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Designing a patient specific helmet

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Abstract

Decompressive craniectomy is a lifesaving medical procedure, where a piece of the skull is removed leaving part of the cranium exposed. It is therefore important to wear a helmet during recovery period until either the original piece or an artificial replacement is inserted back. Due to various factors however, a standardized "one size fits all" helmet may not be an option. By utilizing digital design and reverse engineering techniques in combination with additive manufacturing, it is possible to manufacture a low-cost protective helmet tailored to the individual patient relatively quickly. To make this process more accessible, smartphone photogrammetry could potentially be used in creating a digital model of the patient's head.

In this work, a full helmet design process was performed for a volunteer mimicking a recovering patient. For this, a smartphone photogrammetry application was used to create a digital reconstruction of the patient's head. The mesh was subsequently processed and cleaned, and was then imported into CAD software, where it was used as a reference for creating a CAD-model of the patient specific helmet.

Key words: photogrammetry, CAD, craniectomy, reverse engineering, patient specific helmet, digital design

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1 Introduction

1.1 Designing a patient specific helmet

Decompressive Craniectomy (DC) is a surgical procedure, where a piece of the patient’s skull is removed for the purpose of lowering the intracranial pressure. This is done to reduce or prevent further damage to the brain. Common causes that may require this type of surgery include Traumatic Brain Injury (TBI), Acute Subdural Hematoma (ASDH) and Middle Cerebral Artery (MCA) Infarction. [1]

Decompressive Craniectomy can be divided into two subcategories based on the timing of the surgery. Primary DC is performed within 24 hours of the injury and is aimed to treat the acute mass effect in brain while secondary DC is performed after a longer time interval and its main purpose is to treat post-TBI refractory elevated intracranial pressure. [2]

While these surgeries differ in timing and rationale, they both involve removing a piece of skull from the patient, leaving the head vulnerable. It is therefore imperative that a helmet is worn to protect the exposed area of the cranium post-surgery. Helmet should be fitted by a specialist in a way that minimizes pressure on this area. [3]

Due to high variability in head shapes among humans, combined with the fact that specific details of each surgery such as shape of the removed skull piece and location of the operated region are unique to each patient, it is unlikely that a “one size fits all” solution is feasible for post-craniectomy helmets. Manufacturing a custom helmet, however, requires the attention of a specialist which might be expensive and simply not available in some locations. Rapid technological advancement in fields such as additive manufacturing and 3D- scanning have the potential to enable quick production of uniquely customized medical equipment for a relatively low cost. This is due to technologies such as 3D-printing which make the low-cost manufacturing of objects with complex geometry viable.

In a case report done by Pang et al. [4] a patient specific helmet was designed using existing CT-scan data. After refining and modifying the scan data, a 3D-printer was used to print out the shape of the patient’s head, which was then used to design and fit the inner foam layer of the helmet. Finally, the printed shape fitted with the foam layer was 3D-scanned. Outer shell of the helmet was then designed around this 3D-scan data using special CAD-software tailored to the medical industry, and 3D-printed. According to the report, the helmet had remained intact and in use four months post operation. This case demonstrates that it is possible to manufacture a custom piece of medical equipment relatively fast and cheap, the final helmet taking less than 30 hours to design and manufacture while costing only around 70 USD.

This work explores the possibilities of using photogrammetry combined with CAD-software not specific to medical industry in designing a patient-specific helmet. In the case reported by Pang et al. a 3D-scanner based on structured light technology was used. While this type of 3D-scanner provides accurate results, the hardware might be expensive and not accessible everywhere in the world. In contrast, consumer grade cameras have undergone rapid innovation and improvement in quality over the years, and it is currently possible to create photogrammetry reconstructions even with a mobile phone. With new developments in software, photogrammetry has the potential to be a low-cost alternative to other 3D-reconstuction methods which require specialized equipment.

The proposed workflow is depicted in figure 1. Exact process would heavily depend on the situation. For example, if accurate CT-scan data is available, the optimal route could be to use a mesh constructed from it as a design reference. If the patient has recovered enough, photographs taken in a studio setting with a single or multiple cameras would be used to create a photogrammetric reconstruction. Likewise, the helmet design process has several ways of being executed. Helmet could be designed directly around the cleaned-up CAD-model of the head, or alternatively 3D-printed head shape could be used as a basis for physically fitting and designing the helmet lining, followed by a 3D-scan as done in the case reported by Pang et al.

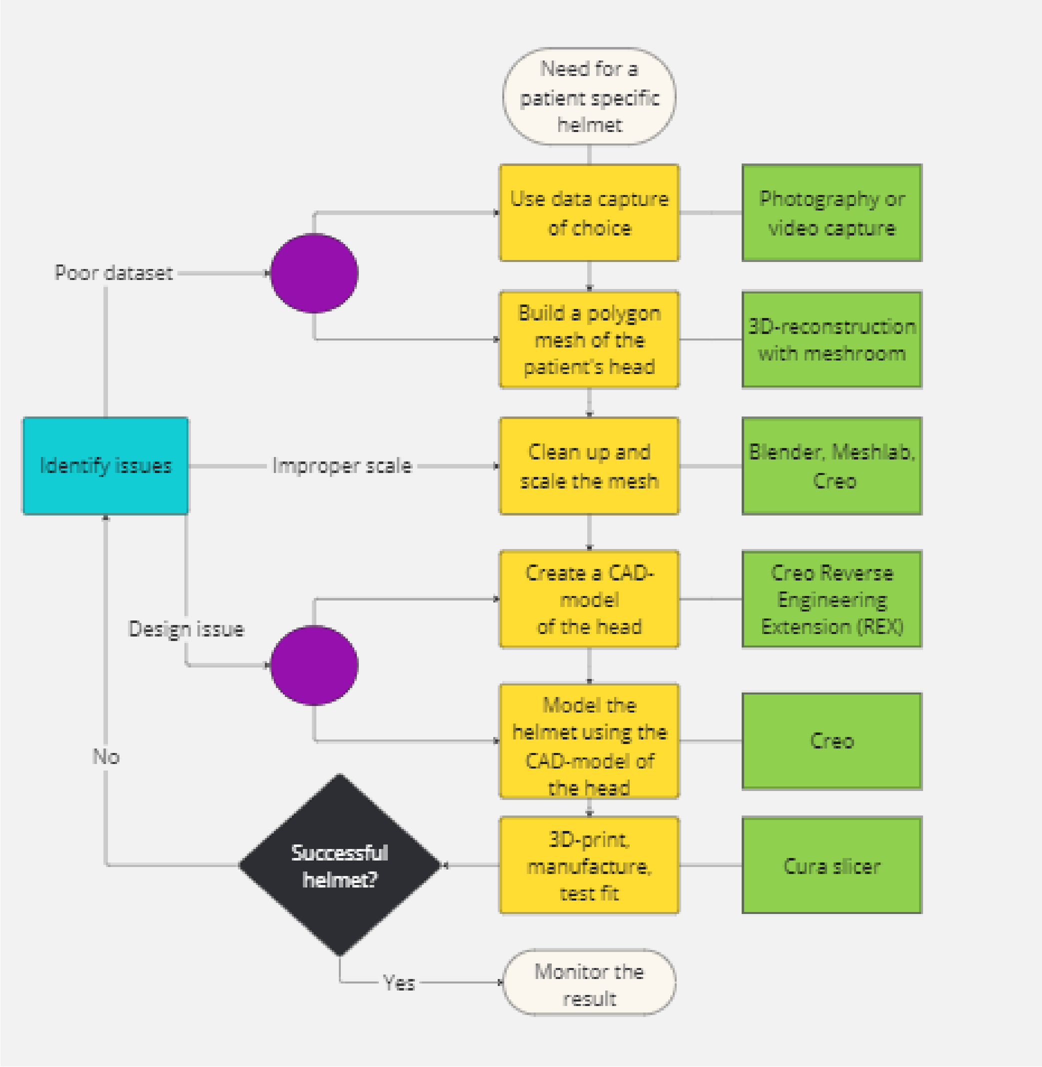


Figure 1: A simplified process chart for designing a patient specific helmet. Green colour indicates the software used, while yellow blocks describe the more general process.

1.2 3D scanning and reverse engineering

The term "3D - scanning" is a generic term used to describe any process that captures data from a real-world object or scene in such a way, that it can be later used to reconstruct the original source as a digital three-dimensional model. Currently there are multiple options available for 3D-scanning, most of which require a specialized device usually referred to as a "3D-scanner". These devices can be categorized based on the scanning method they use, as well as construction and application. For example, they can be stationary or mobile, contact, or non-contact. The scanning process itself can be based on laser triangulation, optical measurements, x-ray or ultrasonic waves, or even mechanical contact. [5]

Some 3D scanning procedures combine multiple scanning types to create a more complete result. For example, physical contact scanning can be used in combination with some non-contact scanning method to capture more data points.

Reverse engineering is a process of recreating an object by measuring and analysing data from the original object, while aiming to capture design intent of the original part. In aerospace and automotive industries reverse engineering is used to recreate parts supplied only by original manufacturers. Most common challenges in reverse engineering project are losses of information due to several factors such as materials being consumed or altered during manufacturing processes. [6]

In modern industry reverse engineering techniques also open possibilities for rapid prototyping and product development. The journal article titled “Innovative design of a helmet based on reverse engineering and 3D printing” (Wang et al.)[7] demonstrates how 3D-scanning can be used to scan a subject’s head and use the scan result to create a parametric surface model, which was subsequently used to design a helmet. With 3D-printing a prototype can be created relatively fast when comparing to traditional manufacturing techniques.

1.3 Photogrammetry

1.3.1 Introduction to photogrammetry

Photogrammetry is the science of deriving the shape and location of an object from a single or multiple photographs. It is used in a wide range of fields, including engineering, architecture, medical, and geoinformatics. It is one of the optical methods for non-contact 3D-measuring, and it combines physical and mathematical models to create an accurate reconstruction of the object being measured. The photogrammetric process as described by Luhmann et al. [8] is depicted in figure 2.

While it is used to create 3D-reconstructions of the real-world objects and scenes, photogrammetry differs from 3D-scanning in such a way that all information can be collected just by taking photographs of the subject. This makes photogrammetry relatively affordable and accessible. In some cases, photography also provides advantages over other non-contact measuring methods. For example, aerial photography can be used to scan large objects such as buildings relatively quickly and efficiently.

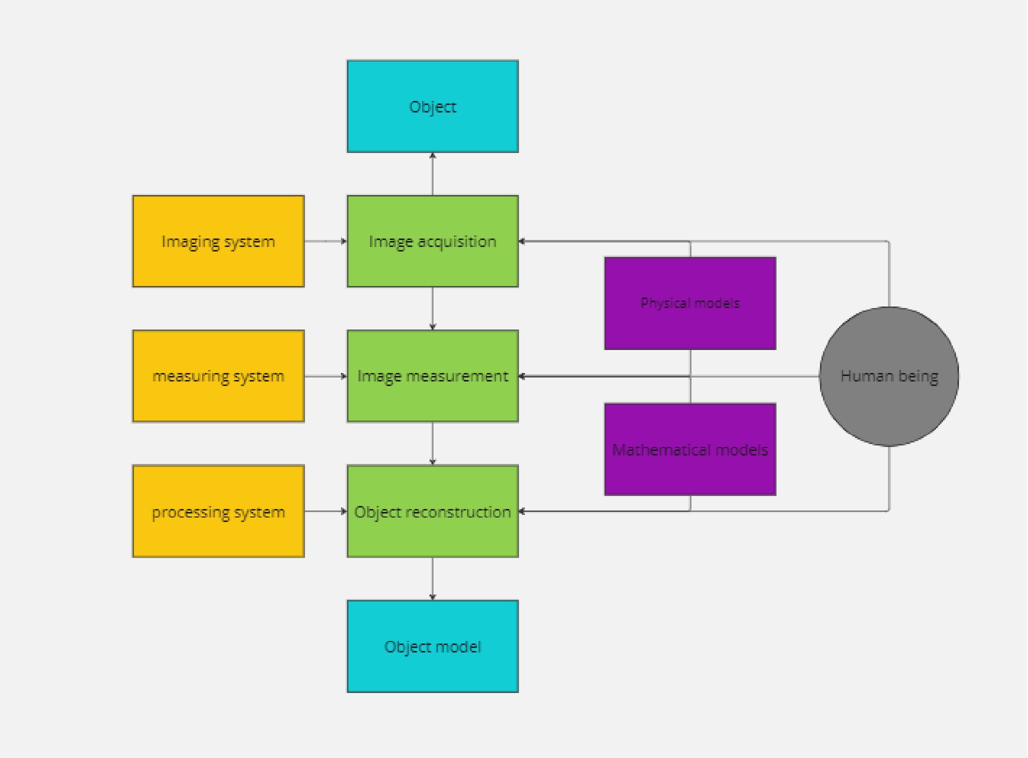


Figure 2: The photogrammetric process, adapted from “Close-range photogrammetry and 3D imaging” (2014), Luhmann et al.

Taking a photograph of a three-dimensional object results in a two-dimensional image. This conversion means, that information is lost. Some parts of the object may not be visible in the image, and therefore not available for reconstruction. There might also be visible areas in the image that are simply not capable of being used in the reconstruction due to size, image quality and contrast differences or lack thereof.

While every point in space can be described with three coordinates, a two-dimensional image is always limited to only two. We can describe the transformation of coordinates from a world coordinate system (WCS) to the image plane (e.g. sensor.) with the following formula:

$$x = PX \qquad 1.)$$

where x represents the 2-dimensional pixel coordinate, X is 3-dimensional world coordinate and P is the projection transformation matrix. Photogrammetry reconstruction requires the knowledge of two types of position parameters. Extrinsic parameters represent the position and rotation of camera in respect to WCS, while intrinsics parameters are specific to internal camera features. An example of intrinsic parameter would be the principal distance, which is the distance between image plane and perspective centre.

By correlating multiple images and matching recognized features, a three-dimensional coordinate can be extracted from the set of two-dimensional images. This is the fundamental principle behind photogrammetry.

1.3.2 Smartphone photogrammetry and it's applications in the medical field

Due to accessibility, portability and relatively low cost of modern smartphones, their use as a photogrammetry tool has increased. They have indeed been already established as capable devices for measuring geometrical properties of objects such as rock particles [9].Compared to traditional consumer grade cameras, smartphone photogrammetry has a lower barrier of entry and is well suited for work in the field. They are also intuitive to use, and many people already own one.

Smartphone photogrammetry is also a trending topic in the medical field. It has applications in prosthetics where it has been used to scan and digitize prosthetics sockets. For example, Hernandez and Lemaire [10] used this method to digitize the interior part of a socket with a relatively high degree of accuracy. Although the result was of poorer quality than with conventional 3D-scanning, it was still potentially usable with prosthetics CAD-software. In the case of digitizing the exterior parts significantly better accuracy can be achieved. Cullen et al. [11] achieved accuracies of 98.09 % and 99.56 % for volume and surface area respectively when digitizing a rectified socket mould.

Using smartphones also offers the possibility of seamlessly integrating custom photogrammetry hardware and software in to one package. A solution like this can make the reconstruction process more user friendly and has already been used as an accessible technique for measuring cranial deformations in the head of an infant[12]. This method involves using a custom cap with coded targets and a phone application. This tool developed by GIFLE is called “PhotoMeDas” (Photogrammetric Medical Deformation Assessment Solutions). Advantage of solutions such as PhotoMeDas over traditional photogrammetry is that it is usable by clinicians without the need for extensive training.

Another possibility of smart phone photogrammetry is to use it as an accessible way to create accurate 3D-models of a subject’s head. This process could have applications in a variety of fields such as industrial design, videogame graphics, and medical practice. This specific category of photogrammetry has also large potential for further improvement. In their article "Three-Dimensional Human Head Reconstruction Using Smartphone-Based Close-Range Video Photogrammetry" Matuzevičius and Serackis [13] were able to improve their baseline reconstruction quality significantly by introducing changes to the algorithm that include automatic background removal and image selection process.

While compact size and light weight provide it with several advantages, a smartphone camera also has some limitations and challenges. As pointed out by Jasińska et al. [14] smartphone cameras typically have worse stability of internal orientation (IO) parameters compared to Digital Single-Lens Reflex (DSLR) cameras. Furthermore, there exists a large variability between IO stability in different phone models. Calibration can be used to reduce errors in the reconstruction. Jasińska et al. used a calibration procedure based on the "Zhang-method [15]" with good results.

1.3.3 Photography for photogrammetry

To create good photogrammetric reconstructions, it is important to have a good dataset. In this chapter, some practical guidelines are given for taking photographs for a 3D reconstruction dataset.

1.3.3.1 Camera parameters

In the case of digital cameras, light is recorded onto the camera sensor that is comprised of large amount of small, light sensitive elements often referred to as "pixels". Each pixel records its intensity and colour value, and the information is stored as a string of bytes onto the camera memory. To get a clear image, camera sensor must be exposed to right amount of light. The exposure is determined by several parameters that can be adjusted on most digital and smartphone cameras:

ISO value determines, how sensitive the camera sensor is to light. It is also sometimes referred to as "sensor speed" [16] A low ISO value (50-200) needs a lot of light but also has very little noise in the images. Higher ISO-values (800-3200) can be used with a lot less light, but a lot more noise would be present in the images.

Shutter speed controls the duration of time sensor is exposed to light. While slow shutter speed allows more light into the sensor, it cannot be used when capturing subjects that move fast, as this would result in the blurring of the image. Meanwhile, it is possible to capture crisp images of moving subjects with fast shutter speed, but this comes at a cost of reduced light intake.

Aperture, also often referred to as the “f-stop”, is the opening through which light enters into the camera. A large aperture lets in more light but also results in a narrow depth of field.

The proper camera parameters will heavily depend on the photography conditions. To keep noise at a minimum, ISO-value should be as low as possible while still maintaining proper exposure. This means that light intake must be increased by means of widening the aperture, increasing the shutter speed, or increasing the ambient light. In many cases it is also desirable to have a good depth of field to keep as much of the subject in focus as possible, meaning that aperture cannot be set too wide. For these reasons, taking photographs in good lighting conditions such as outside on a bright day is often optimal. Alternatively, using a strong artificial light such as a strobe light will also suffice.

1.3.3.2 Other considerations

Since photogrammetry relies entirely on feature recognition, the subject must have plenty of distinctive, recognizable feature points. If necessary, features can be artificially added to the object, for example by coating it in powder or using masking tape. There also exist commercially available scanning sprays that can be used to coat the object. Since photogrammetry software tries to match features, there must be plenty of overlap between the images. Subject must be photographed from several different angles, heights, and ranges to provide most data. There must also not be drastic differences in exposure or shadows between the different images, as this can make matching the features impossible.

Reflections usually make it very difficult for software to interpret images, and therefore must be minimized, or removed altogether. A polarization filter is recommended, and optimally it is used with an artificial light source that has a linear polarization filter. This technique is commonly referred to as “Cross polarization”. Images are ideally stored in “RAW” -format as it allows for more options when processing and cleaning up the images.

1.4 Computer Aided Design (CAD)

Computer Aided Design is a general term for various methods that involve the use of computing and software during different stages of the design process. Typical uses of CAD in engineering applications include part modelling, virtual assemblies and creating engineering drawings with tolerancing (GD&T). It is also used as an information management tool for things such as bill of materials and assembly drawings. Often the software can also be used to simulate things such as deformations due to stresses and behaviour of fluids (CFD).

In many cases, a single commercial CAD-software package has the capability to do all these things, although for some applications such as advanced dynamic simulations the use of special software might be preferred or required.

1.4.1 Geometric Modelling in CAD

Geometric modelling is one of the key aspects of CAD. It can be two-dimensional drawing or three-dimensional modelling. With most commercial CAD-systems, it is also possible to create 2D-drawings directly from a 3D-model. In their book “Computer aided design and manufacturing” [17] Bi and Wang introduce the concept of “feature based modelling”, which is an approach to modelling where an object is defined by its different features such as geometric characteristics and correlations between them. Modelling decisions are based on “design intent”, which is the plan on how a model should behave when different parameters are changed.

Feature based modelling with design intent is the current industry standard for creating CAD-models. Most CAD software packages offer a large variety of different tools for part modelling, and it is designer’s choice to use them according to design intent. Features can be divided into sketched features or built-in features. For example, in most CAD programs a round, fillet or a chamfer is a build-in feature, as it can be applied to an edge of an existing feature and its parameters adjusted in the feature window itself. Sketched features such as sweeps, extrudes, and revolves require the creation of a planar two-dimensional sketch that will drive the resulting geometry.

In general, 3D modelling can be categorized in many ways depending on the style of modelling, resulting topology, and purpose of the model. A polygon model consists of points in space called vertices, that are connected by lines. These lines are borders of a surface often referred to as a “face”. Three-sided faces are triangles, and four-sided faces are often referred to as “quads”. If a face is bounded by more than four edges, it is often called “N-gon”. Many connected faces form a polygon mesh, that is a discrete representation of the model, as every vertex in space has an absolute, three-dimensional coordinate.

A three-dimensional model may also be represented with a continuous representation. An example of this is a surface defined by NURBS (Non-uniform rational B-spline) curves. In the context of computer aided design, a mathematically precise model is often desired due to manufacturing requirements. A complex shape can be represented with multiple NURBS surfaces patched together with defined connections. This type of model enables sharing mathematically exact information about the shape of the object. Feature based solid models created in CAD are also mathematically precise.

1.4.2 Computer Aided Reverse Engineering

Computational tools enable several possibilities in the realm of reverse engineering (RE). With 3D-scanning and software tools, it is possible to create a digital model of a physical subject efficiently. Digital modelling alongside other reverse engineering techniques can also be applied to forward engineering. For example, when designing injection moulding dies, the physical model of a product can be scanned and processed into a CAD model. This model can then be used as a basis for designing the mould itself.

The first stage in digitizing an object is data collection. This can be achieved by using a 3D-scanner, photogrammetry, or some other measuring techniques. Result of the data collection process is usually a point cloud. Point cloud is a set of points that lie on the surface that is being measured. Each point is defined by its x-, y-, and z- coordinates, and the cloud can be then used to create a polygon mesh of the object. This polygon mesh can then further be refined into a parametric surface model or a solid model in CAD software and used in the reverse engineering project.

2 Creating a digital model of the patient’s head

2.1 Data acquisition

Images were taken with Samsung Galaxy A54 mobile phone. Technical specifications of the three rear cameras are described in table 1.

Table 1: Rear camera specifications for Samsung galaxy A54

Lens type	Resolution (MP)	Aperture
Wide	50	f/1.8, (wide), 1/1.56"
Ultrawide	12	f/2.2, 123˚
Macro	5	f/2.4

For image capture, “KIRI Engine” application was used. Maximum allowed amount of 70 images for the free version were taken omnidirectionally using the “auto capture”-function. Dataset was also saved locally to use it later with alternative, open-source, photogrammetry software as described in chapter 2.2.

To mask out the subject’s hair, a thin elastic fabric cover was used. The fabric cover also provides the advantage of reducing reflections and adding feature points due to the texture of the fabric. An example photo from the dataset is presented in figure 3.

To replicate a situation where the user is not an expert in photography, camera was left on default setting. Therefore, key photography parameters such as ISO-value and shutter speed were automatically determined by the “KIRI Engine”-application. This means that the parameters may vary between the images in the dataset. It is also important to observe, that room had poor lighting conditions, which may have affected the image capture.

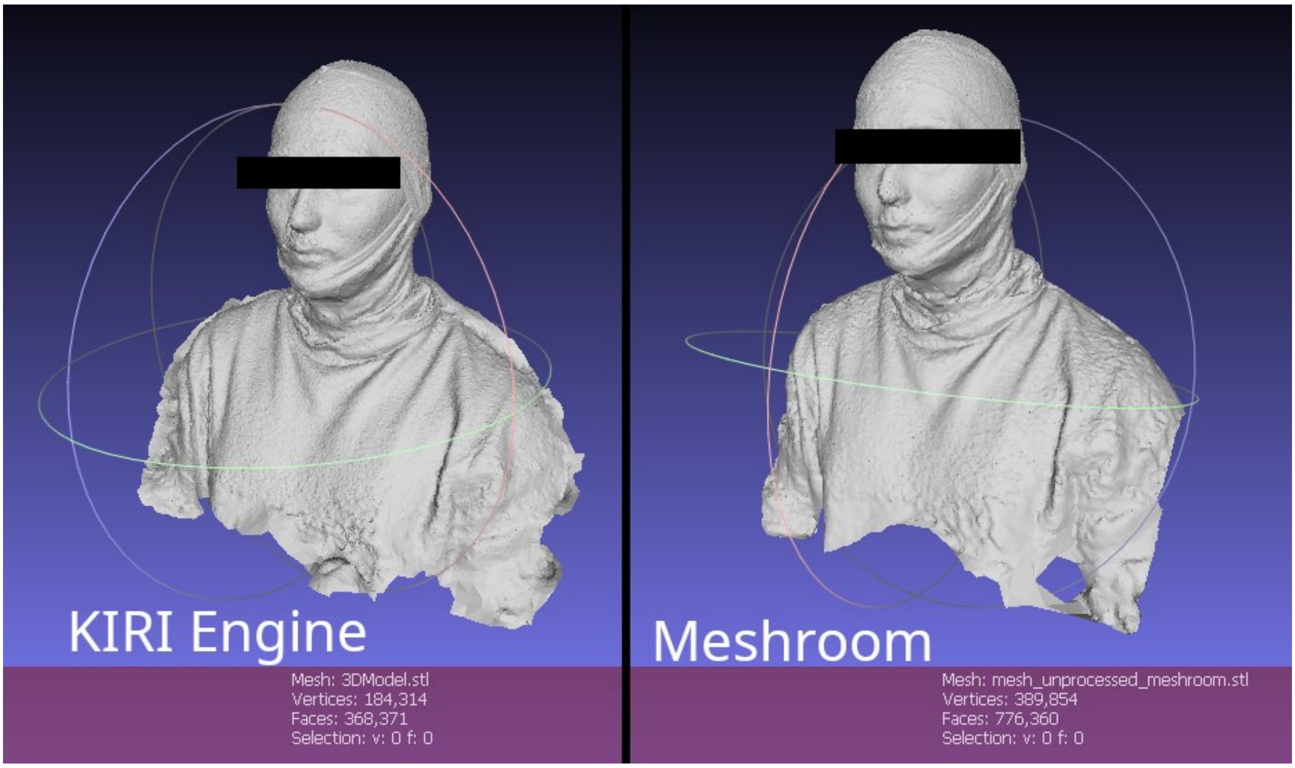

[redacted]

Figure 3: Example image from the dataset

2.2 Constructing, cleaning, and scaling the mesh

To provide some comparison, two different meshes were created: One using the KIRI Engine application and one using open-source software.

For the open-source pipeline, before inputting the image dataset into meshroom, a python program was used to remove image backgrounds. Outputs of both mesh creation methods were set to be in STL-file format. The resulting meshes are depicted in figure 4. Both meshes were inspected visually, and although results were quite similar despite differing face and vertex counts, the one generated with KIRI Engine was chosen for further cleanup due to smoother all around appearance.


[redacted]
[redacted]

```
Mesh: 3DModel.stl
Vertices: 184,314
Faces: 368,371
Selection: v: 0 f: 0
```

```
Mesh: mesh_unprocessed_meshroom.stl
Vertices: 389,854
Faces: 776,360
Selection: v: 0 f: 0
```

Figure 4: Original unprocessed meshes viewed in MeshLab software.

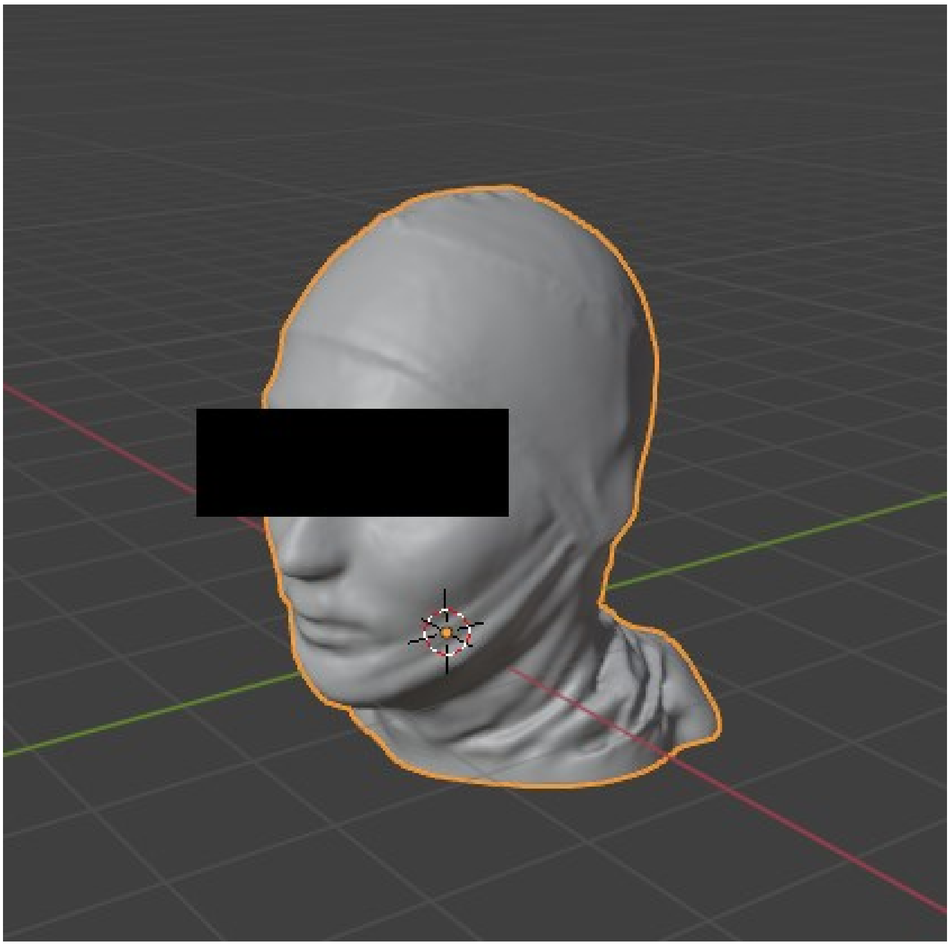
The chosen mesh was then imported into MeshLab for cleanup, where several filters were applied to it. The filters are described in table 2. Finally, the mesh was scaled to its proper size by measuring the distance between two vertices and dividing the real-world measurement from the same location by this distance to acquire the scaling factor. Mesh was then scaled by this factor.

Table 2: Filters applied to the mesh

Filter name
Remove Duplicate Faces
Remove Duplicate Vertices
Repair non-Manifold Edges
Surface Reconstruction: Screened Poisson

After applying the filters, it was exported in the STL-format and imported into Blender, where it was trimmed, and “Sculpting”- workspace was used to manually smooth out rough surfaces. It is good to note that manual smoothing may not be optimal as it slightly alters the geometry of the mesh. However, due to the scale of the model a small loss of detail can be neglected.

The final smoothed and trimmed mesh is depicted in figure 5.



[redacted]

Figure 5: Cleaned and trimmed mesh viewed in Blender

3 Designing and modelling the helmet

3.1 General helmet design considerations

The helmet must protect the vulnerable area of the head by removing all contact and pressure from it. It must also be lightweight and comfortable enough to be worn daily. Another important factor to consider is aesthetics. A low profile, but stylish and streamlined look will affect the user experience in a positive way. For the purpose of this work, it was arbitrarily chosen, that critical area is located at the side of the head. Therefore, top of the head could be left open for increased user comfort.

A two-layer construction was chosen as the design; A hard outer layer made from plastic, and an inner liner made from soft, impact absorbing foam. It is important to note that the helmet is not designed to be used in dynamic, high impact activities, but rather to act as an extra level of protection during the recovery process. Unlike traditional sports helmets, this design does not feature separate impact absorbing layer. This is done to reduce weight and increase user comfort when wearing the helmet for extended periods of time.

Manufacturing the helmet involves the use of two different processes. The outer shell is to be 3D-printed, and while not necessary, the foam liner is to be cut with a laser cutter. This allows for the design of more complex geometries, which in the case of modelling individual head shapes is required.

3.2 Creating a CAD model of the patient’s head

In order to utilize various modelling tools and techniques in CAD-software, it is necessary to convert the relevant parts of the polygon mesh created during the previous steps into a continuous surface model. This conversion will allow precisely offsetting the head-shaped surface without altering the geometry. Having a clean surface model will also enable accurate analysis of properties such as weight and surface area at later stages of the design process.

After processing and cleaning up the mesh, it was imported into Creo by using the “import” function. The model was fixed to a datum coordinate system, which was rotated to desired orientation. After defining the placement, “Decimate” tool was used to reduce the number of facets in geometry by 50 %. Several datum planes were also created to facilitate cross-sectional curves later.

With the reverse engineering extension, a restyle feature containing the curves for the surface model was created. First, a set of curves was created by using “curve from cross section” command to create planar outlines. Due to STL-geometry being triangulated however, the curves themselves were not usable due to them not being smooth. This meant that another set of curves needed to be created on top of the previously created curves with the “curve through snap points” command. Resulting curves are depicted in figure 6.

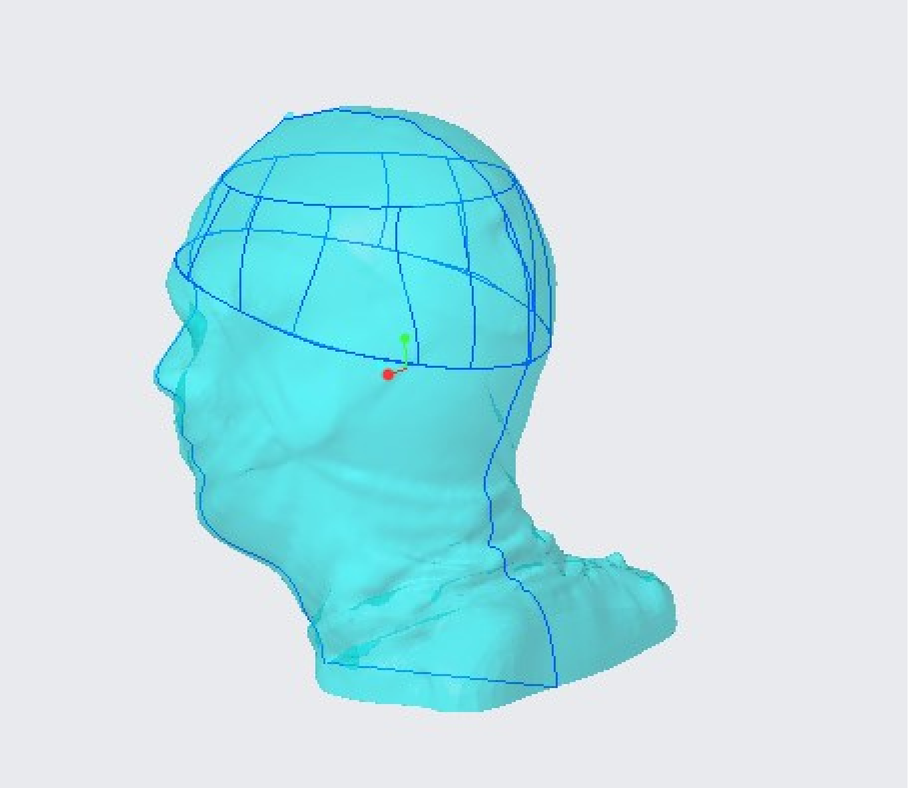


Figure 6: The curves created in restyle

A “boundary blend”- feature was then created by using the created clean spline curves as depicted in figure 7.

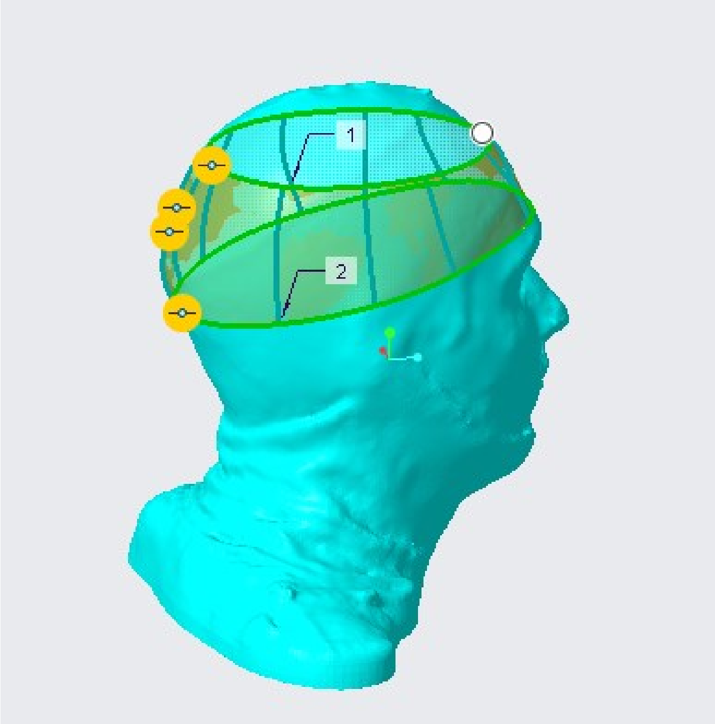


Figure 7: Creating the boundary blend

Resulting surface was inspected with reflection analysis and tested with “offset”-command. Resulting surface and its reflection analysis is presented in figure 8. Using the surface model created as a reference, an offset surface was created to accommodate for manufacturing tolerance, hair, and deviations in the photogrammetry reconstruction and scaling. That layer was further offset by 8 mm to serve as the basis for foam lining and outer shell design. The offsets, as well as arbitrarily chosen trimmed shape representing the surgery area are presented in figure 9.

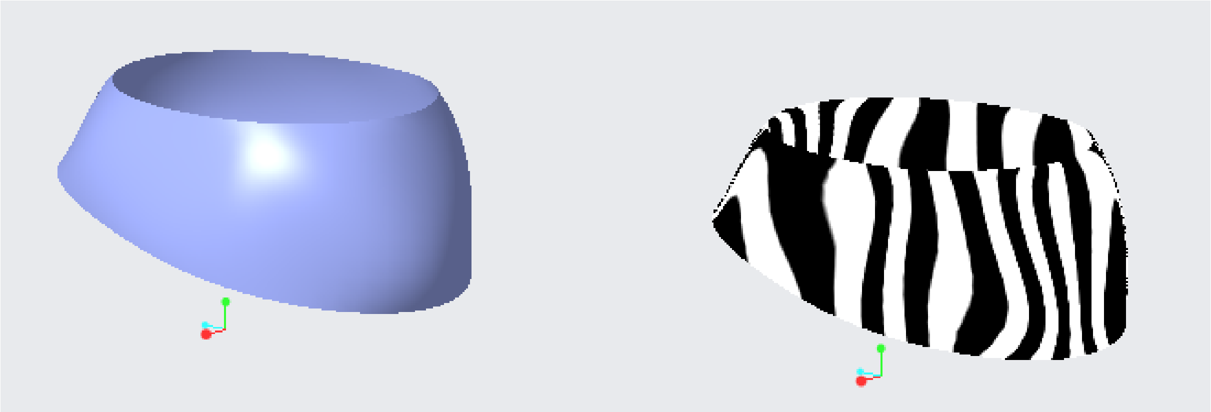


Figure 8: Resulting surface and its reflection analysis

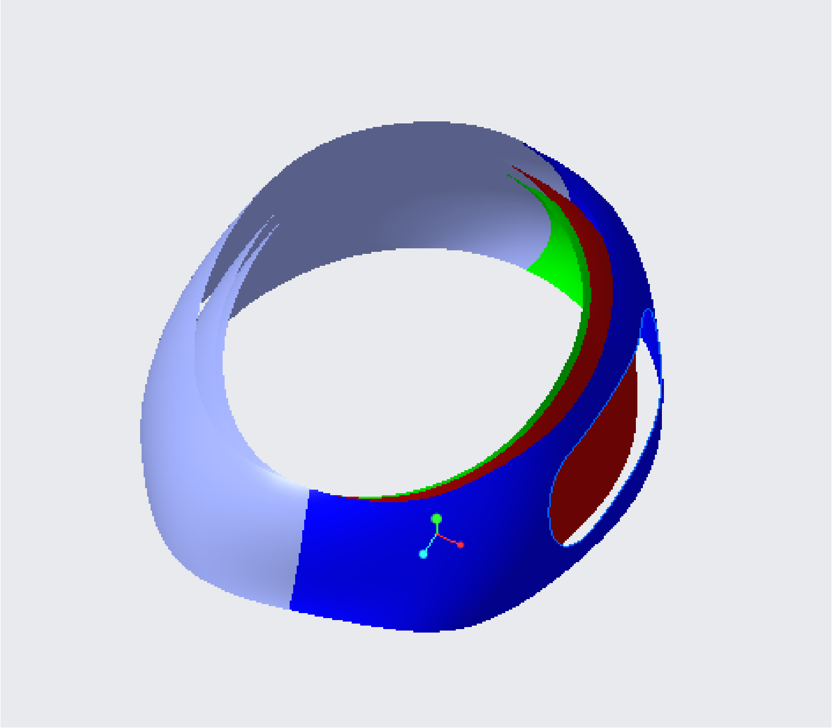


Figure 9: Offset layers; Green is the original surface, red is the first offset, blue is the second offset with trim

3.3 Modelling the helmet

A new part was then created, and previously created offset surface was used as a reference. The reference surface was given a thickness of 8 millimetres. Resulting solid body represents the foam lining presented in figure 10.

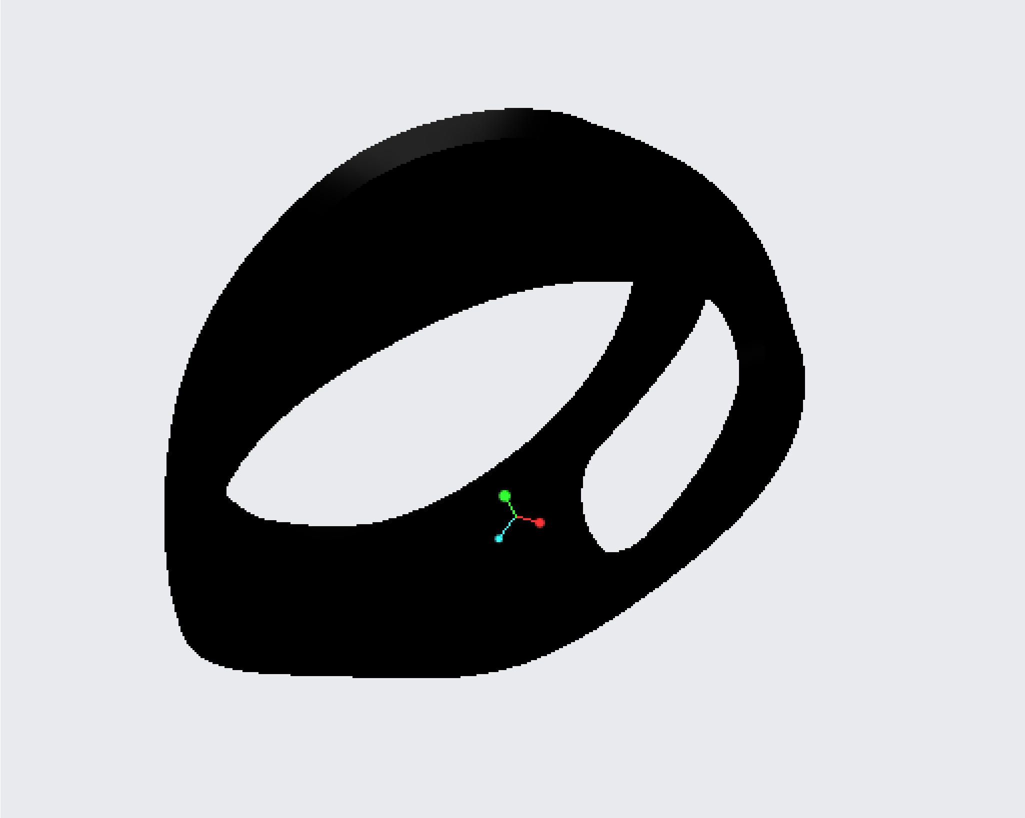


Figure 10: Solid part representing the foam lining

Another part was then created to be the rigid outer shell of the helmet. Like with the model of foam lining, same offset surface was used as a reference, and a uniform thickness of 4 millimetres was given. To reduce weight and material requirements as well as to improve breathability, lattice structures were created at non-critical areas in the front and back of the helmet. First, the areas to be replaced by lattice structures were split from the main helmet by creating planar surface extrudes, which were used as splitting objects. After that, “Lattice” – tool was used to replace these bodies with gyroid structure depicted in figure 11.

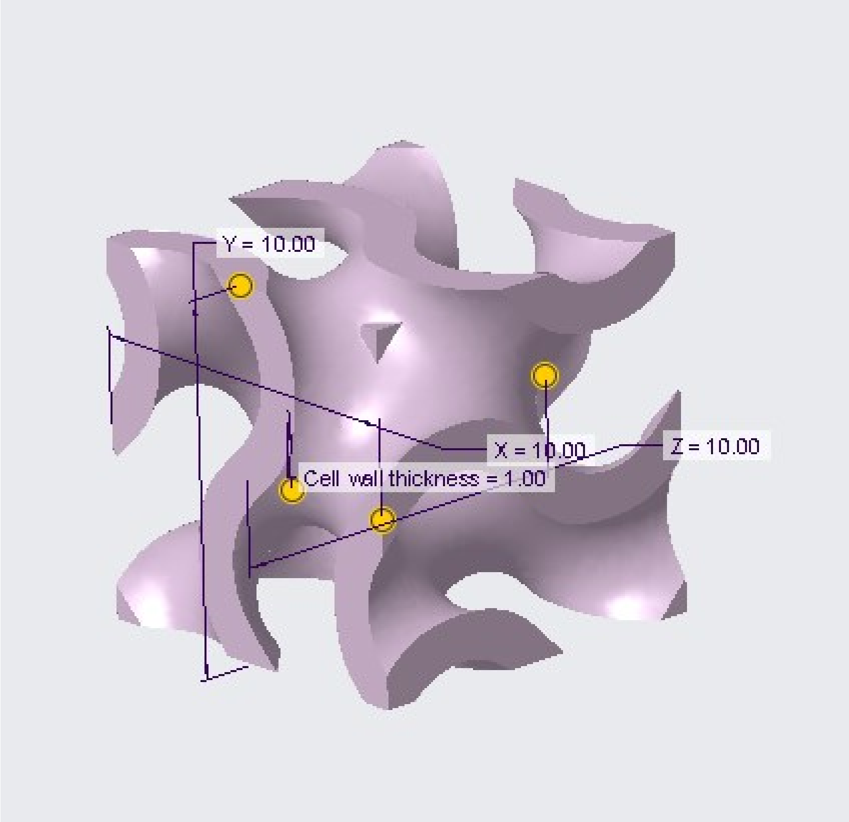


Figure 11: Gyroid lattice structure used in the helmet

3.4 Resulting helmet model

The renderings of the resulting helmet are depicted in figures 12 and 13.

Figure 12: Front view of the helmet with liner


[redacted]

Figure 13: Rendering of the helmet assembly

3.5 Conclusions

This work has demonstrated the theoretical capabilities of using smartphone photogrammetry in designing a patient specific helmet. As a result, a digital model of a helmet was successfully modeled, and the next step would be to verify and optimize the process. With further research and progress accessible reverse engineering techniques such as ones used in this work can surely be applied to a wide range of cases involving the need for custom medical equipment. This is especially important for regions where there might be limited medical resources, and making custom items for large number of patients has not been feasible in the past.

By using open-source software in combination with smartphone photogrammetry, costs of creating a digital model of the patient’s head are minimal. Manufacturing the outer shell of the helmet would also be quite cost effective, as 3D-printing technology has enabled efficient manufacturing of objects with complex geometry. Even though the actual modelling of the helmet was done with commercial CAD software, open-source alternatives exist which could potentially be used instead. While this might not be optimal now, it could be viable in the future.

Although the proposed workflow is accessible and affordable, there are several ways in which it could be optimized. The process consists of several steps that are to be done manually, some of which could possibly be automated. For example, if photogrammetry is to be used, an automatic photography system consisting of multiple cameras would speed up the image capture process. However, the most time-consuming part is creating, cleaning, and converting the polygon mesh into a surface model in CAD. There are automatic tools for this conversion, but to acquire a clean, offsetable surface it is necessary to create multiple spline curves manually, and this takes a lot of time. Perhaps with new developments in artificial intelligence, some algorithms could be created to automate these software processes at least partially.

For practical applications more research is still required. It would be ideal to test the protective capabilities of the helmet with a special simulation software, as well as to manufacture physical prototypes for testing the fit. As the outer shell is to be 3D-printed, it would also be necessary to research how different materials and printing parameters affect the final product.

4 Terminology and software used

Creo Parametric

Creo parametric is an advanced commercial CAD software package developed by PTC. In this thesis, Creo's Reverse Engineering Extension (REX) was used to create a continuous surface model from STL-mesh, as well as to design and model the helmet itself.

KIRI Engine

KIRI Engine is a 3D-scanning application for smartphones, which utilizes photogrammetry. It was used to create the digital model of a patient's head that was used as a reference for modelling the helmet.

Meshroom

Meshroom is an open-source photogrammetry software developed by AliceVision. It was used to create one of the digital models of a patient's head in order to explore the possibilities of a fully open-source workflow.

MeshLab

MeshLab is an open-source software for processing and editing triangular meshes. It was used to clean up meshes created with photogrammetry.

Blender

Blender is a powerful, free, and open-source 3D-software. It was used to clean up meshes created with photogrammetry.

STL

STL is a file format which describes a triangulated surface. Due to its versatility all polygon meshes in this thesis were chosen to be in STL-format.

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