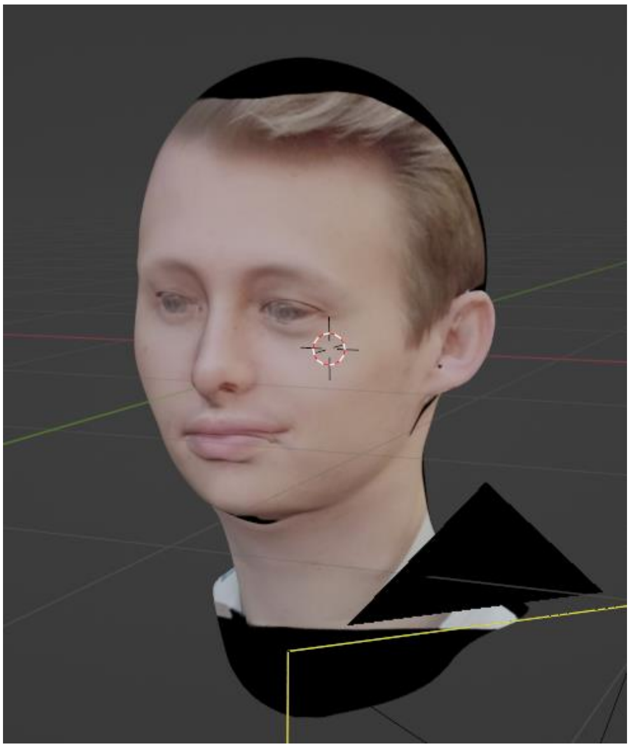


Figure 10: Facebuilder's reconstruction based on 3 three photos

Machine Learning solutions

Another path that was explored quite intensely was that of Machine Learning solutions to reconstruct 3D models of the head. Especially the MICA-model showed great potential with a median reconstruction error of just 0.9 mm. A Metrical 3D model of the head would be generated from a single RGB-image. In figure 11, two examples of the results are shown. The idea of avoiding expensive 3D sensors could save a lot of cost. However, installing these software packages and getting them to work was quite a challenge. On 3 different devices, both Windows and Linux-based, it was tried to get the code to work, however none of the attempts were successful. Moreover it is questionable to what extent the algorithm will be able to generate realistic asymmetrical faces, since the model is most-likely trained on people with regular head shapes.

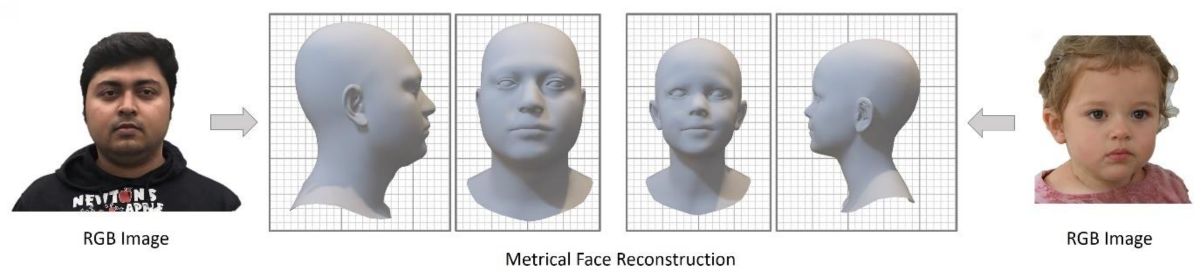
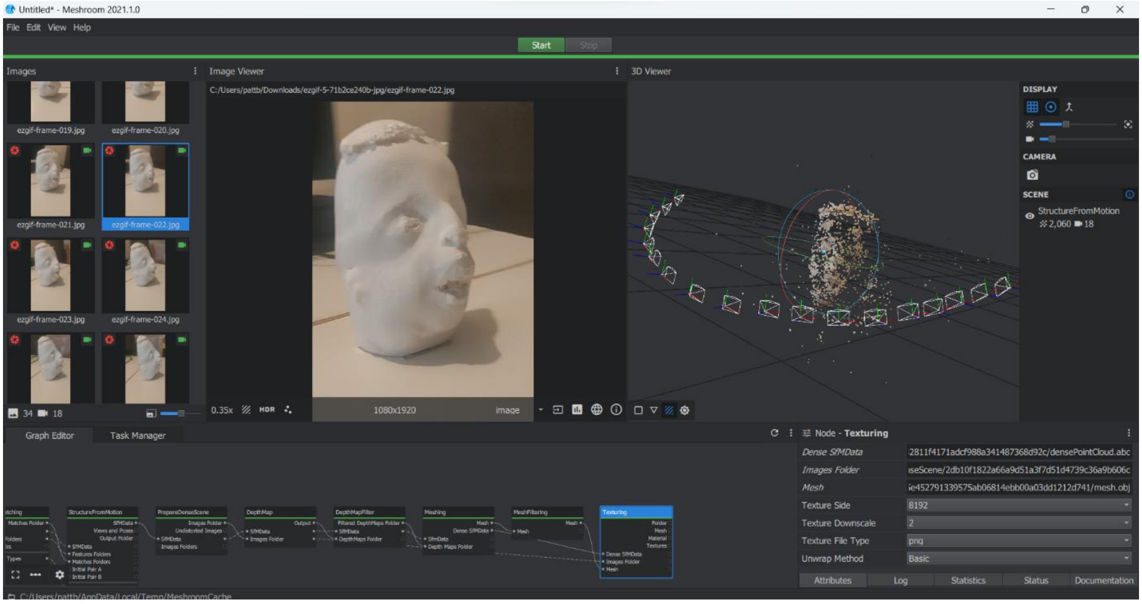


Figure 11: Example of 3D Head reconstruction by MICA-model

Photogrammetry

Similar to the Machine Learning solutions mentioned above, Photogrammetry doesn't require the use of expensive 3D sensors. A simple RGB camera can be used to capture the data, however, compared to the previous method, photogrammetry requires a lot of input data, from as many angles as possible.

Instead of placing many small camera's, experiments have been executed using video data as input. With a framerate of 30 FPS, a lot of data can be captured in a short amount of time. The only problem that occurred however, was the fact that because of the movement of the user, the amount of motion blur was too high sometimes which would lead to a decreased accuracy of the 3D model. When implementing algorithms to select the best frames, the majority of the frames available were neglected.



C:/Users/pattb/Downloads/ezgif-5-71b2ce240b-jpg/ezgif-frame-022.jpg

Node - **Texturing**

Dense SfMData	2811f4171adcf988a341487368d92c/densePointCloud.abc
Images Folder	seScene/2db10f1822a66a9d51a3f7d51d4739c36a9b606c
Mesh	e452791339575ab06814ebb00a03dd1212d741/mesh.obj
Texture Side	8192
Texture Downscale	2
Texture File Type	png
Unwrap Method	Basic

C:/Users/pattb/AppData/Local/Temp/MeshroomCache

Figure 12: Photogrammetry test with 3D printed headshape

The major downside of photogrammetry is the time it takes to combine data from the photos and generate a 3D model. With only 20 frames inputted, the waiting time before seeing the first results could be up to 30 minutes, which makes it very impractical to use for this scenario. Next to that, the cost of this software is quite high, as well as the requirements for software processing. In practice this would mean that the total cost of the 3D Head Scanner would not be lower than using the more expensive 3D sensors, which give immediate results.

Appendix G: Influential factors on 3D scan quality

Appendix F showed that Laser-based scanning techniques (triangulation, phase-shift modulation and Time-of-Flight), structured-light imaging and photogrammetry show enough potential to be researched further. In this chapter the influence of environmental factors on the quality of the scans and how the accuracy of the scans can be improved is explained.

G.1 Laser-based 3D scanning techniques

The most important factors influencing the quality of the 3D scan with laser-based scanning technologies are the laser intensity[1]; ambient light strength, diffuseness and directness; topology of the object to be acquired; 3D scanner position and orientation; and the characteristics of the object material such as colour, glossiness and roughness.

Gerbino et. al concluded that no statistically significant relation can be found between the accuracy of the scan and the directness and diffuseness of the lighting. However Lemes found that the directness of the light can have an influence, depending on the colour of the object[2]. For black and blue objects the strength of directly emitted light only has a weak influence on the quality of the scan, while for red, green, yellow and white objects, this had a large influence on the quality of the scan. The reflected ambient light reduced the number of usable points in this case. The higher the intensity of the light that was emitted, the stronger the effect. A light-grey material gave the best results.
Looking more specifically at 3D scanning of the human skin, Shcherbina et al. found that colour heterogeneities such as birthmarks and a high reflection coefficient of the skin lead to artifacts. Especially children and younger people will have high reflection coefficients, as it decreases with age[3]. Moreover, an excess of soft tissue or scarring may lead to the appearance of artifacts in the scan[4].

Looking at the scanner itself, next to the intensity of the emitted laser beam, also the angular position of the scanner related to the object has a great (significant) effect on the measurement accuracy, with the scanner being perpendicular to the surface gave the best results[5].

Another method how accuracy can be improved is by acquiring the data from a closer position. For large(r) objects this could mean that more scans have to be taken. This could potentially introduce errors during the registration phase[6].

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[1] Power per unit area delivered by the incident laser beam in W/m^2

[2] Lemeš, S., & Zaimović-Uzunović, N. (2009). *Study Of Ambient Light Influence On Laser 3D Scanning*. unknown. https://www.researchgate.net/publication/229149616_Study_Of_Ambient_Light_Influence_On_Laser_3D_Scanning

[3] Matsubara, A. (2011). Differences in the surface and subsurface reflection characteristics of facial skin by age group. *Skin Research and Technology*, *18*, 29–35. https://doi.org/10.1111/j.1600-0846.2011.00537.x

[4] Shcherbina, K., Golovin, M., Suslyaev, V. G., & Zolotukhina, M. v. (2020). *An Electronic Geometric Model for 3D Scanning of Human Body Segments and Its Use in Prosthetics and…* Springer Verlag. https://www.researchgate.net/publication/342939755_An_Electronic_Geometric_Model_for_3D_Scanning_of_Human_Body_Segments_and_Its_Use_in_Prosthetics_and_Orthotics_Causes_of_Defects_and_Methods_for_Their_Elimination

[5] Gerbino, S., del Giudice, D. M., Staiano, G., Lanzotti, A., & Martorelli, M. (2015). On the influence of scanning factors on the laser scanner-based 3D inspection process. *The International Journal of Advanced Manufacturing Technology*, *84*, 1787–1799. https://doi.org/10.1007/s00170-015-7830-7

[6] Process of transforming different sets of data into one coordinate system

G.2 Structured light 3D scanning

For structured light 3D scanning, potential factors influencing accuracy can be wrongly/not calibrated system, resolution of the camera and projector, triangulation angle of the system, type and colour of projected data, ambient lighting conditions and object colour and texture.

As for most optical systems, calibration is required for example to limit radial distortion[7]. This can usually be easily done with the help of a calibration artifact that contains 2D patterns of which the design is known. With these patterns, the calibration parameters can be calculated.

Since structured light scanners often use triangulation to measure the distance to the object, the angle and distance between the camera and projector are of importance[8]. When the angle would be equal to ~0°, large errors will occur due to the uncertainty in calculating the depth. At the other hand, when the angle is ~90° the camera may not capture the emitted pattern, especially when measuring holes[9]. Typically, an angle of ~30° is used in these systems.

Various single- or multi colour patterns can be projected on an object, all having their benefits and limitations. Figure 1 gives an overview of the different possibilities. Interestingly, many newly introduced scanners make use of blue light, with manufacturers claiming that it reduces interference with ambient lighting due to the short wavelength of blue light[10]. Experiments seem to confirm that blue light scanners indeed outperform white light scanners for scanning biological tissue and teeth[11] [12].

---

[7] Distortion where straight lines are bended as general curves and points are moved in the radial direction from their correct position.

[8] The distance to the object is calculated with the following formula: $d = b\ (\ \sin(\alpha)\ \sin(\alpha + \beta)\ )$

[9] Rachakonda, P. K., Muralikrishnan, B., & Sawyer, D. S. (2019). *Sources of Errors in Structured Light 3D Scanners*. https://www.nist.gov/publications/sources-errors-structured-light-3d-scanners

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

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

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

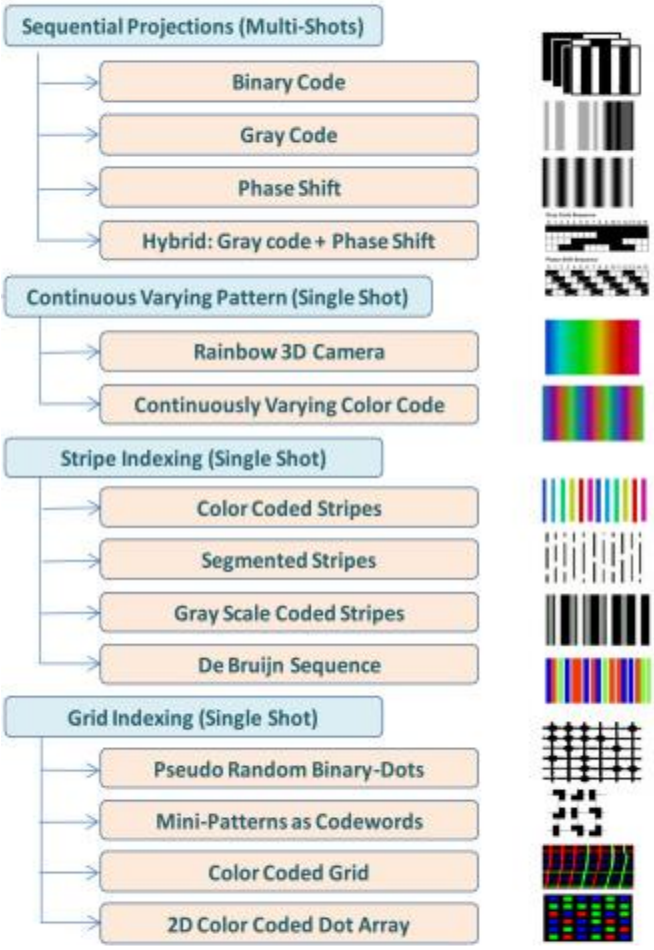

Figure 1: Types of structured light 3D scanning patterns

Voisin et al. showed that there are significant differences in accuracy under various illumination conditions[13]. Moreover, the differences between light and dark skin coloured patches accuracy are hugely in favour of light skin, under some conditions even being twice as accurate[14]. Light skin patches showed least deviation under night circumstances while dark skin patches gave best accuracy under daylight circumstances.
A common technique to increase accuracy for shiny surfaces and/or white surfaces is to add a thin layer of spray powder to the surface of what is going to be scanned. There is choice between temporary or (semi-)permanent sprays that are easy to apply and result in an even surface[15]. From a usability perspective it is however not preferred to apply a spray to the client's face.

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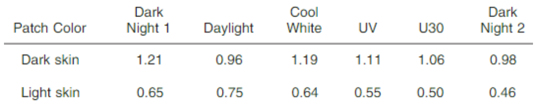
[13] Francois, L. (2019). *When and why should I use spray powder for 3D scanning?* https://peel-3d.com/blog/when-and-why-should-i-use-spray-powder-for-3d-scanning/

[14] 

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

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

G.3 Photogrammetry

Several factors affect the quality of meshes generated by photogrammetry. Since photogrammetry does not emit light but rather uses ambient lighting, these environmental conditions are even more important.
Research showed that the addition of an additional light source can significantly improve accuracy of photogrammetry. Moreover, the colour temperature is also a factor to take into account, with cold light slightly outperforming neutral and warmer colours. Only projecting either red, green or blue light on the product led to improved accuracy compared to having no additional lighting, however, the improvements were not as big as when a wider range of the spectrum was used[16].

Next to the environmental conditions, the resolution of the digital camera(s) plays a big role in the quality of the scan, since it limits the number of points that can be captured in one scan. In photogrammetry it is measured by the Ground Sampling Distance or GSD[17] and it depends on the distance to the object, the focal length of the lens and the width of the sensor.

At the same time does the number of photographs that is available strongly influence the quality of the mesh[18]. Both for the point angles[19] and photo redundancy[20] are influenced by the number of photos taken. For point angle applies that an angle close to 90 degrees is preferred. In terms of photo redundancy, the higher the amount of photos, the better[21].

Calibration of the camera in the software that will be used to convert the imagery to a 3D model can increase the accuracy a lot. Things that the software will adjust for are the focal length of the lens, principal point of the camera and the digitizing scale of the camera. Usually some type of special grid needs to be printed and photographed from different positions and angles, an example of this can be found in figure 2.

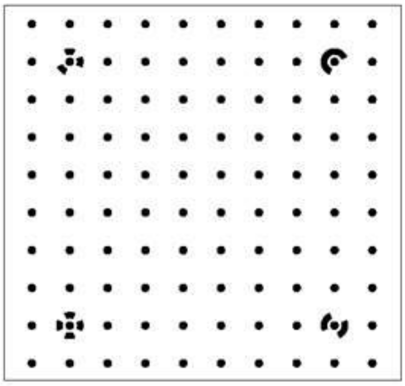


Figure 2: Calibration plate

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[16] Bobkowska, K., Burdziakowski, P., Szulwic, J., & Zielinska-Dabkowska, K. M. (2021). Seven Different Lighting Conditions in Photogrammetric Studies of a 3D Urban Mock-Up. *Energies*, *14*(23), 8002. https://doi.org/10.3390/en14238002

[17] Ground sampling distance of 5 cm = 1 pixel is 5 cm

[18] Galantucci, L., & Percoco, G. (2006). *Accuracy Issues of Digital Photogrammetry for 3D Digitization of Industrial Products*. unknown.

[19] Maximum angle of the light rays that image a point. If a point appears on 3 photos that are all taken 15 degrees apart, the maximum angle for that point is 45 degrees. Point angle is especially important when a point is only present on 2 photo's that are low in angle.

[20] The position of a point is more accurately calculated when it is visible in many photos. For a given marking precision, more images 'average' the error, leading to a higher quality outoput.

[21] PhotoModeler. (2022). *Single Sheet Calibration Sheet*. https://www.photomodeler.com/downloads/OnlineHelp/index.html#!calibrationgrid.htm

Appendix H: Proxemics

Looking at Yaman's prototype, users commented that it "looked big", that "it might be scary for kids" and the general use experience was experienced quite negative, since the device came quite close and was quite intimidating to have with you so closely[1].

To improve this part of the design and get a better grasp the reasons behind it, both theoretical research and pre-liminary user tests have been executed.

H.1 Proxemics theory

Proxemics can be defined as the study of means in which individuals make use of the physical space in the interaction between the individuals[2].
With proxemics, "implicit and explicit interactions can be regulated; interactions can be triggered by continuous movement or switching between proxemic regions; and interpret and exploit people's directed attention to other people and objects"[3].
Within the theory of proxemics, four main spaces can be distinguished, being *Intimate space, personal space, social space* and *public space.*

Figure 1: Definition of proxemic distances

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[1] Gupta, Y. (2021). *Design of a 3D Headscanner: Facilitating the design of ultra-personalized products for the differently-abled.* https://repository.tudelft.nl/islandora/object/uuid%3A295e10a0-22df-4a56-a4c4-351fac597fdd?collection=education

[2] Agnus, O. (2012). *Proxemics: The Study of Space*. https://www.worldlitonline.net/proxemics-the-o.pdf

[3] Ballendat, T., Marquardt, N., & Greenberg, S. (2010). *Proxemic Interaction: Designing for a Proximity and Orientation-Aware Environment*. unknown. https://www.researchgate.net/publication/221540146_Proxemic_Interaction_Designing_for_a_Proximity_and_Orientation-Aware_Environment

Intimate space (< 0.5 m)

The intimate distance is mainly meant for non-verbal communication. Only the intimate people like members of the family and friends can enter into this zone, but it is considered improper for the public places.

Personal space (0.5-1 m)

This zone is also called 'the bubble' and is meant for the people who are well known to us. What can and what cannot be done varies in different cultures and depends on individual's personality and the style of communication.

Social space (1-2.5 m)

This zone is meant for general gatherings and business meetings or generally interacting with someone who is not particularly well known.

Public space (>2.5 m)

Only public interaction is possible in this zone. It demands louder voice, more formal style of language and reduced speech rate.

Ballendat et al. even go one step further by stating that in proxemics not only the position of the entities is of importance, but also the orientation, movement and identity. The orientation provides information about the direction an entity is facing, however this only makes sense when there is a clearly distinguishable front. Movement helps to understand how a person approaches a particular object, while identity focuses on uniquely describing the identity of the people in a particular space. This can be basal information such as 'Non-digital physical object', but it could also refer to 'book' or '50 Shades of Grey'.

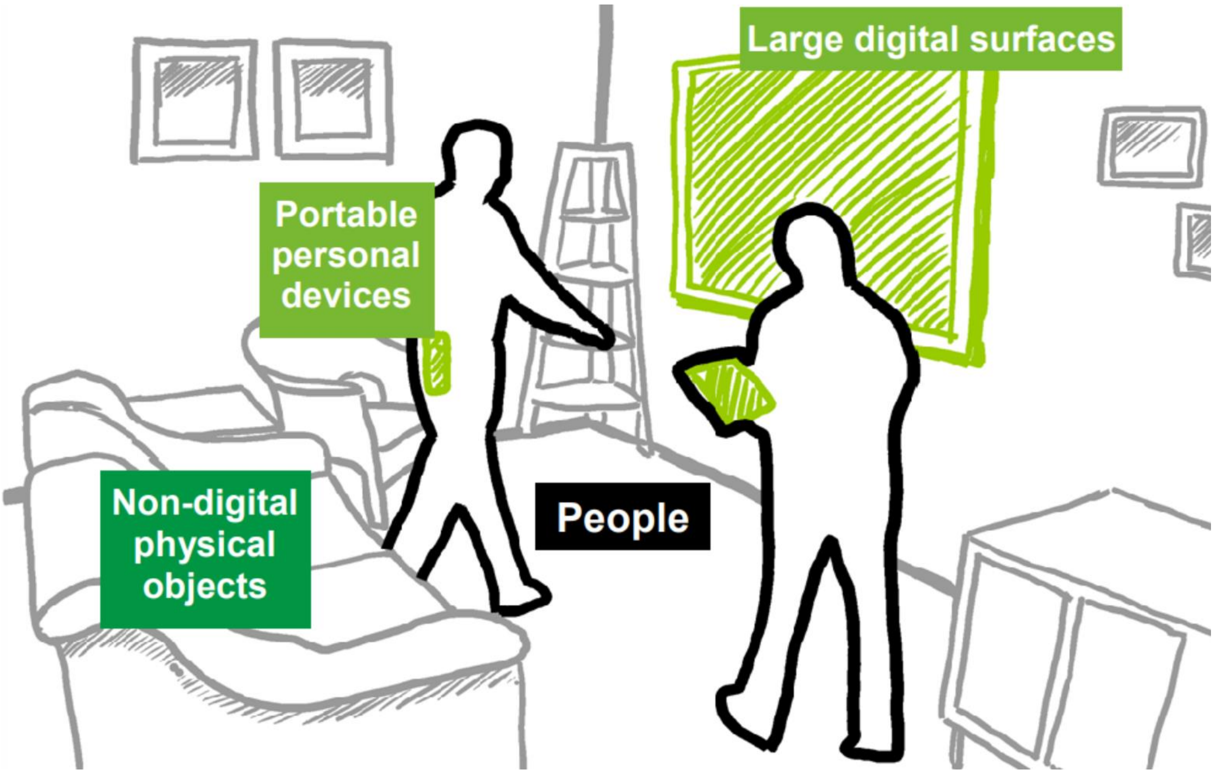


Figure 2: Overview of different types of interaction agents

When trying to apply these principles in a meaningful way, one could think of some examples:

- The system has knowledge about the position of the fixed entrance doors, recognizes when a person comes in and then take implicit action by awaking from standby mode
- The system reacts depending on whether a person is directing his or her attention to the device that holds the system (usually through detection of eye gaze)[4].
- The system detects when a person enters or leaves a discrete proxemic zone, certain actions are triggered in the system[5].
- The system recognizes a person and personalizes all communication

H.2 Initial proxemic experiments

To find out how these theories of proxemics apply for the 3D scanner, initial tests were performed with cardboard models, based on Yaman's design. The test was performed with three subjects.

Figure 3: Initial tests with cardboard models

Movement

The first thing was tested were different movements of the scanner while approaching the user. Both observations and participant experience were noted. An overview of the different movements can be found in figure 4. This test was performed with 3 subjects. Moreover, different movement speeds were tested. A general conclusion of this test was that if the movement was too fast, it would scare the subject, but the exact speed and duration of movement differed per movement.

---

4 Hall, E. T. (1966). The hidden dimension. Anchor Books.

5 Shell, J. S. (2016). Attentive user interfaces: the surveillance and sousveillance of gaze-aware objects - Roel Vertegaal, Jeffrey S. Shell, 2008. https://journals.sagepub.com/doi/10.1177/0539018408092574

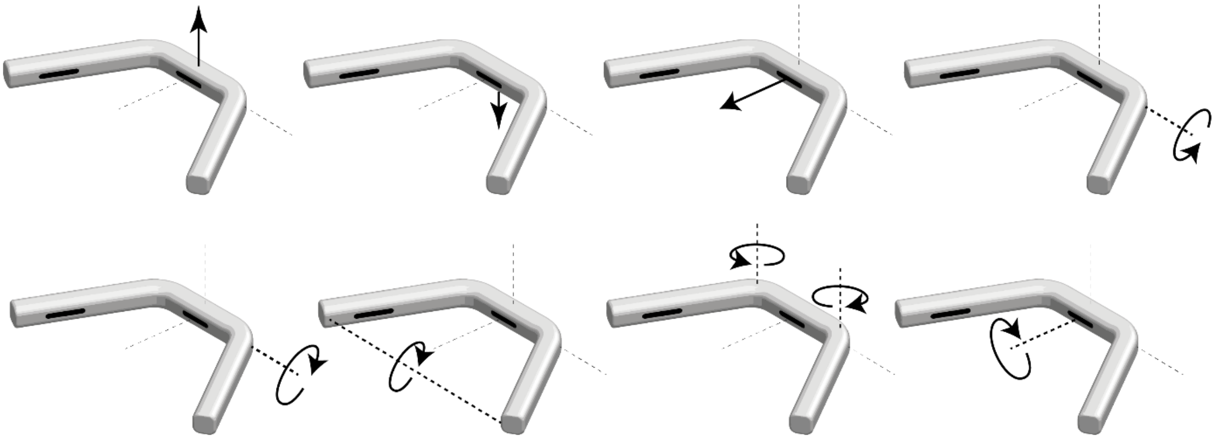


Figure 4: Different types of movement that were tried out

Distance

Interestingly, the distance between the scanner and the person being scanned did not make a difference in terms of the experience. For distances of 0.1 and 0.4 meter, no difference was found in terms of experience. It has to be noted though, that both of these differences were already in the so-called intimate space.

Field of view

In Yaman's design, the view of the subject would be fully blocked. To test to what extent this has a (negative) influence on the use experience, several variants were made and tested, with partial and fully free field of view of the subject, as can be seen in figure 5. As could be expected, did the fully free field of view lead to the most positive use experience.

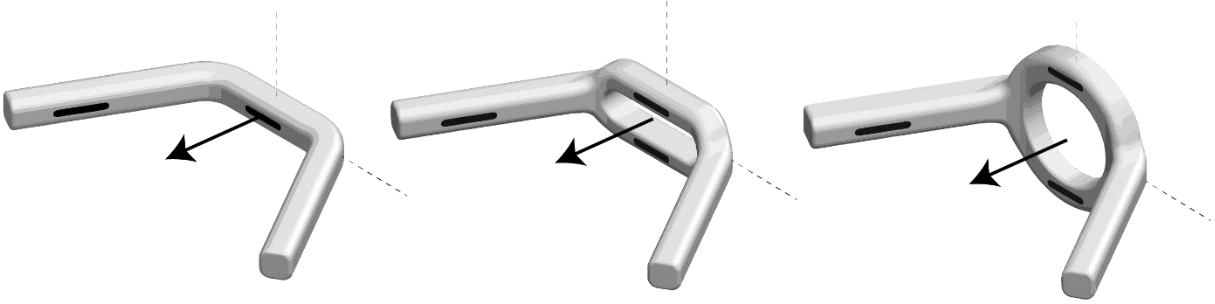
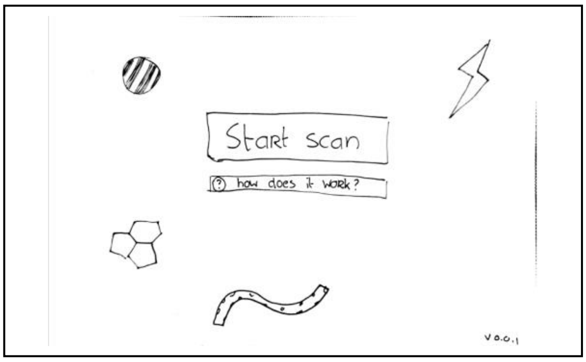


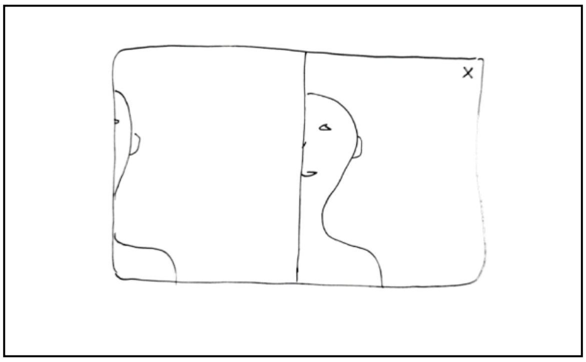
Figure 5: Different variants of open frontal views

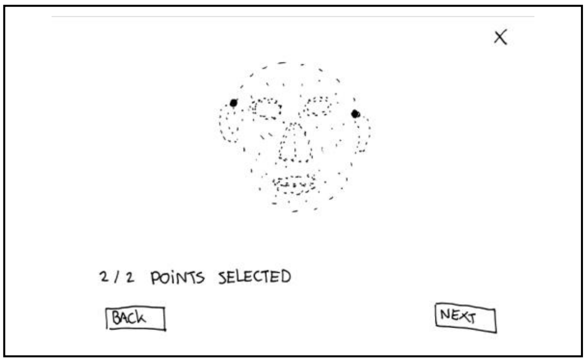
Sense of control

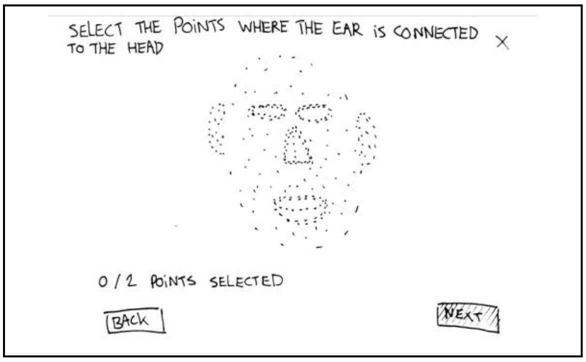
Another interesting topic that was quickly tested was to what extent it is nice to give the subject (a sense of) control. Instead of needing to sit still, the user would need to turn their head left and right. Subjects said that it felt nice to be able to contribute to the project, however not all clients have the mental capacity to be able to contribute themselves (Jan Berend Zweerts, personal communication, October 13, 2022).

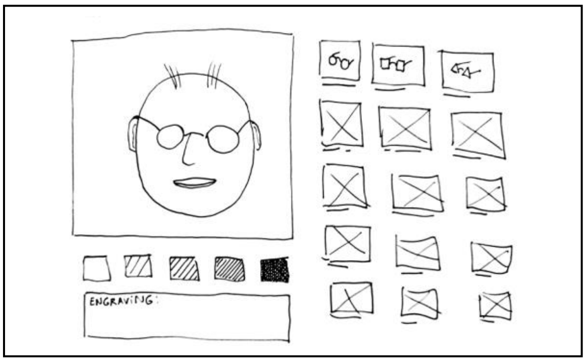
Appendix I: User Interfaces ideation and concepts

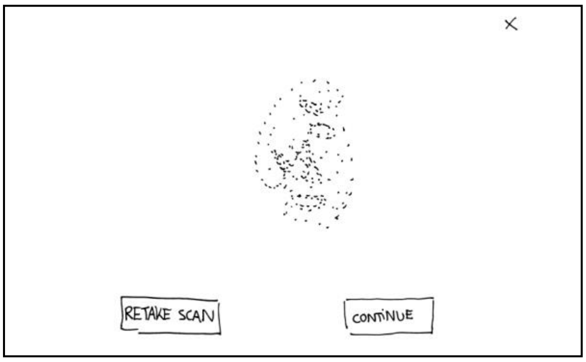


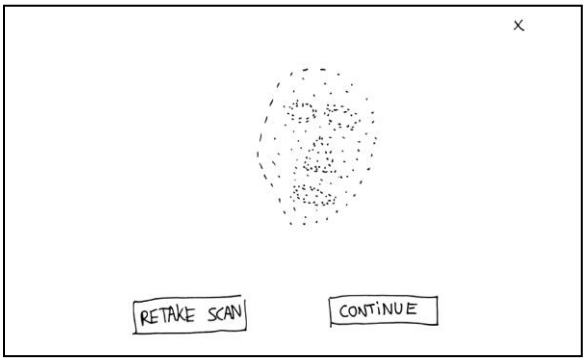


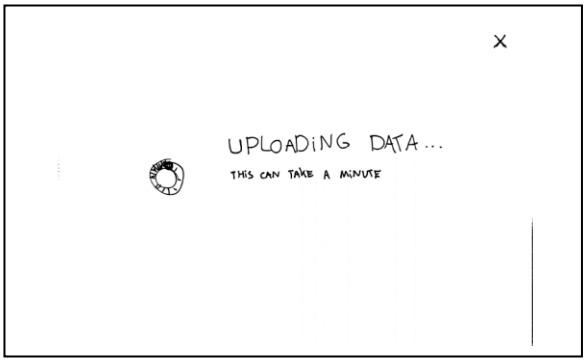






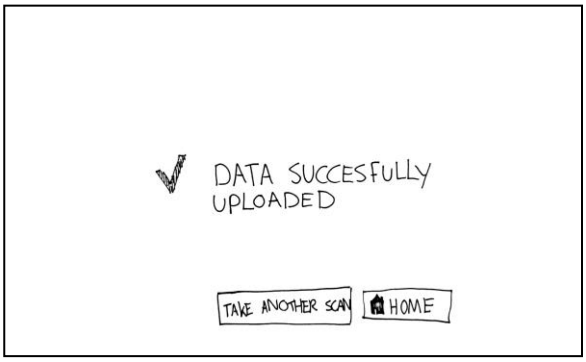


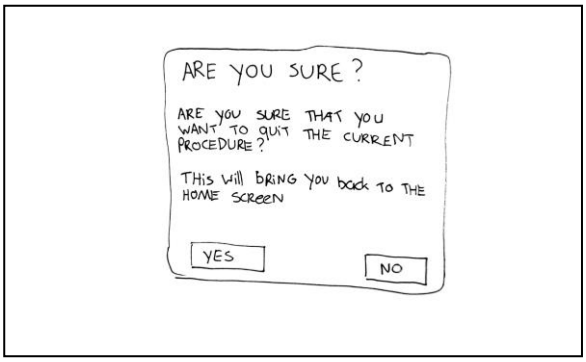




UPLOADING DATA...

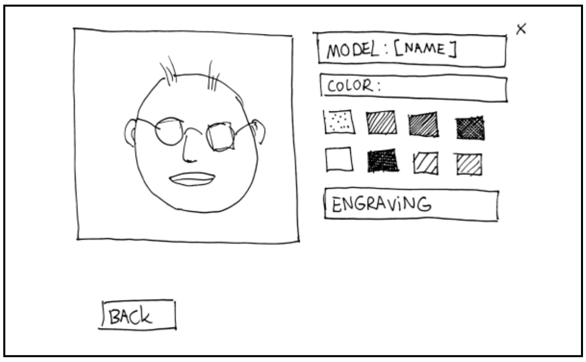
THIS CAN TAKE A MINUTE

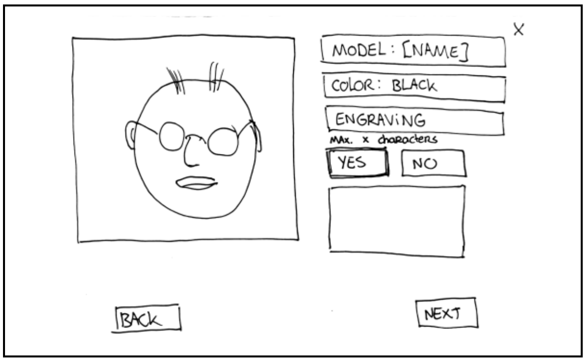

DATA SUCCESFULLY UPLOADED

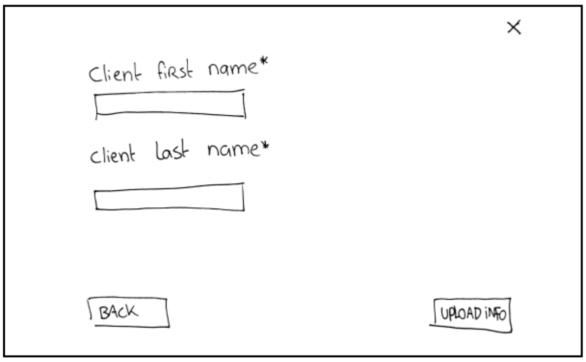

ARE YOU SURE ?

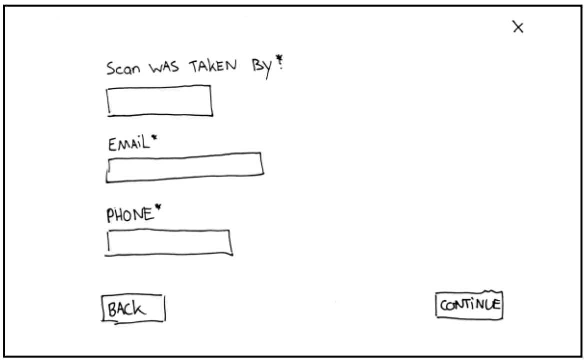
ARE YOU SURE THAT YOU WANT TO QUIT THE CURRENT PROCEDURE ?

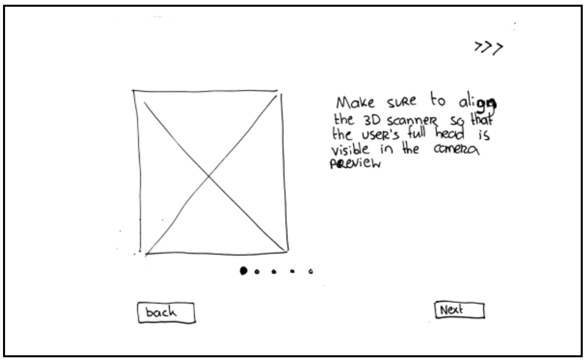
THIS will bRING YOU back TO THE HOME SCREEN



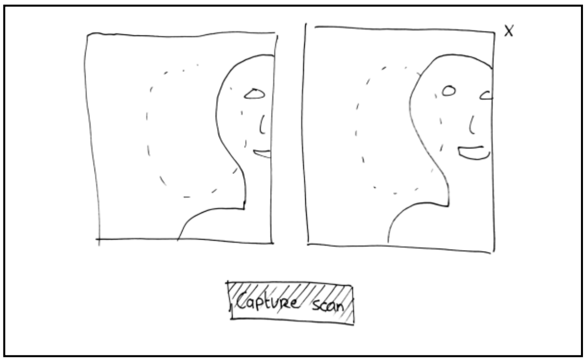


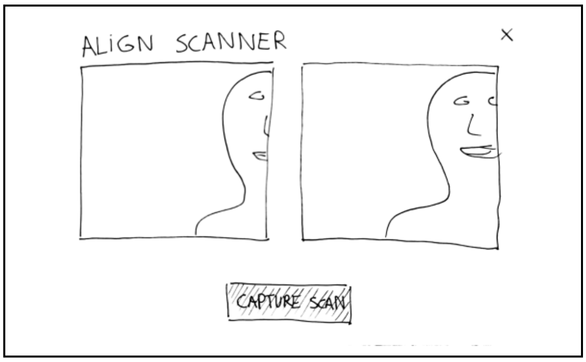




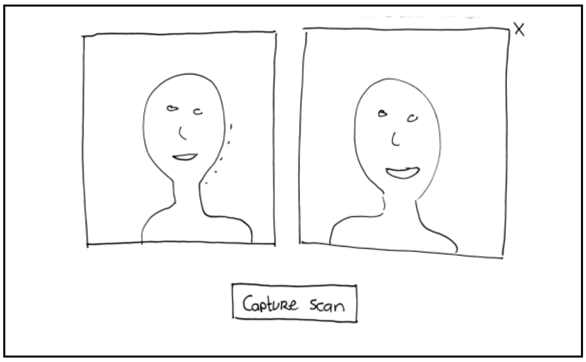


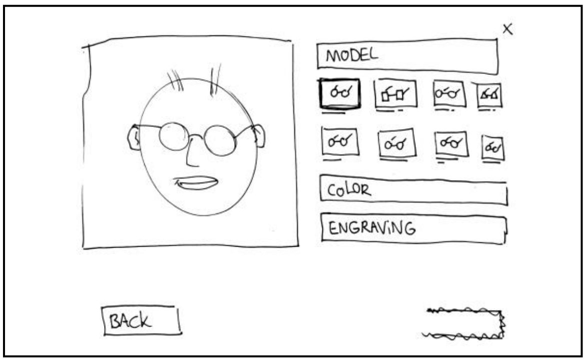
Make sure to align the 3D scanner so that the user's full head is visible in the camera preview

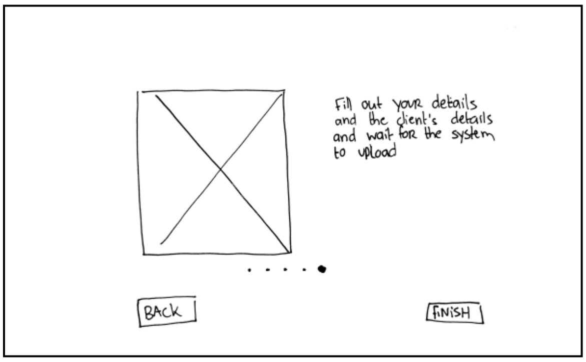


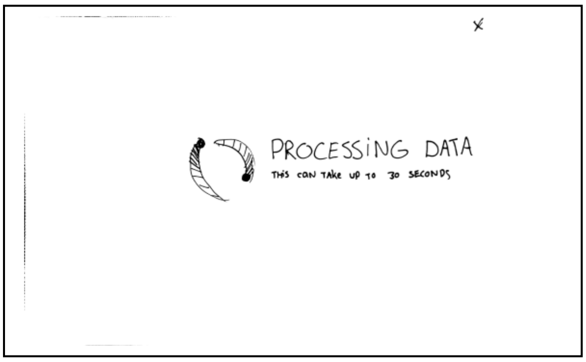


CAPTURING DATA...
ALIGNING SCANS...
CALCULATING TRANSFORMATIONS...

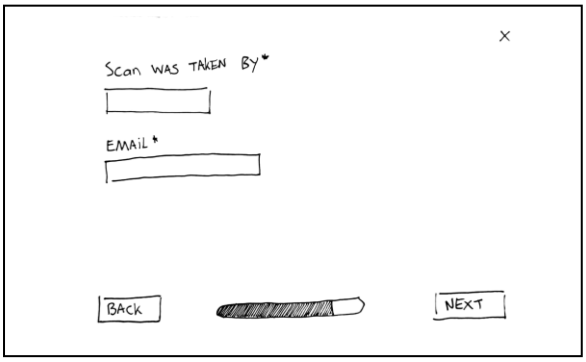


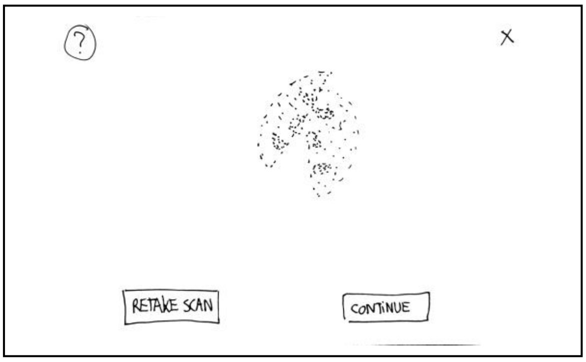


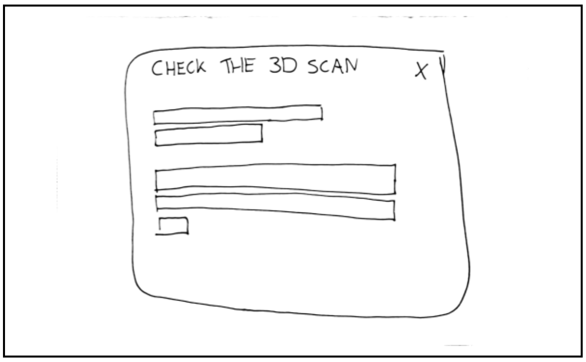

Fill out your details and the client's details and wait for the system to upload



PROCESSING DATA
THIS CAN TAKE UP TO 30 SECONDS







Appendix J: Calculation | Camera angles

> $restart;$

> $with(Optimization):$

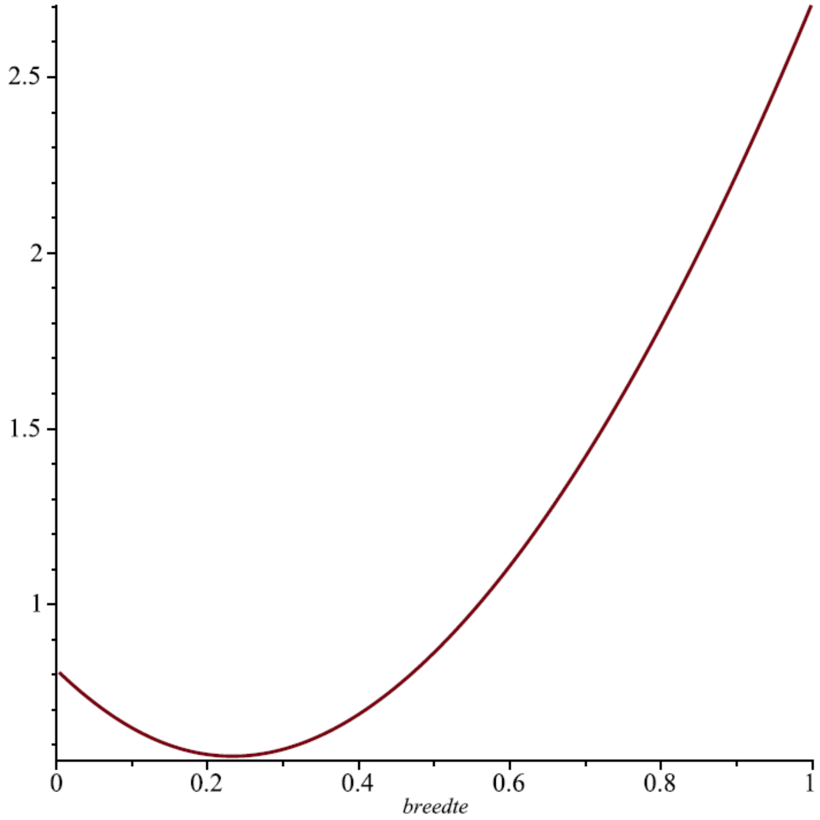
> $afstand := 0.5:$

> $$hoek := \arctan\left(\frac{afstand}{breedte}\right):$$

> $$afstandGebruiker := breedte \cdot \tan\left(\frac{afstand}{breedte}\right):$$

> $$obj := 0.33\left(hoek - \frac{0 \cdot \mathrm{Pi}}{180}\right)^2 + 0.66(2 \cdot breedte - 0)^2:$$

> $plot(obj, breedte = 0\,..1)$



> $s := rhs(evalf(Minimize(obj, breedte = 0\,..1))[2][1]):$

> $$hoek := \frac{\arctan\left(\frac{0.5}{s}\right) \cdot 180}{\mathrm{Pi}};$$

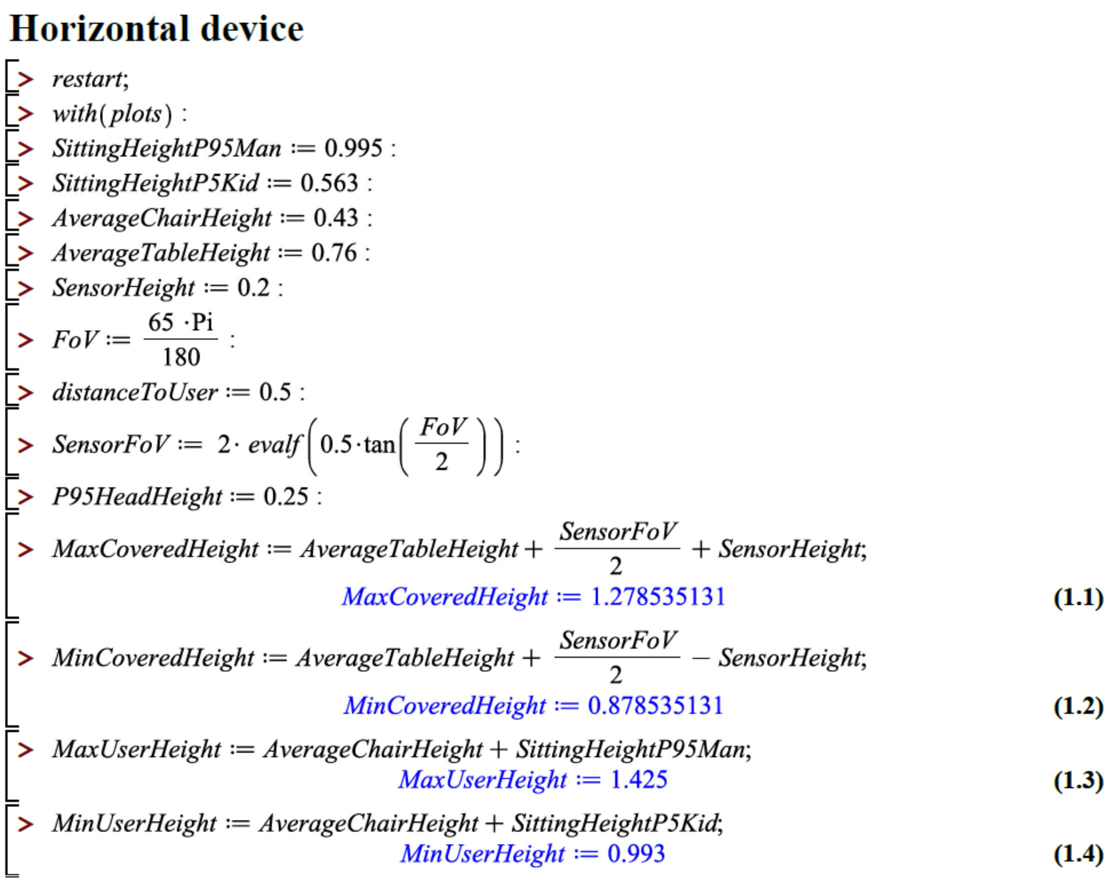
$$hoek := 65.0107447638148 \tag{1}$$

> $breedte := 2 \cdot s$

$$breedte := 0.466079369047588 \tag{2}$$

>

Appendix K: Calculation | Stand height and angles



Horizontal device

$> \mathit{restart};$

$> \mathit{with}(\mathit{plots}):$

$> \mathit{SittingHeightP95Man} := 0.995:$

$> \mathit{SittingHeightP5Kid} := 0.563:$

$> \mathit{AverageChairHeight} := 0.43:$

$> \mathit{AverageTableHeight} := 0.76:$

$> \mathit{SensorHeight} := 0.2:$

$> \mathit{FoV} := \frac{65 \cdot \mathrm{Pi}}{180}:$

$> \mathit{distanceToUser} := 0.5:$

$> \mathit{SensorFoV} := 2 \cdot \mathit{evalf}\left(0.5 \cdot \tan\left(\frac{\mathit{FoV}}{2}\right)\right):$

$> \mathit{P95HeadHeight} := 0.25:$

$> \mathit{MaxCoveredHeight} := \mathit{AverageTableHeight} + \frac{\mathit{SensorFoV}}{2} + \mathit{SensorHeight};$

$$\mathit{MaxCoveredHeight} := 1.278535131 \qquad \textbf{(1.1)}$$

$> \mathit{MinCoveredHeight} := \mathit{AverageTableHeight} + \frac{\mathit{SensorFoV}}{2} - \mathit{SensorHeight};$

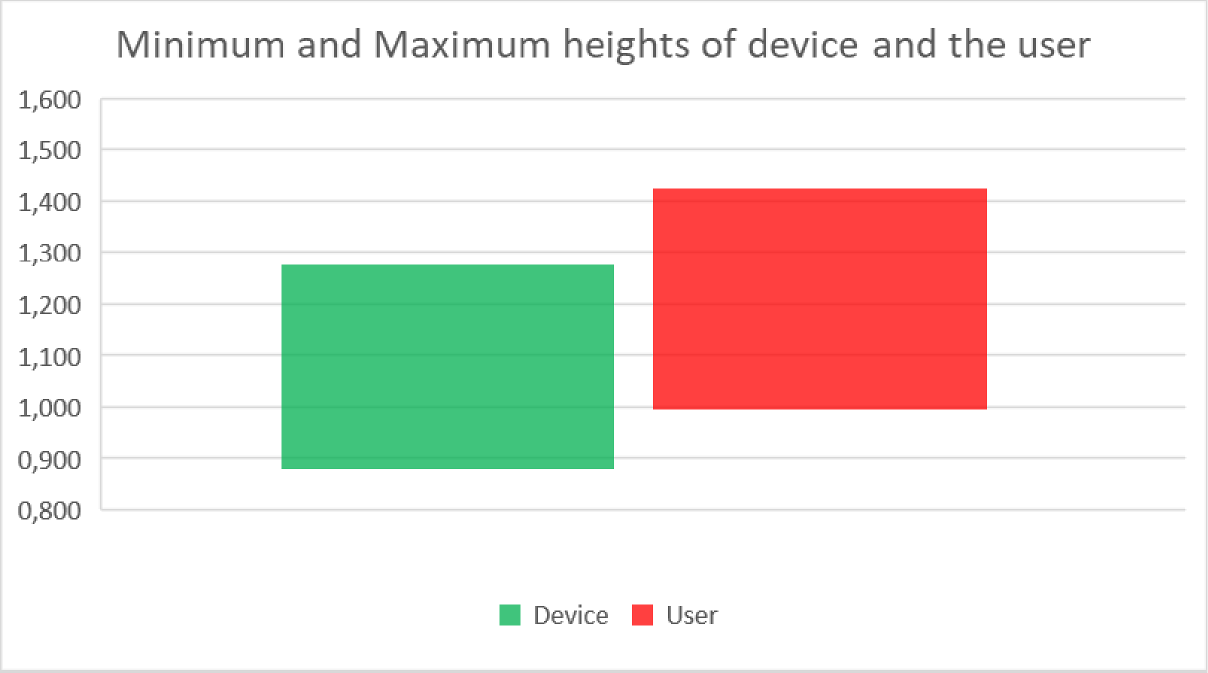
$$\mathit{MinCoveredHeight} := 0.878535131 \qquad \textbf{(1.2)}$$

$> \mathit{MaxUserHeight} := \mathit{AverageChairHeight} + \mathit{SittingHeightP95Man};$

$$\mathit{MaxUserHeight} := 1.425 \qquad \textbf{(1.3)}$$

$> \mathit{MinUserHeight} := \mathit{AverageChairHeight} + \mathit{SittingHeightP5Kid};$

$$\mathit{MinUserHeight} := 0.993 \qquad \textbf{(1.4)}$$



Angled 15 deg

$> \mathit{restart};$

$> \mathit{with}(\mathit{plots}):$

$> \mathit{extraAngle} := \frac{15 \cdot \mathrm{Pi}}{180}:$

$> \mathit{SittingHeightP95Man} := 0.995:$

$> \mathit{SittingHeightP5Kid} := 0.563:$

$> \mathit{AverageChairHeight} := 0.43:$

$> \mathit{AverageTableHeight} := 0.76:$

$> \mathit{SensorHeight} := 0.2:$

$> \mathit{FoV} := \frac{65 \cdot \mathrm{Pi}}{180}:$

$> \mathit{distanceToUser} := 0.5:$

$> \mathit{SensorFoV} := 2 \cdot \mathit{evalf}\left(0.5 \cdot \tan\left(\frac{\mathit{FoV}}{2}\right)\right):$

$> \mathit{angleCorrection} := \mathit{evalf}(0.5 \cdot \tan(\mathit{extraAngle})):$

$> \mathit{P95HeadHeight} := 0.25:$

$> \mathit{MaxCoveredHeight} := \mathit{AverageTableHeight} + \frac{\mathit{SensorFoV}}{2} + \mathit{SensorHeight} + \mathit{angleCorrection};$

$$\mathit{MaxCoveredHeight} := 1.412509727 \qquad \textbf{(2.1)}$$

$> \mathit{MinCoveredHeight} := \mathit{AverageTableHeight} + \frac{\mathit{SensorFoV}}{2} - \mathit{SensorHeight} + \mathit{angleCorrection};$

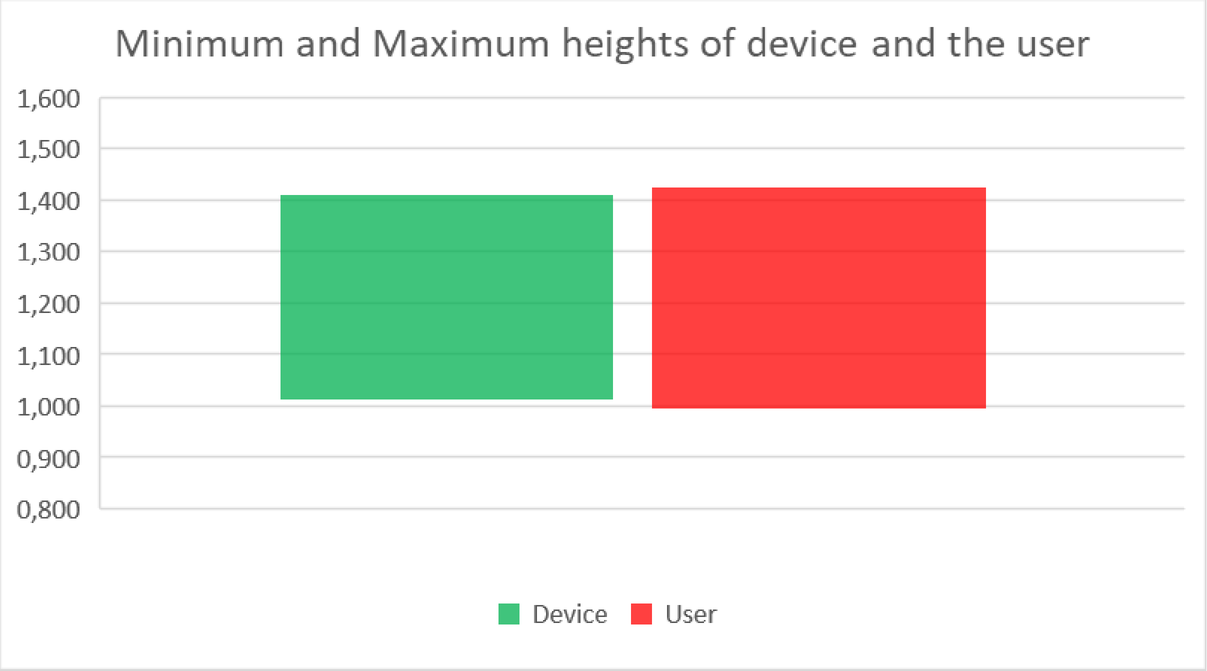
$$\mathit{MinCoveredHeight} := 1.012509727 \qquad \textbf{(2.2)}$$

$> \mathit{MaxUserHeight} := \mathit{AverageChairHeight} + \mathit{SittingHeightP95Man};$

$$\mathit{MaxUserHeight} := 1.425 \qquad \textbf{(2.3)}$$

$> \mathit{MinUserHeight} := \mathit{AverageChairHeight} + \mathit{SittingHeightP5Kid};$

$$\mathit{MinUserHeight} := 0.993 \qquad \textbf{(2.4)}$$



Appendix L: Project Brief

IDE Master Graduation

Project team, Procedural checks and personal Project brief

This document contains the agreements made between student and supervisory team about the student's IDE Master Graduation Project. This document can also include the involvement of an external organisation, however, it does not cover any legal employment relationship that the student and the client (might) agree upon. Next to that, this document facilitates the required procedural checks. In this document:

- The student defines the team, what he/she is going to do/deliver and how that will come about.
- SSC E&SA (Shared Service Center, Education & Student Affairs) reports on the student's registration and study progress.
- IDE's Board of Examiners confirms if the student is allowed to start the Graduation Project.

USE ADOBE ACROBAT READER TO OPEN, EDIT AND SAVE THIS DOCUMENT

Download again and reopen in case you tried other software, such as Preview (Mac) or a webbrowser.

STUDENT DATA & MASTER PROGRAMME

Save this form according the format "IDE Master Graduation Project Brief_familyname_firstname_studentnumber_dd-mm-yyyy". Complete all blue parts of the form and include the approved Project Brief in your Graduation Report as Appendix 1 !

family name: Busser

initials: P given name: Patrick

student number:

street & no.:

zipcode & city:

country:

phone:

email:

Your master programme (only select the options that apply to you):

IDE master(s): ● IPD ○ DfI ○ SPD

2nd non-IDE master:

individual programme: - - (give date of approval)

honours programme: ○ Honours Programme Master

specialisation / annotation: ○ Medisign

○ Tech. in Sustainable Design

○ Entrepeneurship

SUPERVISORY TEAM **

Fill in the required data for the supervisory team members. Please check the instructions on the right !

** chair: Yu Song dept. / section: MD

** mentor: Wim Schermer dept. / section: DA

2nd mentor:

organisation:

city: country:

comments (optional)

Chair should request the IDE Board of Examiners for approval of a non-IDE mentor, including a motivation letter and c.v..

Second mentor only applies in case the assignment is hosted by an external organisation.

Ensure a heterogeneous team. In case you wish to include two team members from the same section, please explain why.

Procedural Checks - IDE Master Graduation

APPROVAL PROJECT BRIEF

To be filled in by the chair of the supervisory team.

chair ______________________ date - - ____________ signature ______________________

CHECK STUDY PROGRESS

To be filled in by the SSC E&SA (Shared Service Center, Education & Student Affairs), after approval of the project brief by the Chair.
The study progress will be checked for a 2nd time just before the green light meeting.

Master electives no. of EC accumulated in total: ________ EC

Of which, taking the conditional requirements into account, can be part of the exam programme ________ EC

List of electives obtained before the third semester without approval of the BoE ____________

○ YES all 1st year master courses passed

○ NO missing 1st year master courses are:

name ______________________ date - - ____________ signature ______________________

FORMAL APPROVAL GRADUATION PROJECT

To be filled in by the Board of Examiners of IDE TU Delft. Please check the supervisory team and study the parts of the brief marked **.
Next, please assess, (dis)approve and sign this Project Brief, by using the criteria below.

- Does the project fit within the (MSc)-programme of the student (taking into account, if described, the activities done next to the obligatory MSc specific courses)?
- Is the level of the project challenging enough for a MSc IDE graduating student?
- Is the project expected to be doable within 100 working days/20 weeks ?
- Does the composition of the supervisory team comply with the regulations and fit the assignment ?

Content: ○ APPROVED ○ NOT APPROVED

Procedure: ○ APPROVED ○ NOT APPROVED

comments

name ______________________ date - - ____________ signature ______________________

Design of an open-source 3D headscanner

project title

Please state the title of your graduation project (above) and the start date and end date (below). Keep the title compact and simple. Do not use abbreviations. The remainder of this document allows you to define and clarify your graduation project.

start date 12 - 09 - 2022

27 - 03 - 2023 end date

INTRODUCTION **

Please describe, the context of your project, and address the main stakeholders (interests) within this context in a concise yet complete manner. Who are involved, what do they value and how do they currently operate within the given context? What are the main opportunities and limitations you are currently aware of (cultural- and social norms, resources (time, money,...), technology, ...).

Ultra-personalized headwear has become increasingly available with the rise of additive manufacturing. People with a deviant headshape could now get 3D-printed glasses for example. The problem however lies in obtaining the data to model this headwear around.

Currently, the LIDAR technology of the Ipad Pro is often used to generate 3D-scan of the head. However, since this requires about 15 seconds to collect the data, it brings challenges for people with special pathologies (e.g. inability to sit still) and leads to invalid 3D-scans. At the same time, faster and more accurate alternatives such as 3D scanners can easily cost a couple of thousand euros. The availability of a fast, accurate and low cost 3D head scanner would therefore allow for easier and cheaper data collection.

Although the use of the product is not limited to people with special pathologies, it is important to realise that these pathologies can vary from person to person and that it is likely that they bring different needs with them as well. Since the interest of the person being scanned is in the end-result (e.g. personalized eyewear), the scanning process should be quick and unobtrusive. The appearance of the product could potentially have a strong influence in the use-experience.

Next to that, there is the person performing the scan. They should be able to provide a positive scanning experience to their client under various (lighting) conditions as the scans are usually taken at the client's home. At the same time, they have interest in easy interaction with the device and easy extracting and processing of the collected data. Next to that, since the project will be open-source, it is important that DIY'ers and people that want to contribute to the project can easily acquire and assemble the required parts, as well as install the software.

The main opportunities for this project are that in the field of 3D scanning the technological developments advance rather quickly at this moment. Next to that, integration of Artificial Intelligence could drastically improve accuracy and/or usuability of the 3D scanner. Moreover, TUDelft has experience in developing 3D scanners in similar projects, which provides a solid knowledge base to start from as well as access to resource and facilities to ideate, build and test in various scenarios.

The main limitation is that this project is not organized by a company and extensive contact and testing with the end-users might therefore be difficult. Next to that, the (prototyping) budget for this project is therefore also limited.

space available for images / figures on next page introduction (continued): space for images

TO PLACE YOUR IMAGE IN THIS AREA:
- SAVE THIS DOCUMENT TO YOUR COMPUTER AND OPEN IT IN ADOBE READER
- CLICK AREA TO PLACE IMAGE / FIGURE

PLEASE NOTE:
- IMAGE WILL SCALE TO FIT AUTOMATICALLY
- NATIVE IMAGE RATIO IS 16:10
- IF YOU EXPERIENCE PROBLEMS IN UPLOADING, COVERT IMAGE TO PDF AND TRY AGAIN

image / figure 1: ______

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image / figure 2: ______

Initials & Name ______ Student number ______

Title of Project ______

PROBLEM DEFINITION **

Limit and define the scope and solution space of your project to one that is manageable within one Master Graduation Project of 30 EC (= 20 full time weeks or 100 working days) and clearly indicate what issue(s) should be addressed in this project.

The 3D-scanners that are being currently used are quite slow, taking about 15 seconds to complete a scan. In this process the participant is expected to keep its head still, which is rather difficult for people with a special pathology. Faster scanners are available but they usually output inconsistent and/or not high enough quality scans, or they are simply too expensive.

Generally, the most interesting geometry to design for/with is that of both the ears and the frontal part of the head. The accuracy of the data aquisition is of utmost importance, since the target group might have unique head shapes and or anthropometric measures, while at the same time the procedure should be fast and cheap.

Next to that, the User Experience for both the person operating the 3D-scanner and the participant are very important. For the person operating the 3D-scanner, ease of transporting and setting up the 3D-scanner, and easy scanning and post-proccessing procedures are important. While for the participant a quick and inobtrusive procedure is important for a pleasant experience, especially when working with children.

ASSIGNMENT **

State in 2 or 3 sentences what you are going to research, design, create and / or generate, that will solve (part of) the issue(s) pointed out in "problem definition". Then illustrate this assignment by indicating what kind of solution you expect and / or aim to deliver, for instance: a product, a product-service combination, a strategy illustrated through product or product-service combination ideas, ... In case of a Specialisation and/or Annotation, make sure the assignment reflects this/these.

I will research scanning technologies, the physical and cognitive needs of the users involved (both the participant and the scanner), and shape modelling. Eventually, I will design and prototype a 3D head scanner for people with special needs that outputs high quality 3D scans whilst being low in cost, intuitive to use and not interfering with cognitive and/or physical needs of the participant. Functional prototypes will be iteratively improved by means of testing.

It is the intention to design and build a physical product/combination of products that represents a 3D head scanner. The concept is still to be configured, based on the scanning requirements, desired user experience and interactions, hardware solutions and limitations and other requirements. Although the scanner will mainly consist of hardware (cameras and/or sensors, housing, etc.), software will be required to combine and post-process the captured data. This layer of software should then (be able to) output a 3D model to design the ultra-personalized headwear around.

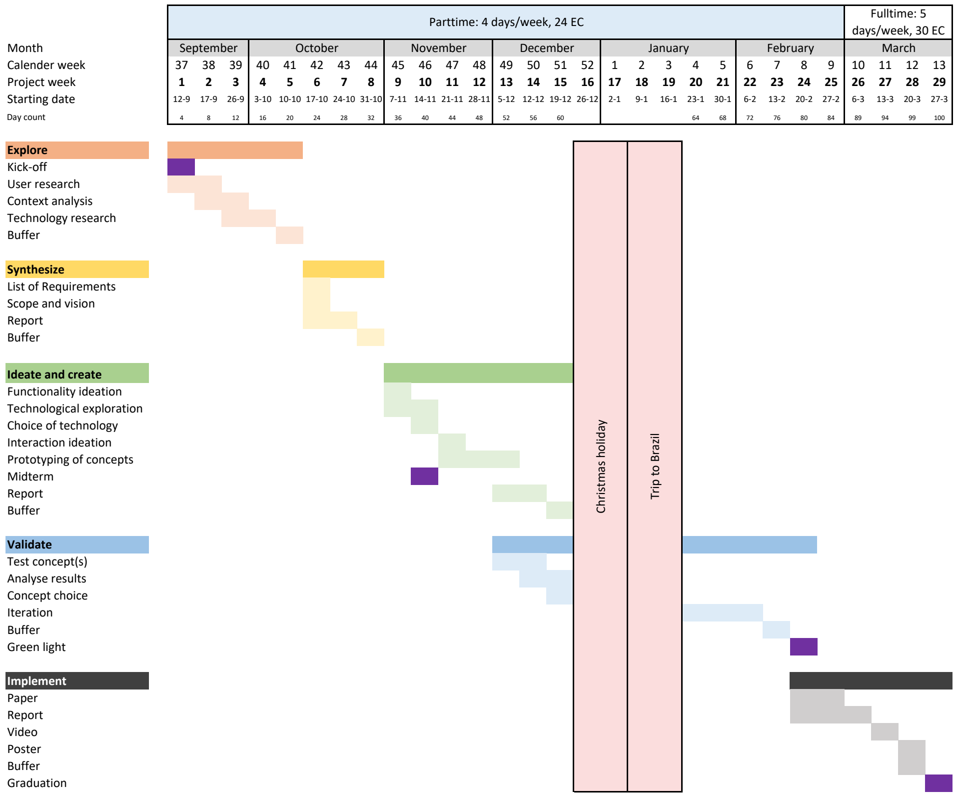
A deepdive into the various scanning techniques is required to better understand their potential, limitations and fit to this usecase. Next to that, it is important to analyze the current scanning process to be able to highlight and improve current bottlenecks leading to a better experience for both the person taking the scan as well as for the participant, especially since the target group might also consist of children. Finally, research should be done regarding statistical shape modeling techniques, since this is essential in understanding how to go from the raw data to a 3D scan that is usable for the client.

Since it might be relatively hard to immediately understand the needs of this target group, it might be beneficial to get into contact with and start testing with the target group as early on in the project as possible.

PLANNING AND APPROACH **

Include a Gantt Chart (replace the example below - more examples can be found in Manual 2) that shows the different phases of your project, deliverables you have in mind, meetings, and how you plan to spend your time. Please note that all activities should fit within the given net time of 30 EC = 20 full time weeks or 100 working days, and your planning should include a kick-off meeting, mid-term meeting, green light meeting and graduation ceremony. Illustrate your Gantt Chart by, for instance, explaining your approach, and please indicate periods of part-time activities and/or periods of not spending time on your graduation project, if any, for instance because of holidays or parallel activities.

start date 12 - 9 - 2022 27 - 3 - 2023 end date



	Parttime: 4 days/week, 24 EC																									Fulltime: 5 days/week, 30 EC			
Month	September			October					November				December				January					February				March			
Calender week	37	38	39	40	41	42	43	44	45	46	47	48	49	50	51	52	1	2	3	4	5	6	7	8	9	10	11	12	13
Project week	**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**
Starting date	12-9	17-9	26-9	3-10	10-10	17-10	24-10	31-10	7-11	14-11	21-11	28-11	5-12	12-12	19-12	26-12	2-1	9-1	16-1	23-1	30-1	6-2	13-2	20-2	27-2	6-3	13-3	20-3	27-3
Day count	4	8	12	16	20	24	28	32	36	40	44	48	52	56	60					64	68	72	76	80	84	89	94	99	100

I split up the process in 5 parts: Explore, Synthesize, Ideate & create, Validate and Implement. Each part has some buffer time at the end. If a buffer is not being used, the planning will update accordingly, allocating more time to building and testing. After the Explore and Synthesize phases, and after the Ideate and create phase, a small report will be written with a summary and conclusion of these phases. These reports will later be merged with the final report.
If everything goes to plan, the expected graduation date is 27th of March.

Remarks:
- Until March I will work parttime at MMID design agency as a workstudent, therefore I will only spend 4 days/week on graduating.
- Just after the christmas holiday I will probably make a 2-week trip to Brazil.

MOTIVATION AND PERSONAL AMBITIONS

Explain why you set up this project, what competences you want to prove and learn. For example: acquired competences from your MSc programme, the elective semester, extra-curricular activities (etc.) and point out the competences you have yet developed. Optionally, describe which personal learning ambitions you explicitly want to address in this project, on top of the learning objectives of the Graduation Project, such as: in depth knowledge a on specific subject, broadening your competences or experimenting with a specific tool and/or methodology, ... Stick to no more than five ambitions.

The project was initiated because of my interest in 3D scanning, which is something I have wanted to learn more about for quite a while, and because I think it offers me the chance to show my capabilities to both deepdive into the technology but at the same time to not forget the user and its (special) needs. I think that during ACD I have shown to be able to work well with users with special needs (Visually Impaired People) while during AED I was responsible for all electronics and coding in the project, but I feel that I lacked a bit the brainstorming and CAD modeling aspects.

That's why I would like to focus on these aspects, resulting in building 'clean' and versatile SolidWorks models for this project.

Next to that, I would like to improve my Python-coding skills. Although I have worked with it before, I think there is a lot to gain still and it would help me to become a more complete design engineer as well.

As I mentioned before already, I'm quite interested in 3D scanning and I would like to get in-depth knowledge and hand-on experience with the topic.

Lastly, I would really like to work on my planning and time management. I have never missed a deadline, but that is mainly because I dedicate all my available time to the project(s). However, I realize that in my professional career this is not an option of course and I should be able to make reasonable time estimations and stick to those.

FINAL COMMENTS

In case your project brief needs final comments, please add any information you think is relevant.

Appendix O: Informed Consent Form

Ontwerp van een 3D scanner voor gepersonaliseerde brillen

U wordt uitgenodigd om deel te nemen aan een onderzoek genaamd Ontwerp van een 3D scanner voor gepersonaliseerde brillen. Dit onderzoek wordt uitgevoerd als onderdeel van de MSc opleiding Industrieel Ontwerpen aan de TU Delft. Student: Patrick Busser

Toestemmingsverklaring participant

Uw deelname aan dit onderzoek is volledig vrijwillig en u kunt zich op elk moment terugtrekken zonder reden op te geven. U bent vrij om vragen niet te beantwoorden.

Ik erken dat ik vooraf voldoende informatie en uitleg heb gekregen over dit onderzoek en al mijn vragen zijn naar voldoening beantwoord. Ik heb de tijd gekregen die ik nodig had om in te stemmen met de deelname. Op elk moment kan ik vragen stellen met betrekking tot het onderzoek.

Mij is bekend dat dit onderzoek bestaat uit:

1. Interviewen

Ik ben mij ervan bewust dat tijdens het onderzoek gegevens worden verzameld in de vorm van bijvoorbeeld aantekeningen, foto's en/of video's. Ik geef toestemming voor het verzamelen van deze gegevens en het maken van foto's en video opnames tijdens het onderzoek.

De foto's, video's en/of geluidsopnames zullen worden gebruikt ter ondersteuning van het analyseren van verzamelde gegevens. Video opnames en foto's kunnen tevens worden gebruikt ter illustratie van onderzoeksbevindingen in publicaties en presentaties over het project.

Ik geef toestemming voor het gebruik van foto's en video opnames van mijn deelname:
(selecteer wat van toepassing is)

○ waarin ik herkenbaar ben voor publicaties en presentaties over het project.
○ waarin ik niet herkenbaar ben voor publicaties en presentaties over het project.
○ enkel voor data analyse doeleinden en niet voor publicaties en presentaties over het project.

2. 3D hoofd scan

Ik ben mij ervan bewust dat tijdens het onderzoek gegevens worden verzameld in de vorm van een 3D scan. Ik geef toestemming voor het verzamelen van deze gegevens tijdens het onderzoek. Ik ben me bewust van het risico dat ik mogelijk herkend wordt op deze data wanneer deze gebruikt zou worden in presentaties en/of publicaties.

De 3D hoofd scan zal worden gebruikt voor het testen van verschillende scan technieken om de meest geschikte techniek voor deze gebruikssituatie te vinden. Een 3D print van deze scan zal worden vervaardigd en gebruikt als test model.

Ik geef toestemming voor het gebruik van de 3D scan van mijn deelname:
(selecteer wat van toepassing is)

○ enkel in dit onderzoek, mits deze data niet wordt gebruikt in presentaties en/of publicaties én mijn data na het onderzoek direct vernietigd wordt.
○ voor onderwijs- en onderzoeksdoeleinden uitgevoerd door leden van het onderzoeksteam. Mijn data mag gebruikt worden voor publicaties en presentaties over het project en ik geef toestemming om gegevens nog maximaal 10 jaar na afloop van dit onderzoek te bewaren en te gebruiken.

Ik erken dat er geen financiële compensatie gegeven wordt voor deelname aan het onderzoek.

Ik ben mij ervan bewust dat de onderzoeker(s) mogelijk niet in staat is/zijn om gedurende het onderzoek op 1.5 meter afstand te blijven. Indien dit het geval is zal/zullen onderzoeker(s) een FFP2 mondmasker dragen en voorafgaand aan het onderzoek een zelf-test uitvoeren.

Ik ben mij ervan bewust dat dit onderzoek niet geschikt is voor mensen met epilepsie en/of andere licht-gerelateerde aandoeningen. Om het visuele comfort te verhogen is mij uitgelegd tijdens het scannen mijn ogen te sluiten. Daarnaast zal er maximaal 20 seconden achter elkaar worden gescand.

Met mijn handtekening bevestig ik dat ik de informatie over het onderzoek heb gelezen en dat ik de aard van mijn deelname heb begrepen. Ik begrijp dat ik mijn deelname aan het onderzoek op elk moment kan intrekken of kan stoppen. Ik begrijp dat ik niet verplicht ben om vragen te beantwoorden die ik niet wil beantwoorden en dat ik dit kan aangeven bij het onderzoeksteam.

________________	________________	___ / ___ / 2023	______________________
Achternaam	Voornaam	Datum (dd/mm/yyyy)	Handtekening

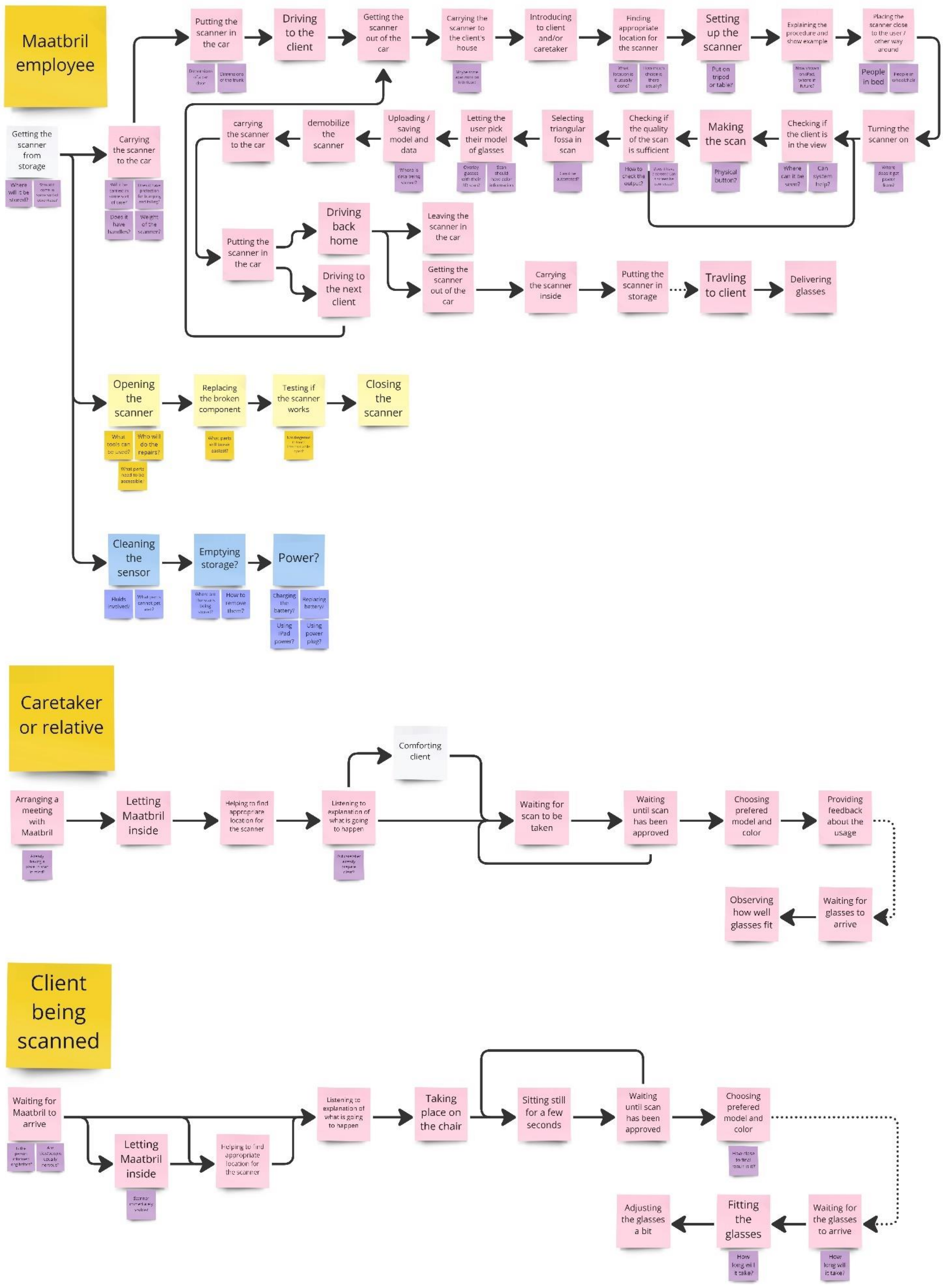
Appendix Q: List of Requirements

Description		*Quantification*					*Verification*		*Tracking*		*Additional Information*
#	*Requirement*	*Unit*	*Target*	*Lower Spec Limit*	*Upper Spec Limit*	*Challenge (C)/ Must have (M)/ nice to have (N)*	**Verification method**	***Result** (PASS/ FAIL/not yet verified)*	*Source*	*Last revision*	*Remarks*
	A | Performance										
1	Average accuracy of the scanner should be	mm	1		2	C	Measure	Fail	Interview Berend Jan Zweerts	22-3-2023	
2	Scanner should be able to make a contactless 3D scan of the client					C	Check	Pass	Interview Berend Jan Zweerts	22-3-2023	
3	Maximum capturing time of the scanner should (near) instantaneous	sec			1	C	Measure	Pass		22-3-2023	
4	Scanner should be able to make a scan of the important landmarks such as nose, eyes and front of the ears					C	Check	Pass	Interview Berend Jan Zweerts	22-3-2023	
5	Scanner must collect 3D mesh data					M	Check	Pass	Interview Berend Jan Zweerts	22-3-2023	Mesh for design, image for client
6	Scanner must collect evenly illuminated texture mesh					M	Check	Fail	Interview Berend Jan Zweerts	22-3-2023	Mesh for design, image for client
8	Scanner should be able to collect heads of various sizes, ranging from 8 month-old kids to P95 adults					M	Measure	Pass	Interview Berend Jan Zweerts	22-3-2023	
9	Scanner should use non-invisible projected light if applicable					M	Check	Pass	Designer	22-3-2023	Avoid causing visual irritation
	B | Environment and circumstances										
1	Scanner should work under lighting conditions that are present in house					M	Test	Pass	Interview Berend Jan Zweerts	22-3-2023	
2	Scanner should be able to ignore unrelated geometry such as the backplate of a chair, a wall or another person standing in the background					N	Test	Pass	Designer	22-3-2023	
	C | Geometry and Weight										
1	Scanner should have relatively smooth and simple surfaces to avoid the collection of dust					N	Check	Pass	Designer	31-10-2022	
2	Scanner should have a mass below	kg			5	M	Check	Pass	Designer	31-10-2022	3.024 kg
3	Scanner should have a longest dimension below	m			1	M	Check	Pass	Designer	31-10-2022	To be able to ship with postal compamy
	D | Safety, Standards, Legislation										
1	Scanner cannot harm the client and/or person operating the scanner in normal use					M	Test	Pass	Designer	14-10-2022	
2	The scanner cannot tip over or fall during normal use					M	Measure	Pass	Designer	14-10-2022	
3	Scanner does not emit harmful radiation such as the radiation emitted by CT scans or X-rays					M	Check	Pass	Designer	31-10-2022	
	E | Storage and transport										
1	Scanner can easily be carried by itself or in a protection cover					N	Check	Pass	Designer	29-10-2022	
2	Electronics should be protected against dust and moisture when being stored					M	Test	Not yet verified	Designer	3-2-2023	IP51, not verified because of risk of damaging Scanner, but should be possible
	F | Installation and maintenance										
1	Maximum installation time of the scanner	min	5			M	Test	Pass	Interview Jan Berend Zweerts	31-10-2022	
2	Maximum removal time of the scanner	min	2			M	Test	Pass	Interview Jan Berend Zweerts	31-10-2022	
3	Scanner maintenance is only needed after	scans	50			N	Test	Not yet verified	Interview Jan Berend Zweerts	31-10-2022	
4	Maximum assembly time of the scanner	min	60			M	Test	Pass	Designer	29-3-2023	
	G | Ergonomics, User Interface, ease of use										
1	The scanner facilitates the mounting of an iPad or tablet					N	Check	Pass	Interview Jan Berend Zweerts	14-10-2022	
2	The scanner allows for evaluating the scan quality directly after taking the scan					M	Check	Pass	Interview Jan Berend Zweerts	14-10-2022	
3	The scanner is straightforward to use, so that caretakers can easily scan clients themselves					N	Test	Pass	Interview Jan Berend Zweerts	14-10-2022	
4	The scanner can be used as a stand-alone device					N	Check	Fail	Interview Jan Berend Zweerts	14-10-2022	
5	The device can be used while the client is sitting on a chair or in a wheelchair					M	Test	Pass	Interview Jan Berend Zweerts	14-10-2022	
6	The scanner can be operated by a single user					C	Test	Pass	Interview Jan Berend Zweerts	14-10-2022	
	H | Product life span										

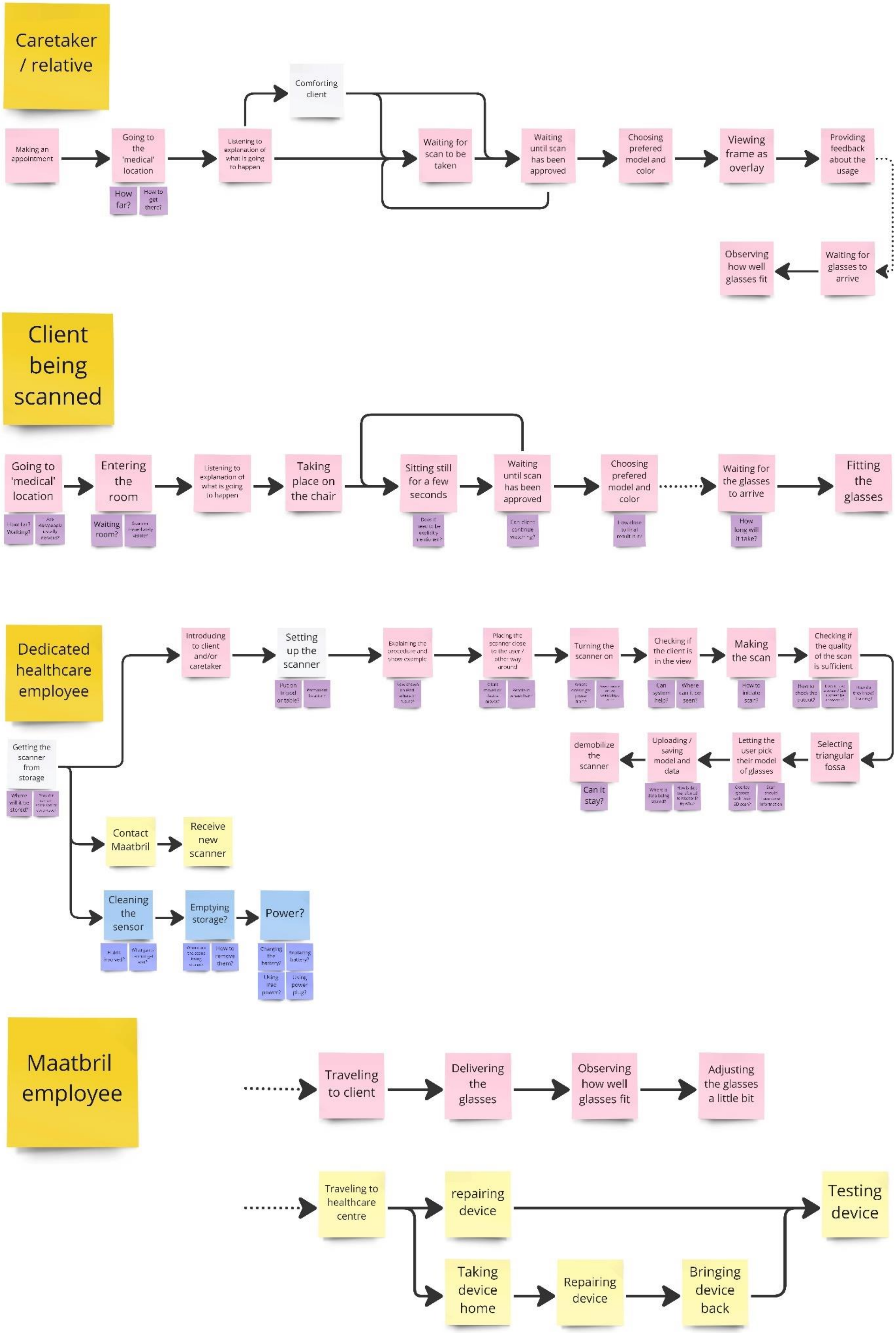
<table>
<tr><th colspan="2">Description</th><th colspan="4">Quantification</th><th></th><th colspan="2">Verification</th><th colspan="2">Tracking</th><th>Additional Information</th></tr>
<tr><th>#</th><th>Requirement</th><th>Unit</th><th>Target</th><th>Lower Spec Limit</th><th>Upper Spec Limit</th><th>Challenge (C)/ Must have (M)/ nice to have (N)</th><th>Verification method</th><th>Result (PASS/ FAIL/not yet verified)</th><th>Source</th><th>Last revision</th><th>Remarks</th></tr>
<tr><td>1</td><td>Minimum operation time of the scanner should be</td><td>year</td><td></td><td>2</td><td></td><td>M</td><td>Test</td><td>Not yet verified</td><td>Designer</td><td>31-10-2022</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="11">I | Cost Price</td></tr>
<tr><td>1</td><td>Production cost of the scanner should be</td><td>€</td><td>800</td><td></td><td>1500</td><td></td><td>Check</td><td>Pass</td><td>Interview Jan Berend Zweerts</td><td>14-10-2022</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="11">J | Production, assembly</td></tr>
<tr><td>1</td><td>The body of the scanner can be 3D printed on a regular-sized 3D print bed (200x200x200mm)</td><td></td><td></td><td></td><td></td><td>M</td><td>Check</td><td>Pass</td><td>Designer</td><td>31-10-2022</td><td></td></tr>
<tr><td>2</td><td>The scanner can be assembled by 1 person within</td><td>hours</td><td>1</td><td></td><td></td><td>M</td><td>Test</td><td>Pass</td><td>Designer</td><td>31-10-2022</td><td></td></tr>
<tr><td>3</td><td>The scanner can be assembled using common tools</td><td></td><td></td><td></td><td></td><td>M</td><td>Check</td><td>Pass</td><td>Designer</td><td>31-10-2022</td><td></td></tr>
<tr><td>4</td><td>The scanner comes with sufficient documentation to asssemble the scanner</td><td></td><td></td><td></td><td></td><td>N</td><td>Check</td><td>Pass</td><td>Designer</td><td>31-10-2022</td><td></td></tr>
<tr><td>5</td><td>The software of the scanner can be accessed online and improved by other contributers</td><td></td><td></td><td></td><td></td><td>N</td><td>Check</td><td>Pass</td><td>Designer</td><td>31-10-2022</td><td></td></tr>
<tr><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td></td><td colspan="11">K | Sustainability</td></tr>
<tr><td>1</td><td>The scanner can be disassembled with simple tools such as a screwdriver and/or tweezers</td><td></td><td></td><td></td><td></td><td>M</td><td>Test</td><td>Pass</td><td>Designer</td><td>14-10-2022</td><td></td></tr>
<tr><td>2</td><td>Components can be replaced by the user to increase product lifespan</td><td></td><td></td><td></td><td></td><td>M</td><td>Test</td><td>Pass</td><td>Designer</td><td>14-10-2022</td><td></td></tr>
</table>

Appendix R: User Journeys

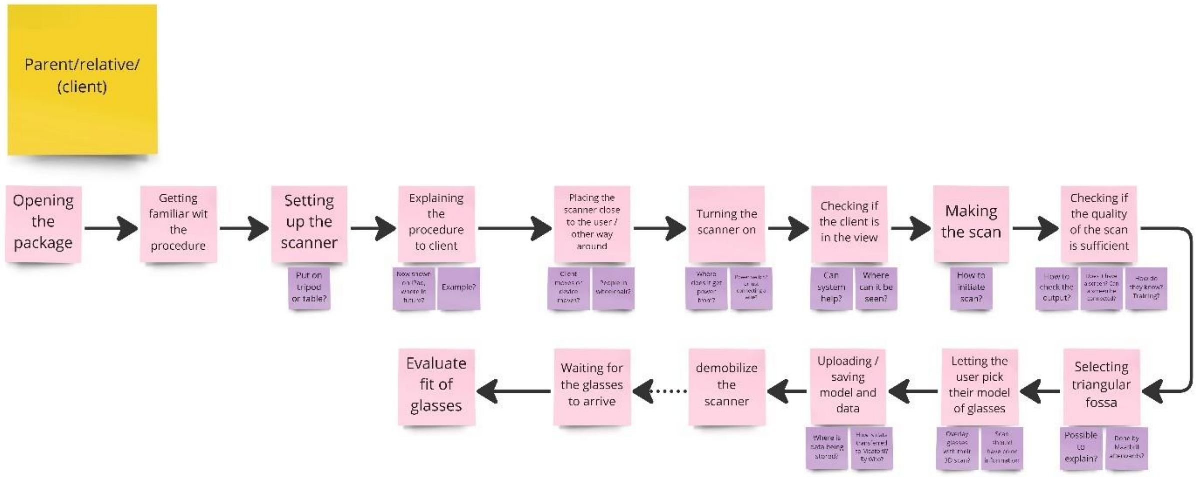
Scenario 1: Visiting a client at home

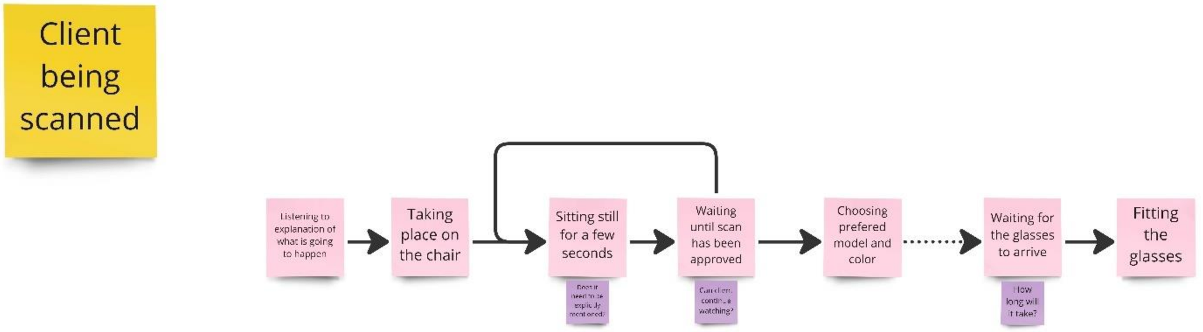


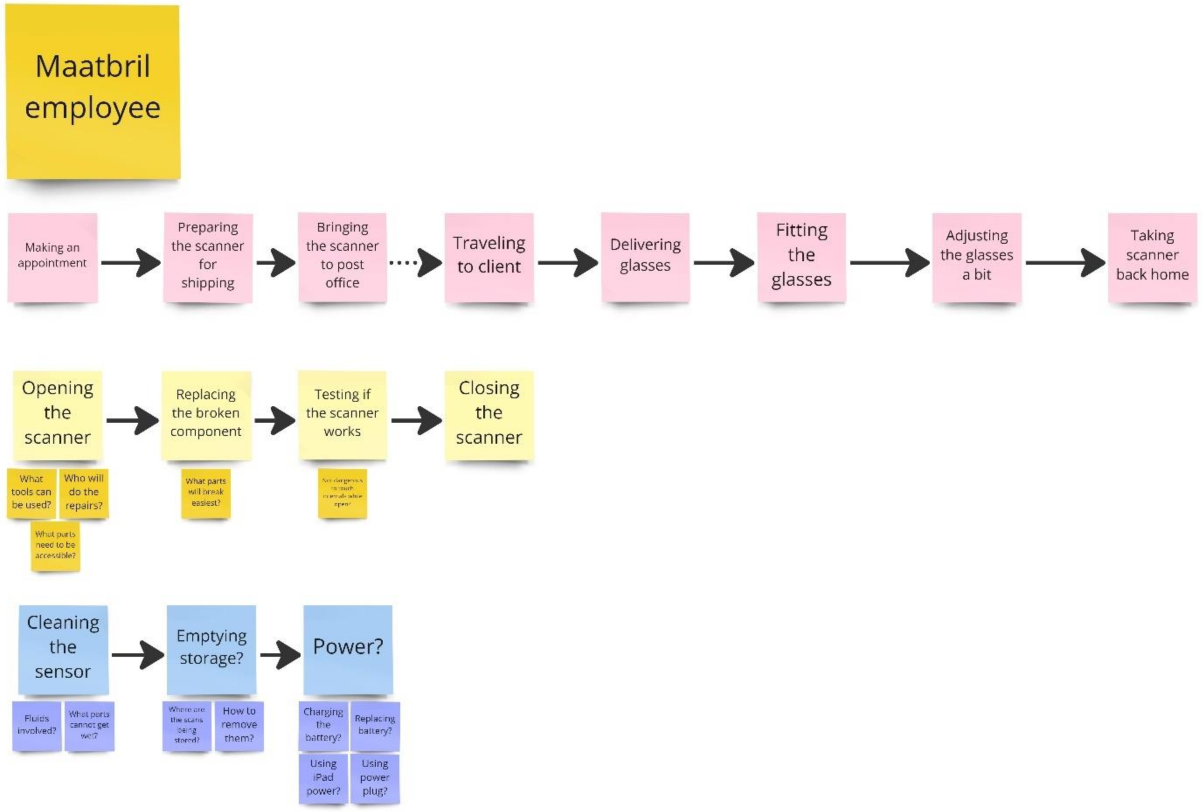
Scenario 2: Scan being taken at Healthcare Institution



Scenario 3: Scanner is sent to client's home address







Appendix S: Potential Use Cases

To find other potential use cases for the 3D Head Scanner, the main search areas that were looked into are ultra-personalised wearables and the medical field where 3D scanners are already being used for quite some applications[1]. Especially the latter provided many opportunities. A short explanation of the most interesting use cases and their requirements will be given in this chapter.

Ear protheses

Children with microtia[2] or anotia[3] often undergo surgery to 'fix' their ear. Since the microtia or anotia usually appears on only one of the ears[4] there is the opportunity to copy the ear that is fully developed[5] [6]. A 3D scan of the 'good' ear is made, mirrored and scaled. If needed some small changes are made before the 3D model is 3D printed from HDPE, see figure 1[7]. This 3D printed model will form the base of the new ear which and is implanted during surgery. After one or two surgeries, both ears will look similar to each other. Although the geometry that has to be scanned is only one of the ears, this geometry is usually quite complex and hard to reach, especially behind the ear. The hair and the shadows inside and behind the ear complicate the process.

Figure 1: Before and after ear reconstruction with 3D scanning

Respiratory mask for children

With the increasing amount of wildfires, the generally decreasing quality of the air around us or (a virus like) the Corona virus, respiratory masks are almost becoming a virtue[8] [9]. However, for children these e.g. N95-masks[10] usually don't fit very well, since they are one size fits all. Several companies have developed tailormade respiratory masks for children that involves 3D scanning of the face and 3D printing a perfectly fitting mask that can fit a standardized disposable filter[11]. The main area of interest are in this case the geometry

---

[1] Haleem, A., & Javaid, M. (2018). *3D Scanning Applications in Medical field: A Literature-based Review*. Elsevier. https://www.researchgate.net/publication/325489301_3D_Scanning_Applications_in_Medical_field_A_Literature-based_Review

[2] Birth defect of a baby's ear: external ear is small and not properly formed

[3] Birth defect of a baby's ear: external ear is missing completely, usually the internal ear is fine

[4] In 90% of the times it is only one ear, usually the right. Larger chance for boys than for girls

[5] CDC. (2019). *Facts about Anotia/Microtia*. https://www.cdc.gov/ncbddd/birthdefects/anotia-microtia.html

[6] Stanford Medicine. (2019). *Microtia - Stanford Children's Health - Stanford Medicine Children's Health*. https://www.stanfordchildrens.org/en/service/microtia/faq

[7] Artec3D. (2022). *How Dr. Sheryl Lewin uses Artec Space Spider to create beautiful new ears for microtia patients*. https://www.artec3d.com/cases/lewin-ear

[8] CDC. (n.d.). *Climate change decrease the quality of the air we breathe*. https://www.cdc.gov/climateandhealth/pubs/AIR-QUALITY-Final_508.pdf

[9] World Meteorological Organization. (2022). *Number of wildfires forecast to rise by 50% by 2100*. https://public.wmo.int/en/media/news/number-of-wildfires-forecast-rise-50-2100#:~:text=Climate%20change%20and%20land%2Duse,according%20to%20a%20new%20report.

[10] The most common particulate-filtering facepiece respirator that filters at least 95% of airborne particles.

[11] Artec3D. (2020). *Perfect fit. Protection. Comfort. This face mask has it all, thanks to 3D technology*. https://www.artec3d.com/cases/flo-mask

around the nose and mouth. Since the mask is usually flexible in some form or way, an accuracy of a few mm should suffice[12].

.

Figure 2: Custom respiratory mask (Left) and Non-invasive breathing mask (Right) designed with 3D scanning

Non-invasive breathing masks

When children are being treated in intensive care units, often their non-invasive breathing masks[13] don't fit very well, and leak oxygen. Although there are various sizes available, due to irregular head shapes- sometimes caused by trauma – the masks don't follow the contours of the head very well. In this case, the face of the kid is scanned and the mask will be designed around that 3D scan. Eventually the mask will be 3D printed from a flexible material. (Rosemijne Pigmans, PhD in non-invase breathing masks, at Amsterdam Medical Centre, personal communication,) The important parts are again the geometry around the nose and mouth and accuracy below 3 mm is not needed, since the mask can easily deform a bit due to the flexible material.

Custom in-earphones, ear plugs or hearing aids

Custom-made earphones have been in the market already for quite some time, however, the method how the 3D model is acquired is changing rapidly. Whereas before some silicon would be placed in your ear to be later recreated, the new trend is to make a 3D scan of the inner part of the ear. Often the user needs to do this himself/herself by using their phone to make a video of the geometry of their ear[14]. The geometry of the inner ear is then used to design the earphones or earplugs. But like mentioned before, the geometry of the ear is quite complicated to capture. A hybrid combination where a 3D scan is combined with a silicon model has also proven to be quite effective[15].

Figure 3: Custom made earplugs

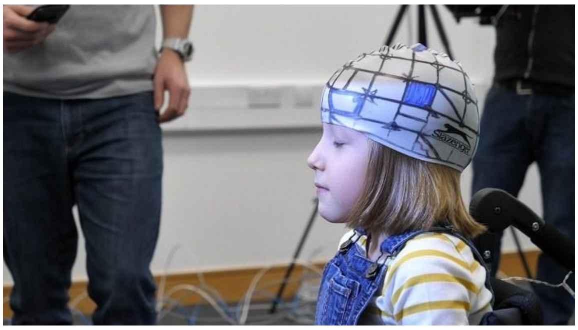


Figure 4: Scanning procedure for custom made helmets

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[12] Artec3D. (2020). Perfect fit. Protection. Comfort. This face mask has it all, thanks to 3D technology. https://www.artec3d.com/cases/flo-mask

[13] Breathing mask that doesn't make use of intubation where a tube is usually inserted into the trachea

[14] Formlabs. (2018). On-Demand Custom Earbuds, Manufactured With 3D Printing. https://formlabs.com/blog/custom-earbuds-manufactured-with-3d-printing/

[15] Hayoung Lee. (2016). Measurement and Application of 3D Ear Images For Earphone Design - Wonsup Lee, Hayoung Jung, Ilgeun Bok, Chulwoo Kim, Ochae Kwon, Teukgyu Choi, Heecheon You, 2016. https://journals.sagepub.com/doi/abs/10.1177/1541931213601244

Custom helmets for people with hydrocephaly

People with hydrocephalus[16] usually have problems fitting (riding) caps and/or helmets due to their large head shape[17]. Personalized helmets and other headwear are usually designed with help of a 3D scanner. However, the hair is usually hard to capture due to it consisting of very small, partially translucent, fibres that scatter the light[18]. As a result, it is often interpreted as noise by the scanner and therefore removed from the scan data. To counter this problem, a cap with marks can be worn over the hair to better capture the shape of the head. For this use case the required accuracy is not as critical as in the previous use cases, however, the scan should contain the complete geometry of the head[19].

Cranial scanning of babies

New-born babies can born with or develop an unevenly shaped head by sleeping too much on one side in the first few months of life. Although usually there are no implications for the internal brain, the visual look can be distressing to the parents. To check whether their baby is okay or if the baby should receive treatment, the shape of the babies head is being 3D scanned[20]. If needed, a special 'helmet' can be designed to reshape the baby's head. Luckily, in about 70% of the cases, the a-symmetry turns out to be less prominent than the parents expected[21] [22]. For this use case, capturing the shape of the head is more important than the actual dimensions. Special 3D scanners for this purpose do already exist, looking like a small crib where you lay the baby in to take the scan, as can be seen in figure 5. The STAR-scanner claims it will capture a 3D model of the infant's head within 2 seconds or less[23].

Figure 5: Special correcting helmet (Left) designed with help of cranial 3D Scanner for babies (Right)

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[16] Abnormal buildup of fluid in the ventricles (cavities) deep within the brain. This excess fluid causes the child's skull to expand since the skull seam is not closed as of yet

[17] HersenStichting. (2022). *Wat is een waterhoofd (hydrocefalie?) - Hersenstichting*. https://www.hersenstichting.nl/hersenaandoeningen/hydrocefalie/

[18] LMI Technologies. (2013). *Tips for 3D Face Scanning with Hair | LMI Technologies*. https://lmi3d.com/blog/tips-3d-face-scanning-hair/#:~:text=Scanning%20hair%20can%20be%20a,removed%20from%20typical%20scan%20data.

[19] Artec3D. (2022). *Creating custom 3D-printed children's helmets at Cerebra with Artec Eva*. https://www.artec3d.com/cases/creating-custom-3d-printed-childrens-helmets

[20] Shock, L. A., Greer, S., Sheahan, L. D., Muzaffar, A. R., & Aldridge, K. (2021). Consistency of Cranial Shape Measures Obtained From Laser Surface and Computed Tomography Imaging. *Journal of Craniofacial Surgery*, *32*, 2763–2767. https://doi.org/10.1097/scs.0000000000007885

[21] Cranial Therapy Centers. (2019). *STARscanner™ | Advanced Scanning of Baby's Head Shape | Cranial Therapy Centers*. https://cranialtherapycenters.com/starscanner/

[22] Novita Tech. (2022). *Cranial Scanning | NovitaTech*. https://novitatech.com.au/cranial-scanning/

[23] Orthomerica. (2022). *STARscanner – Orthomerica Products, Inc.* https://www.orthomerica.com/products/starband/starscanner/

Plastic surgery simulation

With the amount of plastic surgeries ever increasing, nose jobs and facelifts are one of the most performed surgeries[24]. Plastic surgeons now sometimes make 3D scans of their clients' faces, to be able to show them how they could look after the procedure by means of 3D printed masks. Not only is this a nice gimmick to convince the client to perform the surgery, it also makes that the expectations are more realistic. The area of interest is mainly the face, but in some cases the ears are part of the procedure as well[25].

Figure 6: 3D printed mask to preview the results of plastic surgery

Maxillofacial surgery

Examples of maxillofacial surgery[26] that could require 3D scanning are dental implant planning, airway space evaluation, pre-orthodontic procedures, pre-corrective jaw surgery and bone grafting treatments[27]. However, it is hard to capture with structured light scanners, laser scanners or other non-radiation scanning methods. Therefore this use case might not be the best fit to the 3D that will be designed in this graduation project.

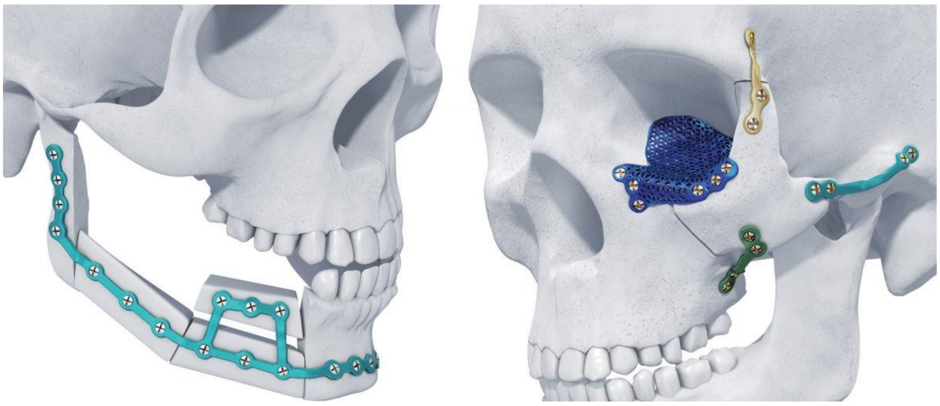

Figure 7: Examples of applications for 3D scanning in maxillofacial surgery

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[24]The Surgical Clinic. (2022). *Plastic Surgery Trends for 2022 That You Need to Know About*. The Surgical Clinic. https://thesurgicalclinics.com/plastic-surgery-trends-that-you-need-to-know-about/#:~:text=And%20as%20the%20ASPS%20reports,the%20popularity%20of%20plastic%20surgery.

[25] Artec3D. (2022). *Plastic surgeon uses Artec Eva to show patients their future faces*. https://www.artec3d.com/cases/3d-scanning-faces-to-3d-print-plastic-surgery-masks

[26] Surgery in or around the mouth and everything that is connected to it. The upper and lower jaw (the maxilla and mandible), the cheekbones (the facial bones), the jaw joints (the TMJs), and the neck.

[27] Oxford Surgery Centre. (2022). *3D Imaging - Oxford Oral & Maxillofacial Surgery Centre*. https://www.oxfordsurgerycentre.com/3d-imaging/

3D scanning in preparation of an excision

In excision[28], large birthmarks on the head are usually cut away under (local) anaesthesia. To fill the newly created gap, as preparation a small inflatable balloon is inserted under the skin. This balloon is slowly filled with gas to make the skin expand enough to later cover the created gap[29]. The amount of gas that is needed is now being (educationally) guessed, however initiatives within the hospital arise to make a 3D scan of the head and of the birthmark to be able to calculate the exact amount of gas that will be needed. (Rosemijne Pigmans, personal communication, December 5, 2022) What makes this use case a bit complicated is that these birthmarks are usually located at the head. Although the hair will locally be shaved away, still challenges may occur in scanning of the hair.

Figure 8: Example of large birthmark that is cut away in excision

Fitting of glasses

For several glasses brands their new models come with an app or system in some sort to make a 3D scan of the user's face, both augment how the glasses would look like on the user's face, and to make sure that the best-fitting model is being selected[30]. Some brands even go as far as 3D printing custom glasses to ensure the ideal fit[31]. Next to that, there are companies like Maatbril that design glasses for people that are not able to wear 'regular' glasses due to some sort of physical pathology. In this use case the eyes, nose and distance to the ears are important to have scanned[32].

Another market to tap into are custom-fit sports glasses, for example for skiing, snowboarding, mountain biking or (road) cycling and/or running. These sports all require headwear with good fits to not lose the glasses during their activities.

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[28] Treatment that surgically removes malignant moles, lesions and tumors from the skin along with a healthy margin around the tumor.

[29] Slingeland Ziekenhuis. (2022). *Aangeboren moedervlekken - Slingeland Ziekenhuis*. https://plastischechirurgie.slingeland.nl/aangeboren-moedervlekken-1#:~:text=Behandeling-,Excisie,bij%20voorkeur%20onder%20narcose%20verricht.

[30] Sfered. (2021). *Frame & I | Sfered*. https://sfered.nl/frameandi/

[31] Roger Bacon Eyewear. (2017). *Glasses*. https://rogerbacon-eyewear.com/glasses/

[32] Maatbril. (2022). *Over ons*. https://maatbril.nl/maatwerk/

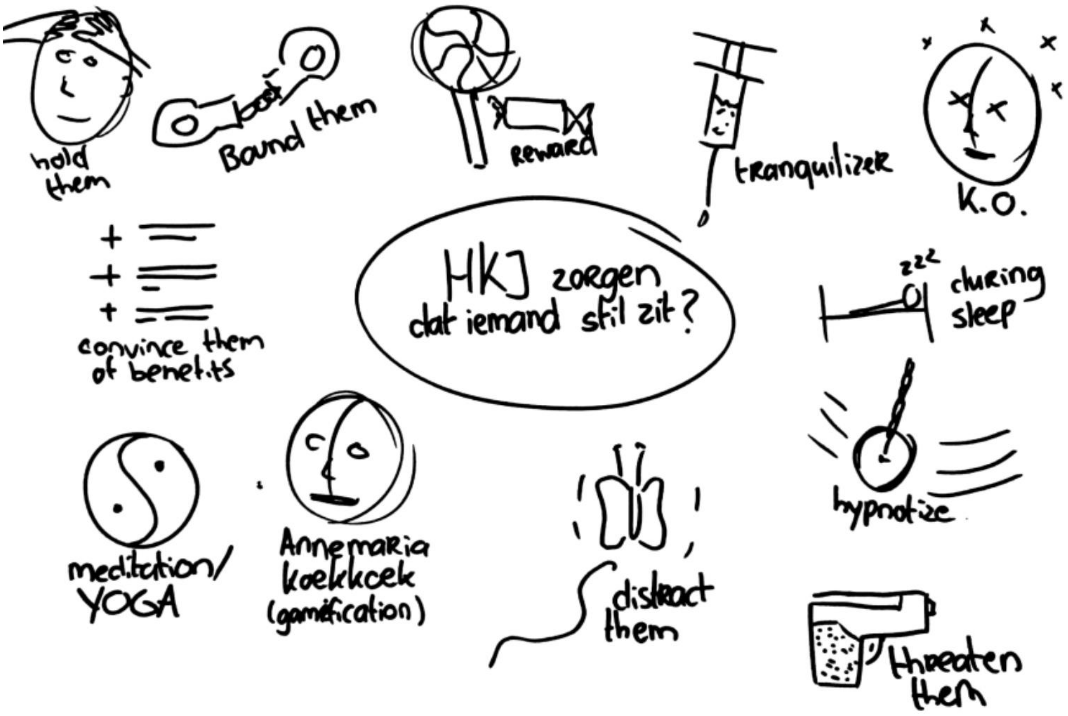
Figure 9: Example of custom-made glasses with help of 3D scanning

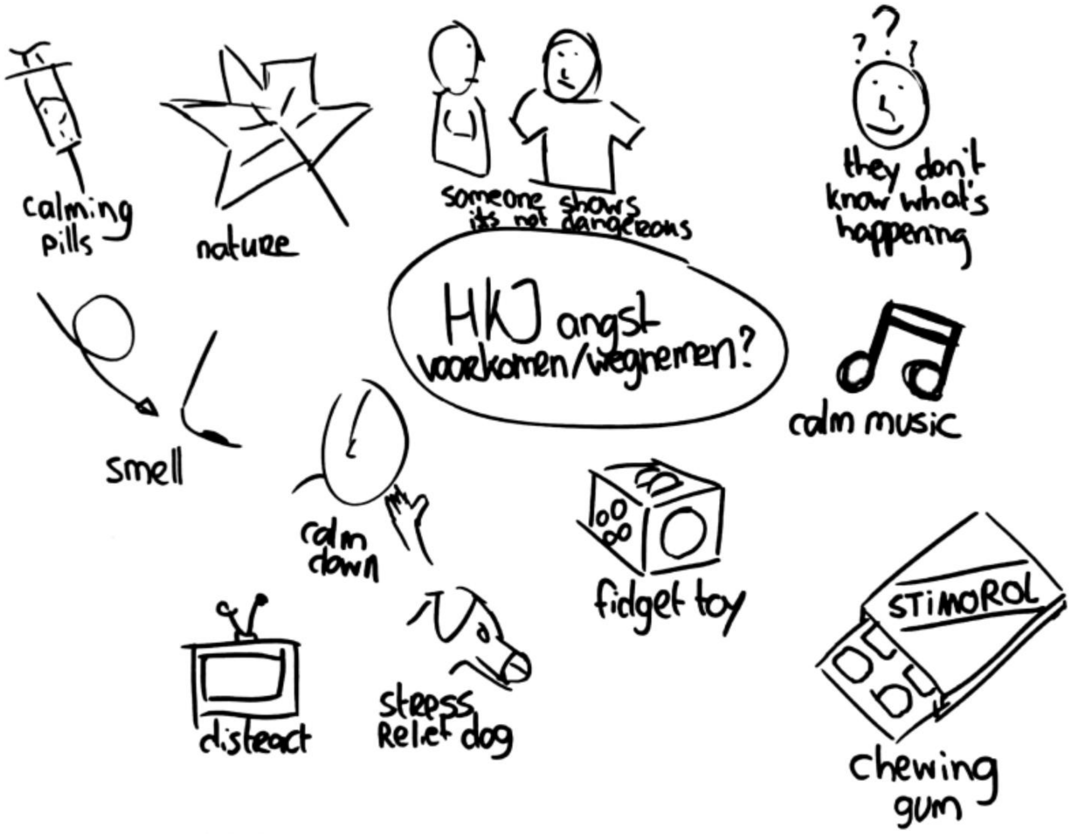
Conclusions

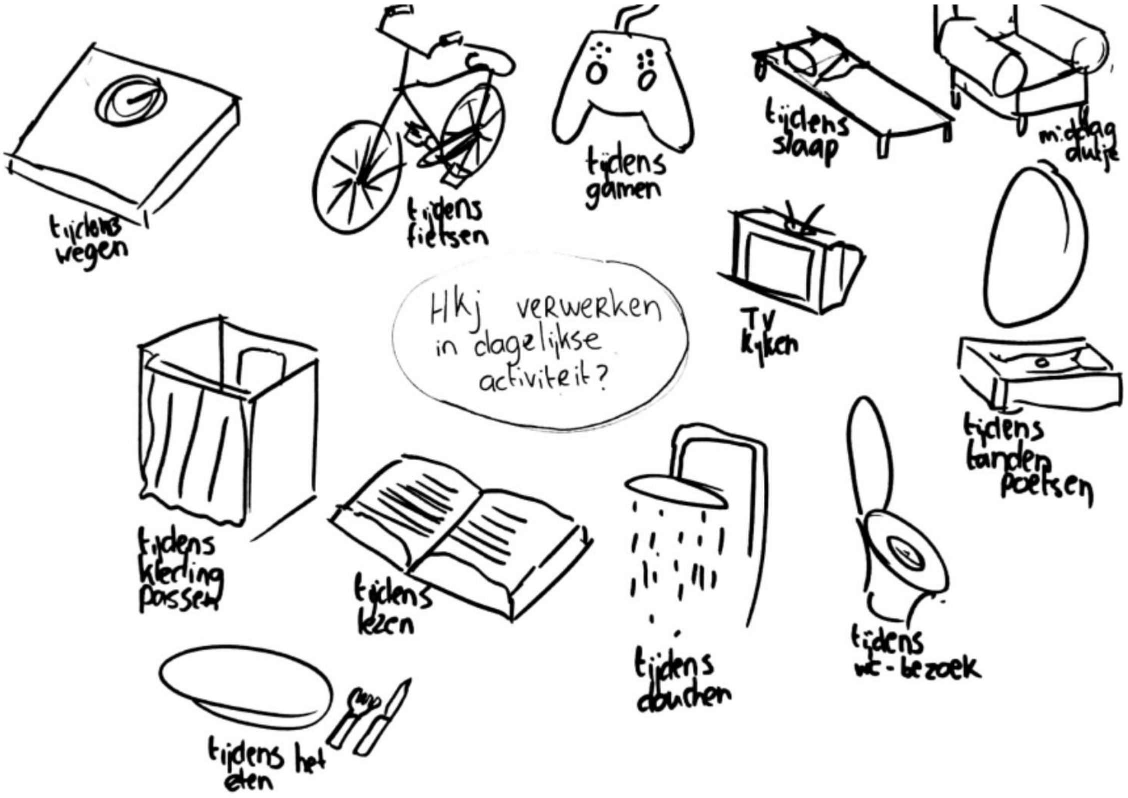
Plastic surgery, masks and custom made glasses are use cases that relatively easy to implement the 3D Head Scanner for. Since they cover practically the same regions of the head as while measuring the head for personalized glasses. Moreover, it has proven to be very complicated to make 3D scans of the inner ear, mainly because of complex geometry and presence of shadow.

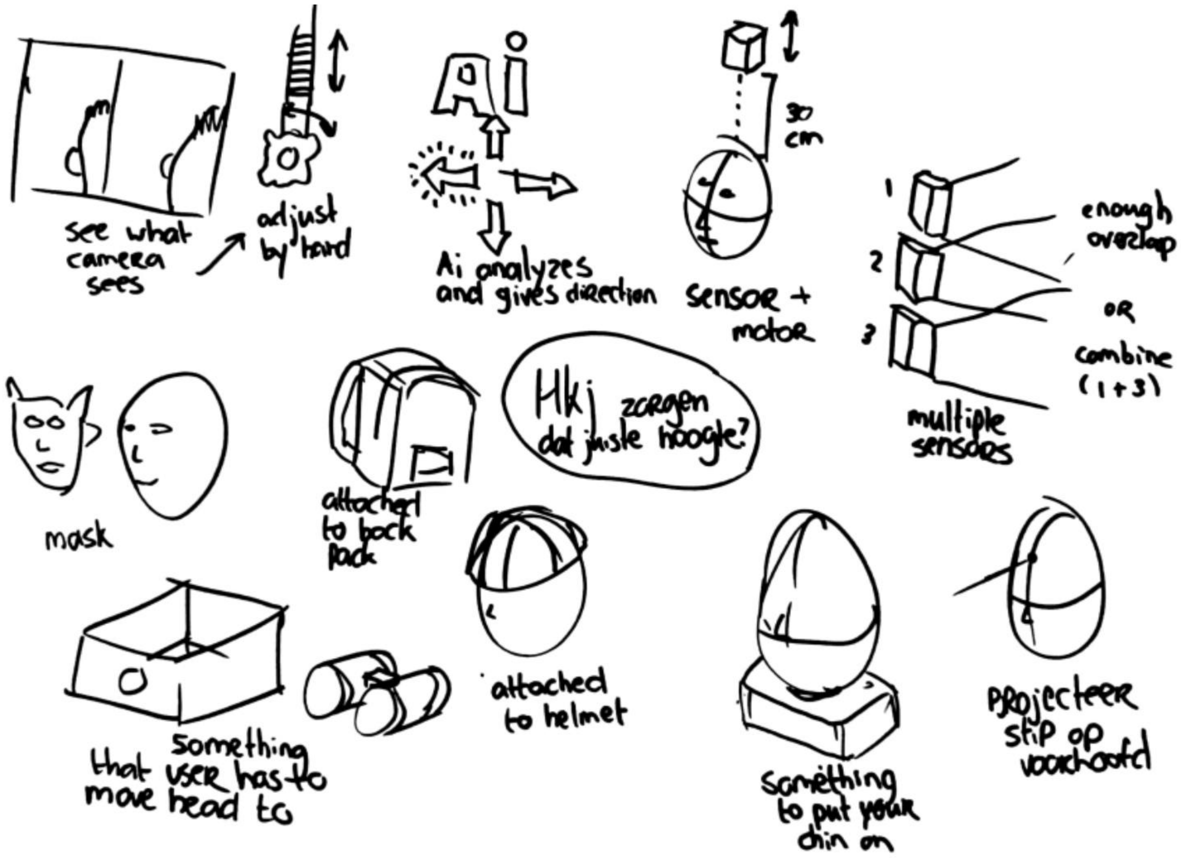
Appendix T: Ideation

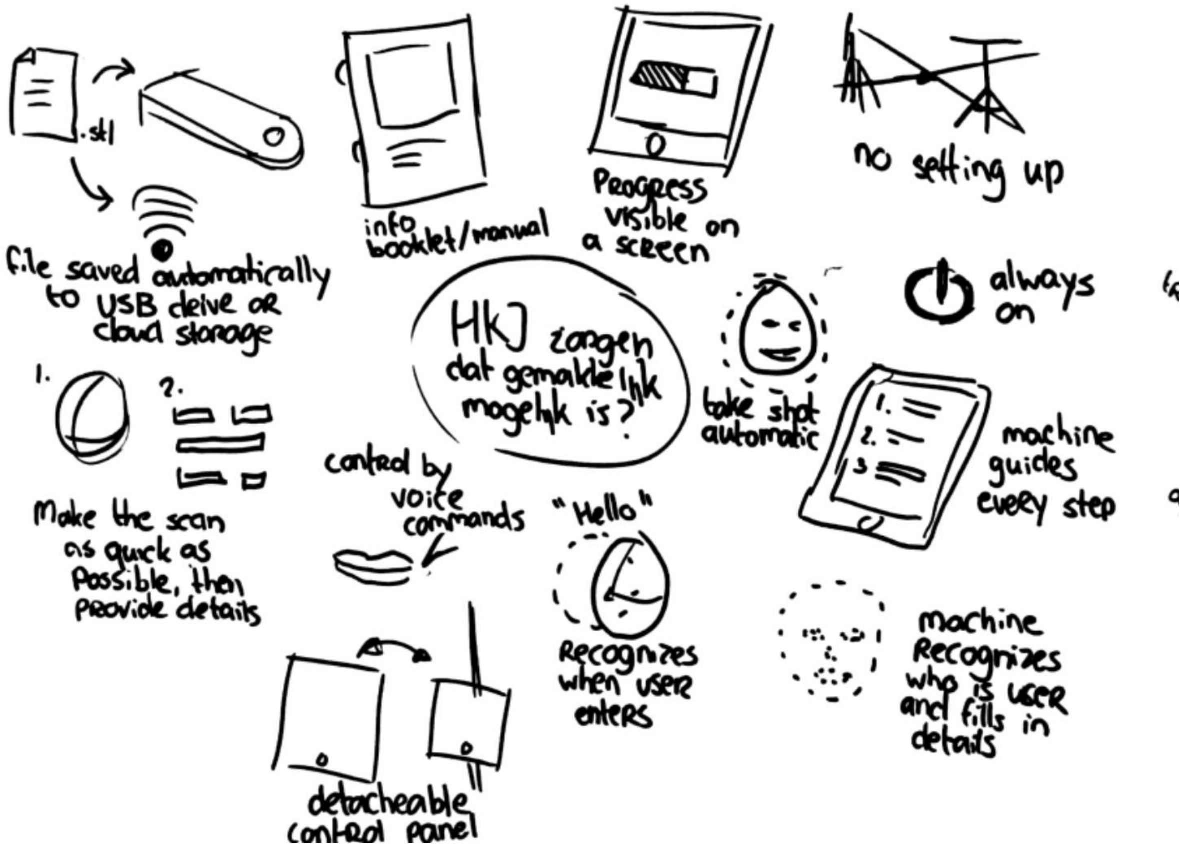
T.1 How To's

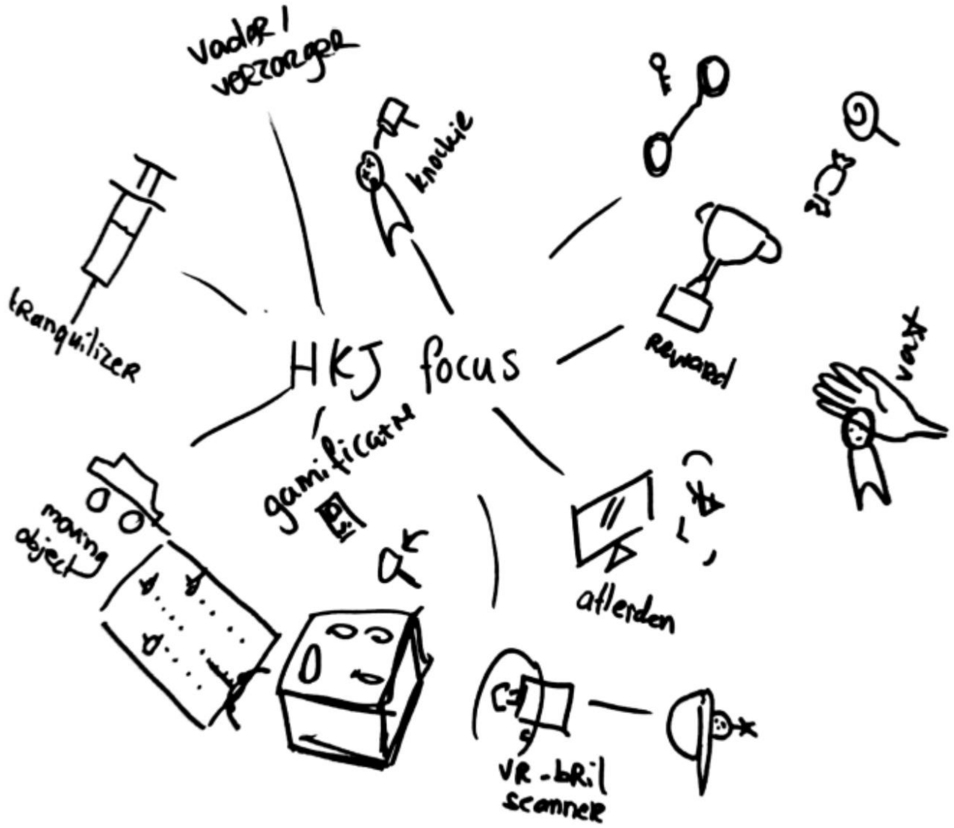


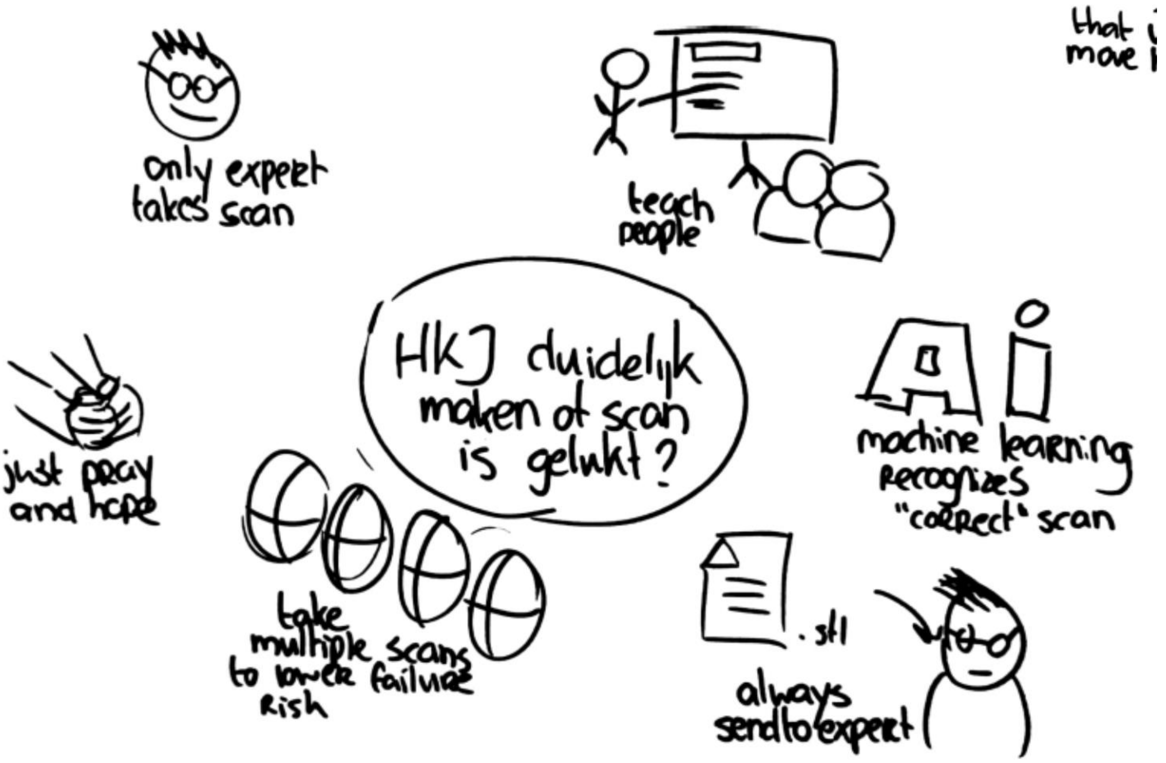



Hkj verwerken in dagelijkse activiteit?
tijdens wegen
tijdens fietsen
tijdens gamen
tijdens slaap
middag dutje
TV kijken
tijdens tanden poetsen
tijdens kleding passen
tijdens lezen
tijdens douchen
tijdens wc-bezoek
tijdens het eten

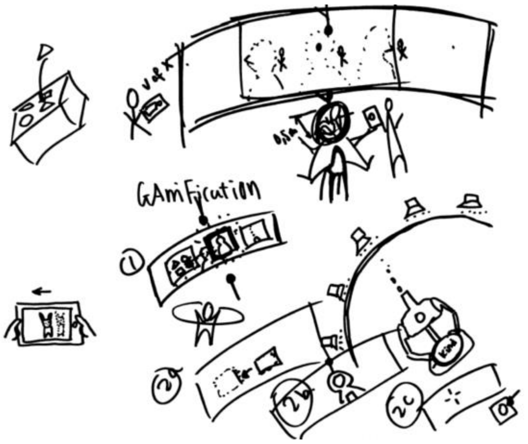

see what camera sees
adjust by hand
Ai
Ai analyzes and gives direction
30 cm
sensor + motor
1
2
3
enough overlap
OR
combine (1+3)
multiple sensors
mask
attached to back pack
Hkj zorgen dat juiste hoogte?
attached to helmet
something that user has to move head to
something to put your chin on
projecteer stip op voorhoofd

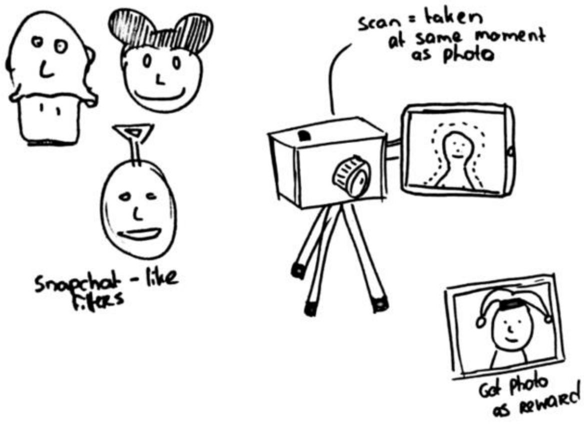

.stl
file saved automatically to USB drive or cloud storage
info booklet/manual
Progress visible on a screen
no setting up
always on
HKJ zorgen dat gemakkelijk mogelijk is?
take shot automatic
1.
2.
3
machine guides every step
1.
2.
Make the scan as quick as possible, then provide details
control by voice commands
"Hello"
Recognizes when user enters
machine recognizes who is user and fills in details
detacheable control panel

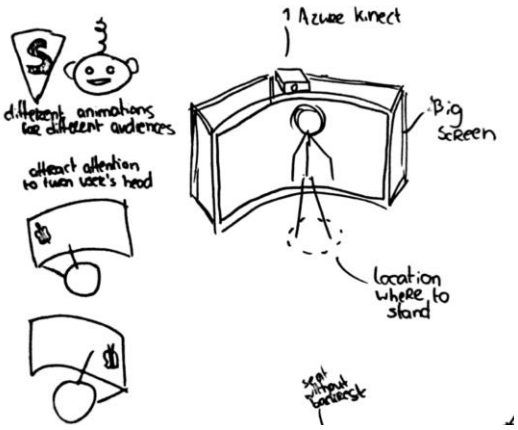

vader / verzorger
knockie
tranquilizer
HKJ focus
gamification
Reward
vast
moving object
afleiden
VR-bril scanner

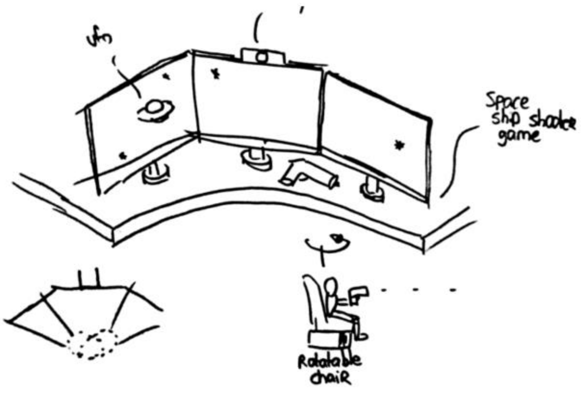


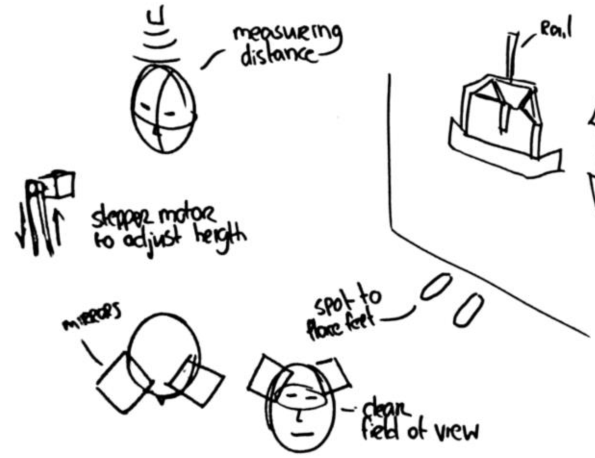
T.2 Product ideas



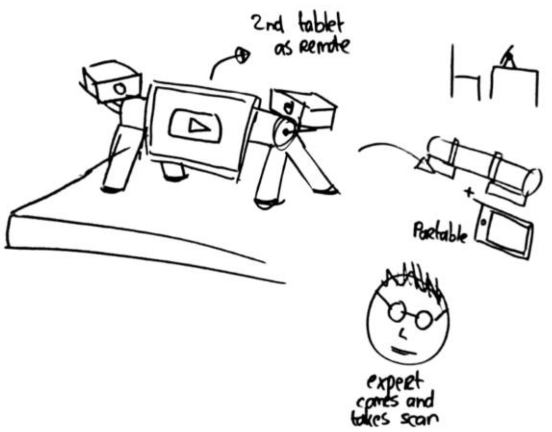




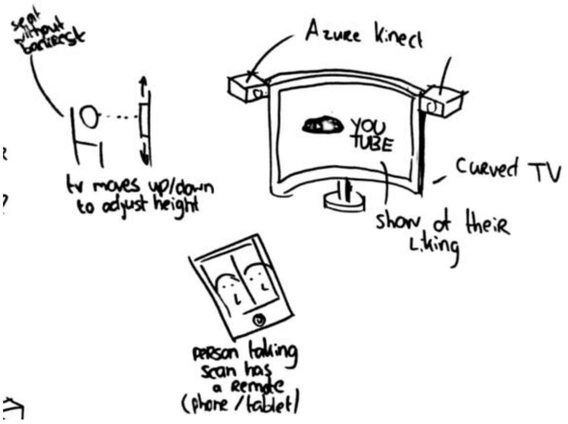


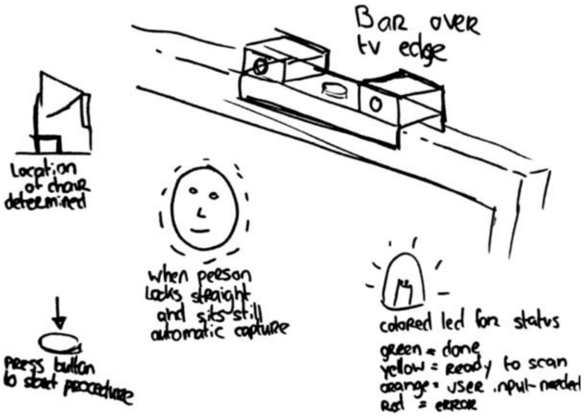

measureing distance
Rail
stepper motor to adjust heigth
spot to place feet
mirrors
clear field of view


integrate in Racing simulator

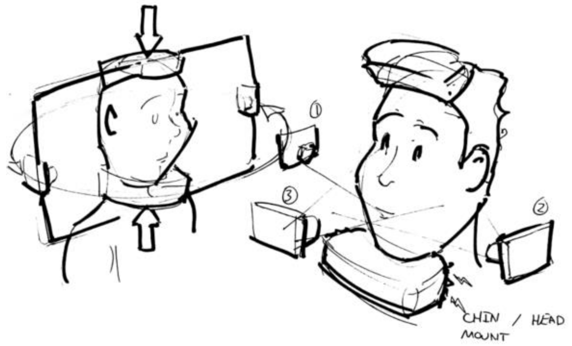

2nd tablet as Remote
+
Portable
expert comes and takes scan

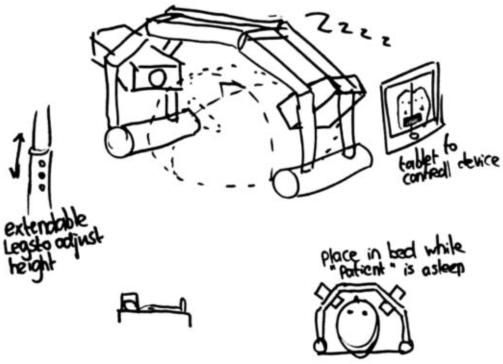

fancy relaxing chair
massage chair
Azure
mirror
? TV ?
scanner mounted to roof
rotating mirrors to adjust for height


seat without backrest
Azure Kinect
YOU TUBE
Curved TV
tv moves up/down to adjust height
show of their liking
person taking scan has a remote (phone / tablet)


Bar over tv edge
Location of chair determined
when person looks straight and sits still automatic capture
press button to start procedure
colored led for status
green = done
yellow = ready to scan
orange = user input needed
red = error

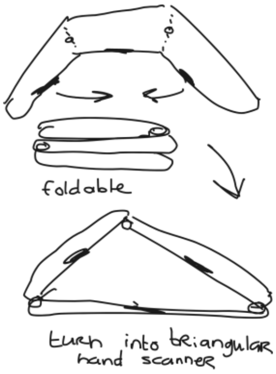

Combine with hair dryer
2 mirrors on side of dryer

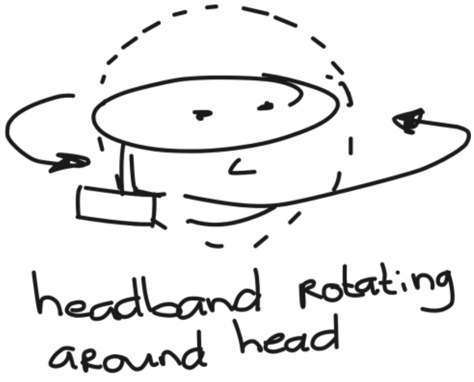

①
③
②
CHIN / HEAD MOUNT

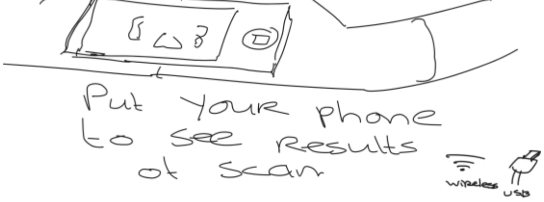

zzzz
extendable Legs to adjust height
tablet to controll device
place in bed while "patient" is asleep


Keep eyes free


use as feet to scan on bed


foldable
turn into triangular hand scanner


headband rotating around head


Put your phone to see results of scan
wireless
USB


Pet + Ketting
+

T.3 Concepts

From the generated ideas, 3 product concepts were derived, with the main focus on interaction with the user. The concepts and vision behind it will be briefly explained in this Appendix.

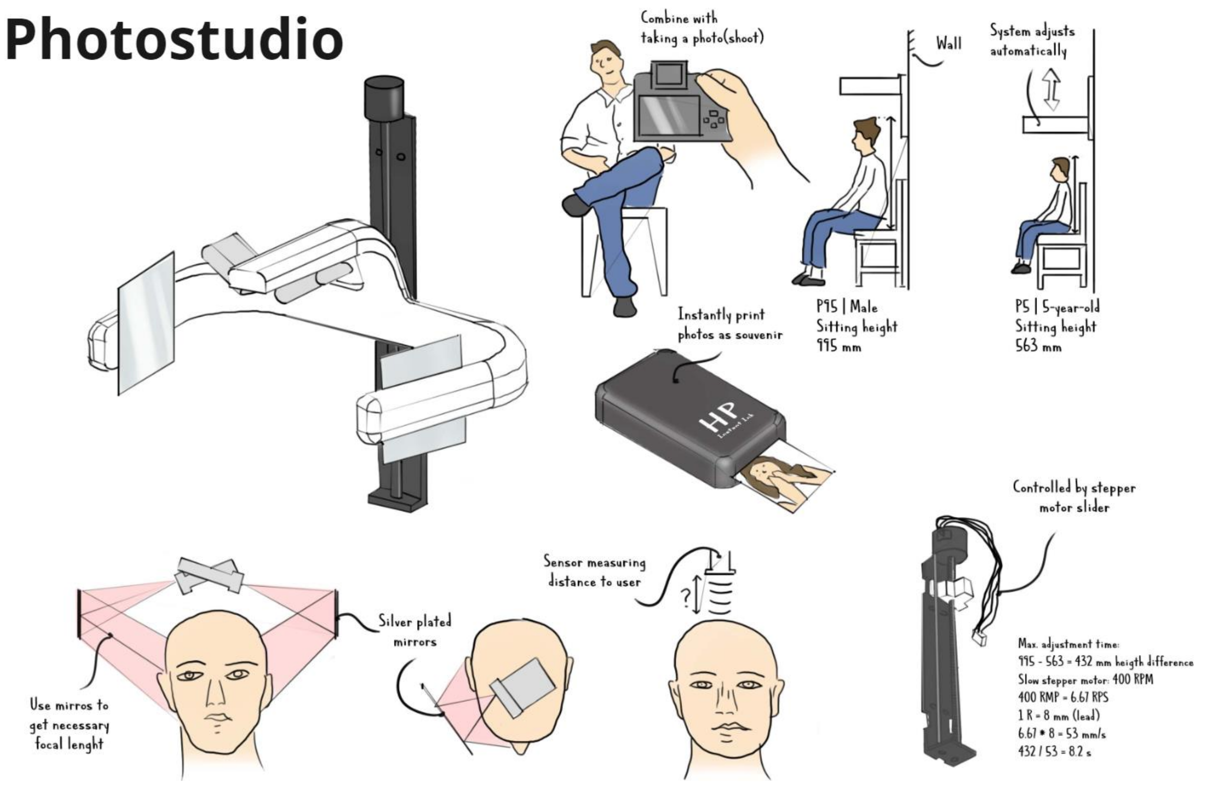


Figure 1: Photostudio concept

With the *Photostudio* concept, the client will be placed on a seat to take a nice photo that will be printed immediately afterwards. The idea is that this will give the client a motivation to sit still for a little bit, at least long enough the capture the 3D scan. When the client is seated, the scanning system automatically adjusts to the client’s sitting height by measuring the distance with a sensor. The system is mounted to a stepper motor slider that will automatically adjust the position of the 3D Head Scanner. The system makes use of mirrors to make sure that the minimal working distance can be reached without making an unnecessarily large product and by doing so, it is not needed to lower the product next to the clients head, but it can stay above the head. This means that the user will not be able to see the 3D Head Scanner, to try to make it feel like as if it was never there.

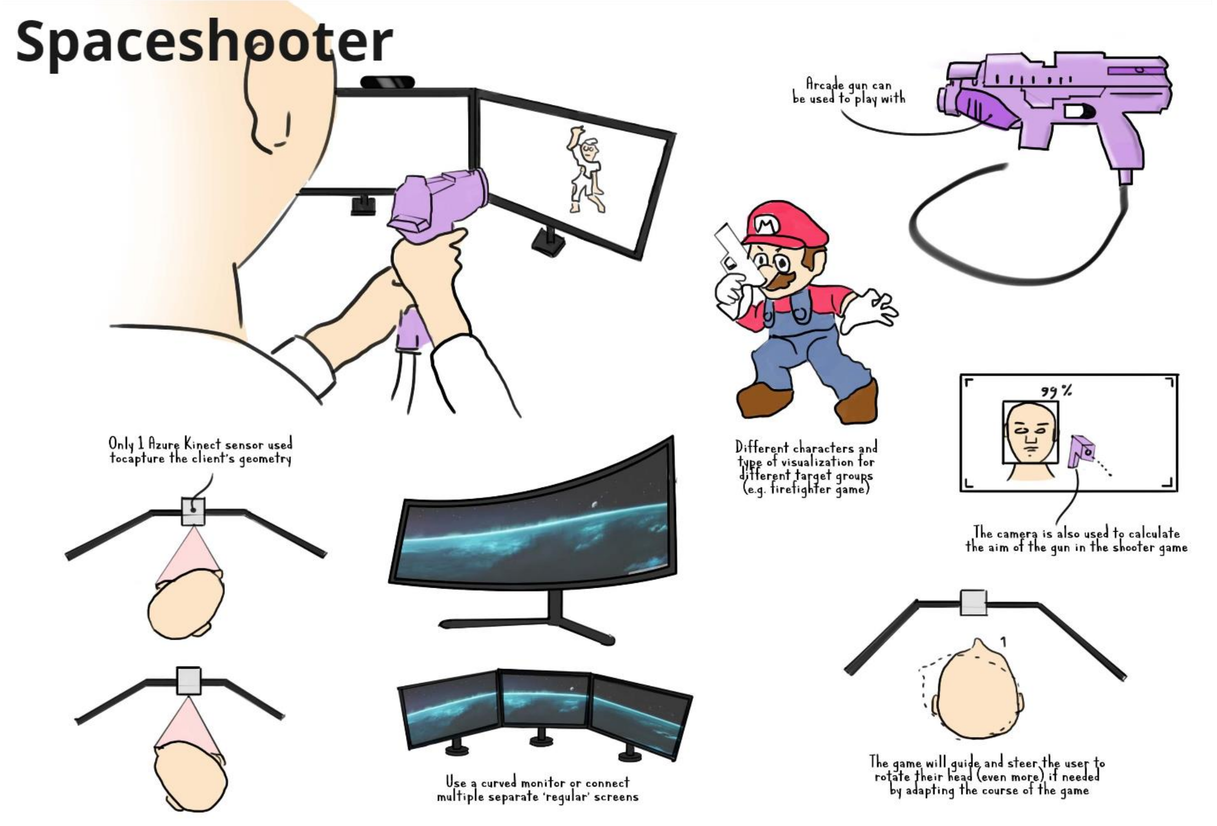


Figure 2: Spaceshooter concept

In the *Spaceshooter*, the user is more actively involved in the 3D scanning procedure. A large curved screen or multiple ‘regular’ screens placed next to each other are placed in front of the client. The client can then either play some sort of game e.g. space shooter or take part in some immersive experience, depending on his/her interests and capabilities. The game and immersive experience are setup in such a way that the client will rotate his/her head sufficiently to make sure that all required geometry is being captured with a single 3D sensor, which would significantly save in cost. For attributes, e.g. weapons, a look could be given to have this is managed in the machines in arcade halls.

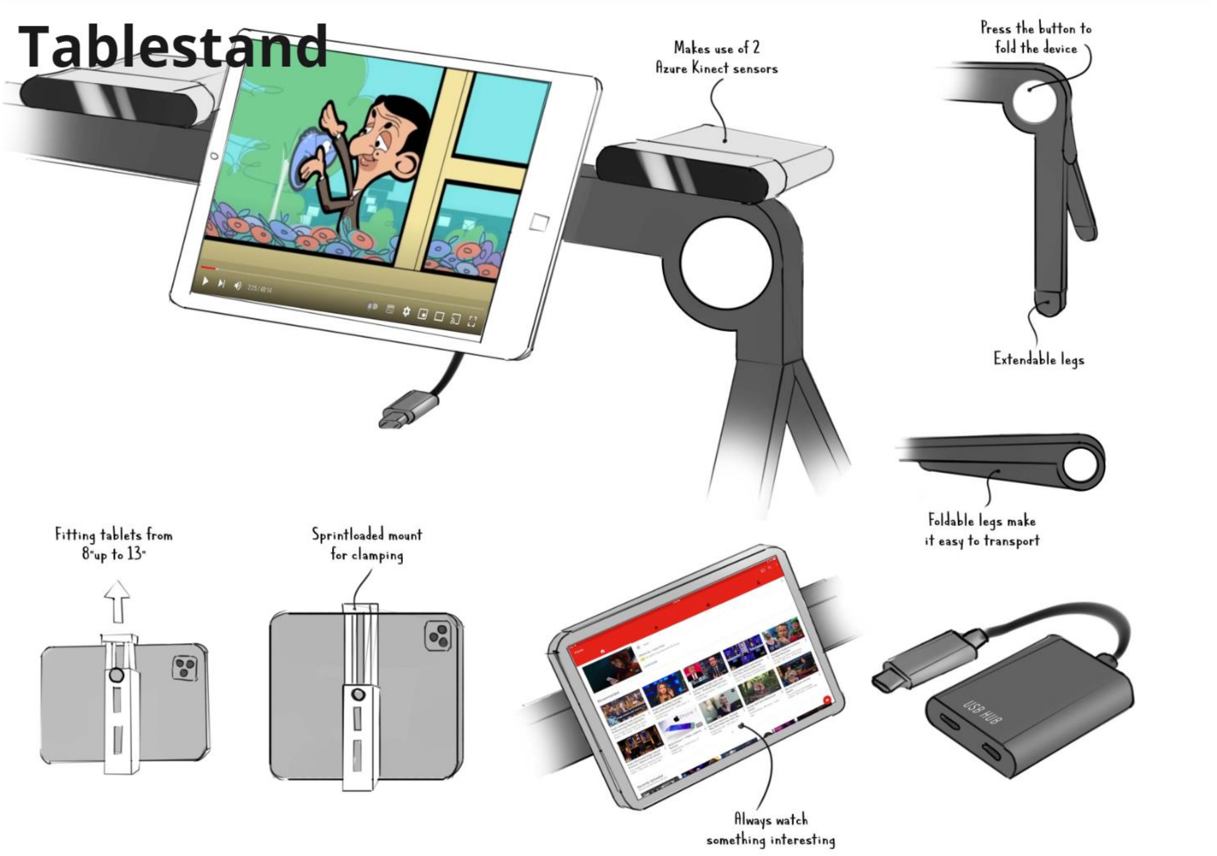


Figure 3: Tablestand concept

With the *Tablestand*-concept, the client is distracted by a video playing on a mobile device or tablet, e.g. via YouTube. This means that the content can be tailored to always display something that that particular client is interested in, which hopefully results in a client that is focussed to the tablet, and sits still. The system is foldable to easily carry it around and contains a universal tablet mount so that any mobile device available at the location can be used. The system implements two 2D sensors located on both sides of the mobile device which are placed under a slide angle, to capture just enough of the side of the head, whilst being as small as possible.

Appendix U: Observations and findings of roleplay sessions

Photostudio

- Scanner moves downwards, client initially doesn't really notice device
- When motors move and make sound, client looks upwards because he hears something
- Has a scare reaction because he didn't expect device to be so close to the head
- Downwards movement of Head scanner was experienced as scary because you don't know if it really will stop in time or what it is doing, especially since it stops so close above your head
- If client would try to stand up, hitting the head is a danger + potential damage to scanner
- The range of the stepper motor slider is probably not large enough, or would take a very long time, especially when the system needs to move so far that the client can stand up

A short brainstorm to improve the interaction/concept was performed with the most important ideas being:

- Use a pully-belt system since it's faster and easier to overcome large(r) distances. Also, this means that the motor can be placed further away, so that the sound that it generates is not noticeable for the user
- Put up some music in the room so that the client won't hear the motors moving
- Remove the motors from the device and let the caretaker or client adjust it by hand. It could be something that lands on the shoulders of the client, however, the whole idea of the client not noticing the scanner is then out of the window
- The scanner could be used as part of the photo studio. Maybe a hat or some other attribute is mounted to it that will appear in the photo that the user receives.

Spaceshooter

- Client needs to follow an object that is moving:
    - If the object moves too slow, the client might follow the object with the eyes instead of turning his/her head
    - If the object moves quickly, the client will be more tempted to move his/her head instead of the eyes
- Objects appear and disappear at different locations:
    - Works quite well, especially because of the 'element of surprise'.
    - If the object appears too far on the side, the client might not see it at all. Maybe intermediary steps are required, but again the danger of only moving the eyes is present when intermediary steps are present.
- Client was quite focused on the game, this made that he didn't have a 'resting' expression and expressions changed over the course of the game.
- When attributes are present in the concept, such as a gun, this might be in the way between the 3D scanner and the client's face.
- Having such a big screen so close by can be quite overwhelming, especially for people with mental disabilities

Figure 1: Roleplay activities with fellow students to test different interaction scenarios

Tablestand

- Scenario where Maatbril visits the client at their house:
  - When sitting in front of the client, it is very distracting and strange, since an unknown person is looking at you the whole time
  - When sitting next to the client, it feels like he/she is invading the personal space of the client, especially since the focus is on the user and he/she will regularly turn the head to check out the client and the 3D head scanner
  - Sitting at the head of the table (90 degrees rotated from client) it feels more natural. Possible to check out the client without making it feel forced
  - Wiring might need extra attention, possibly might look like some sort of Frankenstein model
- Scenario where client is scanned at health institution:
  - Since the device will be mainly stationary, a nice and integrated solution could be made, especially to conceal wiring
  - Similar experience as previous scenario
- Scenario where 3D scanner is sent to client's house:
  - Would be hard to 'control' both the 3D scanner and the kid, especially when alone.
  - Nice that it's your own environment where the client is used to and nobody unknown is present
  - Aligning the scanner is a bit complicated with the two views of the camera's, might need a different solution
  - Maybe an underlayer needs to be included that explains how and where to put the 3D scanner based on the location of the user/edge of the table
  - Process of selecting the triangular fossa is not clear enough. What exactly is it? How precise should it be? Why can't it be done afterwards or by Maatbril?

A short brainstorm to improve the interaction/concept was performed with the most important ideas being:

- Add extra screen to the laptop of the user on the back side so just one device can be used instead of two.
- Many people have a tablet at home, integrating only a mount is sufficient and will save a lot of cost

- To make it easier for transport, the device can be fold in the middle as well
- Instead of the parents doing the scan, it might be nice to have a digital meeting with a Maatbril expert, he can guide through the process and/or take the scan even so that the parents can focus on the client.
- Another idea for aligning the 3D Head Scanner is to place a regular camera in the middle of the device, this way it should be a lot easier to align the system to the client

Appendix V: Concept evaluation and selection

The main criteria used in the selection process are design complexity, 3D scan performance, adaptability, financial cost and user comfort. These criteria are derived from the design drivers that have been mentioned in chapter 3.2. A brief explanation of their contents and relevance will be given in this chapter as well as a rating for the different concepts.

Design complexity

A simpler design is usually easier to produce and could potentially save costs. Factors to take into account are e.g. the number of components, number of functions the design must perform, design tools that are required to make design, and if the systems has complex mechanisms and/or electronic sensors included.

Performance

When evaluating the 3D scanning performance, it is easiest to look at the accuracy the 3D Head Scanner is able to achieve. However, also the capturing speed and risk of failure are important. The latter is especially high when the scans are not captured simultaneously.

Adaptability

By adaptability the capability of the device to function under varying conditions and with different users is meant. Next to that, the size of the 3D head scanner, ability to retract and modularity are taken into account.

Financial cost

Under financial cost not only the estimated cost of the physical prototype will be taken into account, but also the cost to develop (digital) resources that are needed to provided the intended user experience and interaction.

User comfort

When thinking of comfort, both comfort for the person taking the scan and for the person that is being scanned are meant. Factors to think of are the number of actions the person taking the scan has to make, but also time of setting up and retracting the device are important. At the same time is the user experience for the client of utmost importance.

Different weights were given to the different criteria, based on their importance. The different concepts were given a rating on scale 1-10 for these criteria and the total scores have been calculated as can be seen in Table 1.

		Photostudio		*Spaceshooter*		*Tablestand*	
Criteria	Weight	Score	Total	Score	Total	Score	Total
Design compexity	20	5	100	6	120	9	180
Performance	25	6	150	4	100	7	175
Adaptability	15	7	105	3	45	9	135
Financial cost	5	4	20	7	35	5	25
User comfort	35	6	210	8	280	7	245
Total			**585**		**580**		**740**

Table 1: Evaluation of the concepts based on the design drivers

As can be seen from the table, the *Photostudio* concept and the *Spaceshooter* concept have almost the same score, but they are outperformed by the *Tablestand*, especially in terms of design complexity and adaptability. It's a simple physical device with the simplest interaction with the client. Only in terms of financial cost it does not score very high, but the main reason for that is the fact that only one 3D sensor is present in the *Spaceshooter* concept and is something that will be very hard to significantly improve without changing the entire concept. That is why it was decided to continue with this concept.

Appendix W: Python code Camera Alignment test

Option 1: center camera with oval

In [1]:

```
import cv2
import mediapipe as mp
import numpy as np

mp_face_mesh = mp.solutions.face_mesh
face_mesh = mp_face_mesh.FaceMesh(min_detection_confidence=0.5,
min_tracking_confidence=0.5)
cap = cv2.VideoCapture(0)

while 1:
    try:
        success, image = cap.read()

        # Flip the image horizontally for a later selfie-view display
        # Also convert the color space from BGR to RGB
        image = cv2.cvtColor(cv2.flip(image, 1), cv2.COLOR_BGR2RGB)

        # To improve performance
        image.flags.writeable = False

        # Get the result
        results = face_mesh.process(image)

        # To improve performance
        image.flags.writeable = True

        # Convert the color space from RGB to BGR
        image = cv2.cvtColor(image, cv2.COLOR_RGB2BGR)

        img_h, img_w, img_c = image.shape
        face_3d = []
        face_2d = []

        if results.multi_face_landmarks:
            for face_landmarks in results.multi_face_landmarks:
                x1 = face_landmarks.landmark[232].x
                x2 = face_landmarks.landmark[454].x
                y1 = face_landmarks.landmark[10].y
                y2 = face_landmarks.landmark[152].y
                dx = x2-x1
                dy = y2-y1

            for face_landmarks in results.multi_face_landmarks:
                for idx, lm in enumerate(face_landmarks.landmark):
                    if idx == 33 or idx == 263 or idx == 1 or idx == 61 or
idx == 291 or idx == 199:
                        if idx == 1:
                            nose_2d = (lm.x * img_w, lm.y * img_h)
                            nose_3d = (lm.x * img_w, lm.y * img_h, lm.z *
8000)

                        x, y = int(lm.x * img_w), int(lm.y * img_h)
```

```
                    # Get the 2D Coordinates
                    face_2d.append([x, y])

                    # Get the 3D Coordinates
                    face_3d.append([x, y, lm.z])

                # Convert it to the NumPy array
                face_2d = np.array(face_2d, dtype=np.float64)

                # Convert it to the NumPy array
                face_3d = np.array(face_3d, dtype=np.float64)

                # The camera matrix
                focal_length = 1 * img_w

                cam_matrix = np.array([ [focal_length, 0, img_h / 2],
                                        [0, focal_length, img_w / 2],
                                        [0, 0, 1]])

                # The Distance Matrix
                dist_matrix = np.zeros((4, 1), dtype=np.float64)

                # Solve PnP
                success, rot_vec, trans_vec = cv2.solvePnP(face_3d,
face_2d, cam_matrix, dist_matrix)

                # Get rotational matrix
                rmat, jac = cv2.Rodrigues(rot_vec)

                # Get angles
                angles, mtxR, mtxQ, Qx, Qy, Qz = cv2.RQDecomp3x3(rmat)

                # Get the y rotation degree
                x = angles[0] * 360
                y = angles[1] * 360

                #See where the user's head tilting
                if x1 < 0.43:
                    text = "Move 3D scanner left"
                elif x2 > 0.7:
                    text = "Move 3D scanner right"
                elif y1 < 0.3:
                    text = "Turn 3D scanner upwards"
                elif y2 > 0.8:
                    text = "Turn 3D scanner downwards"
                elif dx < 0.1 or dy < 0.3:
                    text = "Move 3D scanner closer"
                elif dx >0.15 or dy > 0.4:
                    text = "Move 3D scanner further away"
                else:
                    text = " "

                # Add the text on the image
                cv2.putText(image, text, (20, 30),
cv2.FONT_HERSHEY_SIMPLEX, 1, (0, 0, 255), 2)

                #Ellipses

                center_coordinates1 = (330, 250)
```

```
                axesLength = (120, 100)
                angle = 90
                startAngle = 0
                endAngle = 360
                if x1 > 0.43 and x2 < 0.7 and y1 > 0.3 and y2 <0.8 and dx
>0.10 and dx < 0.15 and dy >0.3 and dy <0.4:
                    color = (0, 255, 0)
                else:
                    color = (100,100,100)
                thickness = 2
                Ellipse_1 = cv2.ellipse(image, center_coordinates1,
axesLength,
                           angle, startAngle, endAngle, color, thickness)


        cv2.imshow('Head Pose Estimation', image)

        if cv2.waitKey(5) & 0xFF == 27:
            cv2.destroyAllWindows()
            cap.release()
            break

    except:
        break
```

Option 2: center camera with oval and instructions

In [2]:

```
import cv2
import mediapipe as mp
import numpy as np

mp_face_mesh = mp.solutions.face_mesh
face_mesh = mp_face_mesh.FaceMesh(min_detection_confidence=0.5,
min_tracking_confidence=0.5)
cap = cv2.VideoCapture(0)

while 1:
    try:
        success, image = cap.read()

        # Flip the image horizontally for a later selfie-view display
        # Also convert the color space from BGR to RGB
        image = cv2.cvtColor(cv2.flip(image, 1), cv2.COLOR_BGR2RGB)

        # To improve performance
        image.flags.writeable = False

        # Get the result
        results = face_mesh.process(image)

        # To improve performance
        image.flags.writeable = True

        # Convert the color space from RGB to BGR
        image = cv2.cvtColor(image, cv2.COLOR_RGB2BGR)

        img_h, img_w, img_c = image.shape
        face_3d = []
        face_2d = []
```

```
        if results.multi_face_landmarks:
            for face_landmarks in results.multi_face_landmarks:
                x1 = face_landmarks.landmark[232].x
                x2 = face_landmarks.landmark[454].x
                y1 = face_landmarks.landmark[10].y
                y2 = face_landmarks.landmark[152].y
                dx = x2-x1
                dy = y2-y1

            for face_landmarks in results.multi_face_landmarks:
                for idx, lm in enumerate(face_landmarks.landmark):
                    if idx == 33 or idx == 263 or idx == 1 or idx == 61 or
idx == 291 or idx == 199:
                        if idx == 1:
                            nose_2d = (lm.x * img_w, lm.y * img_h)
                            nose_3d = (lm.x * img_w, lm.y * img_h, lm.z *
8000)

                        x, y = int(lm.x * img_w), int(lm.y * img_h)

                        # Get the 2D Coordinates
                        face_2d.append([x, y])

                        # Get the 3D Coordinates
                        face_3d.append([x, y, lm.z])

                # Convert it to the NumPy array
                face_2d = np.array(face_2d, dtype=np.float64)

                # Convert it to the NumPy array
                face_3d = np.array(face_3d, dtype=np.float64)

                # The camera matrix
                focal_length = 1 * img_w

                cam_matrix = np.array([ [focal_length, 0, img_h / 2],
                                        [0, focal_length, img_w / 2],
                                        [0, 0, 1]])

                # The Distance Matrix
                dist_matrix = np.zeros((4, 1), dtype=np.float64)

                # Solve PnP
                success, rot_vec, trans_vec = cv2.solvePnP(face_3d,
face_2d, cam_matrix, dist_matrix)

                # Get rotational matrix
                rmat, jac = cv2.Rodrigues(rot_vec)

                # Get angles
                angles, mtxR, mtxQ, Qx, Qy, Qz = cv2.RQDecomp3x3(rmat)

                # Get the y rotation degree
                x = angles[0] * 360
                y = angles[1] * 360

                #Ellipses
```

```
                center_coordinates1 = (330, 250)
                axesLength = (120, 100)
                angle = 90
                startAngle = 0
                endAngle = 360
                if x1 > 0.43 and x2 < 0.7 and y1 > 0.3 and y2 <0.8 and dx
>0.10 and dx < 0.15 and dy >0.3 and dy <0.4:
                    color = (0, 255, 0)
                else:
                    color = (100,100,100)
                thickness = 2
                Ellipse_1 = cv2.ellipse(image, center_coordinates1,
axesLength,
                           angle, startAngle, endAngle, color, thickness)


        cv2.imshow('Head Pose Estimation', image)

        if cv2.waitKey(5) & 0xFF == 27:
            cv2.destroyAllWindows()
            cap.release()
            break

    except:
        break
```

Option 3: 1 side camera with oval

In [3]:

```
import pyk4a
import open3d as o3d
import numpy as np
import cv2
import datetime
import json
import copy
from pyk4a import Config, PyK4A
import tkinter
from tkinter import ttk
from tkinter.scrolledtext import ScrolledText
import zipfile
import re
import os

# button dimensions (y1,y2,x1,x2)
button = [20,60,50,400]

def close_all():
    cv2.destroyAllWindows()
    k4a_p1.stop()

# function that handles the mousclicks
def process_click(event, x, y,flags, params):
    # check if the click is within the dimensions of the button
    if event == cv2.EVENT_LBUTTONDOWN:
        if y > button[0] and y < button[1] and x > button[2] and x <
button[3]:
            close_all()
```

```
cv2.namedWindow('Button')
cv2.setMouseCallback('Button',process_click)

# create button image
control_image = np.zeros((80,450), np.uint8)
control_image[button[0]:button[1],button[2]:button[3]] = 180
cv2.putText(control_image, 'Start
capturing',(100,50),cv2.FONT_HERSHEY_PLAIN, 2,(0),3)

#show 'control panel'
cv2.imshow('Button', control_image)

k4a_p1 = PyK4A(
    Config(
        color_resolution=pyk4a.ColorResolution.RES_720P,
        depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
        synchronized_images_only=True,
    ), device_id=0
)

k4a_p1.start()

while 1:
    try:
        capture1 = k4a_p1.get_capture()
        color_p1 = capture1.color[:,:,:3]

        if np.any(capture1.color):
            Hori_small = cv2.resize(color_p1, (0,0), fx=0.5, fy=0.5)
            cv2.putText(Hori_small, "Left camera", (20,30),
cv2.FONT_HERSHEY_SIMPLEX, 0.75, (255,255,255),2)

            #Ellipses
            center_coordinates1 = (330, 180)
            axesLength = (150, 120)
            angle = 90
            startAngle = 0
            endAngle = 360
            color = (100, 100, 100)
            thickness = 2
            Ellipse_1 = cv2.ellipse(Hori_small, center_coordinates1,
axesLength,
                                   angle, startAngle, endAngle, color,
thickness)

            cv2.imshow("Image", Ellipse_1)
            key = cv2.waitKey(10)
            if key != -1:
                cv2.destroyAllWindows()
                k4a_p1.stop()
                break
    except:
        break
```

Option 4: 2 side cameras with oval

In [2]:

```
import pyk4a
import open3d as o3d
import numpy as np
```

```
import cv2
import datetime
import json
import copy
from pyk4a import Config, PyK4A
import tkinter
from tkinter import ttk
from tkinter.scrolledtext import ScrolledText
import zipfile
import re
import os

# button dimensions (y1,y2,x1,x2)
button = [20,60,50,400]

def close_all():
    cv2.destroyAllWindows()
    k4a_p1.stop()
    k4a_p2.stop()

# function that handles the mousclicks
def process_click(event, x, y,flags, params):
    # check if the click is within the dimensions of the button
    if event == cv2.EVENT_LBUTTONDOWN:
        if y > button[0] and y < button[1] and x > button[2] and x <
button[3]:
            close_all()


cv2.namedWindow('Button')
cv2.setMouseCallback('Button',process_click)

# create button image
control_image = np.zeros((80,450), np.uint8)
control_image[button[0]:button[1],button[2]:button[3]] = 180
cv2.putText(control_image, 'Start
capturing',(100,50),cv2.FONT_HERSHEY_PLAIN, 2,(0),3)

#show 'control panel'
cv2.imshow('Button', control_image)

k4a_p1 = PyK4A(
    Config(
        color_resolution=pyk4a.ColorResolution.RES_720P,
        depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
        synchronized_images_only=True,
    ), device_id=0
)
k4a_p2 = PyK4A(
    Config(
        color_resolution=pyk4a.ColorResolution.RES_720P,
        depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
        synchronized_images_only=True,
    ), device_id=1
)

k4a_p1.start()
k4a_p2.start()
```

```
while 1:
    try:
        capture1 = k4a_p1.get_capture()
        capture2 = k4a_p2.get_capture()

        color_p1 = capture1.color[:,:,:3]
        color_p2 = capture2.color[:,:,:3]

        if np.any(capture1.color) and np.any(capture2.color):
            Hori = np.concatenate((color_p1, color_p2), axis=1)
            Hori_small = cv2.resize(Hori, (0,0), fx=0.5, fy=0.5)
            cv2.putText(Hori_small, "Left camera", (20,30),
cv2.FONT_HERSHEY_SIMPLEX, 0.75, (255,255,255),2)
            cv2.putText(Hori_small, "Right camera", (660,30),
cv2.FONT_HERSHEY_SIMPLEX, 0.75, (255,255,255),2)

            #Ellipses
            center_coordinates1 = (330, 180)
            center_coordinates2 = (1000, 180)
            axesLength = (150, 120)
            angle = 90
            startAngle = 0
            endAngle = 360
            color = (100, 100, 100)
            thickness = 2
            Ellipse_1 = cv2.ellipse(Hori_small, center_coordinates1,
axesLength,
                               angle, startAngle, endAngle, color,
thickness)
            Ellipse_2 = cv2.ellipse(Ellipse_1, center_coordinates2,
axesLength,
                               angle, startAngle, endAngle, color,
thickness)

            cv2.imshow("Image", Ellipse_2)
            key = cv2.waitKey(10)
            if key != -1:
                cv2.destroyAllWindows()
                k4a_p1.stop()
                k4a_p2.stop()
                break
    except:
        break
```

In [ ]:

Appendix X: Python code Head pose estimation

```
import cv2
import mediapipe as mp
import numpy as np
import time
import pyk4a
import math
from pyk4a import Config, PyK4A
```

In [2]:

```
from pyk4a import PyK4A, connected_device_count
cnt = connected_device_count()
if not cnt:
    print("No devices available")
    exit()
print(f"Available devices: {cnt}")
for device_id in range(cnt):
    device = PyK4A(device_id=device_id)
    device.open()
    print(f"{device_id}: {device.serial}")
    device.close()
```

```
Available devices: 1
0: 000125924512
```

In [3]:

```
k4a_p1 = PyK4A(
    Config(
        color_resolution=pyk4a.ColorResolution.RES_720P,
        depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
        synchronized_images_only=True,
    ), device_id=0
)
```

In [ ]:

```
k4a_p1.start()

mp_face_mesh = mp.solutions.face_mesh
face_mesh = mp_face_mesh.FaceMesh(min_detection_confidence=0.5,
min_tracking_confidence=0.5)
mp_drawing = mp.solutions.drawing_utils
drawing_spec = mp_drawing.DrawingSpec(thickness=1, circle_radius=1)

while 1:
    try:
        capture1 = k4a_p1.get_capture()
        color_p1 = capture1.color[:,:,:3]

        start = time.time()
        image = color_p1
        image = np.ascontiguousarray(image, dtype=np.uint8)

        rgb_image = cv2.cvtColor(image, cv2.COLOR_BGR2RGB)


        image.flags.writeable = False
        results = face_mesh.process(rgb_image)
        image.flags.writeable = True

        img_h, img_w, img_c = image.shape
```

```
        face_3d = []
        face_2d = []


        if results.multi_face_landmarks:
            for face_landmarks in results.multi_face_landmarks:
                pt1 = face_landmarks.landmark[130]
                pt2 = face_landmarks.landmark[359]
                x1 = int(pt1.x * img_w)
                y1 = int(pt1.y * img_h)
                x2 = int(pt2.x * img_w)
                y2 = int(pt2.y * img_h)
                cv2.circle(image, (x1,y1), 5, (100,100,0), -1)
                cv2.circle(image, (x2,y2), 5, (100,100,0), -1)
                dx = x2-x1
                dy = y2-y1
                angle = round(math.atan2(dy,dx)*180/np.pi,1)

                cv2.putText(image, "angle = " + str(angle), (300,50),
cv2.FONT_HERSHEY_SIMPLEX, 1, (0,0,255),2)

            for face_landmarks in results.multi_face_landmarks:
                for idx, lm in enumerate(face_landmarks.landmark):
                    if idx ==33 or idx==263 or idx==61 or idx==1 or
idx==291 or idx==199:
                        if idx ==1:
                            nose_2d = (lm.x * img_w, lm.y * img_h)
                            nose_3d = (lm.x * img_w, lm.y * img_h, lm.z *
3000)


                        x, y = int(lm.x*img_w), int(lm.y*img_h)
                        face_2d.append([x,y])
                        face_3d.append([x,y,lm.z])
                face_2d = np.array(face_2d, dtype = np.float64)
                face_3d = np.array(face_3d, dtype = np.float64)
                focal_length = 1 * img_w
                cam_matrix = np.array([ [focal_length, 0, img_h/2],
                                        [0, focal_length, img_w/2],
                                        [0,0,1]])
                dist_matrix= np.zeros((4,1), dtype=np.float64)
                success, rot_vec, trans_vec = cv2.solvePnP(face_3d,
face_2d, cam_matrix, dist_matrix)

                rmat,jac = cv2.Rodrigues(rot_vec)
                angles,mtxR, mtxQ, Qx,Qy,Qz = cv2.RQDecomp3x3(rmat)

                x=angles[0]*360
                y=angles[1]*360
                z=angles[2]*360

                if angle <15 and angle >-15:
                    if y < -5:
                        text = "Looking left"
                        count=0

                    elif y> 5:
                        text = "Looking right"
                        count=0
```

```
                    elif x<0:
                        text = "Looking down"
                        count=0

                    elif x>6:
                        text = "Looking up"
                        count=0
                    else:
                        text = "Forward"
                        count+=1
                        if count == 30:
                            print("Photo taken")
                else:
                    text = "Head tilted"
                    count = 0

                nose_3d_projection, jacobian = cv2.projectPoints(nose_3d,
rot_vec, trans_vec, cam_matrix, dist_matrix)

                p1 = (int(nose_2d[0]), int(nose_2d[1]))
                p2 = (int(nose_2d[0]+y*10), int(nose_2d[1]-x*10))

                cv2.line(image, p1, p2, (255,0,0),3)

                cv2.putText(image, text, (20,50), cv2.FONT_HERSHEY_SIMPLEX,
1, (0,255,0),2)
                cv2.putText(image, "x = " + str(np.round(x,2)),(1100,50),
cv2.FONT_HERSHEY_SIMPLEX, 1, (0,0,255),2)
                cv2.putText(image, "y = " + str(np.round(y,2)),(1100,100),
cv2.FONT_HERSHEY_SIMPLEX, 1, (0,0,255),2)
                cv2.putText(image, "z = " + str(np.round(x,2)),(1100,150),
cv2.FONT_HERSHEY_SIMPLEX, 1, (0,0,255),2)

            end = time.time()
            totalTime = end-start

            fps = 1/totalTime
            #print('FPS: ', fps)

            cv2.putText(image, f" FPS:
{int(fps)}",(20,670),cv2.FONT_HERSHEY_SIMPLEX, 1,(0,0,255),2)

            mp_drawing.draw_landmarks(
                image = image,
                landmark_list = face_landmarks,
                connections = mp_face_mesh.FACEMESH_CONTOURS,
                landmark_drawing_spec = drawing_spec,
                connection_drawing_spec=drawing_spec)

        cv2.imshow('Head Pose Estimation', image)

        if cv2.waitKey(5) & 0xFF == 27:
            cv2.destroyAllWindows()
            k4a_p1.stop()
            break

    except:
        break
```

Appendix Y: Python code final prototype

Import requirements

In [51]:

```
from pathlib import Path

def _add_dll_directory(path: Path):
    from ctypes import c_wchar_p, windll  # type: ignore
    from ctypes.wintypes import DWORD

    AddDllDirectory = windll.kernel32.AddDllDirectory
    AddDllDirectory.restype = DWORD
    AddDllDirectory.argtypes = [c_wchar_p]
    AddDllDirectory(str(path))

def kinect():
    if sys.platform != "win32":
        return
    env_path = os.getenv("KINECT_LIBS", None)
    if env_path:
        candidate = Path(env_path)
        dll = candidate / "k4a.dll"
        if dll.exists():
            _add_dll_directory(candidate)
            return
    # autodetecting
    program_files = Path("C:\\Program Files\\")
    for dir in sorted(program_files.glob("Azure Kinect SDK v*"), 
reverse=True):
        candidate = dir / "sdk" / "windows-desktop" / "amd64" / "release" / 
"bin"
        dll = candidate / "k4a.dll"
        if dll.exists():
            _add_dll_directory(candidate)
            return
```

In [52]:

```
import pyk4a
import open3d as o3d
import numpy as np
import cv2
import datetime
import json
import copy
from pyk4a import Config, PyK4A
import tkinter
from tkinter import ttk
from tkinter.scrolledtext import ScrolledText
import zipfile
import re
import os
```

List devices

In [53]:

```
from pyk4a import PyK4A, connected_device_count
cnt = connected_device_count()
if not cnt:
    print("No devices available")
    exit()
print(f"Available devices: {cnt}")
for device_id in range(cnt):
    device = PyK4A(device_id=device_id)
    device.open()
    print(f"{device_id}: {device.serial}")
    device.close()
```

Preview of camera's

In [54]:

```
# button dimensions (y1,y2,x1,x2)
button = [20,60,50,400]

def close_all():
    cv2.destroyAllWindows()
    k4a_p1.stop()
    k4a_p2.stop()

# function that handles the mousclicks
def process_click(event, x, y,flags, params):
    # check if the click is within the dimensions of the button
    if event == cv2.EVENT_LBUTTONDOWN:
        if y > button[0] and y < button[1] and x > button[2] and x <
button[3]:
            close_all()


cv2.namedWindow('Button')
cv2.setMouseCallback('Button',process_click)

# create button image
control_image = np.zeros((80,450), np.uint8)
control_image[button[0]:button[1],button[2]:button[3]] = 180
cv2.putText(control_image, 'Start
capturing',(100,50),cv2.FONT_HERSHEY_PLAIN, 2,(0),3)

#show 'control panel'
cv2.imshow('Button', control_image)

k4a_p1 = PyK4A(
    Config(
        color_resolution=pyk4a.ColorResolution.RES_720P,
        depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
        synchronized_images_only=True,
    ), device_id=0
)
k4a_p2 = PyK4A(
    Config(
        color_resolution=pyk4a.ColorResolution.RES_720P,
        depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
```

```
        synchronized_images_only=True,
    ), device_id=1
)

k4a_p1.start()
k4a_p2.start()

while 1:
    try:
        capture1 = k4a_p1.get_capture()
        capture2 = k4a_p2.get_capture()

        color_p1 = capture1.color[:,:,:3]
        color_p2 = capture2.color[:,:,:3]

        if np.any(capture1.color) and np.any(capture2.color):
            Hori = np.concatenate((color_p1, color_p2), axis=1)
            Hori_small = cv2.resize(Hori, (0,0), fx=0.5, fy=0.5)
            cv2.putText(Hori_small, "Left camera", (20,30),
cv2.FONT_HERSHEY_SIMPLEX, 0.75, (255,255,255),2)
            cv2.putText(Hori_small, "Right camera", (660,30),
cv2.FONT_HERSHEY_SIMPLEX, 0.75, (255,255,255),2)

            #Ellipses
            center_coordinates1 = (330, 180)
            center_coordinates2 = (1000, 180)
            axesLength = (150, 120)
            angle = 90
            startAngle = 0
            endAngle = 360
            color = (0, 255, 0)
            thickness = 1
            Ellipse_1 = cv2.ellipse(Hori_small, center_coordinates1,
axesLength,
                               angle, startAngle, endAngle, color,
thickness)
            Ellipse_2 = cv2.ellipse(Ellipse_1, center_coordinates2,
axesLength,
                               angle, startAngle, endAngle, color,
thickness)

            cv2.imshow("Image", Ellipse_2)
            key = cv2.waitKey(10)
            if key != -1:
                cv2.destroyAllWindows()
                k4a_p1.stop()
                k4a_p2.stop()
                break
    except:
        break
```

Setup device and settings

In [55]:

```
k4a_1 = PyK4A(Config(
            color_resolution=pyk4a.ColorResolution.RES_1080P,
            depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
            synchronized_images_only=True,
        ), device_id=0
)
```

```
k4a_2 = PyK4A(Config(
            color_resolution=pyk4a.ColorResolution.RES_1080P,
            depth_mode=pyk4a.DepthMode.NFOV_UNBINNED,
            synchronized_images_only=True,
        ), device_id=1
)
```

Capture info

In [57]:

```
k4a_1.start()
k4a_2.start()

# Get the next capture (blocking function)
capture_1 = k4a_1.get_capture()
img_color_1 = capture_1.color
img_depth_1 = capture_1.depth

capture_2 = k4a_2.get_capture()
img_color_2 = capture_2.color
img_depth_2 = capture_2.depth

k4a_1.stop()
k4a_2.stop()
```

Convert depth image to pointcloud

In [58]:

```
pcl_1 = pyk4a.depth_image_to_point_cloud(depth=capture_1.depth,
calibration=capture_1._calibration, thread_safe=capture_1.thread_safe)
pcl_2 = pyk4a.depth_image_to_point_cloud(depth=capture_2.depth,
calibration=capture_2._calibration, thread_safe=capture_2.thread_safe)

pcloud_1 = o3d.geometry.PointCloud()
pcloud_2 = o3d.geometry.PointCloud()

pcloud_1.points = o3d.utility.Vector3dVector(pcl_1.reshape((-1, 3)))
pcloud_2.points = o3d.utility.Vector3dVector(pcl_2.reshape((-1, 3)))

pcloud_r1 = copy.deepcopy(pcloud_1)
pcloud_r2 = copy.deepcopy(pcloud_2)

R = pcloud_1.get_rotation_matrix_from_xyz((0, np.pi, np.pi))
R = pcloud_2.get_rotation_matrix_from_xyz((0, np.pi, np.pi))

pcloud_r1.rotate(R, center=(0, 0, 0))
pcloud_r2.rotate(R, center=(0, 0, 0))

#o3d.visualization.draw_geometries([pcloud_r1,pcloud_r2])
```

Crop pointclouds

In [59]:

```
sphere_mesh = o3d.geometry.TriangleMesh.create_sphere(radius=250)
sphere_tx = copy.deepcopy(sphere_mesh).translate((0, 150, -500))
sphere_tx.compute_vertex_normals()
sphere_ply = sphere_tx.sample_points_uniformly(number_of_points=500)
bbox = sphere_ply.get_axis_aligned_bounding_box()
```

```
bbox.color = (1, 0, 0)
#o3d.visualization.draw_geometries([sphere_ply, bbox, pcloud_r1,pcloud_r2])

cropped_1 =pcloud_r1.crop(bbox)
cropped_2 =pcloud_r2.crop(bbox)
#o3d.visualization.draw_geometries([cropped_1,cropped_2])
```

Save .ply files

In [60]:

```
# Create save_to_ply object
#o3d.io.write_point_cloud(f"Scan_Left_{timestamp}.ply", cropped_1)
#o3d.io.write_point_cloud(f"Scan_Right_{timestamp}.ply", cropped_2)

#o3d.io.write_point_cloud(f"Scan0.ply", cropped_1)
#o3d.io.write_point_cloud(f"Scan1.ply", cropped_2)

o3d.io.write_point_cloud(f"Test0.ply", cropped_1)
o3d.io.write_point_cloud(f"Test1.ply", cropped_2)
```

Open pointclouds

In [61]:

```
def load_point_clouds():
    pcds = []
    for i in range(2):
        pcd = o3d.io.read_point_cloud("Test%d.ply" %
                                      i)
        pcd.normals = o3d.utility.Vector3dVector(np.zeros(
            (1, 3)))  # invalidate existing normals
        pcd.estimate_normals()
        pcd.orient_normals_consistent_tangent_plane(100)
        #o3d.visualization.draw_geometries([pcd], point_show_normal=True)
        pcds.append(pcd)
    return pcds
```

Load and visualize pointclouds

In [62]:

```
pcds = load_point_clouds()
o3d.visualization.draw_geometries(pcds)
```

Pairwise registration definition

In [63]:

```
def pairwise_registration(source, target):
    print("Apply point-to-plane ICP")
    icp_coarse = o3d.pipelines.registration.registration_icp(
        source, target, max_correspondence_distance_coarse, np.identity(4),
        o3d.pipelines.registration.TransformationEstimationPointToPlane())
    icp_fine = o3d.pipelines.registration.registration_icp(
        source, target, max_correspondence_distance_fine,
        icp_coarse.transformation,
        o3d.pipelines.registration.TransformationEstimationPointToPlane())
    transformation_icp = icp_fine.transformation
    information_icp =
o3d.pipelines.registration.get_information_matrix_from_point_clouds(
```

```
        source, target, max_correspondence_distance_fine,
        icp_fine.transformation)
    return transformation_icp, information_icp
```

Full registration definition

In [64]:

```
def full_registration(pcds, max_correspondence_distance_coarse,
                      max_correspondence_distance_fine):
    pose_graph = o3d.pipelines.registration.PoseGraph()
    odometry = np.identity(4)

pose_graph.nodes.append(o3d.pipelines.registration.PoseGraphNode(odometry))
    n_pcds = len(pcds)
    for source_id in range(n_pcds):
        for target_id in range(source_id + 1, n_pcds):
            transformation_icp, information_icp = pairwise_registration(
                pcds[source_id], pcds[target_id])
            print("Build o3d.pipelines.registration.PoseGraph")
            if target_id == source_id + 1:  # odometry case
                odometry = np.dot(transformation_icp, odometry)
                pose_graph.nodes.append(
                    o3d.pipelines.registration.PoseGraphNode(
                        np.linalg.inv(odometry)))
                pose_graph.edges.append(
                    o3d.pipelines.registration.PoseGraphEdge(source_id,
                                                             target_id,

transformation_icp,

information_icp,

uncertain=False))
            else:  # loop closure case
                pose_graph.edges.append(
                    o3d.pipelines.registration.PoseGraphEdge(source_id,
                                                             target_id,

transformation_icp,

information_icp,

uncertain=True))
    return pose_graph
```

Perform full registration

In [65]:

```
print("Full registration ...")
voxel_size = 0.01
max_correspondence_distance_coarse = voxel_size * 30000
max_correspondence_distance_fine = voxel_size * 3000
with o3d.utility.VerbosityContextManager(
        o3d.utility.VerbosityLevel.Debug) as cm:
    pose_graph = full_registration(pcds,
                                   max_correspondence_distance_coarse,
                                   max_correspondence_distance_fine)
```

Optimizing posegraph

In [66]:

```
print("Optimizing PoseGraph ...")
option = o3d.pipelines.registration.GlobalOptimizationOption(
    max_correspondence_distance=max_correspondence_distance_fine,
    edge_prune_threshold=0.5,
    reference_node=0)
with o3d.utility.VerbosityContextManager(
        o3d.utility.VerbosityLevel.Debug) as cm:
    o3d.pipelines.registration.global_optimization(
        pose_graph,
        o3d.pipelines.registration.GlobalOptimizationLevenbergMarquardt(),
        o3d.pipelines.registration.GlobalOptimizationConvergenceCriteria(),
        option)
```

Transform and show results

In [67]:

```
print("Transform points and display")
for point_id in range(len(pcds)):
    print(pose_graph.nodes[point_id].pose)
    pcds[point_id].transform(pose_graph.nodes[point_id].pose)
o3d.visualization.draw_geometries(pcds)
```

Combine pointcloud

In [17]:

```
pcds = load_point_clouds(voxel_size)
pcd_combined = o3d.geometry.PointCloud()
for point_id in range(len(pcds)):
    pcds[point_id].transform(pose_graph.nodes[point_id].pose)
    pcd_combined += pcds[point_id]
pcd_combined_down = pcd_combined.voxel_down_sample(voxel_size=voxel_size)
o3d.io.write_point_cloud("multiway_registration.pcd", pcd_combined_down)
#o3d.visualization.draw_geometries([pcd_combined_down])
```

In [18]:

```
pcd_combined_down.paint_uniform_color([0.7, 0.7, 0.7])
o3d.visualization.draw_geometries([pcd_combined_down])
```

Remove outliers

In [85]:

```
def display_inlier_outlier(cloud, ind):
    inlier_cloud = cloud.select_by_index(ind)
    outlier_cloud = cloud.select_by_index(ind, invert=True)

    print("Showing outliers (red) and inliers (gray): ")
    outlier_cloud.paint_uniform_color([1, 0, 0])
    inlier_cloud.paint_uniform_color([0.8, 0.8, 0.8])
    o3d.visualization.draw_geometries([inlier_cloud,outlier_cloud])
    o3d.io.write_point_cloud("inlier_cloud.pcd", inlier_cloud)
```

In [86]:

```
cl, ind = pcd_combined_down.remove_statistical_outlier(nb_neighbors=20,
                                                        std_ratio=2.7)
display_inlier_outlier(pcd_combined_down, ind)
```

```
inlier_cloud= o3d.io.read_point_cloud("inlier_cloud.pcd")
```

Select points around ears

In [87]:

```
vis = o3d.visualization.VisualizerWithEditing()
vis.create_window()
vis.add_geometry(inlier_cloud)
vis.run()
vis.destroy_window()
EarPoints = []

point1 = vis.get_picked_points()[0]
point2 = vis.get_picked_points()[1]

SelectedPoint1 = np.asarray(inlier_cloud.points[point1])
SelectedPoint2 = np.asarray(inlier_cloud.points[point2])

SelectedPoints = np.row_stack((SelectedPoint1, SelectedPoint2))
```

Calculate normals

In [88]:

```
inlier_cloud.normals = o3d.utility.Vector3dVector(np.zeros(
        (1, 3)))  # invalidate existing normals
inlier_cloud.estimate_normals()
inlier_cloud.orient_normals_consistent_tangent_plane(100)

#normals = np.asarray(inlier_cloud.normals)
# flip normals
#inlier_cloud.normals = o3d.utility.Vector3dVector(normals)

#o3d.visualization.draw_geometries([pcd], point_show_normal=True)
```

Make Mesh

In [89]:

```
print('run Poisson surface reconstruction')
with o3d.utility.VerbosityContextManager(
        o3d.utility.VerbosityLevel.Debug) as cm:
    mesh, densities =
o3d.geometry.TriangleMesh.create_from_point_cloud_poisson(
        inlier_cloud, depth=12)
#print(mesh)
o3d.visualization.draw_geometries([mesh])
```

In [90]:

```
mesh = mesh.filter_smooth_simple(number_of_iterations=10)
mesh.compute_vertex_normals()
o3d.visualization.draw_geometries([mesh])
```

In [91]:

```
mesh = mesh.filter_smooth_taubin(number_of_iterations=10)
mesh.compute_vertex_normals()
o3d.visualization.draw_geometries([mesh])
```

Remove surfaces with low densities

In [92]:

```
vertices_to_remove = densities < np.quantile(densities, 0.03)
mesh.remove_vertices_by_mask(vertices_to_remove)
mesh = o3d.geometry.TriangleMesh.compute_triangle_normals (mesh)
o3d.visualization.draw_geometries([mesh])
```

Save details

In [93]:

```
def saveData():
    scanner = scanner_entry.get()
    phone = phone_entry.get()
    email = email_entry.get()
    firstname = first_name_entry.get()
    lastname = last_name_entry.get()
    model = model_combobox.get()
    color = color_combobox.get()
    engraving_value=engraving_status.get()

    if engraving_value == "1":
        engraving = "Yes"
    else:
        engraving = "No"

    remarks = remarks_box.get("1.0","end")
    ref_point1 = SelectedPoints[0]
    ref_point2 = SelectedPoints[1]

    with open(f"Form_{timestamp}.txt", "w") as text_file:
        text_file.write("Organization: Bartiméus Zeist\n")
        text_file.write(f"Scanned by: {scanner}\n")
        text_file.write(f"Phone number: {phone}\n")
        text_file.write(f"Email address: {email}\n\n")
```

```
        text_file.write(f"First name: {firstname}\n")
        text_file.write(f"Last name: {lastname}\n\n")
        text_file.write(f"Preferred model: {model}\n")
        text_file.write(f"Preferred color: {color}\n")
        text_file.write(f"Engraving: {engraving}\n")
        text_file.write(f"Remarks: {remarks}\n")
        text_file.write(f"Ear reference point coördinates:
\n{ref_point1}\n{ref_point2}")

    window.destroy()

timestamp = datetime.datetime.now().strftime("%Y-%m-%d_%H-%M-%S")

window = tkinter.Tk()
window.title("Welcome to Maatbril")

frame = tkinter.Frame(window)
frame.pack()

contact_info_frame = tkinter.LabelFrame(frame, text="Contact information")
contact_info_frame.grid(row='0', column='0', padx=20,pady=20, sticky = 'w')

scanner_label = tkinter.Label(contact_info_frame, text="Scan taken by")
scanner_label.grid(row='0', column = '0', sticky = 'w')
scanner_entry = tkinter.Entry(contact_info_frame)
scanner_entry.grid(row='1', column = '0', sticky = 'w')

phone_label = tkinter.Label(contact_info_frame, text="Phone number")
phone_label.grid(row=0, column =1, sticky = 'w')
phone_entry = tkinter.Entry(contact_info_frame)
phone_entry.grid(row=1, column =1, sticky ='w')

email_label = tkinter.Label(contact_info_frame,text="Email")
email_entry = tkinter.Entry(contact_info_frame)
email_label.grid(row=0, column=2, sticky="w")
email_entry.grid(row=1, column=2, sticky= 'w')

for widget in contact_info_frame.winfo_children():
    widget.grid_configure(padx=10, pady=5)

user_info_frame = tkinter.LabelFrame(frame, text="Client information")
user_info_frame.grid(row='1', column='0', padx=20, pady=20, sticky = 'w')
first_name_label = tkinter.Label(user_info_frame, text="First name")
first_name_label.grid(row='0', column='0', sticky ='w')
last_name_label = tkinter.Label(user_info_frame, text="Last name")
last_name_label.grid(row='0', column='1', sticky = 'w')

first_name_entry = tkinter.Entry(user_info_frame)
last_name_entry = tkinter.Entry(user_info_frame)
first_name_entry.grid(row="1", column="0", sticky="w")
last_name_entry.grid(row="1", column="1", sticky="w")

for widget in user_info_frame.winfo_children():
    widget.grid_configure(padx=10, pady=5)

glasses_info_frame = tkinter.LabelFrame(frame, text="Glasses selection")
glasses_info_frame.grid(row='2', column='0', padx=20, pady=20, sticky =
'w')
```

```
model_label = tkinter.Label(glasses_info_frame, text='Preferred Model')
model_label.grid(row="0", column="0", sticky="w")
model_combobox = ttk.Combobox(glasses_info_frame, values=
      ["Twins U",'Twins M','Twins F',"Facet U",'Facet M','Facet F',"Edge
U",'Edge M','Edge F', "RB01", "RB02", "RB03",
      "RB04","RB05", "RB06", "RB07"])
model_combobox.grid(row="1",column="0")

color_label = tkinter.Label(glasses_info_frame, text="Preferred Color")
color_label.grid(row="0", column="1", sticky='w')
color_combobox = ttk.Combobox(glasses_info_frame, values=
      ["Black",'Anthracite','Denim',"Midnight blue", "Brown", "Green",
"Petrol","Violet", "Wine red","Crimson"])
color_combobox.grid(row="1",column="1", sticky='w')

for widget in glasses_info_frame.winfo_children():
    widget.grid_configure(padx=10, pady=5)

engraving_frame = tkinter.LabelFrame(frame, text='Engraving')
engraving_frame.grid(row='3', column = '0', padx=20, pady = 20, sticky =
'w')

engraving_status = tkinter.StringVar()
engraving_check = tkinter.Checkbutton(engraving_frame,
                                      text = "Engraving in glasses",
                                      variable = engraving_status,
                                      onvalue = 1,
                                      offvalue = 0)
engraving_check.grid(row=0, column=0)
engraving_check.deselect()

confirmation_frame = tkinter.LabelFrame(frame, text='Additional Remarks')
confirmation_frame.grid(row='4', column = '0', padx=20, pady = 20, sticky =
'w')

remarks_box = tkinter.Text(confirmation_frame, height = 5, width = 40)
remarks_box.grid(row=1, column=2, padx=5, pady=5)

button = tkinter.Button(frame, text="Export data", command = saveData)
button.grid(row=4 ,column=0, padx=20, pady=20, sticky = 'se')

window.mainloop()
```

Calculate normals and save as .stl file

In [94]:

```
with open(f'Form_{timestamp}.txt') as inf:
    for line in inf:
        line = line.split(': ')
        line[0] = line[0].strip()
        if line[0] == 'First name':
            firstname = line[1].split('\n')
        elif line[0] == 'Last name':
            lastname = line[1].split('\n')
mesh = o3d.geometry.TriangleMesh.compute_triangle_normals (mesh)
o3d.io.write_triangle_mesh(f"{firstname[0]}_{lastname[0]}.stl", mesh)
```

Save ZIP file

In [95]:

```
os.rename(f"Form_{timestamp}.txt", f"{firstname[0]}_{lastname[0]}.txt")

with zipfile.ZipFile(f"{firstname[0]}_{lastname[0]}.zip", "w",
compression=zipfile.ZIP_DEFLATED) as zf:
    zf.write(f"{firstname[0]}_{lastname[0]}.txt")
    zf.write(f"{firstname[0]}_{lastname[0]}.stl")
    zf.write(f"Scan_Left_2023-01-19_19-53-01.ply")
    zf.write(f"Scan_Right_2023-01-19_19-53-01.ply")
#     zf.write(f"Scan_Left_{timestamp}.ply")
#     zf.write(f"Scan_Right_{timestamp}.ply")

os.remove(f"{firstname[0]}_{lastname[0]}.txt")
os.remove(f"{firstname[0]}_{lastname[0]}.stl")
#os.remove(f"Scan_Left_{timestamp}.ply")
#os.remove(f"Scan_Right_{timestamp}.ply")
```

Appendix Z: Analysis of current procedure

To analyse the current process, various interviews and observations were performed with both Maatbril employees, clients and/or their caretakers. Figure 1 shows the current procedure.

3D scan collection (#1-4)

After making an appointment, an employee of Maatbril performs a 3D scan of the client's face at their home or at a healthcare facility. The session usually starts with explaining the procedure and showing previous results. After that, the scanning is performed with an Occipital Structure Sensor Pro, mounted on a tablet. The client has to sit on a chair and stay as still as possible while the specialist moves around them, holding the tablet. In total, the scanning takes approximately 20 to 30 seconds, and is performed at a distance of around 1 to 1.5 m. In this phase, the quality of the scan will be negatively affected by movement and the presence of hair.

Model selection (#5-6)

Once the 3D scan has been taken and reviewed, which sometimes might require several takes- the specialist and client discuss potential special requests (ex. Integrating a hearing aid, a wheelchair with headrest, etc.) to be taken into account while designing the frame of the glasses. When all comments are included, the scan is uploaded in the application. After a minute or so, the scan has been processed and a 3D model of the client’s head can be viewed and used as underlay to augment the different frame models in different variations of colours on. Physically fitting the different types of frames is usually done to see how well a frame would fit looks-wise. The actual ergonomic fit of the frames is not evaluated.

Frame design (#7)

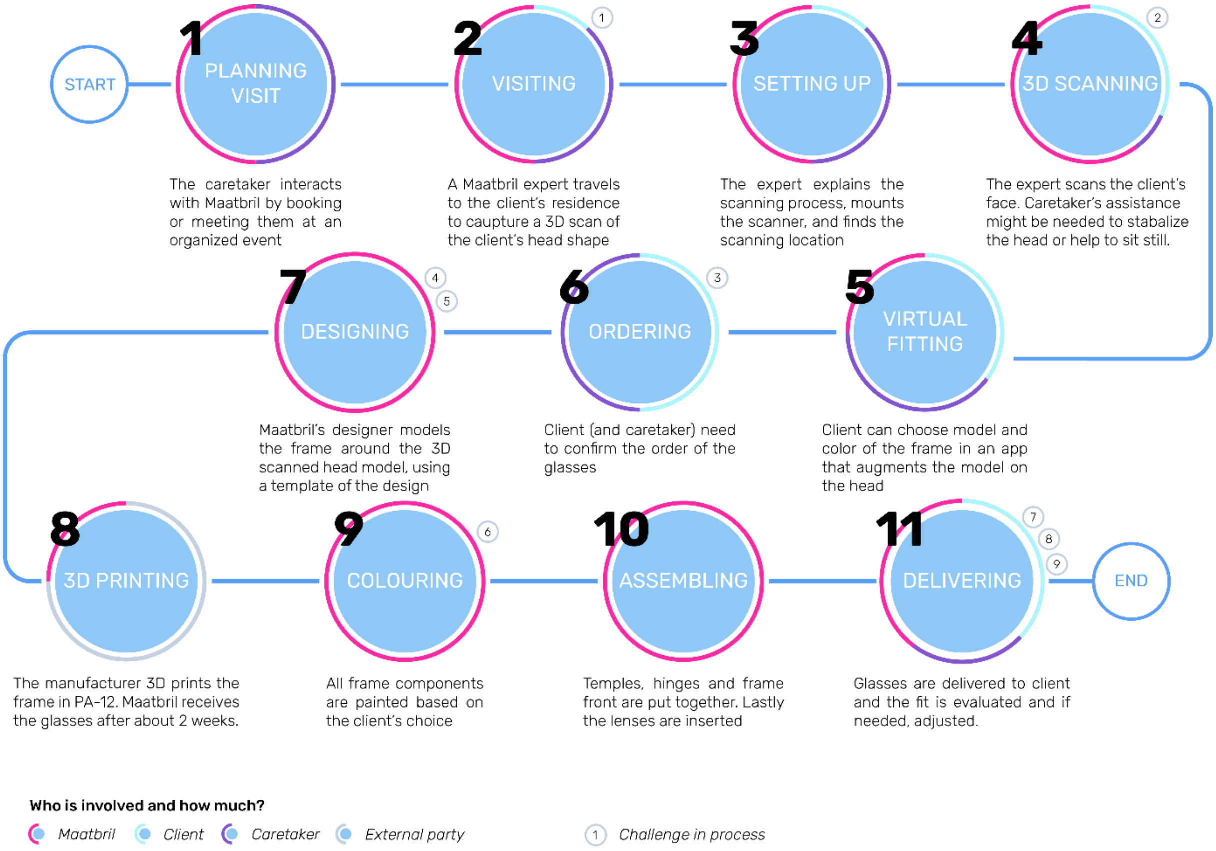
Starting with the mesh of the 3D scan, Maatbril's designer modifies the frame of choice to get a perfect fit. To do so, the frame is adjusted in terms of: length, inclination, size, and placement of each of its components. In some cases, such as in the presence of extreme asymmetries or anomalies (missing ear, missing nose), this step is particularly challenging.

Frame production (#8-10)

Once the design of the frame is finalized, it will be send to the producer, which is either a 3D printing company (Materialise, Belgium) or a producer that can mill the glasses out of acetate plates. See Appendix C for a more complete overview of both production techniques. When 3D printing, on average it takes about 3 weeks before the frame is produced (Kijk op Ogen employee, personal communication, October 28, 2022). Once Maatbril receives the printed (white) frame components, they can be coloured in the colour of choice. The next step is to add the lenses and assemble the different parts of the glasses.

Delivery and final adjustments (#11)

The finished glasses are delivered to the client for the (final) fitting test. This way, if necessary, the curvature and/or bending point of the temples can be adjusted. Usually, the temple tips are heated and then they can be easily remoulded. Sometimes only after a period of testing the frame issues are reported. In these cases, it is often required to reprint components or even the entire frame to solve the problems.



The caretaker interacts with Maatbril by booking or meeting them at an organized event

A Maatbril expert travels to the client's residence to caupture a 3D scan of the client's head shape

The expert explains the scanning process, mounts the scanner, and finds the scanning location

The expert scans the client's face. Caretaker's assistance might be needed to stabalize the head or help to sit still.

Client can choose model and color of the frame in an app that augments the model on the head

Client (and caretaker) need to confirm the order of the glasses

Maatbril's designer models the frame around the 3D scanned head model, using a template of the design

The manufacturer 3D prints the frame in PA-12. Maatbril receives the glasses after about 2 weeks.

All frame components are painted based on the client's choice

Temples, hinges and frame front are put together. Lastly the lenses are inserted

Glasses are delivered to client and the fit is evaluated and if needed, adjusted.

Figure 1: Current procedure Maatbril

Bottlenecks in current procedure

① Maatbril has to visit the client's houses without guarantee that the client will eventually order the glasses. This might lead to additional costs and time wasted, especially when the client lives relatively far away.

② The scanning process is complicated if the client has an uncontrollable spasm and/or moves his/her head to follow the iPad and/or is disturbed by the unfamiliarity with the situation and/or the caretaker/parent needs to help holding the client's head still for the required 20-30 seconds

③ A lot of time and effort goes into making a scan and therefore it is problematic if an order falls through

④ The quality of the 3D scan is often (locally) compromised affecting the usability and the scan needs to be retaken

⑤ The design of the glasses' temples is compromised in terms of length and temple tip design if the 3D scan does not include the ears

⑥ The dye colour does not behave as expected in some cases. Results might differ from the requested colour

⑦ Delivery in person requires time and effort but is necessary to evaluate the fit on the spot

⑧ If the fit of the frame presents issues, Maatbril tries to resolve them on the spot using a heating tool to remodel the temple tips' geometry

⑨ When it's not possible to resolve the issues immediately, a reprint of (part of) the frame is necessary, costing extra time and money

Appendix AA: Stakeholder analysis

Next to Maatbril and their clients, there are several other stakeholders involved in the process of designing and making tailor-made glasses. A brief overview of who exactly we are dealing with, what they want to achieve and how they are trying to achieve these things will be given in this chapter. Next to that, the stakeholders are placed in an influence-interest diagram – Figure 2 – to show how interested and how influential all stakeholders are concerning the topic of this Master's graduation project. The diagram is divided into four sections called *Key Players*[1], *Context Setters*[2], *Concerned Citizens*[3] *and Bystanders*[4], where each of the different quadrant requires a different way of interaction. Depending on the use scenario, it could be that one person has two roles, e.g. being the caretaker and being the person that takes the scan.

Person that takes the scan

Most likely an employee from Maatbril will take the scan, but it is not excluded that this will be done by a caretaker/relative or employees of an interest group. Next to helping clients get specialty glasses by 3D scanning their faces, their biggest concern is a quick, easy and stress-free scanning procedure for both the client and him-/herself (Jan Berend Zweerts, personal communication, October 13, 2022). The way they are trying to reach this is by having a 3D scanner that is quick, outputs high-quality meshes, and is easy to set-up and use.

Client

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

Figure 1: Overview of target users Maatbril

To give an idea of the variance in head shape among Maatbril's clients, some examples are depicted in figure 1. From the figure it can be seen that among the clients, the reason why choosing a Maatbril might differ from oddly shaped noses, to atypical location of the eyes and or deformation of the skull. A complete overview of the pathologies, characteristics and their prevalence can be found in Appendix E. It has to be noted that a significant part of the clients is making use of a wheelchair.

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[1] People or organisations that are essential to have as allies. They should be fully engaged in discussions and decision making

[2] People or organisations that are influential, but initially uninterested. They should be kept satisfied

[3] People or organisations that are affected but lack power. They should be consulted for their opinions and informed about decisions

[4] People or organisations that have little interest or influence. They should be monitored and informed of decisions

Caretaker / relative

In 90% of the cases, a caretaker, parent or other relative is present (Jan Berend Zweerts, personal communication, October 13, 2022). Some of the clients simply need this because either they are a child or they suffer from mental disabilities. These caretakers usually have the best interest in the (mental) wellbeing of the person they are taking care of, and will usually try to keep them relaxed and/or stand up for the interests of the person being scanned.

Glasses designer

The designer of the glasses is a designer employed by Maatbril. He will take the raw scanning data, clean it up and design the glasses around it. He wants to be able to quickly deliver well-fitting glasses, and will need high quality 3D scans that require little post-processing to be able to do so. Next to that, a clear set of requirements and wishes should be delivered.

Interest groups

There are several interest groups related to this topic, of which the most famous being Bartiméus[5] and Koninklijke Visio[6]. They want to improve the quality of life by offering housing with special care, trainings, education, daytime activities and specialistic (eye-) healthcare[7] [8]. Some of Maatbril's clients live at such facilities. For the latter situation could it be interesting to teach some of their employees how to operate the 3D Head Scanner.

Glasses manufacturer

Producers of custom glasses can either be additive and/or subtractive manufacturing companies. Currently, most of the glasses are created with SLS 3D printing technology[9] [10]. These companies simply want to earn money by delivering high quality products with a short lead time.

3D-scanner manufacturer

The person building, assembling and or repairing the 3D scanner can either be a DIY-enthusiast or it could be done by a small company or sheltered employment. They want to be able to quickly and easily (dis)assemble the 3D scanners. The ability to only have to use basic tools and the availability of clear documentation would help with this. Whether the scanner will be made by Maatbril, a DIY-er or some other entity will also largely influence the business model of the scanner.

Designer

A special place has been allocated to the designer of the 3D scanner. Whereas now the designer has a high influence on the eventual product and process and has contact with basically all other stakeholders in the project, when this Master's Graduation Project comes to an end, other stakeholders will have to step in to partly take over some of the responsibilities. According to Maatbril it could be a realistic future scenario that e.g. employees of Bartiméus or Koninklijke Visio get taught how to operate the scanner, to improve the experience of the user and/or to optimize the workflow. That is why in the diagram some of the desired future roles of stakeholders have been drawn.

---

[5] The largest Dutch organisation providing services for people with visual, mental or multiple impairments.(Bartiméus, 2023; Visio, 2023)

[6] Expertise centre for people with visual impairments, with a focus on stimulating scientific research

[7] Bartiméus. (2023). *Dagbesteding bij Bartiméus*. https://bartimeus.nl/dagbesteding-en-logeren

[8] Visio. (2023). *Wonen & Dagbesteding*. Visio. https://www.visio.org/wonen-dagbesteding/

[9] FormLabs. (2022). *How a Swiss Eyewear Manufacturer Uses SLS 3D Printing to Produce High-Quality Eyewear*. https://formlabs.com/blog/swiss-eyewear-manufacturer-uses-sls-3d-printing/

[10] Roger Bacon Eyewear. (2017). *Glasses*. https://rogerbacon-eyewear.com/glasses/

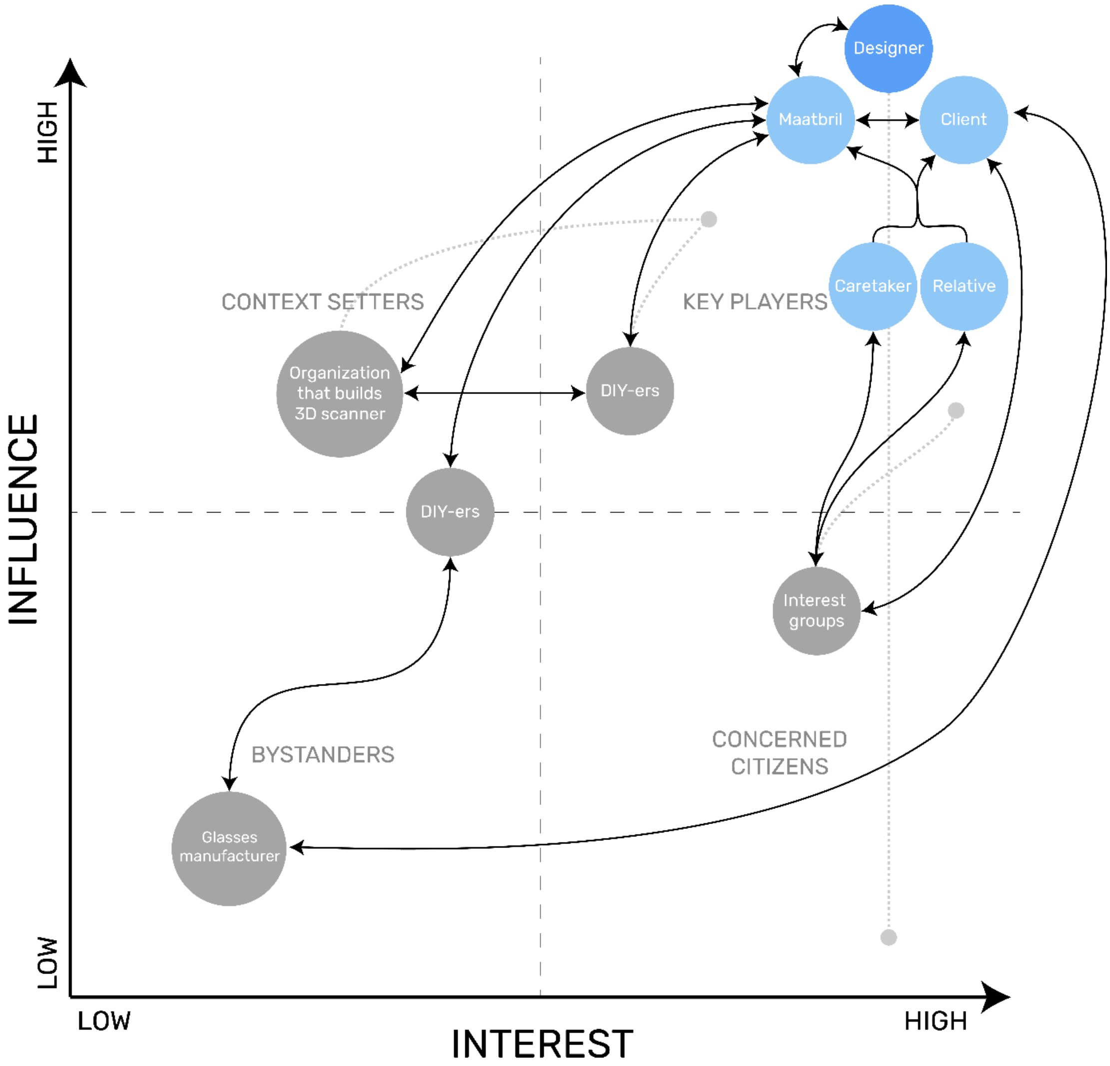


Figure 2: Stakeholder map

Appendix AB: Bill of Materials

Component name	**Specs.**	**€/piece**	**Qty.**	**Link**	**Date checked**
Off the shelf components					
Azure Kinect SDK		€ 333,10	2	https://www.microsoft.com/en-us/d/azure-kinect-dk/8pp5vxmd9nhq?activetab=pivot:overviewtab	*22-3-2023*
USB-C cable	min. USB 3.0	€ 4,91	2	https://a.aliexpress.com/_EQZW47d	*22-3-2023*
Tablet		€ 84,24	1	https://www.geekbuying.com/item/BDF-M107-10-1-Inch-4G-LTE-Tablet-for-Kids-Octa-Core-Black-518781.html	*22-3-2023*
Tablet holder	4.7-12.9"	€ 14,99	1	https://www.amazon.nl/dp/B0B879B5M5/ref=pe_28126711_487805961_TE_item	*22-3-2023*
Foldable legs		€ 12,99	2	https://www.bol.com/nl/nl/p/voomy-laptopstandaard-tablet-tripod-verstelbaar-antislip-zwart/9200000105987836/?Referrer=ENTcli_order_confirmation2008093611	*22-3-2023*
Aluminium profile	T-slot 20x20	€ 15,50	1	https://www.123-3d.nl/123-3D-Aluminium-profiel-2020-zwart-lengte-1-m-123-3D-huismerk-HFSB5-2020-1000-i3765-t14576.html	*22-3-2023*
Philips screw M3x8	rounded head	€ 0,03	12	https://a.aliexpress.com/_Ez4YEd1	*22-3-2023*
Sliding nuts M3		€ 0,09	12	https://a.aliexpress.com/_EQWg0UX	*22-3-2023*
Imperial nut	1/4 20 UNC	€ 0,20	1	https://a.aliexpress.com/_EusOfbt	*22-3-2023*
3D prints					
Sensor mount left	PLA | 6 hr 39 min	€ 16,95	0,129		*22-3-2023*
Sensor mount right	PLA | 6 hr 39 min	€ 16,95	0,129		*22-3-2023*
Tablet mount connector	PLA | 1 hr 59 min	€ 16,95	0,038		*22-3-2023*
Tablet mount spacer	PLA | 0 hr 14 min	€ 16,95	0,006		*22-3-2023*
Optional					
Laptop	Refurbished	€ 95,00	1	https://www.remarkt.nl/dell-latitude-e5250-intel-core-i5-5e-gen-12-inch-laptop-op-maat-a-grade	*22-3-2023*
USB hub		€ 14,95	1	grijs/9300000091173001/?Referrer=ADVNLGOO002013-G-135735704102-S-1681056711835-9300000091173001&gclid=CjwKCAjwzuqgBhAcEiwAdj5dRlAMtg2jlThFcEZEziRXzxRISVnaFZ_TVeBDKVlJK2c52PGSvAK-TxoCU9MQAvD_BwE	*22-3-2023*
Travel bag	85 x 15 x15 cm	€ 10,10	1	https://a.aliexpress.com/_EwrKmoJ	*22-3-2023*
Tripod		€ 10,82	1	https://a.aliexpress.com/_ExfAbOn	*22-3-2023*

Total cost	€ 823,44

Required tools
Soldering iron
M3 HEX key
Metal saw

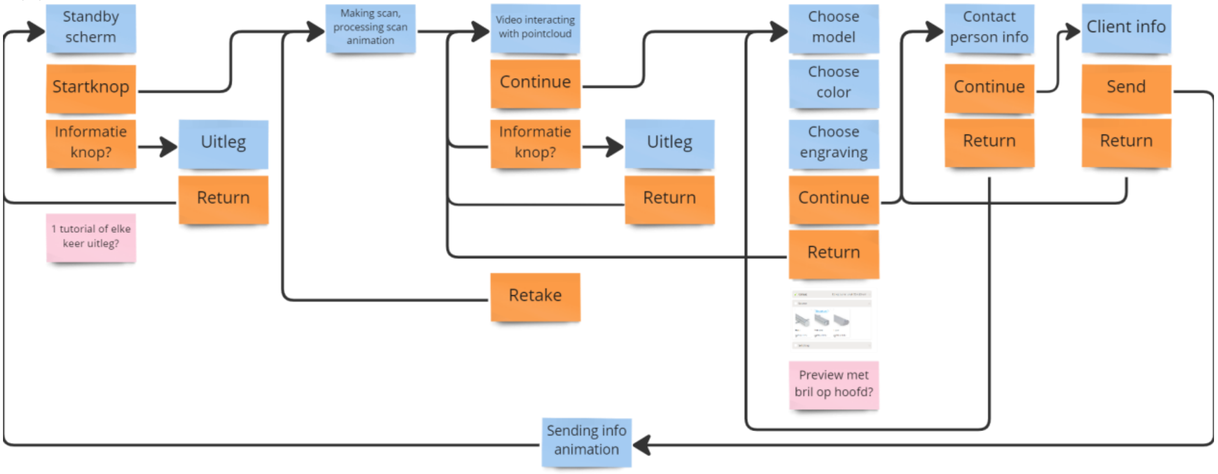
Appendix AC: UI tests

UI test 1.0 (n=3)

Procedure:

1. Explain procedure
    a. *Bedankt dat je mee wilt doen aan deze test, het duurt zo'n 5 a 10 minuten. Gedurende deze test speel jij de rol van een verzorger van een mentaal beperkt persoon die ook nog eens een bijzonder gevormd hoofd heeft. Deze persoon heeft een bril nodig, moet daarom ingescand worden en aan jou de taak dit te doen. Je krijgt zo een tablet in je handen waarmee je in principe alles kan regelen. Probeer hardop te denken bij alles wat je doet, denkt of over twijfelt. Wees vooral niet bang om gewoon te doen wat je het meest logisch zou lijken en als er iets fout is, ligt dit aan het ontwerp. Voor dat we beginnen zou ik willen vragen of je de informed consent forms zou willen invullen.*
2. Sign informed consent forms
3. Observations
4. Present options and choose between alternatives
    a. Tutorial at homescreen, '?', or both
    b. Type of selection for model and color
    c. How to know if user is aligned
    d. Amount of information while waiting
    e. Progress bar at specific screens
5. Design ideas
    a. How to make it clear that point clouds are interactive?
    b. How to give feedback for automated sequence
6. Other remarks/tips

App flow scheme:



Prototype:

See appendix I

Results:

Participant 1: Doesn't want to read the tutorial (dyslectic), doesn't want to press the same button again because something went wrong. Tutorial is not complete when going back and reading it. Not clear that point clouds are interactive. "What is meant with engraving?"

Participant 2: Wants to have texts 'left scanner' and 'right scanner' in the image preview. Wants to have a title and comment at every screen. When something goes wrong, doesn't want to use the same button again

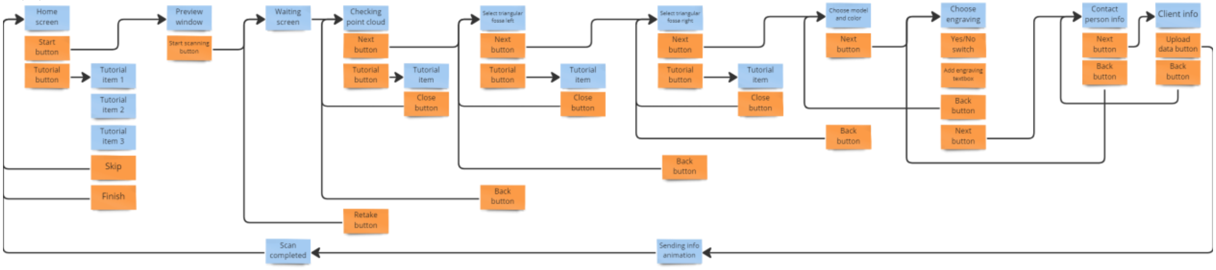
Participant 3: Everything went fluently, but participant knew about the procedure. Participant finds it nice to see what is happening under the hood, not a black box.

UI test 2.0 (n=6)

Procedure:

1. Explain procedure
    a. *Bedankt dat je mee wilt doen aan deze test, het duurt zo'n 5 a 10 minuten. Gedurende deze test speel jij de rol van een verzorger van een mentaal beperkt persoon die ook nog eens een bijzonder gevormd hoofd heeft. Deze persoon heeft een bril nodig, moet daarom ingescand worden en aan jou de taak dit te doen. Je krijgt zo een tablet in je handen waarmee je in principe alles kan regelen. Probeer hardop te denken bij alles wat je doet, denkt of over twijfelt. Wees vooral niet bang om gewoon te doen wat je het meest logisch zou lijken en als er iets fout is, ligt dit aan het ontwerp. Voor dat we beginnen zou ik willen vragen of je de informed consent forms zou willen invullen.*
2. Sign informed consent forms
3. Observations
4. Other remarks/tips

App flow scheme:



Results:

Participant 1: Thinks he doesn't need the tutorial. Understands that the screens with point clouds are interactive. Immediately understood how to align the 3D head scanner and recognized when point clouds were not aligned properly. Filled out all details correctly. Participant has experience with computer vision.

Participant 2: Didn't make use of the tutorial and understood how to align the cameras. When the scan seemed wrong, she didn't know what to do because "didn't want to do the same thing twice". Has no idea what to do with the ear selection points. Did not see the '?" buttons to get more information. Participant is confused what information to put where. Difference between client and person taking the scan not clear enough.

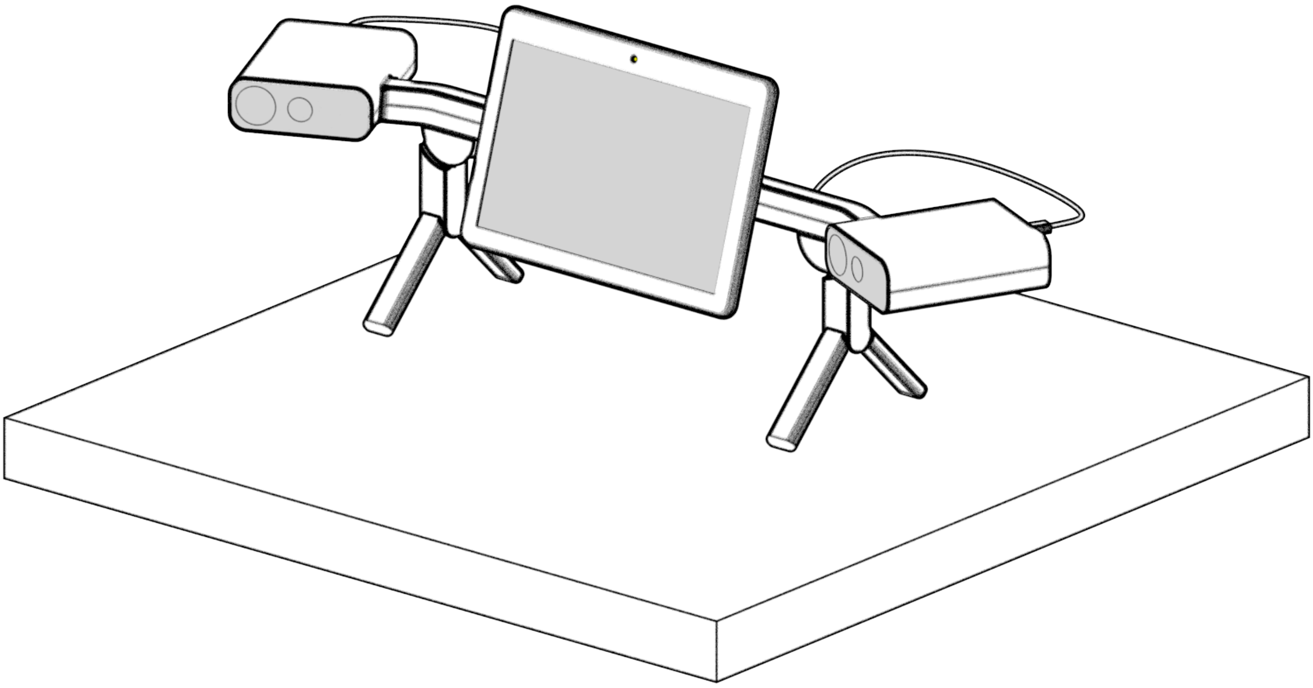
Participant 3: Thinks that the tablet is small and gives a cheap appearance. Clicks ‘Next” when seeing the misaligned heads because he thinks that the aligning part is yet to come. Understood that point clouds are interactive. “Getting feedback from salesperson would be nice when fitting the different models”. Doesn’t understand why organizational information is required/needed. Wonders if more info is needed about the caretaker/parents of the client. Button with “?” was not noticed. Thinks it might be a good idea to make the tutorial obligated, but a bit easier to skip if already completed before. Participant would not trust the head scanner to take the scan by itself, prefers to click a button to capture the scan. Participant wonders how to change points of ears, maybe only one point can be selected and two different screens are opened after one another. Participant has idea to make the interactiveness stand out more by integrating arrows to show that inclination, zoom, rotation are possible.

Participant 4: Finds the colour blue very intense. Doesn’t do the tutorial and says she would never follow a tutorial. Realizes that scan is good, but not aligned properly. Text ‘Camera 1’ and ‘Camera 2’ are vague. Better would be to rename them to left and right. Doesn’t understand the engraving part. Would like to have an option where it is greyed out.

Participant 5: When seeing camera view: “Is this live? Or is this an example?” Finds it nice that the ovals change to green when in picture. Selects 2 points on the same ear. Why engraving? Doesn’t understand what organization information is. Would never follow a tutorial, if something isn’t right, I’ll find out.

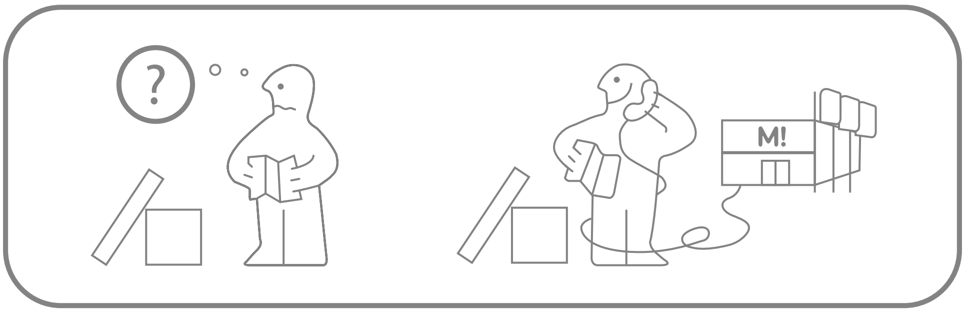
Participant 6: “Skipping button in tutorial is unclear, maybe better to use an ‘X’”. For second tutorial item: “Not clear if scan is made here already or not”. “Multiple scans are made?” Wonders what happens if scans are not aligned and user presses continue. “What is the meaning of geometry?” “Ear connection points? Triangular Fossa?” Finds presentation of data such as titles and commands inconsistent.

Appendix AD: Quick Start Guide



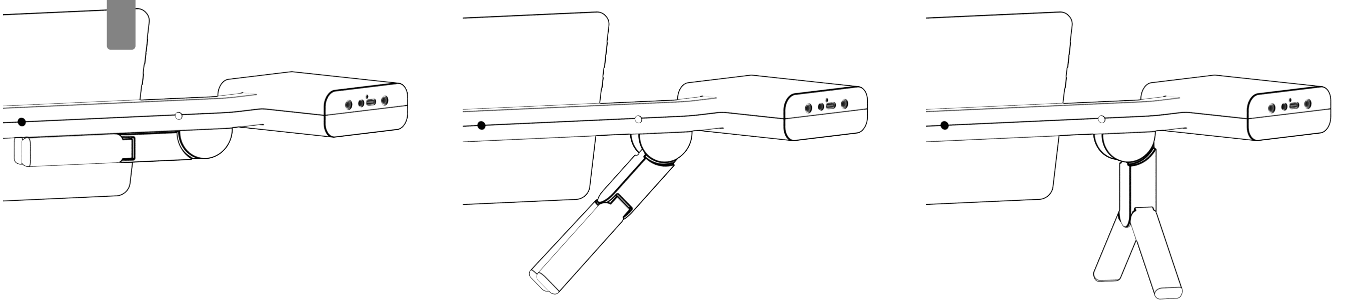
Quick Start Guide.

Unfold. Plug in. Scan.

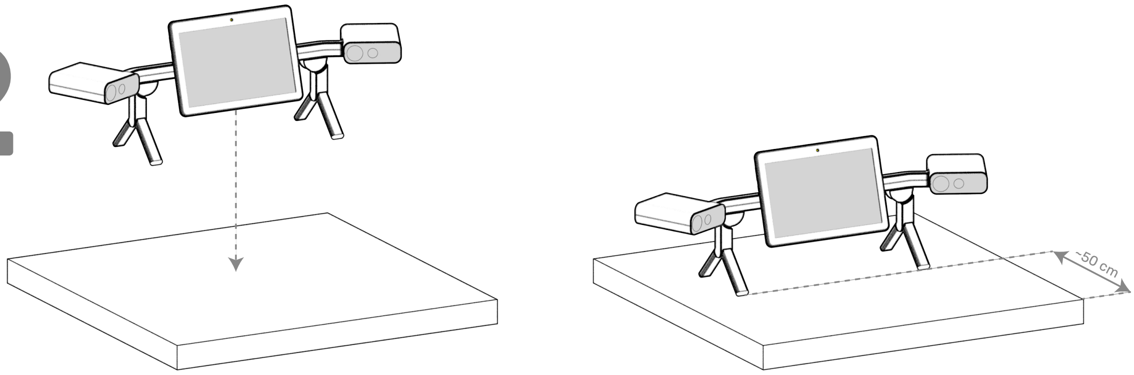


M!
Maatbril

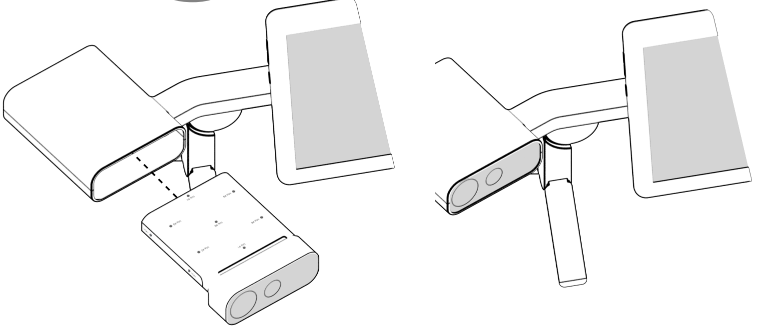
1



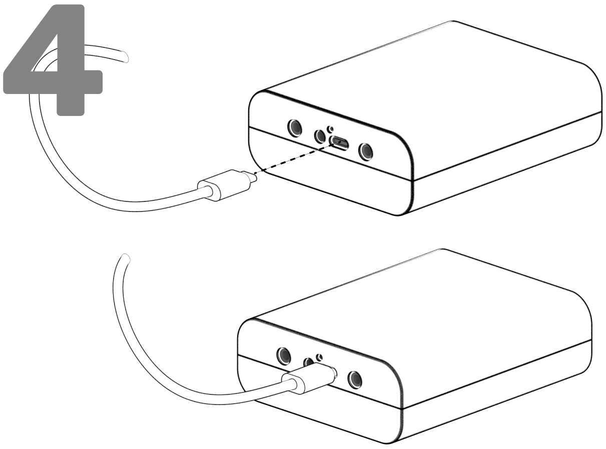
2



3



4



5

6

Appendix AE: Evaluation sessions with experts

Evaluation with Bertus Naagen

- Positively surprised by visual appearance, looks quite small
- Likes how tablet is integrated in device to distract people
- Likes that it fits in a tripod bag so it's easy to carry
- Thinks the legs are a bit flimsy, suggests to fix them or drill holes in the legs to put pin inside
- Is surprised by capturing time, is used to scanning times of 30-60 seconds with the Artec 3D Scanners
- Notices that nose bridge is a bit wider than in reality, zooms in further and notices small misalignment between the two scans, but thinks that this could be easily fixed.
- Suggests to implement functionality to do initial global registration by hand for when the software fails/keeps failing
- Some double surfaces around the left eye noticed, revealed by cutting away the unnecessary surfaces (with low density), maybe filter is too aggressive.
- Face is not smooth after filters, maybe result was even better before applying filters
- Optimization of post processing steps are needed to get 3D scans of higher quality
- Is positive about the burst-concept to reduce noise and inefficiencies, however immediately realizes that this goes at cost of processing/waiting time
- Concludes with "All in all, really good results for an individual, especially since usually entire departments work on developing such processing software."

Evaluation with Jan Berend Zweerts

- Likes how easy it is to ship it in the bag
- Thinks that the time it takes to setup the device is okay
- Agrees that putting it on a tripod is not the nicest idea, but likes to have the option if needed
- Finds this design direction a really interesting approach
- Is slightly disappointed that he cannot just take it right now and use it for his scans, but that it needs some work
- Thinks the legs are currently too unstable, since they collapsed a few times
- Is happy that the proposed concept looks a bit tougher and sturdier
- Asks if two separate USB cables are needed
- Ideally would like to see something 'headless', wonders if Raspberry Pi is an option
- "I'm really impressed with all small details that have been integrated in this design"
- Wonders if it's possible to integrate texture in the point clouds and 3D model as well
- Mentions that addition of lights is needed to get evenly illuminated texture maps
- Needs to sit a bit lower to fit into the view (but only because 15 degree angle is not implemented currently)
- Agrees that all important geometry is captured in the 3D scan
- Says the 3D scan without smoothing is not good enough for him to use currently and doesn't look professional enough to show to client
- Prefers to have the file in .OBJ format instead of .STL as is used now
- Notices small double nose in the 3D scan
- Thinks that the concept will really work in terms of interaction, based on his experience
- Likes that the prototype doesn't look overwhelming and/or intimidating
- Is impressed with the cost of the prototype

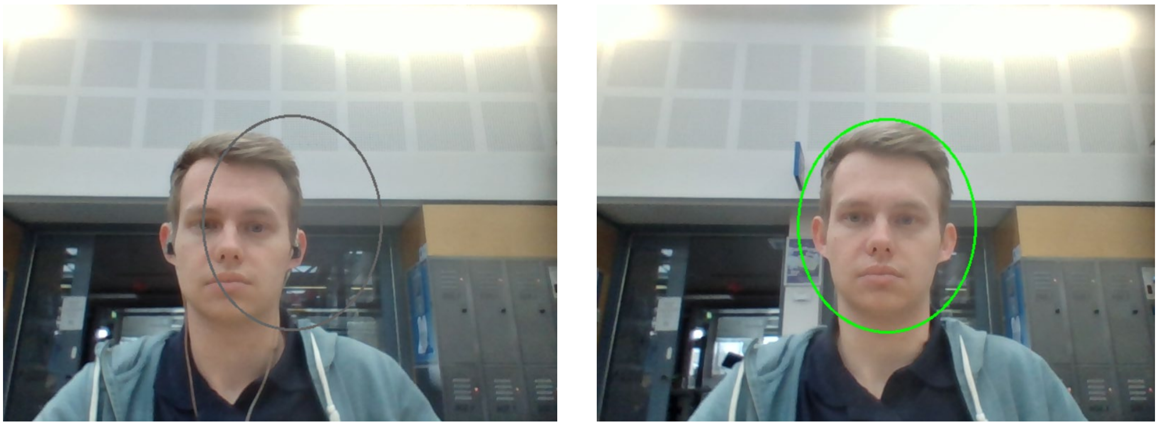
Appendix AF: Scanner alignment test

Objective:
Find out what is the easiest way to align the scanner to the client

Procedure:

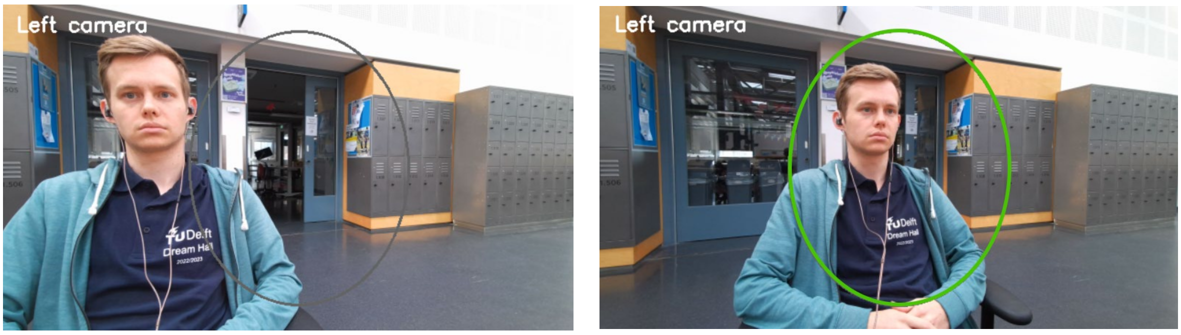
- Show and explain the different options available
- Have someone sit down as fake client
- Let the participant align place and align the scanner with the fake client, trying out all different design options, but in different orders to avoid order effect
- Ask participants to think out loud
- Observe what goes well and what not
- Let them rank the alternatives

Alternatives:
1. Use camera on tablet for aligning the scanner. When face is located in the oval, oval will turn green.



2. Use camera on tablet for aligning the scanner. When face is located in the oval, oval will turn green. When face is not located in oval, system will help in placing the 3D scanner.

3. Use one of the two scanners from the 3D head scanner. Only the left or right preview will appear and the participant has to align the 3D scanner in such a way that the head is completely inside the oval. If so, the oval will turn green.



4. Use both cameras from the 3D head scanner. The participant has to align the 3D scanner in such a way that the head is completely inside the oval in both shots. If so, the oval will turn green.

5. Use both cameras from the 3D head scanner. The participant has to align the 3D scanner in such a way that the head is completely inside the oval in both shots. If so, the oval will turn green. When face is not located in oval, system will help in placing the 3D scanner.

Results:

Participant 1:

“A bit frustrating that sometimes it’s green and sometimes not, while there doesn’t seem to be a lot of difference in the position” (about alternative 1), likes alternative 2 therefore a lot better. For alternative 3, tries to fit my head completely in the oval, but realizes halfway that this is not going to work. Is confused about how to solve it. Likes that alternative 4 seems less strict in placement than concept 1. Also likes alternative 5 more than 4 for the same reason as before.

Preferred order: 2-5-1-4-3

Participant 2:

Finds alternative 2 unnecessary since alternative 1 is quite similar and it’s easy enough to adjust the system. Keeps walking back and forth between the laptop and the scanner to adjust it for alternatives 3, 4 and 5. Manages to align the 3D Scanner without too much difficulty in all scenarios.

Preferred order: 5-4-1-2-3

Participant 3:

Wonders if alignment needs to be really that precise for alternatives 1 and 2. Asks me to look into the left camera for alternative 3 and tries to make my head fit the oval, but quickly realizes that it is strange. Has trouble aligning the system for alternative 4, moves it the wrong way, suggests that maybe the preview should be mirrored. Is happy with the instructions provided in scenario 5, calls it a ‘big improvement’.

Preferred order: 5-4-2-1-3

Participant 4:
Seems to have good spatial awareness, manages to align the scanner correctly without too much effort, but finds it strange why only the left camera in alternative 3. Wonders if you can also choose to only see the right camera in case of difficult back-lighting. Smartly rotates the laptop to be able to see the result when adjusting the scanner for alternatives 3, 4 and 5. Takes significantly longer to perform alternative 4 than alternative 5, but says he realizes now what direction the scanner needs to be moved in.

Preferred order: 2-1-5-4-3

Participant 5:
Asks me to move left and right instead of moving the scanner, but hard follow the instructions, since it's easy to overshoot the movement. Then asks if it's okay to align it for himself and then I will sit down at the same place and it will be set up already. When I follow him, it turns out that the height is different for us, meaning that system still has to be adjusted. Finds alternative 3 strange since you see the client from the side, but only one side, feels natural to rotate the scanner to have it focus from the front. Also thinks alternative 4 and 5 feel a lot more natural because of that.

Preferred order: 1-2-4-5-3

General observation:
As the person sitting down to align the scanner to, it felt quite intrusive when using the screen on the iPad for alignment. While sitting and waiting someone is adjusting the system. Especially when they are trying to read the text on the iPad, they come quite close. Moreover, it was strange a bit of a strange cross-over between the camera-preview on the tablet and putting on something on YouTube.

Conclusion:
Although the alternatives that made use of the integrated camera in the tablet were considered easiest for the person aligning the 3D head scanner, it has been chosen not to continue with alternatives 1 and 2. The reason for this is the experience for the person that is being scanned. Alternatives 3, 4 and 5 felt a lot more natural and less forced/intrusive. Alternative 3 was rated worst by all participants and is therefore not considered as a valid option. Looking at alternatives 4 and 5, they are quite similar, but when looking at the ratings, all except participant 5 preferred alternative 5 over alternative 4. Alternative 5 will therefore be implemented in the design. If someone feels like it's unnecessary he/she can also just ignore the text alternatively.

Appendix AG: Assembly test

Goal:
Goal of the experiment is to find potential bottlenecks in the assembly procedure. Next to that, the time needed to assemble the 3D Head Scanner.

Setup:
- Place all parts and required tools on a table
- Give participant a photo of the prototype and ask him/her to assemble all parts to get a prototype
- Measure the time needed to remove the support from the 3D prints
- Measure the time needed to assemble the complete prototype
- Observe what goes wrong

Results:
Participant 1:
Time needed to remove support: 28 min
Time needed to assemble prototype: 19 min
Observations: Doubts if the screen mount should have been placed on before already

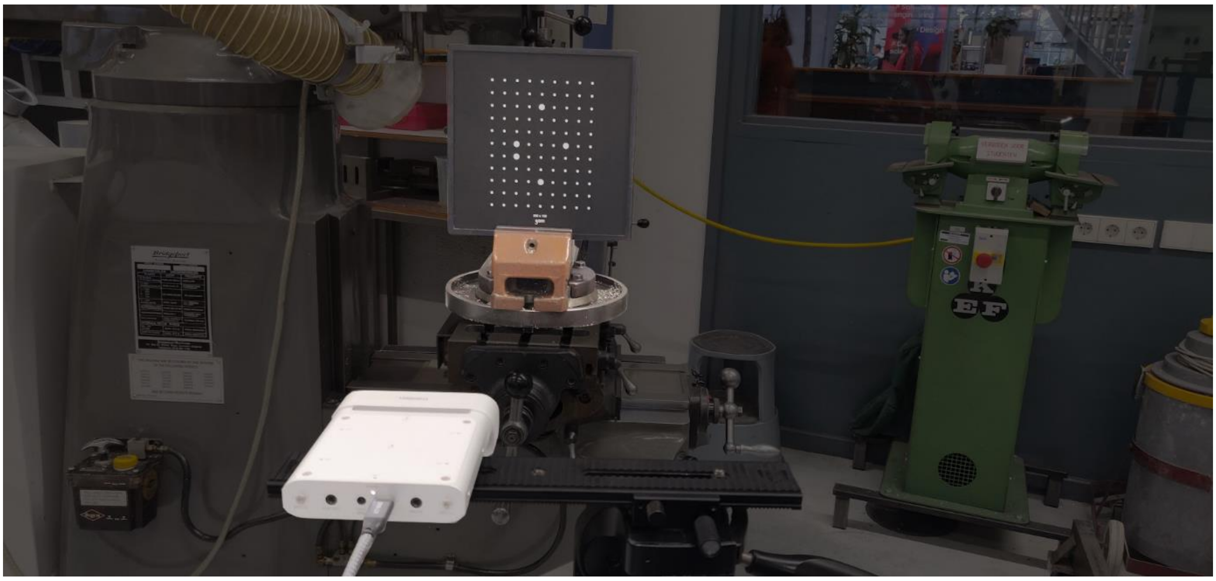
Participant 2:
Time needed to remove support: 17 min
Time needed to assemble prototype: 12 min
Observations: -

Appendix AH: Flatness measurement test

Goal: This experiment is executed to find out the maximum achievable accuracy of the Azure Kinect SDK sensor under ambient conditions that are similar to the conditions that can be expected in the use scenarios.

Setup:

1. Place the Azure Kinect SDK on a tripod
2. Place a calibration plate with calibrated flatness 400 mm away from the sensor (on a milling machine)



3. Measure the ambient light intensity
4. Capture a 3D scan of the plate with the Azure Kinect SDK and save as .PLY
5. Repeat this for a total of 5 times
6. Repeat steps 2 to 5 also for 500, 600, 700, 800 and 900 mm
7. Crop the 3D scans so that only the flat plate is still in the scan
8. Import the 3D scans to Rhino and Grasshopper
9. Perform plane fitting by using the 'Plane fit'-component
10. Calculate the average distance between the individual points and plane by using Root Mean Square (RMS) formula $RMS = \sqrt{\frac{x1^2+x2^2+\cdots xn^2}{n}}$

Results:

All results were captured with an ambient lighting strength of about 250 Lux.

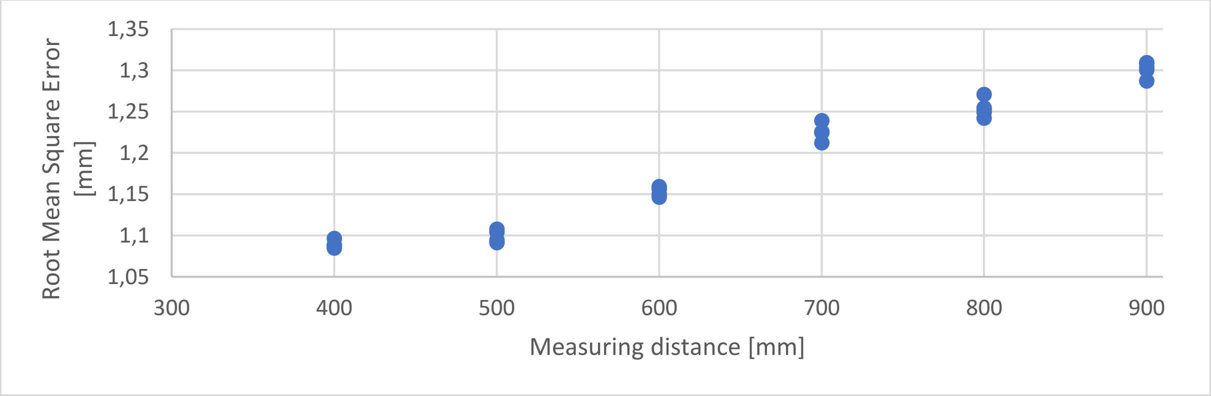


Figure 1: Root Mean Square error measurements for different measuring distances

Table 1 gives an overview of the calculated Root Mean Square errors, while Figure 1 gives a visual overview.

Table 1: Root Mean Square error calculated for individual measurements

Distance [mm]	Measurement #	Root Mean Square error [mm]
400	1	1.087993
	2	1.085974
	3	1.096666
	4	1.088383
	5	1.084912
500	1	1.104544
	2	1.091422
	3	1.092821
	4	1.094773
	5	1.107776
600	1	1.15667
	2	1.150476
	3	1.157197
	4	1.146754
	5	1.15939
700	1	1.224929
	2	1.225461
	3	1.212526
	4	1.239213
	5	1.225479
800	1	1.252408
	2	1.270935
	3	1.249462
	4	1.254869
	5	1.242229
900	1	1.309261
	2	1.303817
	3	1.309488
	4	1.287261
	5	1.300545

Not only were the individual errors calculated, also the average Root Mean Square value per distance and its' standard deviation were calculated and can be found in Table 2.

Table 2: Average Root Mean Square and Root Mean Square standard deviation

Distance [mm]	Average Root Mean Square [mm]	Standard deviation RMS [mm]
400	1.0887856	0.004142484
500	1.0982672	0.006611245
600	1.1540974	0.004717573
700	1.2255216	0.008446262
800	1.2539806	0.009478733
900	1.3020744	0.008141514

Conclusion:
Looking at the data provided in Table 2, it can be seen that for the ideal working distance, 500 mm, the average root mean square value is equal to ~1.1 mm. The further away the scanned object, the higher the average error, up to ~1.3 mm at 900 mm distance. Looking at the standard deviation values, it can be concluded that the Azure Kinect Scanner is also quite precise.

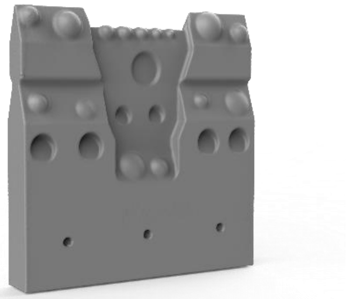
Discussion:
Since this experiment is executed on a flat plane, it does not conclude yet if the resolution of the Azure Kinect SDK is high enough to capture complex geometry as can be expected while scanning facial features.

Appendix AI: Accuracy test | Complex object

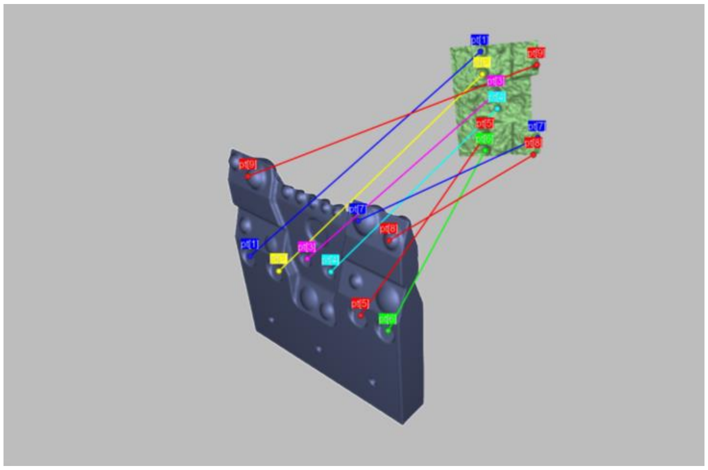
Goal: This experiment is executed to find out the maximum achievable accuracy of the Azure Kinect SDK sensor under ambient conditions that are similar to the conditions that can be expected in the use scenarios.

Setup:

1. Place the Azure Kinect SDK on a tripod
2. Place the calibration object 400 mm away from the sensor (on a milling machine)



3. Measure the ambient light intensity
4. Capture a 3D scan of the plate with the Azure Kinect SDK and save as .PLY
5. Repeat this for a total of 5 times
6. Repeat steps 2 to 5 also for 500, 600, 700, 800 and 900 mm
7. Crop the 3D scans so that only the calibration object is still in the scan
8. Make a 3D scan of the calibration object with the Artec Spider
9. Import both scans to Artec Studio
10. Align both scans



11. Calculate the average distance between the individual points and plane by using Root Mean Square (RMS) formula $RMS = \sqrt{\frac{x1^2+x2^2+\cdots\ xn^2}{n}}$

Results:

All results were captured with an ambient lighting strength of about 250 Lux.

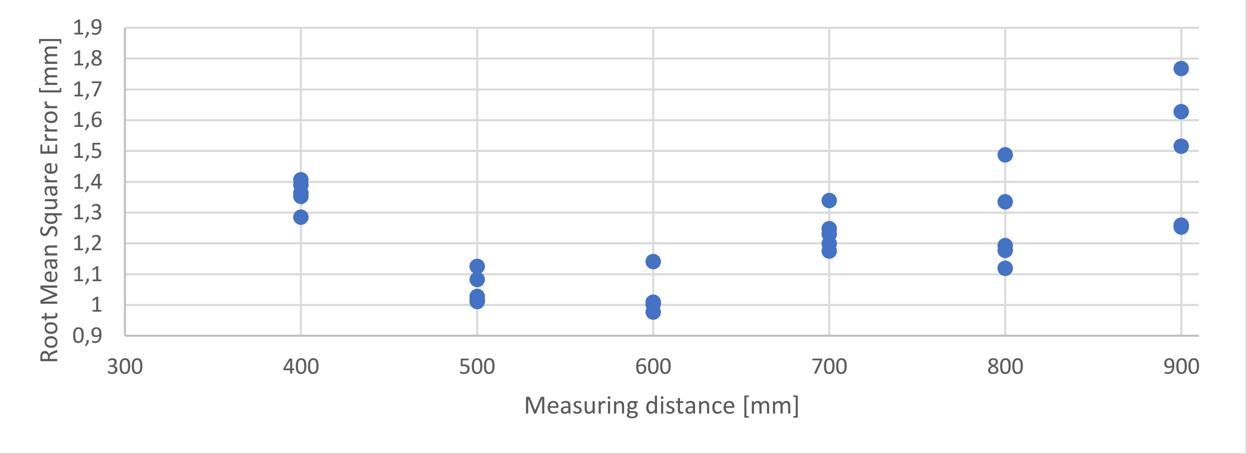


Figure 1: Root Mean Square error measurements for different measuring distances

Table 1 gives an overview of the calculated Root Mean Square errors, while Figure 1 gives a visual overview.

Table 1: Root Mean Square error calculated for individual measurements

Distance [mm]	Measurement #	Root Mean Square error [mm]
400	1	1.36434
	2	1.28555
	3	1.40677
	4	1.35291
	5	1.38998
500	1	1.01539
	2	1.02743
	3	1.08324
	4	1.01161
	5	1.12553
600	1	1.00320
	2	0.97654
	3	1.14109
	4	1.00928
	5	1.00861
700	1	1.17497
	2	1.19874
	3	1.33951
	4	1.24773
	5	1.23033
800	1	1.17701
	2	1.48753
	3	1.33565
	4	1.11893
	5	1.19255

900	1	1.51536
	2	1.76782
	3	1.62834
	4	1.25968
	5	1.25364

Not only were the individual errors calculated, also the average Root Mean Square value per distance and its' standard deviation were calculated and can be found in Table 2.

Table 2: Average Root Mean Square and Root Mean Square standard deviation

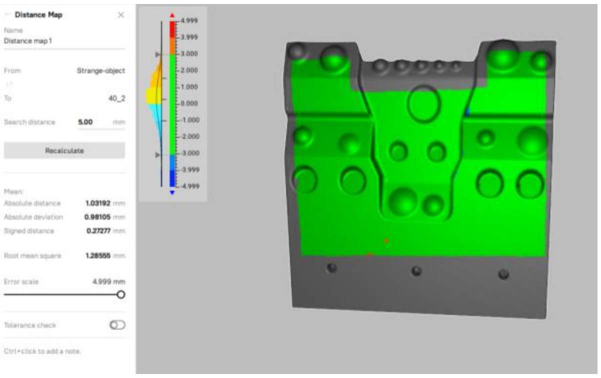
Distance [mm]	Average Root Mean Square [mm]	Standard deviation RMS [mm]
400	1.35991	0.04171
500	1.05264	0.04462
600	1.02774	0.05793
700	1.23825	0.05651
800	1.26233	0.13326
900	1.48496	0.20285

Conclusion:

Looking at the data provided in Table 2, it can be seen that for the ideal working distance, 500 mm, the average root mean square value is equal to ~1.0 mm. The further away the scanned object, the higher the average error, up to ~1.5 mm at 900 mm distance. Interestingly, for 400 mm the average root mean square value is equal to 1.36 mm.

Discussion:

For the evaluation, the maximum comparison distance was set to 5.0 mm. When this value would be increased, the root mean square error significantly improves as can be seen in the figures below. The main reason for this are inefficiencies in the 3D scan captured by the Artec Spider. When increasing the distance between the geometry and the Azure Kinect SDK, the resolution became lower which made it harder to accurately align both scans. This could mean that part of the error found, could be caused by misalignment and not by scanner error.



Distance Map

Name: Distance map 1

From: Strange-object

To: 40_2

Search distance: 5.00 mm

Mean:

Absolute distance: 1.03192 mm

Absolute deviation: 0.98105 mm

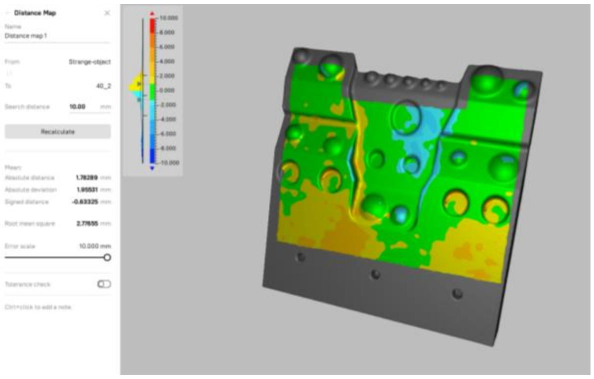
Signed distance: 0.27277 mm

Root mean square: 1.28555 mm

Error scale: 4.999 mm

Tolerance check

Ctrl+click to add a note.



Distance Map

Name: Distance map 1

From: Strange-object

To: 40_2

Search distance: 10.00 mm

Mean:

Absolute distance: 1.78289 mm

Absolute deviation: 1.95531 mm

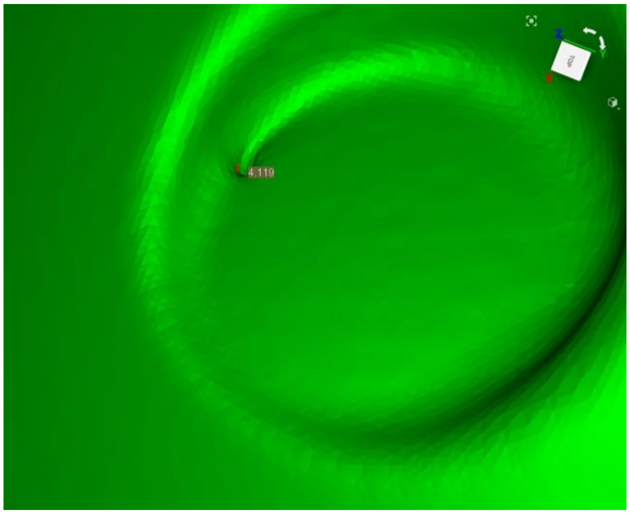
Signed distance: -0.83325 mm

Root mean square: 2.77655 mm

Error scale: 10.000 mm

Tolerance check

Ctrl+click to add a note.

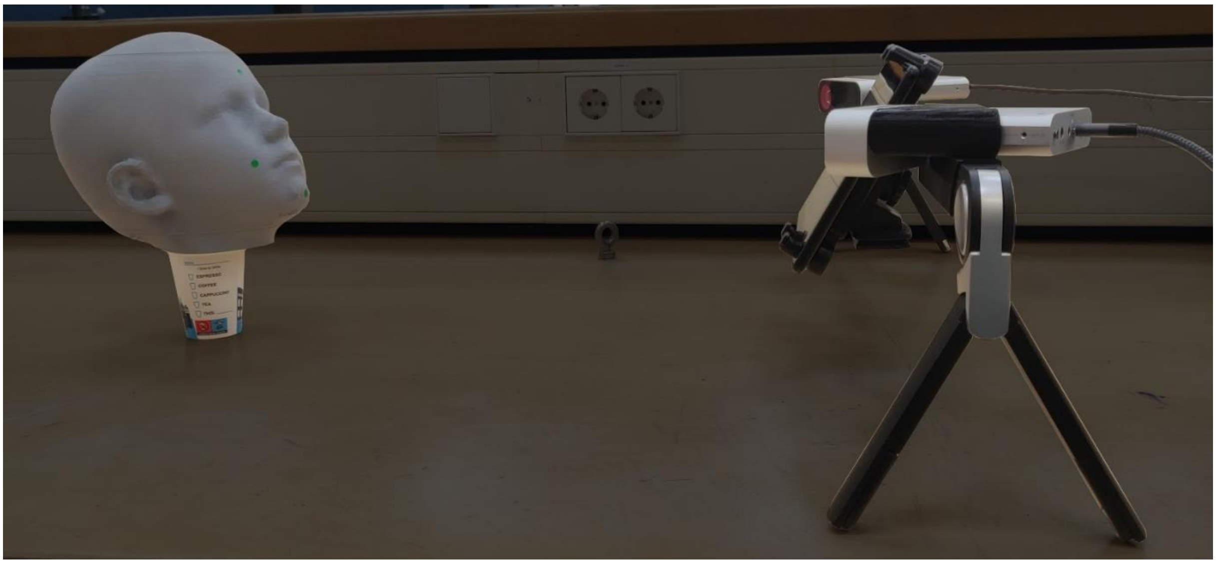

4.119
Z
Y
X
Top

Appendix AJ: Accuracy | 3D printed head shape

Goal: This experiment is executed to find out what is the accuracy of the 3D Head Scanner prototype under ambient conditions that are similar to the conditions that can be expected in the use scenarios.

Setup:

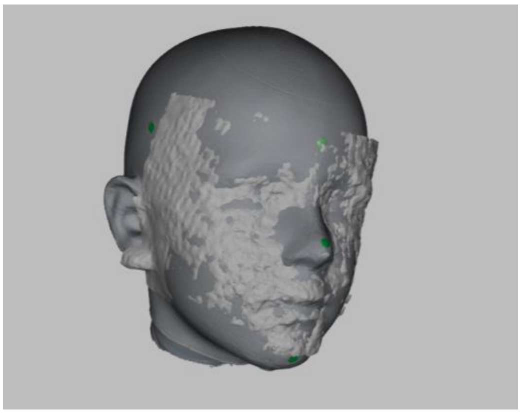
1. Place the 3D Head Scanner on a flat surface
2. Place the 3D printed head 500 mm away from the sensor

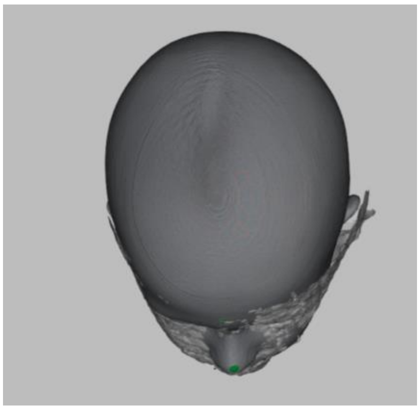


3. Measure the ambient light intensity
4. Capture a 3D scan of the 3D printed head with the 3D Head Scanner prototype and save as .PLY
5. Crop the 3D scan so that only the 3D printed head is in the scan
6. Make a 3D scan of the 3D printed head with the Artec Spider
7. Align both scans in Artec Studio
8. Calculate the average distance between the individual points and plane by using Root Mean Square (RMS) formula $RMS = \sqrt{\frac{x1^2 + x2^2 + \cdots xn^2}{n}}$

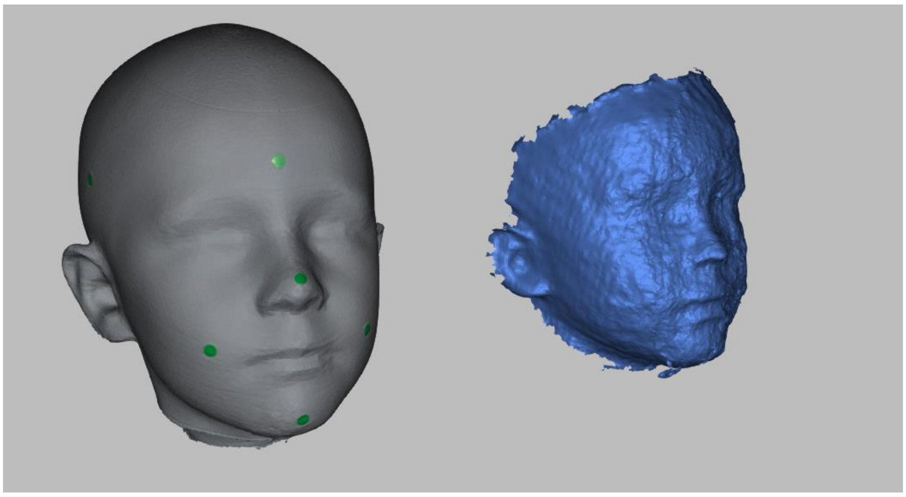
Results:

When aligning the 3D model generated by the 3D Head Scanner to the 3D head model capture by the Artec Spider, it became apparent that the alignment of the 2 separate scans that the 3D Head Scanner consists of, was not that accurate.

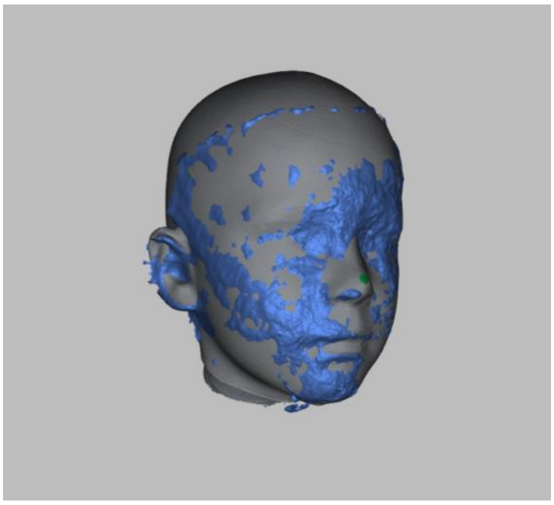


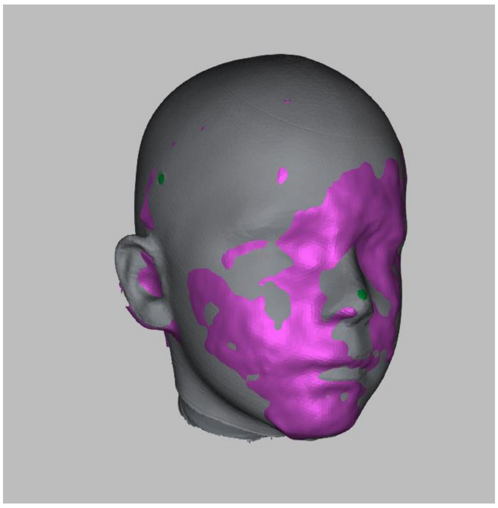


Whereas the left side of the scans seem to be aligned quite tightly, from the top view it can be observed that the right side of the scan sticks out significantly. In total this results in an average Root Mean Square error of ~2.2 mm.



When aligning the scans not with the ICP algorithm, but by the alignment functionality integrated in the Artec Studio software, this problem does not occur. In that case, the Root Mean Square error is equal to 1.26 mm. Moreover, the Root Mean Square error has also been calculated for a smoothed version of the 3D scan. In that case, the Root Mean Square error is equal to 1.20 mm.





Conclusion:
From the results, it can be observed that the current ICP algorithm is causing the system to be less accurate. When making use of a better aligned scan, the accuracy of the 3D Head Scanner can be up to 1.2 mm. A small difference was observed between using a smoothed version and the raw version of the 3D scan. Not only does it look visually more attractive and professional, it also caused a slightly higher accuracy.

Discussion:
While at first thought, it might be assumed that maybe the overlapping surface area of both 3D scans is not high enough for accurate alignment, the algorithms in Artec Studio have showed that good alignment is possible with this amount of overlap. The parameters of the current ICP algorithm should be tweaked, and/or a better starting point for alignment could be given since the location of the sensors is known.

Appendix AK: Evaluation session with Maatbril clients

Goal:

The goal of this evaluation is to find out if the designed interaction really works out in practice as imagined. The idea is that the client will be focused on the tablet, causing him to sit still enough to take the scan.

Participant 1

- When arriving at their home, they had already put a chair ready, which they had remembered from the previous scanning session with Maatbril
- Participant is highly sensitive to light. He needs quite a bit of light to be able to see well, but too much will cause irritation. For a short period of time, exposure to a brighter light would be possible (when the system would have integrated lighting)
- Only a round table was available
- When opening the bag, some loose screws could be found on the bottom, but this is likely the result of the assembly test where some screws might not have been completely tightened
- Because of the width of the device and shape of table, the scanner was placed a bit further away
- Resulting scan was slightly cropped since the scanner was further away than expected
- Participant wanted to watch something from van Kooten en de Bie. This was already put on while the final steps of setup were performed (putting in cables)
- Interestingly, scanners sometimes don’t get recognized, but flipping the USB-C cable upside down in the laptop solves this(?)
- Without adjusting anything or measuring beforehand, the used was good (enough) in view
- Again trouble with the legs of the device that collapsed once or twice due to the 90-degree angle of legs and relatively high mass
- After a while, participant asked when the test would start, at that moment the 3D scan was already aligned and processed, participant was very surprised, had not noticed anything.
- Although video had not finished yet, it was easy to distract the participant by showing the 3D scan of his head
- In general, participant was happy with the scanning procedure: “It went by very quickly and I actually didn’t even notice when the scan was taken”
- “The 3D Scanner looks quite cool, how does it work exactly?”

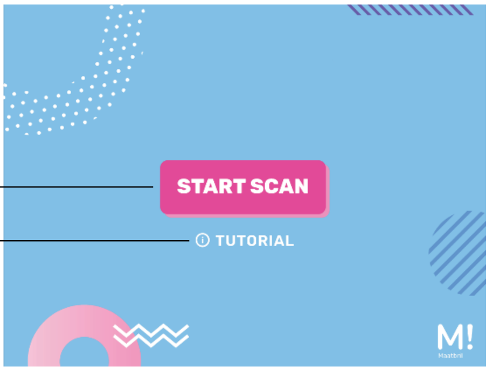
Participant 2 and 3

- Only a trapezoid shaped table was available
- Table was quite small, meaning that it was a bit cramped to sit on the table as well with the control device
- Bumba was already playing when participants arrived
- Participants both suffered from Coffin Siris syndrome
- Both participants rushed to the seat to watch Bumba
- Both participants were still wearing their glasses upon arrival, with help of caretaker, they were removed
- One of the participants was wearing a cloth that he was biting on, caretaker helped removing it since it might affect the shape of the head
- Participant 2 was quite focused on the tablet and didn’t really notice other things that were going on in the room

- Participant 3 was more easily distracted. Moved his head quite a bit while watching the screen of the tablet, also tried to watch the screen from a distance of about 10 cm
- Participants were not asked to sit still, no interference at all took place
- Finishing the interaction was a bit difficult for participant 2. Caretaker paused the video and participant tried a few times to click play again, but relatively easy to move the attention and focus of the participants to something else.
- Participant 2 told caretaker afterwards that he liked it and that he would want to do it again
- Scan made from Participant 2 came out good immediately
- Scan made from Participant 3 needed to be retaken because participant started moving after researcher clicked the capture button
- No adjustments were needed to the height of the 3D Head Scanner, legs were folded out, but not extended

Appendix AL: Final User Interface

1

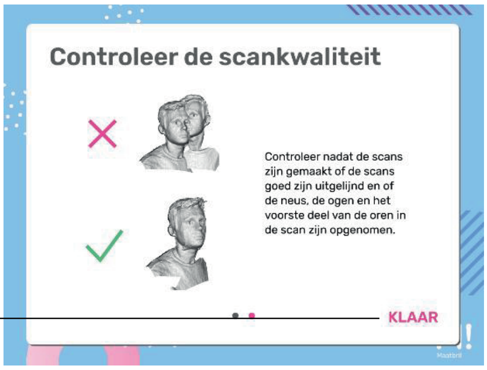


2


Positioneer de scanner

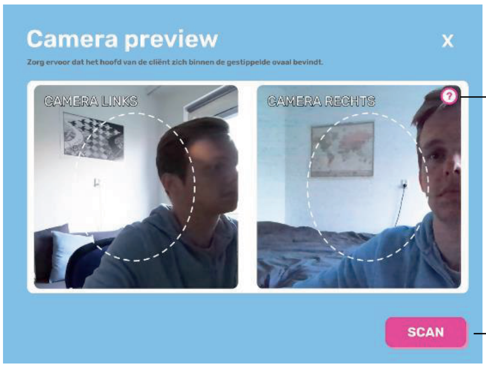
Zorg ervoor dat de scanner zo wordt geplaatst dat het hoofd van de cliënt zich in het gemarkeerde gebied voor beide camera's bevindt.

3


Controleer de scankwaliteit

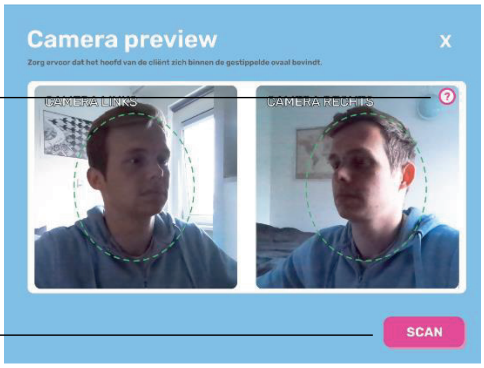
Controleer nadat de scans zijn gemaakt of de scans goed zijn uitgelijnd en of de neus, de ogen en het voorste deel van de oren in de scan zijn opgenomen.

4


Camera preview

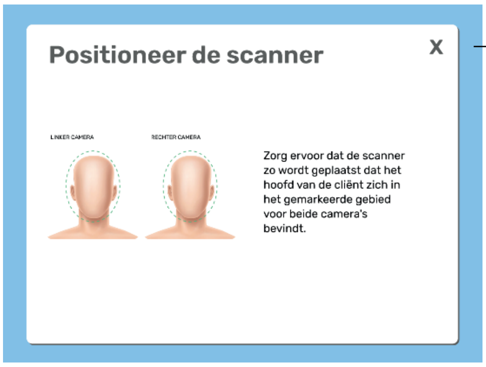
Zorg ervoor dat het hoofd van de cliënt zich binnen de gestippelde ovaal bevindt.

5


Camera preview

Zorg ervoor dat het hoofd van de cliënt zich binnen de gestippelde ovaal bevindt.

6


Positioneer de scanner

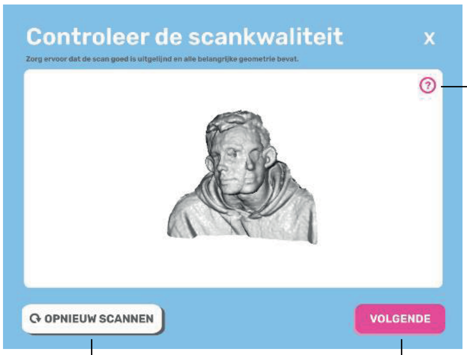
Zorg ervoor dat de scanner zo wordt geplaatst dat het hoofd van de cliënt zich in het gemarkeerde gebied voor beide camera's bevindt.

7


3D scan maken

Data verzamelen...
Pointclouds uitlijnen...
Pointclouds samenvoegen...

8


Controleer de scankwaliteit

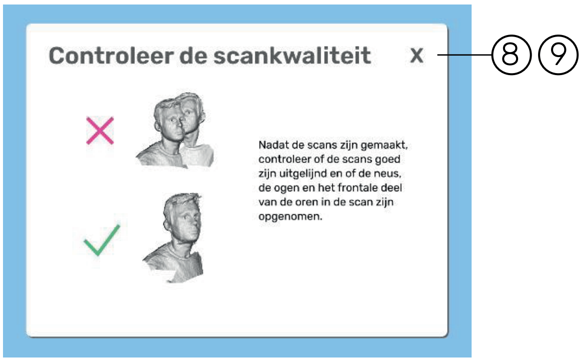
Zorg ervoor dat de scan goed is uitgelijnd en alle belangrijke geometrie bevat.

9

Controleer de scankwaliteit

Zorg ervoor dat de scan goed is uitgelijnd en alle belangrijke geometrie bevat.

10



Controleer de scankwaliteit

Nadat de scans zijn gemaakt, controleer of de scans goed zijn uitgelijnd en of de neus, de ogen en het frontale deel van de oren in de scan zijn opgenomen.

11

Selecteer een montuur

Selecteer het gewenste montuur

12

Selecteer een montuur

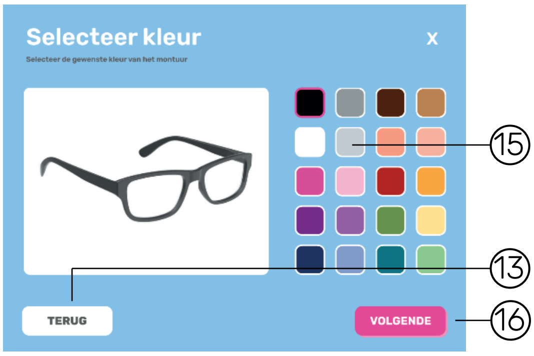
Selecteer het gewenste montuur

13

Selecteer een montuur

Selecteer het gewenste montuur

14



Selecteer kleur

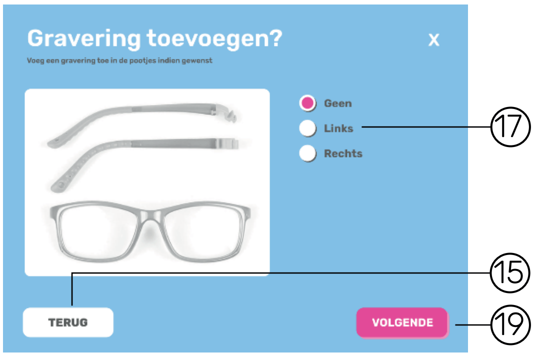
Selecteer de gewenste kleur van het montuur

15

Selecteer kleur

Selecteer de gewenste kleur van het montuur

16

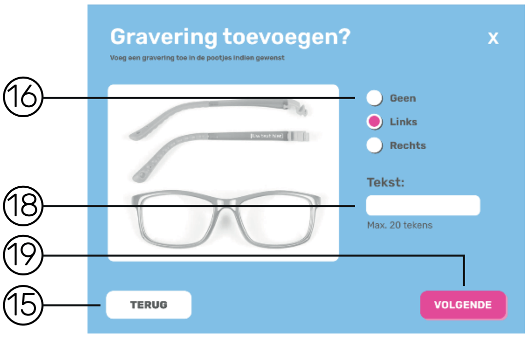


Gravering toevoegen?

Voeg een gravering toe in de pootjes indien gewenst

● Geen
○ Links
○ Rechts

17



Gravering toevoegen?

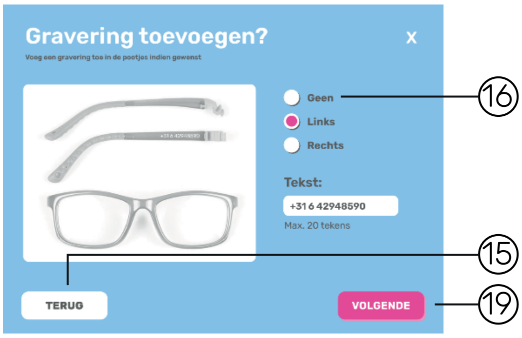
Voeg een gravering toe in de pootjes indien gewenst

○ Geen
● Links
○ Rechts

Tekst:

Max. 20 tekens

18



Gravering toevoegen?

Voeg een gravering toe in de pootjes indien gewenst

○ Geen
● Links
○ Rechts

Tekst: +316 42948590

Max. 20 tekens

19

Contactinformatie organisatie

Vermeld de contactgegevens zodat Maatbril contact met u kan opnemen als er vragen zijn.

Scan gemaakt door:*

Maatbril
Externe Partij

20

Contactinformatie organisatie

Vermeld de contactgegevens zodat Maatbril contact met u kan opnemen als er vragen zijn.

Scan gemaakt door:* Maatbril

Voornaam: Patrick

Achternaam:* Busser

21

Contactinformatie organisatie

Vermeld de contactgegevens zodat Maatbril contact met u kan opnemen als er vragen zijn.

Scan gemaakt door:* Externe Partij

Voornaam: Patrick

Achternaam:* Busser

E-mailadres:* pattbusser@gmail.com

Telefoonnummer:* +31 642948590

22

Contactinformatie cliënt

Vermeld de contactgegevens zodat Maatbril contact met u kan opnemen als er vragen zijn.

Voornaam:*

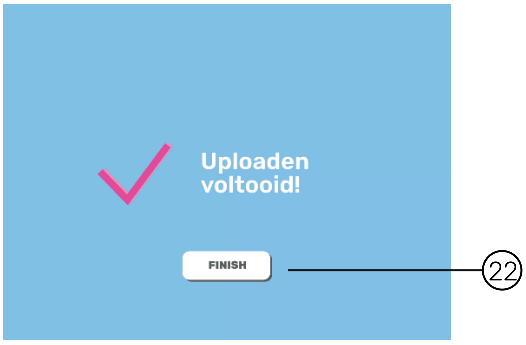
Achternaam:*

23

3D scan uploaden

Dit kan een aantal minuten duren....

24



Uploaden voltooid!

Appendix AM: Evaluation session with non-Maatbril clients

Setup:

1. Give participant bag with 3D Head Scanner and USB Cables, Quick Start Guide, and a 3D printed head that will serve as their scanning subject
2. Give participants assignment to make a 3D scan of the subject and order 'Edge F' glasses in Light Grey with engraving on the left temple
3. Ask participants to think out loud with every step they do
4. Make observations and give hints where needed
5. When finished, reverse roles, make a 3D scan of participant and ask about their experience

Participant 1:

- Thinks the 3D Head Scanner is quite wide
- Doesn't extend the legs, places the legs in 135 degree angle instead of 90 degrees
- Thinks that the tablet is part of the scanner controls, starts looking for app
- Cannot find cable in the bags and uses imaginary cable
- Thinks that the scanners are not plugged in correctly, because the light that goes on 2 sec when plugged in is only visible on one side when participant looked
- Performs tutorial before starting the procedure
- Would rather move the scanner instead of the kid
- Takes about 0.5 minute to correctly align the 3D Head Scanner, tries to increase the size of the head to fit the oval
- Thinks the 3D Head Scanner needs to be placed closer because of the size of the oval
- When previewing the result, sees the 3D model moving and assumes it's an interactable 3D scan
- When entering the engraving, wants to click 'Uw tekst hier' to enter text (in image)
- Wonders how to know what software to open on the laptop
- As a professional, it could be nice to let the kid help with setting up of the device
- For non-professionals, nicest to have the device already setup (maybe even playing some media) before asking the client to sit down
- Thinks it would be more clear to have a headshape outline
- (Physical sheet of) instructions would be nice to have when setting up the 3D Head Scanner

Participant 2:

- Unfolds one side of the legs to 90 degrees, the other one to 135 degrees
- Takes a while before participant realizes that there is a button that needs to be pushed before unfolding the legs, expected it on the Quick Start Guide
- Suggests to use arrows instead of dotted lines on the Quick Start Guide
- Thinks it's nice that both sides of the cables are USB-C so that it is foolproof
- Doesn't realize that the live-view is a live view and thinks it's a tutorial/example
- Skips the tutorial immediately
- Tries to capture the scan before the 3D Head Scanner was aligned
- When seeing the result, doubts if it's good, and what is the meaning of important geometry
- Eventually clicks on the "?"-button and understands the assignment, retakes the scan

- Participant would move the 3D Scanner instead of the child, finds a good spot within 15 seconds, but actually wants to put the 3D Head Scanner closer to fill the oval shape, also because that was how it was displayed in the tutorial
- Would prefer if the 3D Head Scanner is already set up before inviting the client, otherwise the tension would only rise.
- Participant noticed when 3D Head Scanner was capturing by the lights turning on and off

Participant 3:

- Opens first zipper that is visible and takes out USB cables
- Opens other zipper and takes out 3D Head Scanner
- Unfolds legs of the 3D Head Scanner and opens them in 120 degree angle
- Starts looking for a measuring tape in the bag to measure the ~50 cm
- Wonders which scanner should go left and which one should go right
- Puts in Azure Kinect scanners
- Puts everything ready before inviting participant to take a scan
- Wonders if it's possible to see a preview of what the camera sees, thinks that when you click the 'start' button it will scan immediately
- Makes scan in correct way
- When evaluating scan, wonders what is the important geometry
- Thinks it's quite hard to align the scanner correctly because the laptop is away
- Thinks it would be nice if the quick start guide is also present digitally
- Did not see the question marks when evaluating the 3D scan

Participant 4:

- Opens the bag, takes out the 3D Head Scanner
- Notices that there is still something heavy inside the bag
- Looks in the bag, but doesn't see anything
- Tries to unfold the legs, but doesn't press the button to rotate the legs
- Places left legs under different angle as right legs, but notices almost instantly
- Places both legs under 120 degree angle
- Is looking for cables, finds them in bag
- Thinks that the tablet is needed for the 3D scanning procedure
- To align scanner, tries to rotate the individual sensors, notices it is not possible
- Moves the scanner instead of child
- Notices quite quickly that it won't fit in both ovals
- Immediately presses 'next' when evaluating the 3D scan
- Doesn't notice question mark for more information
- Rest of procedure runs smoothly
- Participant doesn't notice that 3D was being taken (twice)