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TECHNOLOGY, COMMUNICATION AND TRANSPORT

TRANSFORMING POINT CLOUD DATA TO A SOLID 3D MODEL

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THESIS
Abstract

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Abstract

The purpose of this thesis was to make a study of how a scanned point cloud data can be transformed into a solid 3D model that can be used in further studies in the form of simulations. To simulate a scanned part, it must be as accurate as possible when compared to a real-world object. A more detailed model allows for more accurate results to be obtained from the simulations, which in turn leads to better results for product development.

The thesis presents the theoretical part of 3D scanning, which includes the history of 3D scanning as well as various 3D scanning techniques and devices that enable the acquisition of reliable scanning material. The thesis also presents various real-world applications for 3D scanning, which introduces the use of 3D scanning today.

The project was carried out in Metso's measurement room and utilized a non-contact laser scanner and coordinate measuring machine system, as well as various scanning software developed for processing scanned data. The thesis describes the steps of the scanning process and the post-processing of the point cloud data. Three different methods were used to transform the point cloud data into a solid 3D model.

The project resulted in three solid 3D models using three different methods. For these solid 3D models, a difference comparison was made between their original scanned point cloud mesh to detect changes in surface geometry of the parts in the process. Color maps were made for each process to show the changes caused by the process from the point cloud to the solid 3D model. Examining these development points was also part of the purpose of the thesis. At the end of the thesis, the results obtained from the difference comparison were examined and conclusions are drawn based on them.

Based on the results of the thesis, the importance of scanning during the process of creating solid 3D model was detected. A properly performed scanning process creates a solid starting point for the entire model creation process, which determines how accurate the final model is. Focusing on the coverage of the scanning and to the resolution of the scan leads to more accurate and better models. Additional processes in post-process phase were also found to affect the accuracy of the final 3D model. By following the development points observed in the thesis, better solid 3D model can be created in the future.

Keywords
3D-scanning, Point Cloud, 3D-Model

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ABBREVIATIONS AND DEFINITIONS

3D = Three dimensional (x, y, z)

ALS = Airborne laser scanners

BIM = Terrestial laser scanners

CAD = Computer aided design

CARE = Computer aided reverse engineering

CMM = Coordinate-measuring machine

CNC = Computer numerical control

CT = Computerized tomography

DXF = Drawing exchange format

IGES = Initial graphic exhance specification

LIDAR = Light detection and ranging

Mesh = Structure of a 3D model consisting of polygons

MRI = Magnetic resonance imaging

NURBS = Non-uniform rational basis spline

STEP = Standard for the exchange of product data

STL = Stereo lithography

TLS = Terrestial laser scanner

ToF = Time of flight

1 INTRODUCTION

The purpose of this thesis is to focus on the process of transforming point cloud data into a solid 3D model that can be used in various tests in a form of simulations. This thesis introduces the history of 3D scanners, different 3D scanning applications and methods and the theory used in a point cloud modeling. The goal is to make a solid 3D model as accurate as possible so that it overestimates or filters measurement errors as little as possible. The transformation process will be done in three different ways. These options are the surface recognition method, the NURBS method and the cross-section method.

The commissioner of the thesis is Metso Flow Control Oy, which is located in Hakkila, Vantaa. The company focuses on the process industry and was founded in 2014. Metso Flow Control Oy is one of the leading industrial companies in its field, offering its customers marketing, design, measurement equipment, flow management and safety systems, as well as related software and services.

The purpose is to reverse engineer a 4-inch ball valve ball and its seal by creating solid 3D models from the scanned point cloud data. The solid 3D model is created into a form that can be used in simulations for further research. The surface recognition method and the NURBS method are applied to the ball valve ball and the cross-section method to the ball seat. The solid 3D models transformed from the point cloud are then compared to the mesh models made form the original point cloud data in order to perform a differential analysis to see the changes caused by the different transformation processes. This thesis also illustrates the various development points of the process in transforming the point cloud data to a solid 3D model and demonstrates the importance of the accuracy of the 3D scanning process.

To develop valves in the process industry, it is important to have a realistic 3D model of the components manufactured to make the product simulations as reliable as possible. A more detailed analysis of the parts provides better starting values for modifying them, leading to a more efficient, concise, and reliable product.

At the beginning of this thesis, the history of 3D scanning and the different techniques of 3D scanning is reviewed, which includes contact techniques and non-contact techniques. Following, an introduction of various 3D scanning applications, ranging from the metal industry to the entertainment industry. Lastly, the reconstruction of a 3D model is reviewed. The actual processing phase of the thesis is started with the examination of the tools and equipment used for the project. Following with the introduction of the 4-inch ball valve ball and its seal. Next, the steps of the 3D scanning process and the various methods of transforming the scanned data from the point cloud to a solid 3D model are described. At the end of the thesis, the results of the process were examined, and the conclusions were drawn based on them.

2 THE FIRST INTRODUCTION TO 3D SCANNERS

The first 3D scanning method was born at the end of the 20th century. It immediately became helpful in areas of research and design. The first versions of a 3D scanner utilized camera, projectors, and light to create models. The hardware at the time was often so limited that the 3D scanning process took a lot of time and effort. Although manufacturers were able to create very complex models, the main problem was creating the model digitally. (Ebrahim 2011.)

Different 3D scanning technique was developed by the toolmaking industry in the 1980’s that introduced the usage of a contact probe. To collect data points the contact probe had to physically touch the object the needed amount for the task to be able to create a 3D model. The number of data points required to create a 3D model varied with the task. This process proved to be very time consuming and therefore newer and more efficient methods were developed.
(Chougule, Gosavi, Dharwad-kar & Gaind 2018.)

For this reason, the development shifted from contact scanners to non-contact scanners that utilized optics. Using a light as a main source for scanning the object was much faster that using a physical probing system. The non-contact method also made it possible to scan fragile objects that would otherwise have been deformed or disintegrated from the probing process. After the year 1985 the combination of camera, projector and light that was used to 3D model an object was replaced with techniques that used white light, lasers and shadowing the object. At the end of 1980’s only three different methods were available for non-contact scanning process: point method, area method and stripe method. The point method was similar to the contact probe technique, which scans one data point at the time in three-dimensional space. This method was the slowest of all three options. Area method was used for scanning one specific area at the time and was technically the most difficult from all three options. The stripe method was the fastest of all options because it was able to scan a line of data points at a time from objects and it also proved to be very accurate. (Ebrahim 2011.)

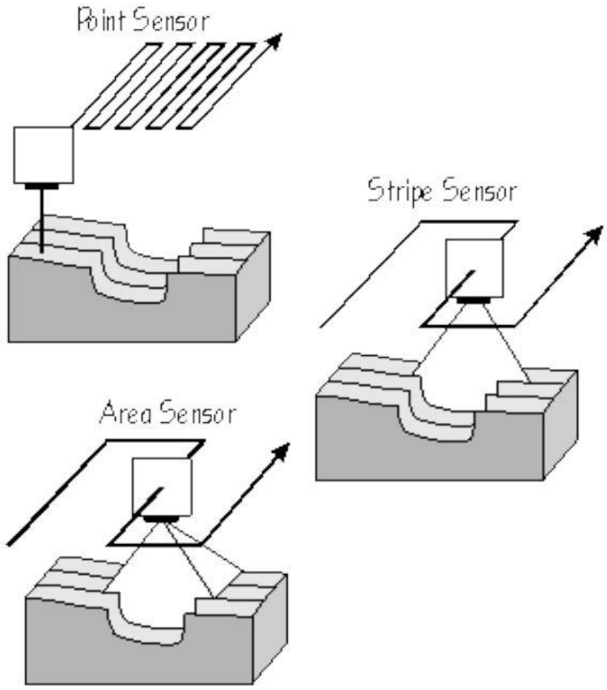

FIGURE 1: The three different scanning methods (Ebrahim 2011)

As 3D scanning techniques evolved to become more efficient and faster, the problems shifted from hardware to software. The amount of data collected from a single scanning session was too overwhelming for the software to handle. That was because the software was not programmed to sift out any duplicated data points coming from the scanner.

After the development of computers many high detail scanners were created from Cyberware, Digibotics, Immersion and Faro Technologies. At the end, the created systems were either too inaccurate or too slow for general usage.

In 1996, a company called 3D Scanners made a breakthrough with a manually operated mechanical arm and a stripe 3D scanner. The combination of two different 3D scanning systems was fast and accurate. This combined system was the world's first reality capture system. It was able to produce complex digital models in just a few minutes. (Ebrahim 2011.)

3 3D SCANNING TECHNIQUES

There are small range of different 3D scanning technologies that enables to collect the shapes of the real objects from the real world and converting the scanned data to digital 3D model. The 3D techniques can be listed in two different categories: contact techniques and non-contact techniques. The non-contact techniques can be further split down to two main categories: active techniques and passive techniques. Most of the 3D scanners drop down to the non-contact category. (Ebrahim 2011.)

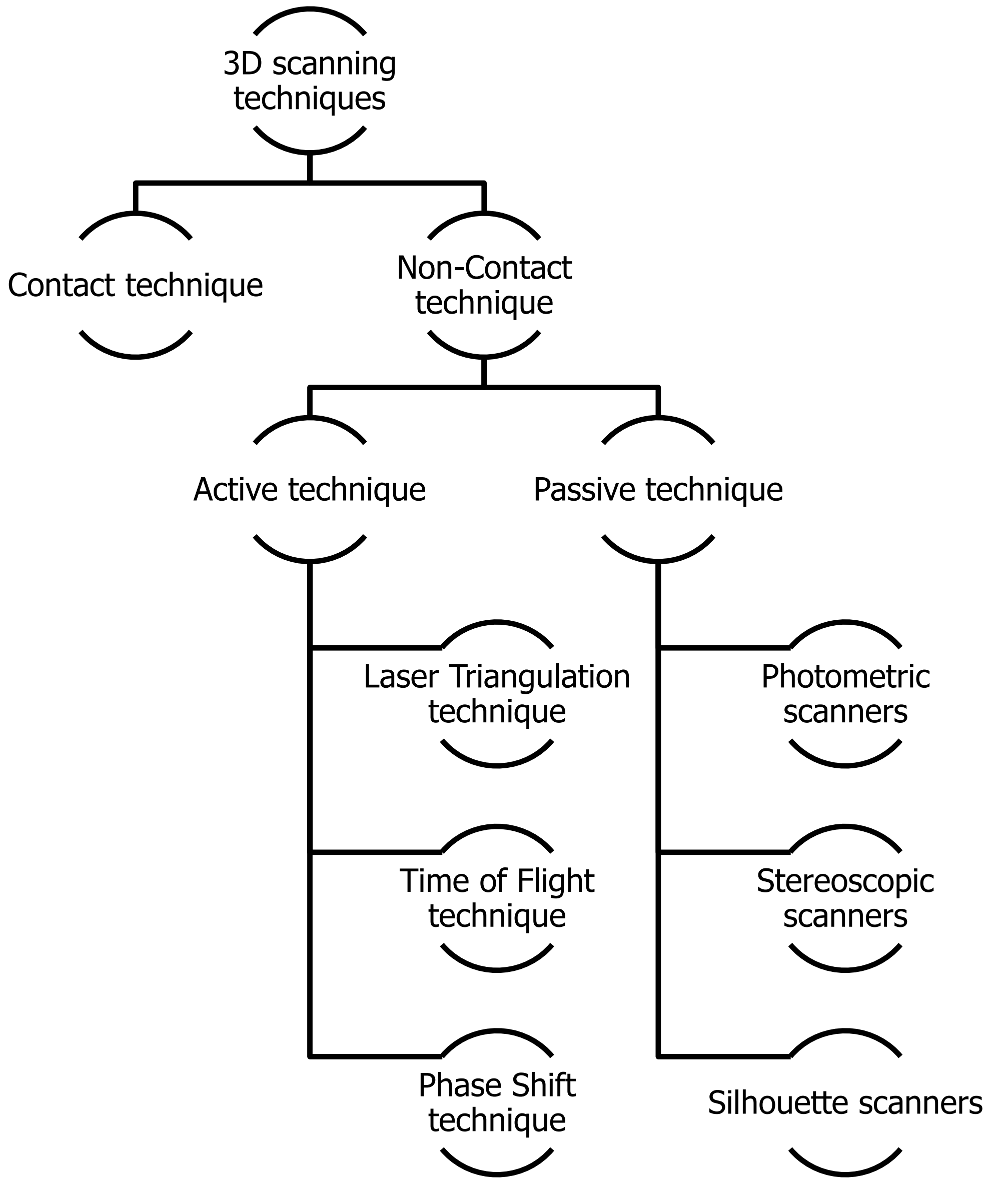

FIGURE 2: 3D Scanning techniques

3.1 Contact techniques

Contact 3D scanners are referring to a system that is using 3D contact scanning technique, in which data is collected from a physical object by touching its surface by using a probe. Data is acquired from the probe that is often located at the end of a mechanical arm. As the probe contacts the surface of the object the scanner records the position of the probe in three-dimensional space by measuring the position of the mechanical arm. The recorded measurements form a point cloud that can be turned to the 3D mesh via the computer program. Contact scanners used by the manufacturing industry are called Coordinate Measuring Machine (CMM). They are used for quality control by examining the product to prevent assembly problems during the manufacturing process. (Ebrahim 2011.)
The main problem for CMM (Coordinate Measuring Machine) is the optimizing of the operation environment. The temperature, humidity, external vibrations, and external forces must be adjustable and maintained throughout the measurement process.

3.1.1 Coordinate Measuring Machine (CMM)

The CMM scanning systems consists of three components: a main structure with at least three-axial measurement device, a probe system and a computer software operating the CMM system. By tracking all positions of the mechanical arm of the CMM system, the location of the probing system can be calculated in 3D space. The probe attached to the mechanical arms of the CMM system can measure distances within nanometers. (3DScanCo 2019.)

FIGURE 3: Coordinate Measuring Machine (Direct industry 2020)

CMM systems can achieve very accurate measurements of an object, but to reconstruct a 3D-model using data points it is very slow compared to non-contact systems. This is because the fastest coordinate measuring machines operate only at few hundred hertz, while laser scanning system

operates at 10–500 kHz. The movement of the mechanical arm holding the probe is also a slow process, which slows down the overall 3D scanning process. The CMM system can not automatically create a 3D model from the object with the measured data points but needs a separate software.
Coordinate measuring machine is mostly used to displace conventional measuring equipment in the manufacturing industry. For example, measured objects can be compared to the small tolerances of technical drawings. Therefore, it is excellent for component inspection and general quality control. (Rensi Finland Oy 2020.)

3.1.2 Portable measuring arm

Portable measuring arm systems differ from a typical CMM systems by being portable. The portability allows the system to be used wherever fast and accurate measurement is required.
The system typically has six to seven axles and encoders within every articulated joint. The systems are also lightweight compared to traditional CMM systems.
The sensors on the system can detect the position of the arm and the program calculates the exact position of the probe. The movable mechanical arm gives portable measuring arm systems greater measuring distances compared to CMM systems.
Portable measuring arm systems are multi-functional because they can be customized to the user's needs. For example, a laser scanner can be added to the system without the need for additional calibration. The system can automatically detect the added probing device and adjust the measurement setting based on the added probe. (Hexagon 2020.)

FIGURE 4: Hexagon compact portable measuring arm (Hexagon 2020)

3.2 Non-Contact techniques

Non-contact 3D scanners are different from contact 3D scanners because they do not make a physical contact on the surface of the object. This allows you to scan objects that are fragile and do not withstand the surface treatment of traditional contact scanners. Non-contact 3D scanners rely on passive or active techniques to be able to scan the physical object. The result of the scan is accurate cloud of measurement points that can be used for reverse engineering, quality inspecting, engineering analysis, virtual assembly or just surface inspection.
The biggest difference to contact scanning technique is the speed at which data points are generated. While the best contact 3D scanners can operate at few hundred Hz, non-contact 3D scanners can operate at 10–500 kHz. As a result, non-contact scanners are faster and more cost-effective and do not require any preparations for scanning. (Ebrahim 2011.)

3.2.1 Active technique

Active 3D scanners create their own source of light or radiation for scanning the physical object. When the light radiation hits the object, it reflects it back to the 3D scanning hardware that receives the light radiation. Because the speed of light is known, the distance of the data points can be determined by calculating the travel time of the light. The light source can be light, ultrasound or x-ray. (Ebrahim 2011.)

Active 3D non-contact scanners can generally be divided into three categories: laser triangulation, time of flight and phase shift. These scanning techniques are generally used independently but can be used together to form more complex and versatile scanning systems. (3DScanCo. 2019.)

The main difference between the scanning techniques are acquisition distance, acquisition frequency and data resolution/accuracy. For example, the time of flight technique has the greatest acquisition distance, but the downside is the lower acquisiton rate and lower overall data accuracy compared to other techniques. Phase shift technique is called being the fastest scanning technique of all three active systems for scanning over 100000 points per second but falls short compared to TOF (time of flight) by only having maximum acquisiton range of 120 meters. Both previously mentioned techniques are great for terrrestial scanning where the scanning area is from 5 meters to multiple kilometers. Triangulation scanners typically have the acquisition range of less than 5 meters. They are commonly referred as a short-range system and are great for scanning smaller objects from 1 cm up to 2–3 meters. (Archaeology Data Service, Digital Antiquity. 2019.)

3.2.1.1 Time of Flight

Time of flight technique is typically used for long range scanning. TOF (Time of Flight) scanner sends a laser pulse to the object under observation. The scanner detects the reflected laser pulse and calculates the time taken from transmission to reception, which is used to determine the distance traveled by the laser. Because the speed of light c is known, the distance between the reflecting laser point and the scanner can be calculated based on the travel time of the laser.
The distance can be calculated with the following formula:

$$l = c * \frac{t}{2} \tag{1}$$

c = speed of light
t = total traveling distance
l = distance between the scanner and the object

The accuracy of the TOF system is based on how precisely the system can measure time.
Typical laser rangefinder uses the same principle as a TOF scanner, but the main difference between the two systems are that the TOF system can detect the distance over 10000–100000 points per second whereas while the laser rangefinder can only detect the distance of a one point. (Ebrahim 2011.)

TOF scanner is great for long distance scanning. The best systems can scan objects over 1 kilometer away, but the typical TOF scanner operates from 5 meters up to 300 meters. The accuracy for commonly used TOF scanner is 4 to 10 millimeters. With the lastest TOF scanners, it is possible to capture colors either with a separate camera of with a built-in camera. (Archaeology Data Service, Digital Antiquity, 2019.)

3.2.1.2 Phase shift

Phase shift scanners use the same principle as the TOF scanner but differs in the use of the laser. Without using a laser pulse like in TOF scanner, the phase scanner utilizes a continuous laser beam.
In a phase shift technique, the distance light travels can be collected based on the phase difference between the transmitted laser beam and the reflected laser beam.
The phase difference between the two waveforms yields the time delay. The scanned range can then be calculated with the Formula (1) that is used by the TOF scanner.
Typical commercially used phase shift scanners are operated at the range under 80 meters and the best systems can detect distances over million points per second.
The Phase shift systems are more accurate than TOF systems especially at closer range, thus making it ideal for interior or restricted spaces.
Like in TOF systems, the phase shift systems can also capture colors, if further modified with camera. (Vosselman, George & Maas, Hans-Gerd 2010.)

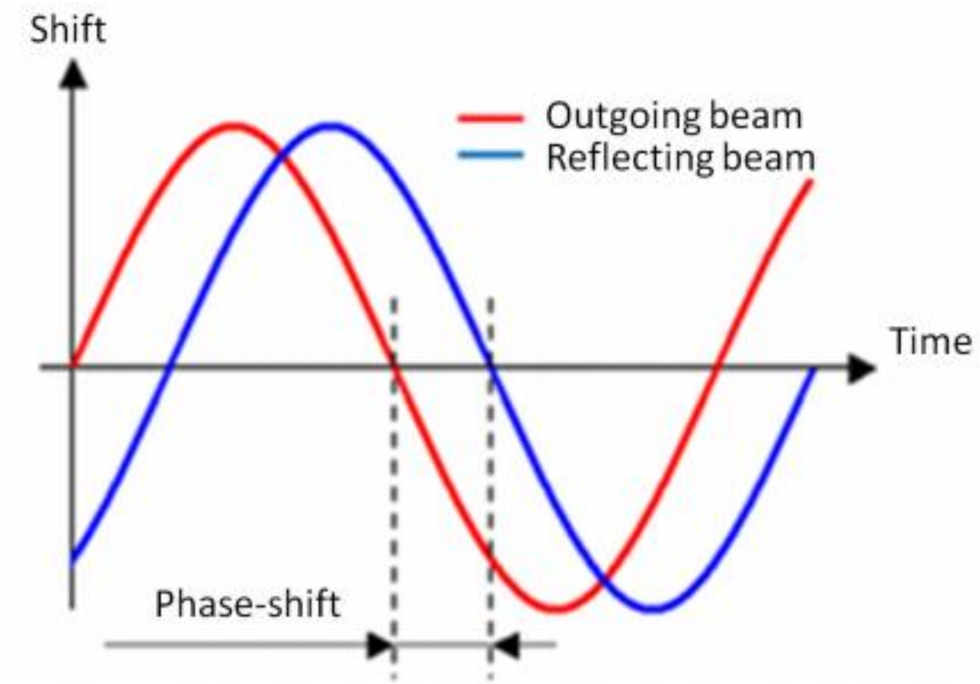

FIGURE 5: The phase shift difference between two waveforms (Ellmann, A. 2011).

3.2.1.3 Triangulation

Of all the active non-contact 3D scanning techniques the triangulation technique is the most used for short range and typically used for scanning individual objects.

Triangulation systems uses the principle of triangulation, where the 3D laser scanner sends a laser beam to the object under observation. Scanners inbuilt or external camera then captures the reflected laser light from the object and uses the CCD-array inside of the camera to transform the reflected laser light to a digital signal.

Triangulation technique is mostly used for situations where the operating range is between 0,5–2 meters and it can easily and reliably measure objects with micrometric accuracy.

(Archaeology Data Service, Digital Antiquity, 2019.)

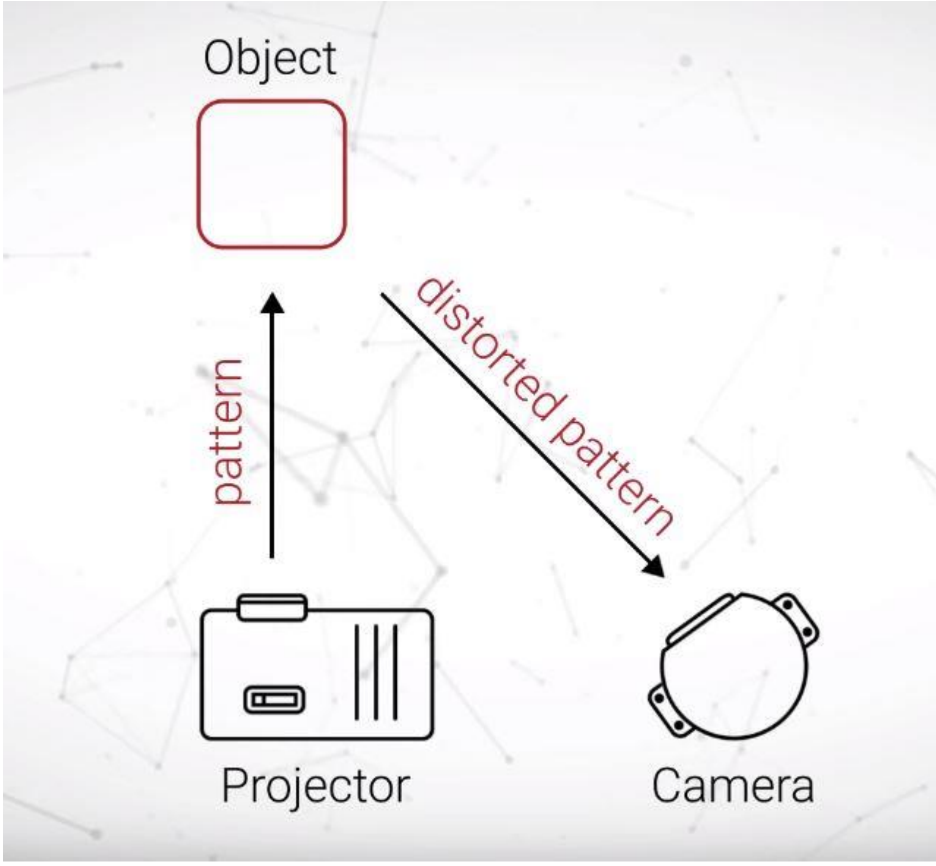

FIGURE 6: Laser triangulation technique (RangeVision 3D Scanners 2019)

The technique is called triangulation because the laser, the camera and the observed object form a triangle like presented in Figure 6.

The distance between the laser and camera is known and the angle of the laser emitter is also known by default. The camera angle can be determined by locating the laser reflected from the object. These three data points allow the scanner to calculate the surface of the triangle and distance of the laser point that is located at the corner of the triangle.

In most cases a laser strip is used instead of a laser dot to speed up the scanning process as show in Figure 7. (Ebrahim 2011.)

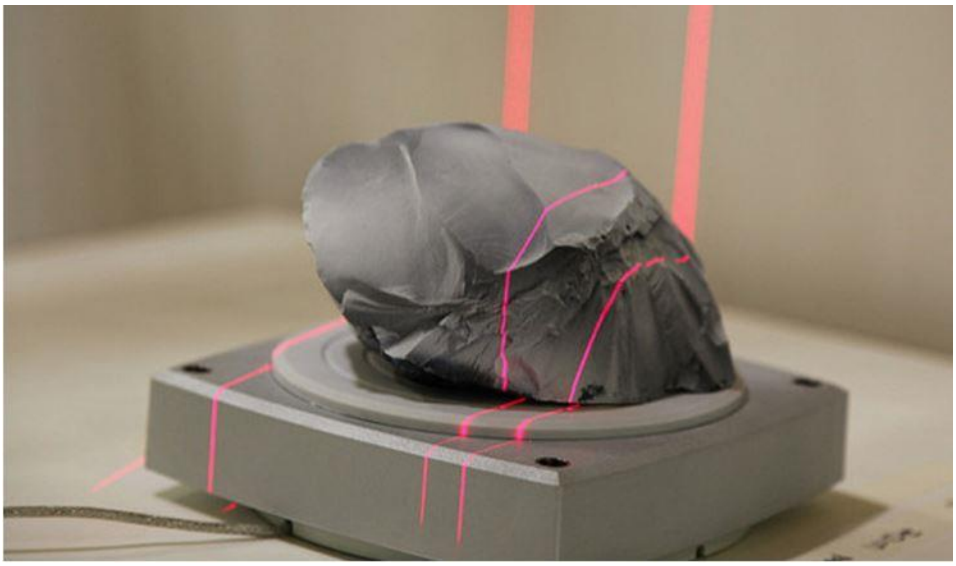

FIGURE 7: Laser triangulation technique with laser strip (3Dnatives 2017)

3.2.2 Passive technique

Passive 3D-scanning techniques do not create any light for scanning but provides the necessary light radiation from the environment. The object to be scanned reflects light from the surface, such as light emitted by the sun, which is then used by the 3D scanning system to record the measuring points. Passive 3D scanners consist mainly of a systems camera and computer software. Most commonly used non-contact 3D passive scanners are photometric scanners, stereoscopic scanners, and silhouette scanners. (Pezzati, Lica & Fontana, Raffaaella.)

3.2.2.1 Photometric Systems

Photometric systems differ from typical 3D laser scanning in that they use photographs instead of light to collect data. To create a 3D model using photogrammetry, you need many images from different angles to capture all the geometric parts of the object. The photograps must slightly overlap between the photos. Because the photos overlap, the software can align them correctly when importing photos to a computer. To be able to make a good 3D-model at least 100 images are required. After all the photos are imported to the computer, the computer software aligns the photos using image processing to find the refence points in the overlapping photographs.
With the photos aligned correctly the software can then calculate the distances and locations of the data points. The data points then form a point cloud that can be turned to a 3D model with separate software.
Compared to other systems, the photometric system can be very time consuming with one operating camera. The object must be turned manually, or the camera angle has to be manually changed between the photos. The total process time can be speeded up using a multicamera system. Because the entire system is solely based on camera quality and resolution, photometric systems are generally less accurate than other 3D scanners. (3space 2019.)

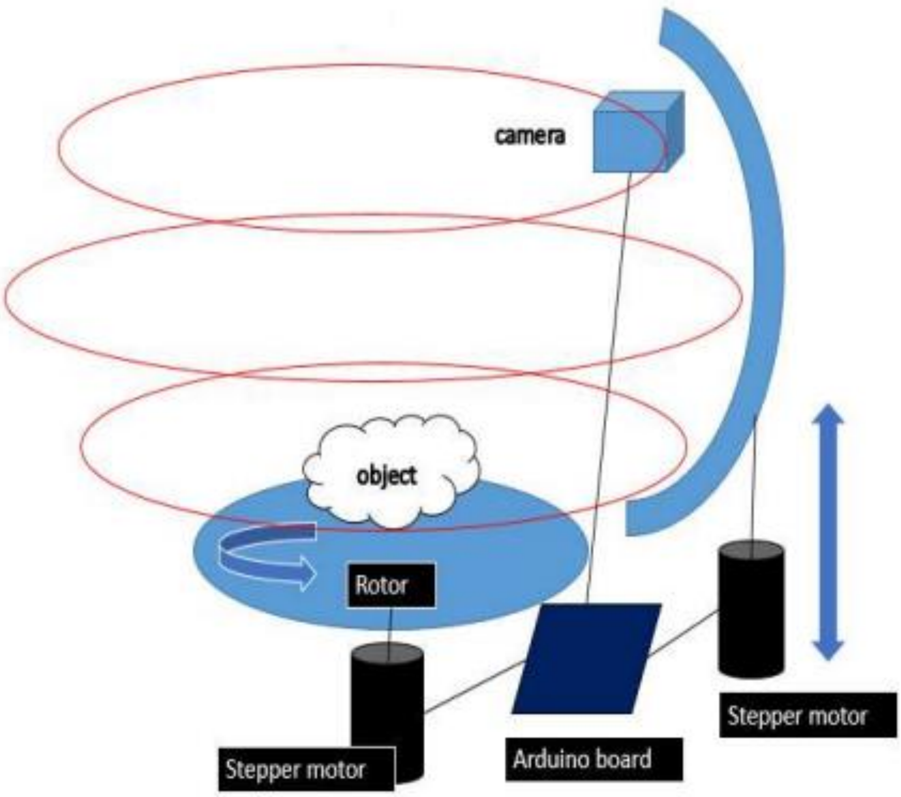

FIGURE 8: Camera taking photos at different angles (Chougule, Gosavi, Dharwad-kar & Gaind, 2018)

3.2.2.2 Stereoscopic Systems

The stereoscopic scanning system is typically two video cameras directed in the same direction to create a stereoscopic 2D image of the observed object. The video cameras are slighty apart from each other but looking at the same scene as seen in Figure 9. The slight difference between the two 2D images is enough for the software to calculate the location and the distances of the data points by using triangulation. This technique essentially imitates the principle of human stereoscopic vision. (Daqri 2018.)

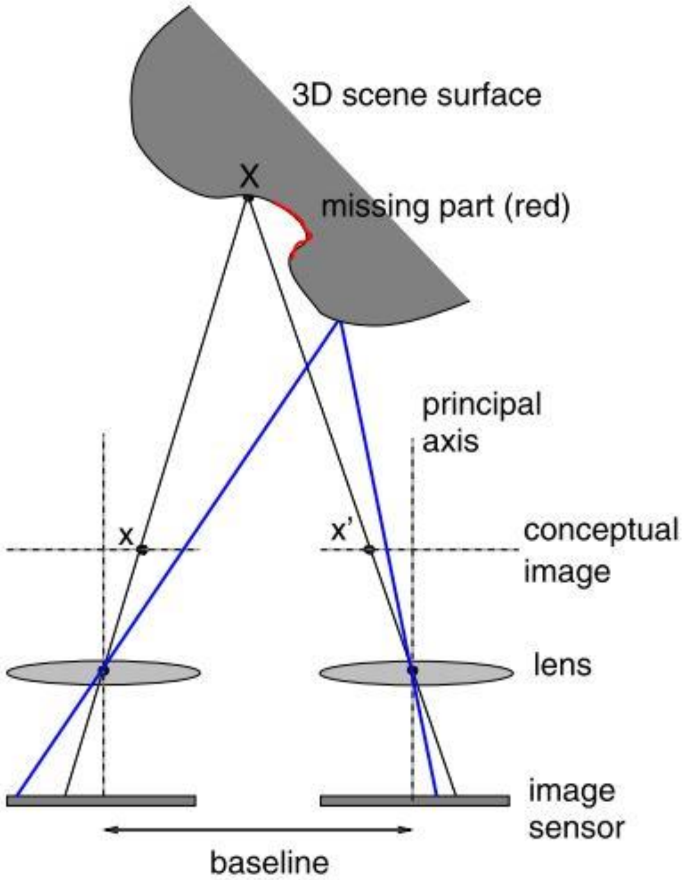

FIGURE 9: Top view of the stereoscopic 3D scan operation (Se, Stephen & Pears, Nick. 2012)

3.2.2.3 Silhouette Systems

Silhouette passive 3D scanning system only includes a simple camera and a turntable. It is based on capturing the outer boundaries of the object with multiple camera images from different angles. For a complete object scan, a photograph must be taken from each predefined angle of the object until the turntable has done one complete turn.

When all the images of the object have been acquired from predefined angles, the outer boundries are extracted from the images and combined to make a digital representation of the object.

Downside for using this technique is that it cannot collect data from objects that has small concavities, because it's based on the silhouette. The camera must also be maintained at the same place for the whole scanning process to be able to have reliable data from the object. (Olsson, Karin & Persson, Therese. 2002)

4 REAL WORLD APPLICATIONS FOR 3D SCANNING

There are many different industries that have integrated the use of 3D scanning technology within their services. 3D scanners have become significantly more efficient, smaller and more usable over the years. Because of the growing popularity in engineering, other fields of science have also adopted them in their own applications. Today the 3D laser scanning is used in entertainment industry, metal industry for reverse engineering and quality control, archeology, construction and terrain survey and in medicine. As the systems continue to evolve, it is possible that they can be integrated into commercial applications for use in everyday electronics such as mobile phones.

4.1 Metal industry

There are many ways for product designers and quality inspectors to utilize 3D scanning systems in the metal industry. This chapter focuses on the utilization of the 3D scanning in reverse engineering and quality control in the metal industry.

4.1.1 Reverse engineering

The concept of reverse engineering can have different definitions for engineers in different fields. For example, computer engineers and software designers refer to reverse engineering to determine the functionality of an algorithm, whereas mechanical engineers and product designers see it as a way to digitize a physical part in the form of a 3D model. In this section we are focusing on Computer-Aided Reverse Engineering or otherwise called CARE. In making of a Computer Aided Design (CAD) model the designed part is typically created digitally from technical drawings, which already have been done in advance. CARE is the exact opposite of the CAD process. In CARE the 3D model of the part is created from measurements taken from the physical part (Page, David & Koschan, Andreas & Abidi, Mongi. 2017.)

Figure 10 illustrates the CARE process in detail. First the physical part is laser scanned, where it becomes a point cloud. Computer software then creates a CAD model from the point cloud by aligning the reference points collected from the scanner. The 3D model can then be used for various simulations, further product development, CNC code creation or technical drawings. (Shabani, Betim & Pandilov, Zoran. 2017.)

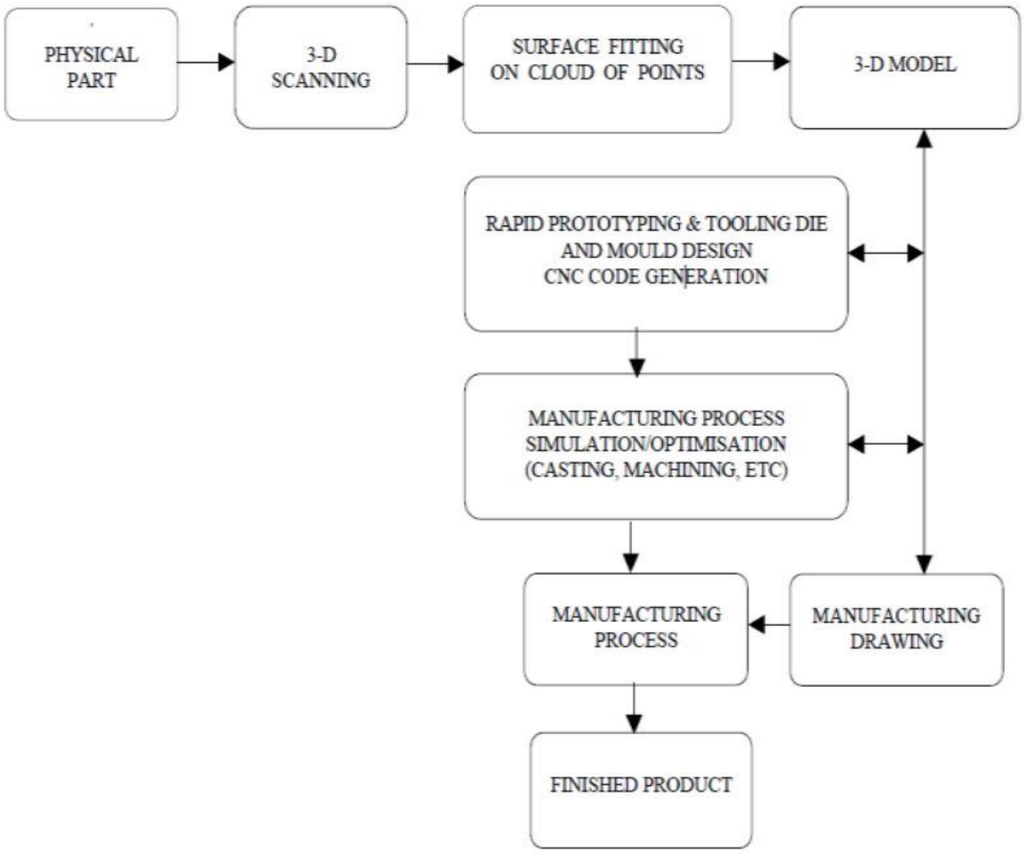

FIGURE 10: Computer Aided Reverse Engineering process (Shabani, Betim & Pandilov, Zoran. 2017)

For industrial applications, the CARE method can provide many improvements to product design and quality control by providing a more efficient and faster way to measure parts compared to conventional hand-held techniques. For example, an engineer or technician can make quick measurements of parts and compare them to technical drawings or CAD files for quick inspection of parts tolerances. The digitalization of physical parts also has the advantage of being easier to send to different locations via computers. This opens up opportunities for better business cooperation, which can lead to better part quality, save time and lower the overall costs.

There have been many cases where engineers have encountered a situation where a designed and manufactured part has been altered on the field, with very little or no knowledge of the change. The problem is when the field operator is not sufficiently trained to communicate about the modifications to the engineer. Without any accurate information about the modified part the engineers are not able to integrate the modification in future products. However, with proper instructions and with the use of 3D scanners the field operator is able to scan the modified part and transmit it to the engineers. The CARE method allows engineers to gather information about changes made and modify the original part to produce a better product.

(Page, David & Koschan, Andreas & Abidi, Mongi. 2017.)

4.1.2 Quality control

For decades, 3D contact scanners have been superior compared to 3D non-contact scanners in quality control, due its high accuracy. Because laser scanners are constantly evolving, they have reached to the point where they are approaching to the accuracy of conventional probing systems. 3D laser scanners also provide the operator with more information and detail, thus providing more information compared to traditional non-contact 3D scanning systems. Therefore, manufacturing industries have started to move towards 3D non-contact scanning systems. The accuracy of the 3D laser scanning system is solely based on the quality of its components and the accuracy of its calibration. Technology is rapidly evolving, as are the components of 3D laser scanners. Therefore, the peak accuracy for the 3D laser scanners have not been reached yet. Because of the portability of 3D laser scanners, it can be brought to the production line where the part is located, thereby reducing unnecessary downtimes. Whereas the traditional CMM system must be stationary in a controlled environment. Only the parts that require high tolerances are measured with the probing system.

Compared to CMM systems, the 3D laser scanner is simpler to use, and the data collected much easier to interpret. As shown in Figure 11, 3D laser scanning provides a color map of the inspected portion, which allows the user to quickly see whether the part is within the required tolerances and whether the part is deformed. (Bull, Guillaume. 2018.)

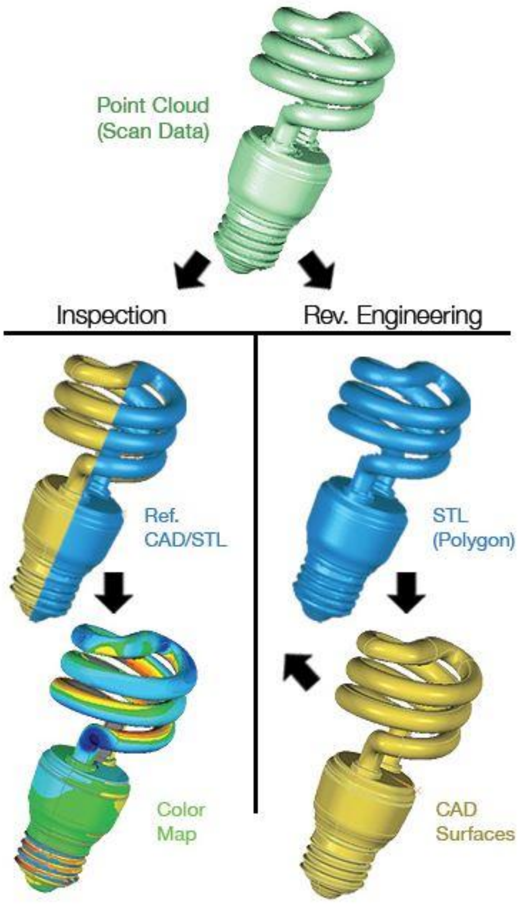

FIGURE 11: 3D Laser scanning process (Laser Design 2020)

3D laser scanning systems is a necessary tool in manufacturing industry for quality control. The 3D laser scanners are not completely replacing the CMM systems but can share some of the workload that has been shifted to CMM systems. This frees up more space for CMM systems to focus on parts that require higher tolerance checks.

4.2 Archaeology

3D scanning systems are on the rise in archeological research because of their unique way of preserving, restoring, and reproducing historical artifacts. The scanning technology provides the researchers new tools for research and ways to digitize the ancient objects. By scanning a historical site, researchers or archaeologists can gain far more information than the normal human eye can detect.

Instead of relying on 2D images, which can only provide information from a certain angle, the 3D model can be viewed from any angle, while providing the high accuracy needed to understand the objects details. Historical sites can be scanned from the air with the use of airplanes or drones to 3D map the historical location. 3D scanning of the historical site can be done using a photogrammetry as seen in Figure 12. This can prevent natural disasters, erosion of time or armed conflicts from destroying the location. (Arrighi, Pierre-Antoine. 2020.)

FIGURE 12: The Tower of Daymark 3D scanned with the use of photogrammetry (3deepmedia. 2017)

With the combination of 3D printing device and the 3D scanner it is possible to restore historical artifacts. To restore an object, it must first be 3D scanned before it can be rendered into a CAD model. The digitized 3D model can then be processed and used to make a plastic copy of a broken or worn piece. This is widely used in museums worldwide. (Arrighi, Pierre-Antoine. 2020.)

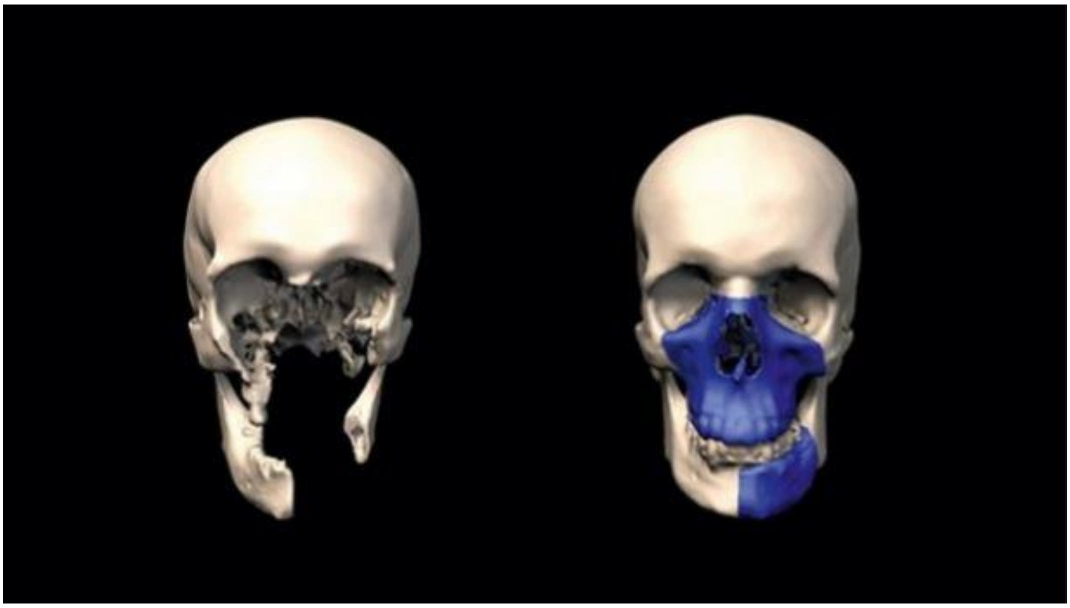

FIGURE 13: Restoration of an ancient skull with the use of 3D scanning (Arrighi, Pierre-Antoine. 2020)

4.3 Construction industry

3D laser scanning is a fast, efficient, and accurate way to collect data over a large area, making it an indispensable tool for today's construction industry and field surveys. To be able to perform 3D laser scanning throughout the entire construction site, scanners must be capable of long range and accurate resolution. The most used 3D laser scanners for long-range scanning are the TOF and Phase scanners. These long-range scanning systems allow acquisition distances from 5 meters to a few kilometers. The 3D scanning can be done with a mobile scanner, a terrestrial scanner, a handheld scanner, or with drones. Figure 14 is an example of a 3D laser scanning process from field conditions to a building information model (BIM). The interior of the building is scanned with a 3D laser scanner, which is then converted to a point cloud. The software converts the point cloud to a building Information model (BIM) that can be used for quality control and documentation.

Laser scanning is not a new technology in the construction industry. At first, it was only used for construction and maintenance work in industrial areas, but nowadays, due to the popularity of 3D scanners, they are also used in more demanding tasks.

Being able to make a 3D mapping of large areas almost instantly simplifies construction site design and visualization before construction begins. Another major benefit of laser scanning is building coordination between different systems, such as electrical, plumbing and ventilation systems. A digitalized model of a building can be shared with different groups for better understanding of building. This allows for better cooperation between companies working in the same building. Laser scanning can be performed several times between different work stages and between the milestones for better documentation.

Capturing all the details of a building by laser scanning during construction gives the owner and the property manager the information they need for any further work, renovation or even demolition of the building. (PlanGrid 2019.)

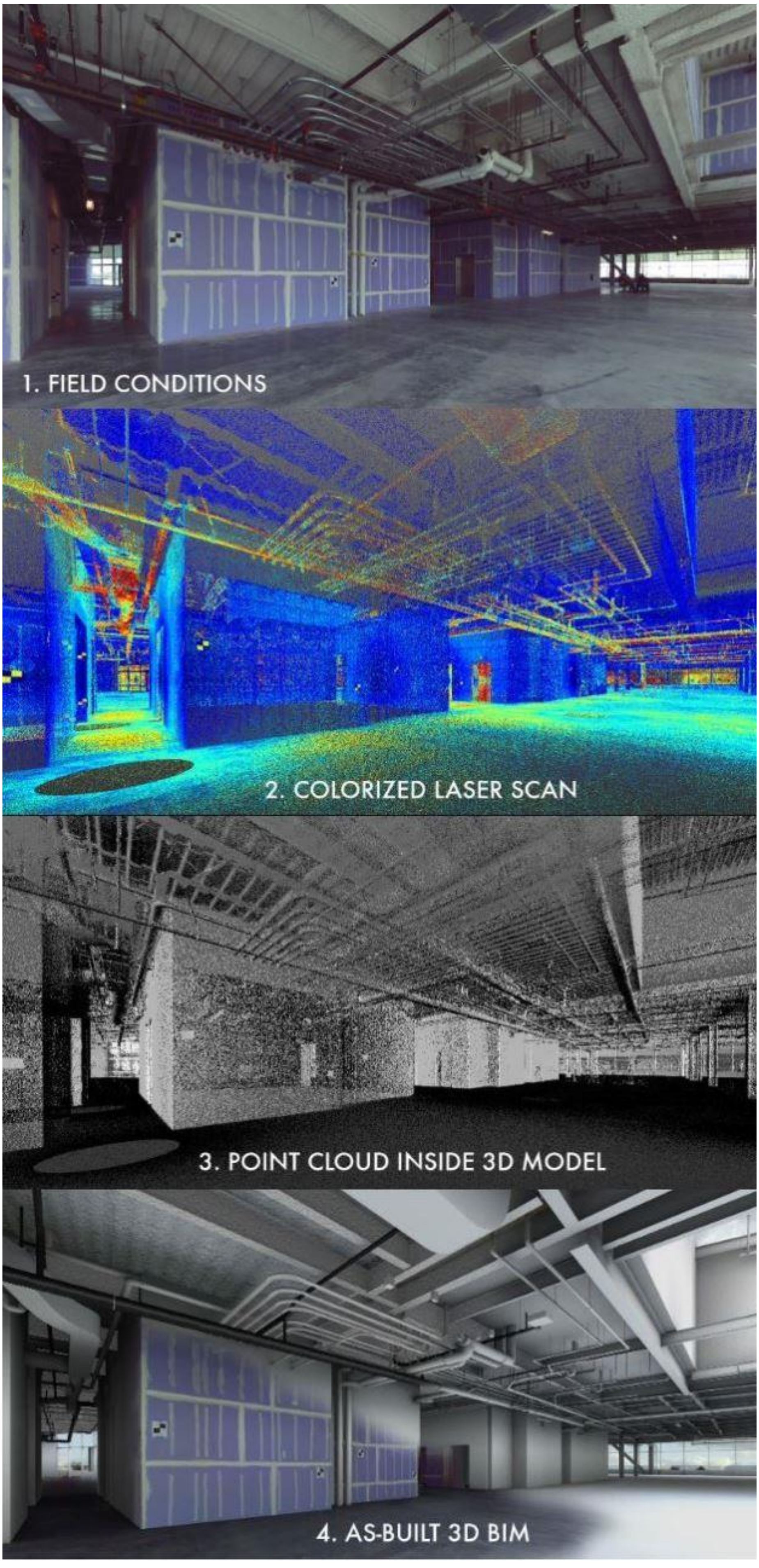

FIGURE 14: Building information modeling with laser scanning (BuildingPoint West. 2020)

4.4 Terrain survey

LIDAR, which stands for light detection and ranging is a 3D scanning system that is mostly used in todays terrain surveys. LIDAR systems distance measuring is based in time of flight and phase shift techniques. The LIDAR system can be separated into two categories: terresial laser scanners (TLS) and airborne laser scanners (ALS).

TLS is a ground-based system designed to measure precise distances and angles. It is used to measure surfaces that are perpendicular to the laser beam, such as steep hills, rocky mountain walls, and deep slopes. (Se, Stephen & Pears, Nick. 2012.)

ALS is a new technology used to collect highly accurate data from an airplane, helicopter, or drone with the use of a laser. When used in conjunction with digital aerial imagery, they can be used to create terrain models. The ALS sends a high-frequency laser pulse to the ground, which then reflects into the system. The scanner calculates the time taken from transmission to reception, which is used to determine the distance traveled by the laser like seen in the Figure 15. With the help of global positioning system (GPS) and inertial measurement unit (IMU) that are integrated to the aircraft, the data obtained from the ALS can be converted into a color-coded altitude map with the use of a computer software as seen in Figure 16. (Arizona State University. 2008.)

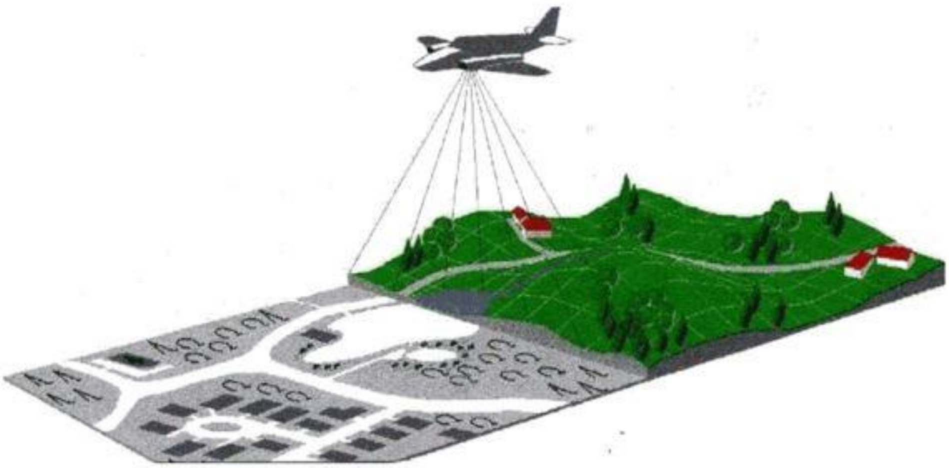

FIGURE 15: Acquisiton of data points with ALS (Simon, M. & Schymitzek, Irene & Vandrie, Rudy. 2009)

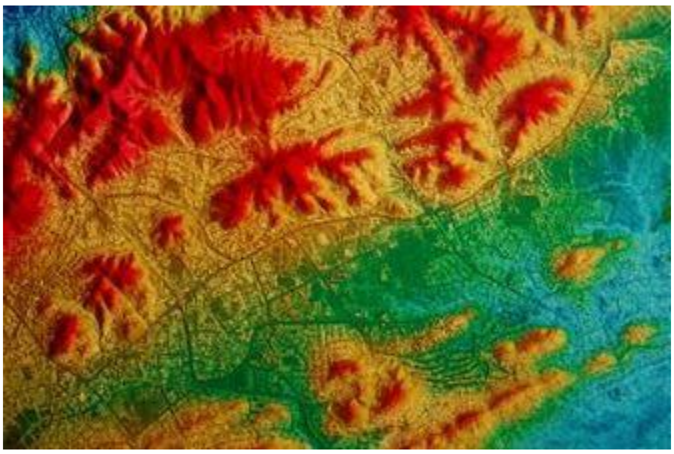

FIGURE 16: Color coded altitude map (Arizona State University. 2008)

4.5 Medical

In medicine, there have always been many different advanced techniques that have enabled data to be collected on the external or internal structure of individuals. In recent decades, diagnosis and disease monitoring have been done with the help of computed tomography (CT), X-ray, magnetic resonance imaging (MRI) and ultrasound. With the continued rise of 3D scanning and printing applications, 3D scanning systems have gained a foothold in medicine. This is because 3D scanners have advanced to the point where they are efficient, accurate and fast enough to produce data that can be used for medical use, which has also reduced the manual measurement process.

The point clouds collected from a 3D scanner can be used to create body shapes, implants, prostheses, or other anatomical designs.

The most important difference between 3D scanning systems and CT, X-ray, MRI or ultrasound systems is that the 3D scanner only provides information from the outside of the body, while other scanning systems can provide information about the internal geometry of the body.

The external surface of the human body is filled with complex shapes that can be difficult to handle with typical manual measurement systems. 3D scanning can perform this task quickly with one simple scan to capture the external geometry of the model. Because of the fast processing speed and flexibility of the 3D scanning system, patients waiting times are also reduced.

Non-contact 3D laser scanners also allow data to be collected without physical contact with the patient as seen in Figure 17. (Haleem, Abid & Javaid, Mohd. 2018.)

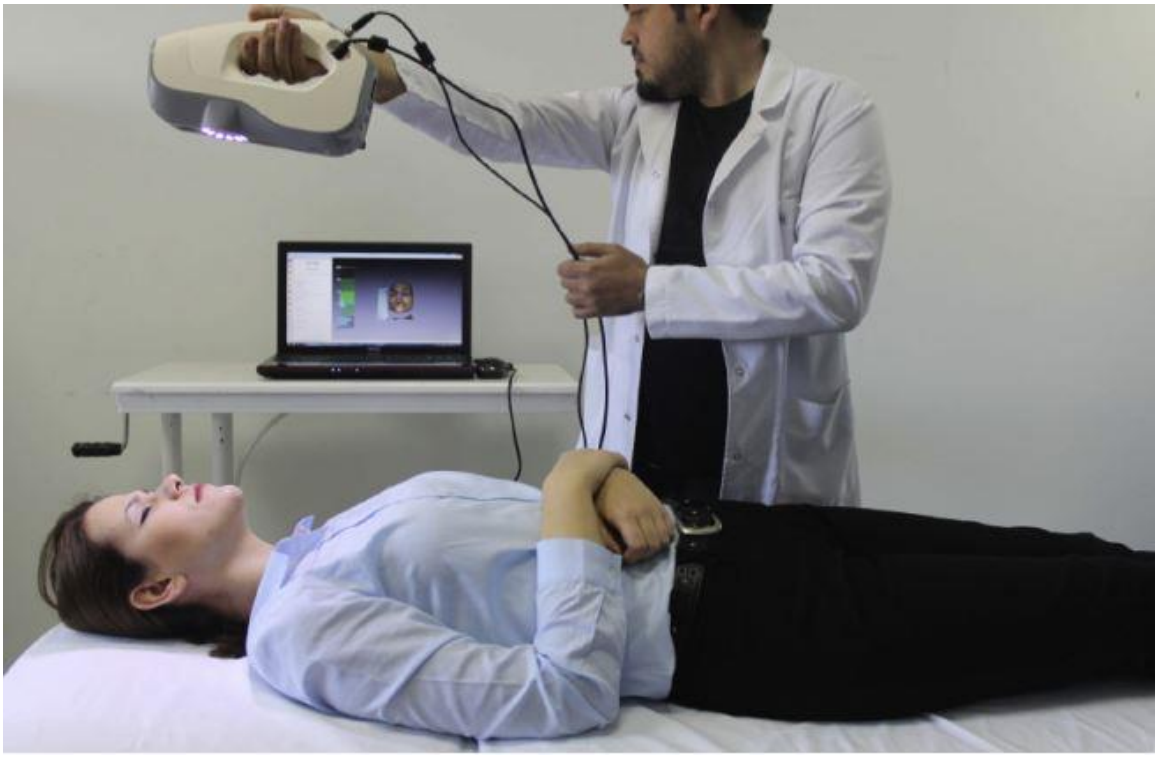

FIGURE 17: Patient face scanning with 3D scanning system (Artec3D. 2020)

This ensures that the scan is accurate as there is no interference. This also allows for the scanning of patients who cannot be touched, such as burned victims.
The medical industry has achieved many improvements with 3D scanning systems. Improvements have been made in human-body metric scanning, skin surface scanning, body size and shape scanning and in 3D visualization of the patient's body. As mentioned in previous chapters, the reverse engineering is also applicable in the medical field. Data scanned from the patient's body can be reverse engineered to improve the fit of the prosthesis. The same method can also be applied to medical devices to improve properties, for example, to meet a patient's needs.
(Haleem, Abid & Javaid, Mohd. 2018.)

4.6 Entertainment industry

The video game and film industries are constantly using high-quality special effects in their production, which require modelling of complex objects and environment such as fictional worlds. The process of making a high quality and complex model manually with a 3D modelling software is very time consuming therefore the video game and the film industries have adopted 3D scanners to capture real-life objects and environment digitally, to speed up the modeling process. For example, using 3D scanning technology, a copy of the real-world environment can be digitally collected. This can then be used as a template for constructing a new fictive reality. By manipulating the scanned data from the real-life environment with use of 3D design software, the film and the gaming industry can produce new worlds that have never been seen before. (Europac3d. 2017.)

The same techniques that are used in medical, terrain survey, construction industry, archaeology and metal industry can also be used in entertainment industry. For large open areas or buildings, ToF or phase shift lasers can be used from the ground or from the air, such as in the construction industry and field research. For scanning complex objects or parts of the human body that require accurate modeling, triangulation scanners can be used as in medicine.

5 MODEL RECONSTRUCTION

3D Model Reconstruction is a process where computer vision and computer graphics are used to collect information about real objects. The process of reconstructing a 3D model consists of measuring the object with various techniques that collects information about the surface of the object. The information gathered includes the object's form and properties, which are used to reconstruct a digitalized version of the real-life object. (Intwala, Aditya & Magikar, Atul. 2016.)

5.1 Point cloud

Point cloud is a term that is used for a set of data points that forms the surface of an 3D scanned object or environment. A point cloud can contain millions of measured data points, each of which has an exact location in three dimentional space.

The data points are most produced with non-contact or contact 3D scanners. The color of the data point can also be specified if the system used for 3D scanning is also capable of collecting color information. Point Clouds can be used for the direct measurement and visualization, but in most cases, it is used in its post-processed form such as a polygonal 3D model, a NURBS surface model or the CAD model. (Ebrahim 2011.)

5.2 The stages of 3D model reconstruction

The 3D reconstruction process can be represented in four different stages: collecting information about the object with the use of scanning or probing systems, processing of the information collected from the object, segmenting, and creation of the CAD model.

The first stage is the most important of all four stages of the 3D model reconstruction. The data acquisiton can be made with two different methods: the non-contact method that includes active and passive techniques and contact method that is based on physically contact the object with the use of CMM systems. Non-contact techniques are the most popular because of their fast data acquisition rates compared to CMM systems, but contact techniques are still more accurate in the measurement. That is why they are used more often in projects that require more accuracy in measurements.

After finding the suitable method for the scanning process the data points can be collected from the object and formed to a point cloud.

The second stage involves the processing of the point cloud data collected from the object. The data processing involves the removing of the unnecessary data points that may have been the caused by an error in scanning process or by poor reflection of the material. For example, the non-contact scanning method is a much faster in data acquisiton than traditional CMM system, the point cloud produced by non-contact method contains a lot of noise, which reduces the accuracy of the 3D model.

The third stage of the 3D model reconstruction is the segmentation and classification procedure. In point cloud segmentation, data points are logically sorted into subsets based on the similarities they posses as seen in Figure 18. There are two commonly used methods for segmenting point clouds: edge based and face based method. In edge-based method the outlines of the point cloud data are detected by locating the change in the intesity in the data points in a certain region of the point cloud. This method extracts the outlines from the point cloud to obtain segmented regions. The edge method allows for rapid segmentation, but its accuracy is lowered when there is noise or uneven density in the point cloud.

The face-based method is the exact opposite of the edge-based method, because it tries to combine data points with similar properties, group them and classify them on the same surface. Face-based process uses a large amount of points in the segmentation process, which reduces the possibility of an error in the segmentation.

The fourth stage of the process is the 3D model creation. The point cloud data is in IGES (Initial Graphic Exhance Specification), DXF (Drawing Exchange Format) or STL (Stereo Lithography) format, which can be opened with any commercial CAD software.

After pre-processing and segmenting the point cloud data, the data can be imported into CAD software, where the point cloud is converted to polygon mesh model, NURBS surface model, triangle mesh model or CAD model through reverse engineering. (Intwala, Aditya & Magikar, Atul. 2016.)

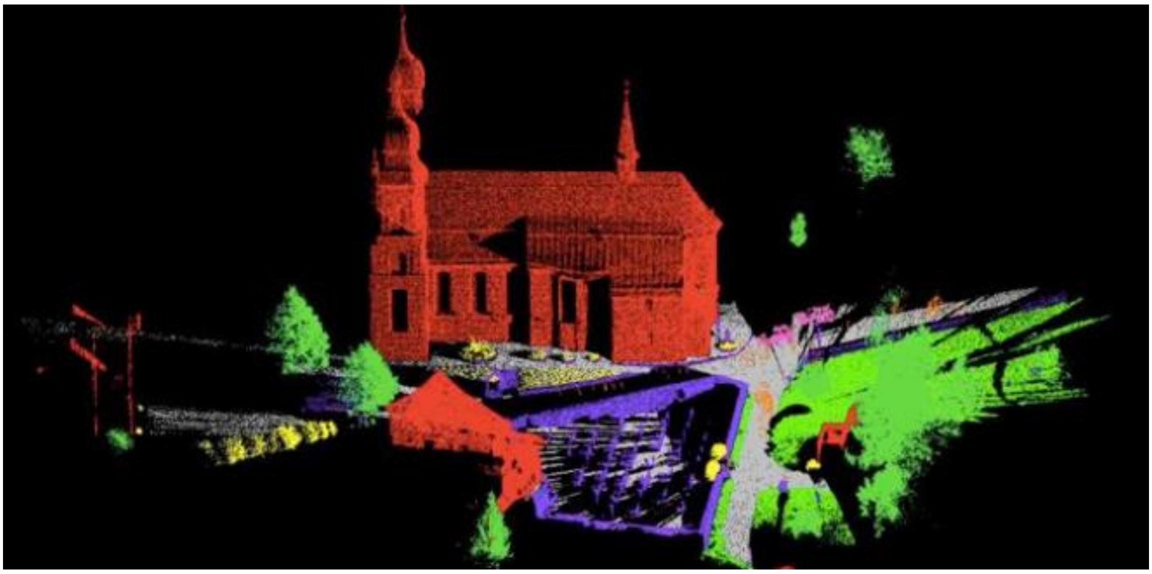

FIGURE 18: segmented and classified point cloud (Grilli, Eleonora & Menna, Fabio & Remondino, Fabio. 2017)

6 THE HARDWARE AND THE SOFTWARE USED FOR THE PROJECT

6.1 Hexagon absolute arm 6-axis

Hexagon absolute arm is a portable measuring arm system that has six rotary axles and joints. The system has encoders at every articulation point for calculating position of the probe. The hexagon's encoders eliminate the need for warm-up times or encoder referencing. The base of the system is made of carbon-fibre, which maintains the strength and thermal stability under all environmental conditions. With the lightweight structure and inbuilt Wi-Fi and battery, the measuring arm can be transferred to any workstation, where measuring is needed.

The portable measuring arm is specialised for high-accuracy probing but can also be used as a laser scanner with the proper attachments. (Hexagon 2020.)

6.2 Hexagon HP-L-8.9 laser scanner

Hexagon HP-L-8.9 laser scanner as shown in Figure 19 is an attachment for all the Hexagon's 6-axis portable measuring arms. The probe of the measuring arm can be swapped with the laser scanner to enhance the capabilities in point-cloud measurement.

The HP-L-8.9 is a 3D laser scanner that is based on the triangulation technique. The laser scanner sends a laser pattern to the object. The inner camera then captures the reflected laser and calculates the distances of the datapoints from the distorted laser pattern reflected from the object like seen in Figure 7. The technical information about the laser scanning system can be seen in Figure 20.

The laser scanner is equipped with high-grade optics which is capable of measuring surface types like carbon-fibre, leather, and steel. The system does not need any reference markers or targets in the object like used in hand-held laser scanning systems. This is because the position and rotation of the laser scanner is calculated with the portable measuring arm.

HP-L-8.9 laser scanner is used for example in reverse engineering, different stages of product designing and rapid prototyping. The laser scanner attachment can be mounted to the mechanical measuring arm with a minimal effort. With a short training, this allows the operator to use the system as efficiently as possible. The HP-L-8.9 has a built-in rangefinder that guides the operator through color coding to use the laser scanner at the optimum distance for the best measuring information. (Hexagon 2020.)

FIGURE 17: HP-L-8.9 laser scanner (Hexagon 2020.)

Technical information	Hexagon HP-L-8.9
Scanner type	Red laser line scanner
Accuracy	0,04 mm (2σ)
Point acquisition rate	45000 points/s
Points per frame	750
Frame rate	60 Hz
Line width (mid)	80 mm
Standoff	135 ± 45 mm
Laser class	2
Minimum point spacing	0,08 mm
Operating temperature	5-40°C
Weight	0,32 kg

Figure 20 Hexagon HP-L-8.9 (Hexagon 2020.)

6.3 InnovMetric – Polyworks

In order to use the data points collected from the laser scanner, it must be processed and saved with a suitable computer program. This project used Polyworks Inspector and Polyworks Modeller software. Both computer softwares are part of the Metrology Suite software platfrom which is made by InnovMetric.

Polyworks Inspector is a 3D metrological software that is used with non-contact scanning systems and probe operating systems to measure dimension of tools or parts. The software guides the operator throughout the scanning process in real time, by visually displaying the progress of the process on the computer screen. The scanned data can then be converted to a 3D mesh model by aligning and merging the data points collected from different scan sessions.

Polyworks Modeller is a reverse engineering software which is used for creating polygonal, surface and solid models from pre-processed point cloud data created from polyworks inspector. With its advanced modeling features, the operator can create NURBS patches to the 3D model and produce accurate and smooth surfaces by trimming and matching polygons. After the process, the software can convert the NURBS surfaces into a standard format (IGES or STEP) that can be opened with any commercial CAD software for later use. (Innovmetric. 2020.)

7 SCANNED PARTS

The parts scanned in the project are the ball and the seat of the ball of the Metso's 4" modular ball valve product. The ball valve is manufactured for pressure class 300 and the valve body's material is AISI 1030 carbon steel.

The principle of sealing properties of ball valves is based on a ball-shaped closure member. The closure member has a channel that goes through the ball, that enables the flow through the valve. By turning the ball 90° degrees on its axle the flow channel can be opened and closed. (Metso Flow Control Inc. 2020.)

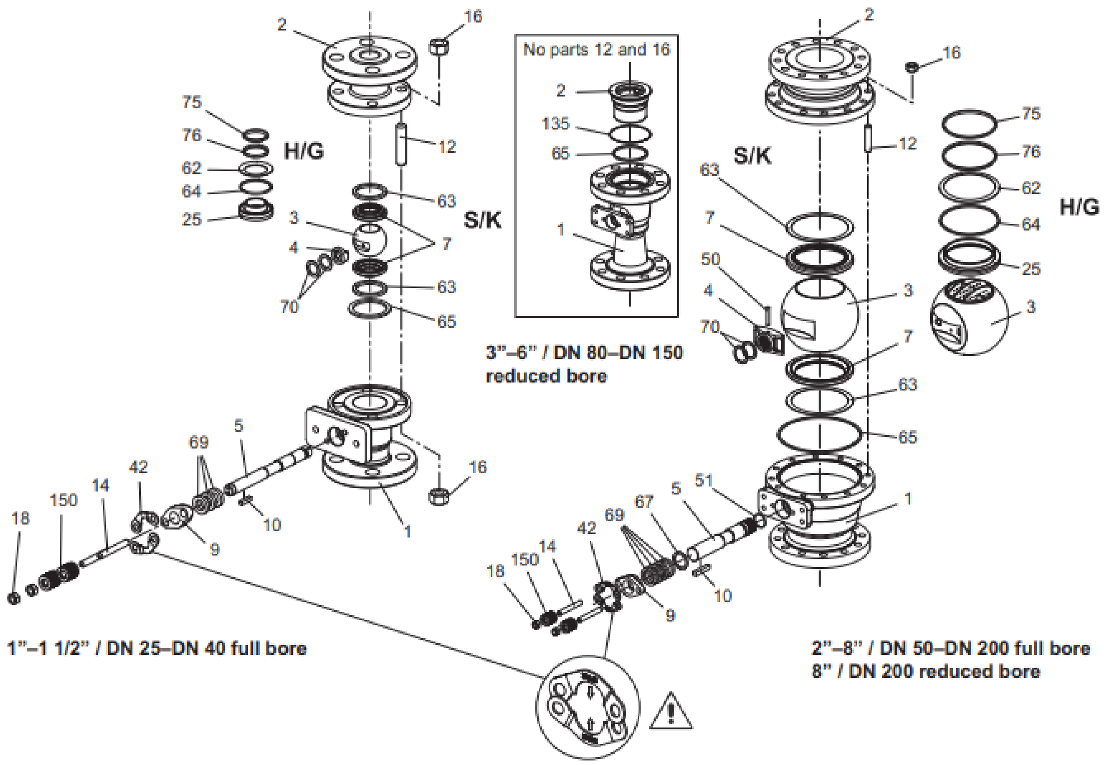

FIGURE 18: Exploded view of the ball valves parts. Part 3 - the ball and item 25 – the ball seat (Metso Flow Control Inc. 2020)

7.1 XA04 – Ball

The XA04 ball valves ball is made from 316 stainless steel and is coated with hard chrome. The XA stands for ball valve ball that is full bored and is seat supported. The 04 indicates the diameter of the flow channel of the ball which is 4 inches. The XA04 ball valve ball is made for pressure class 300. (Metso Flow Control Inc. 2020.)

FIGURE 19: XA04 - Ball

7.2 XA04 H – Ball seat

The ball seat of the 4-inch ball valve is made of 316 stainless steel and has coating made out of cobalt based hard facing. The purpose of the ball seat to prevent leakage. The smoothness and the quality of the steel seat surfaces of the ball seat are the most important factors in keeping the valve leakage to a minimum. Sealing surfaces of the ball seat must have the same surface roundness as the ball surface, to maximize the effectivity of the metal seal.

FIGURE 23: XA04 H - Ball seat

8 TRANSFORMING 3D MEASUREMENT DATA TO SOLID 3D MODEL

This project presents three different methods for converting point cloud measurement data to a solid 3D mode with the use of Polyworks inspector and polyworks modeller metrology softwares:
Cross-section based method, surface recognition method and transformation to solid 3D model from NURBS patches.
To demonstrate the different methods for transforming measurement data to solid 3D model two objects were used, XA04 H – Ball seat and XA04 - ball. The Cross-section method was used for the XA04 H – Ball seat and the other two methods were used for the XA04 – Ball.

8.1 XA04 – Ball

8.1.1 Data acquisition

The ball valve’s ball is attached to a mounting bracket to prevent the ball from moving during the 3D scanning process. The ball is 3D scanned with Hexagons 3D laser scanner at Metso’s measurement room with the help of Iiro Laaksonen.
The ball was first measured with a probe system to obtain the height and width of the edges of the data points. The measured data points are used to position the ball at the center of the coordinate system. To be able to scan both sides of the ball, the 3D scanning process had to be split into two sessions. Typically, glossy surfaces, such as chromium, cause errors in scanning processes, but in this scanning process the glossy surface did not interfere in the acquisition of data points.

In the first scan session, 795646 data points were collected from the left side of the ball, while in the second scan session, which was performed to the second half of the ball, 1052822 data points were collected. After the scanning was finished and both point clouds were created from the ball, they were combined in Polyworks Inspector to complete the 3D scan as seen in Figure 24.
The merge process is performed in Polyworks Inspector using the Best fit data point feature that recognizes similar sets of data points in both point clouds. Both point clouds are placed in the same coordinate system, and with point cloud recognition the software can determine the position of the point clouds in the coordinate system using point cloud data similarities. This process can also be performed manually by placing reference points on both point clouds.

With both point clouds combined the total number of data points was 1,8 million.

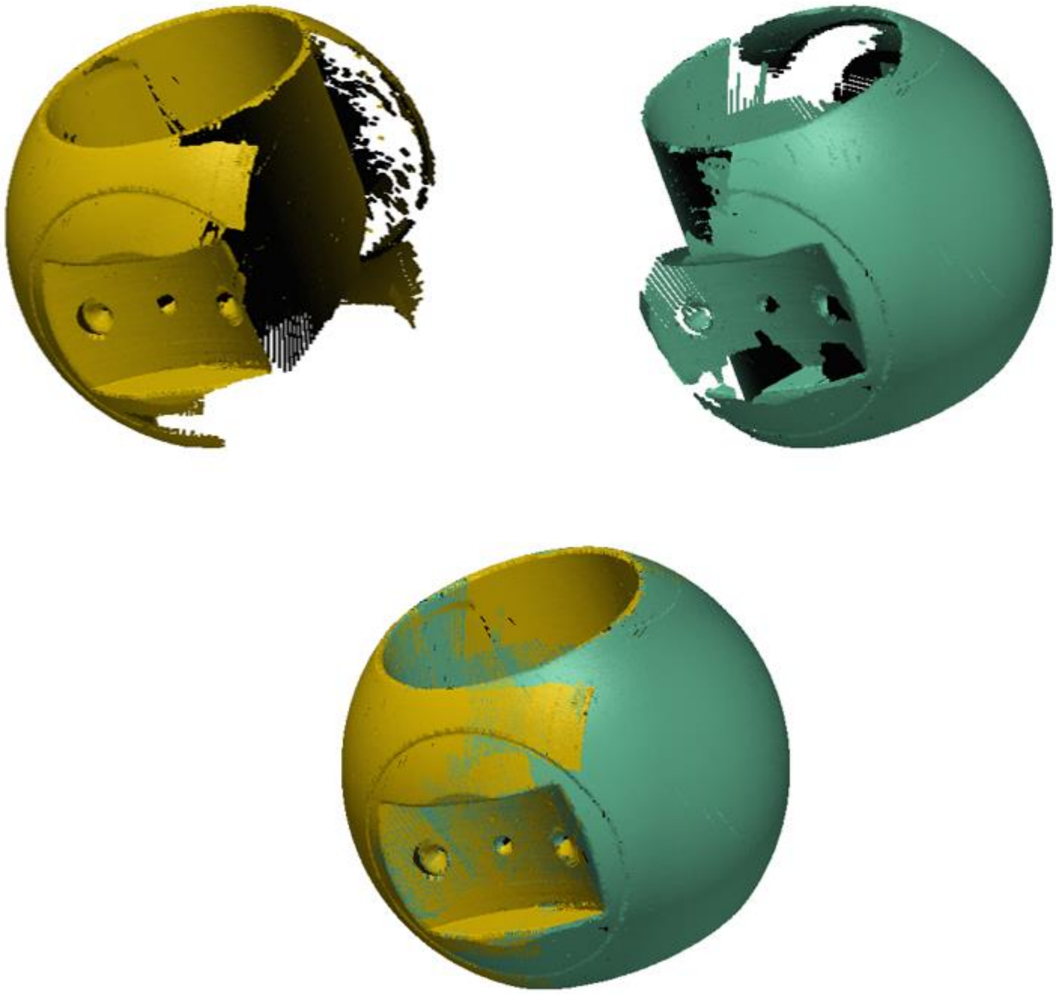

FIGURE 24: Combining the point clouds of the ball

8.1.2 Processing of the scanned data

Before point cloud data can be further processed, unwanted data points must be removed from the point cloud. The unwanted data points are from the used mount and unwanted reflections during the scan session. Removing the unwanted data points is proceeded with the use of select elements tool in Polyworks Inspector.
The combined point cloud is transformed into a mesh model. Polyworks Inspector uses a preset that changes the polygon size of the mesh model to 0,05 mm. This reduces the total data points used for the creation of the mesh model, because of the limitation of the surface area of the ball. The merged point cloud data of the ball is transformed to a mesh model with the use of create polygonal model in Polyworks Inspector, which resulted in 165833 data points and 327194 triangles.

After the mesh model is created the mesh model is imported to Polyworks Modeller. The surface of the mesh model is smoothed with different filters that reduces the inconsistent data points on the mesh model. The mesh model is then waterproofed by filling the mesh gaps that are caused by poor data point registration of the 3D scanner or incomplete scanning process. The filling of the mesh gaps is done with the fill holes feature in Polyworks Modeller. The software can automatically detect the gaps and reconstructing the mesh by filling the holes by inspecting the surface around the gap as seen in Figure 25. Larger mesh holes must be filled manually because the software does not have enough reference surface to automatically fill the holes accurately. The holes in the mesh model can be manually filled by copying the surrounding surface geometry and overlapping the hole with the copied surface.

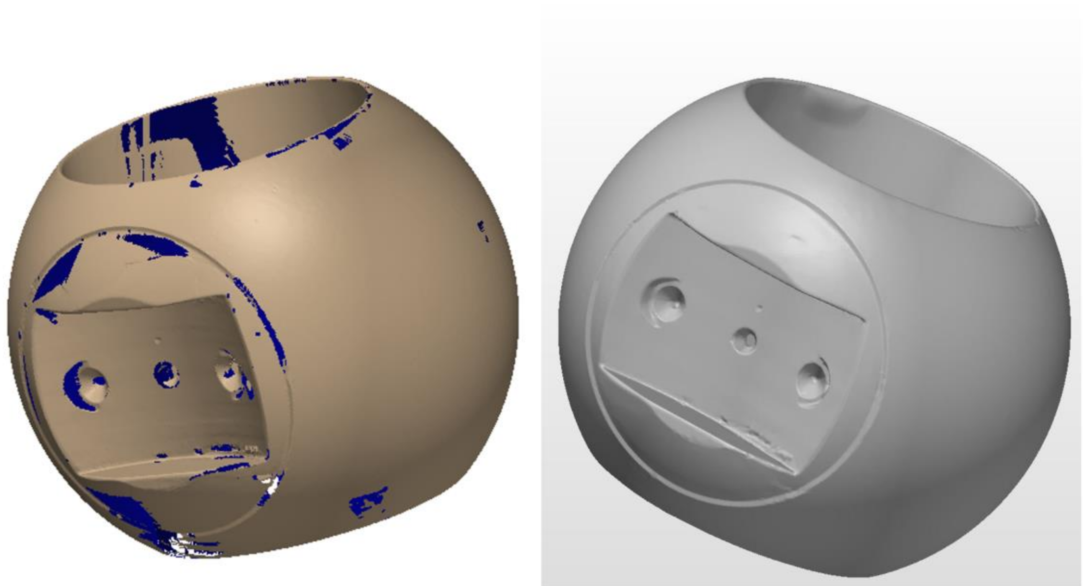

FIGURE 25: Smoothing of the surface and filling the gaps of the mesh model

8.1.3 Converting to solid 3D model

8.1.3.1 Solid 3D model from surface recognition

The surface recognition method divides the mesh model into smaller surface geometries with the use of surface recognition. The created surfaces are used as boundaries for creating the solid 3D moel. This method is used when the part is not symmetrical and only the general design of the model is needed from the object.

The mesh model is segmented into smaller surface geometries using data point segmentation methods. Polyworks Inspector indentifies the surfaces of the mesh model and creates a geometric surface from the inspected surface. With all the surfaces segmented they are aligned and made parallel for each other. The total surfaces generated from the ball are: two spheres, one cylinder and seven planes as seen in Figure 26.

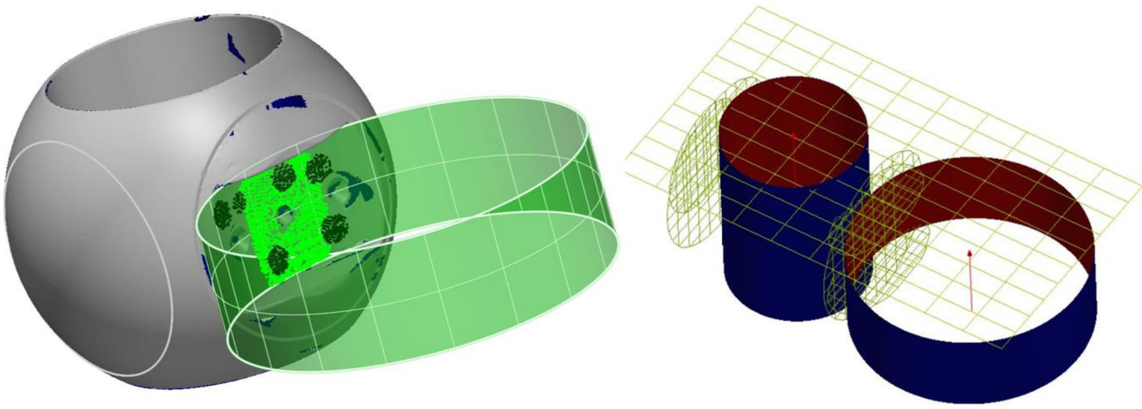

FIGURE 26: The surfaces generated from the ball with the use of surface recognition

After the surfaces are made from the mesh model and aligned for each other the surfaces are exported to Solidworks. The exported files are in format of IGES that can be opened with every commercial CAD software.

The surfaces made from the Polyworks Inspector are then trimmed off from the 3D model with the use of trim surface feature in Solidworks. The trimming procedure consists of manually removing the surfaces that are splitting the model in multiple different angles. By leaving the geometric surfaces forming the spherical surface of the ball and removing unwanted surfaces, the result is the surface of the scanned mesh model as seen in Figure 27.

After the trimming procedure the surfaces are transformed to a solid 3D model in Solidworks.

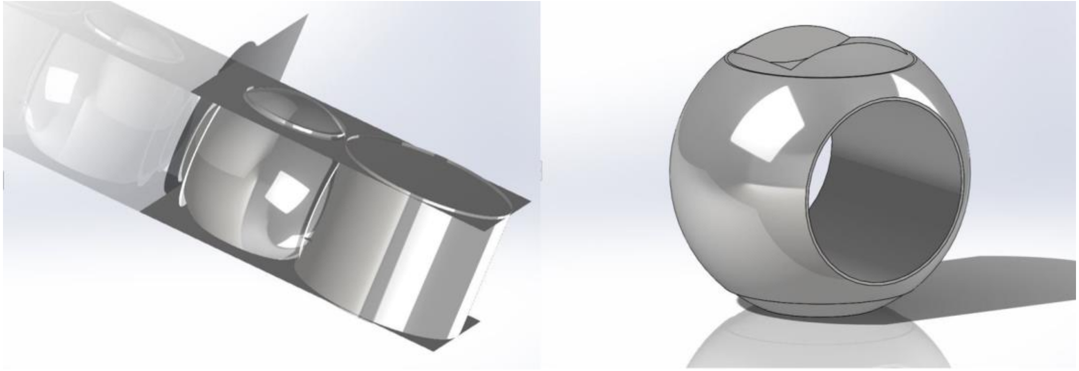

FIGURE 27: Trimming of the generated surfaces in Solidworks

8.1.3.2 NURBS (Non-uniform Rational B-Spline) model

This method provides the best accuracy compared to other mentioned methods, because it represents the exact geometry of the part. NURBS patches are manually added to the surface of the mesh model to identify the geometric surfaces of the part. The patches are then fitted to the mesh model, which is then transformed to a solid 3D model.

The mesh model is segmented by manually adding NURBS curves to the surface of the mesh model. Process can also be performed automatically by the software, but to increase accuracy, the process was done manually. The software cannot automatically detect the mesh surface accurate precisely enough to be used in this modeling.

The curves are added to the surface of the mesh model for recognizing the surface geometry of the mesh model and for creating the NURBS patches.

NURBS patches are created from rectangular patterns made from curves placed on the surface of the mesh model. The NURBS patches follow the exact surface pattern that is on the surface of the model as seen in Figure 28.

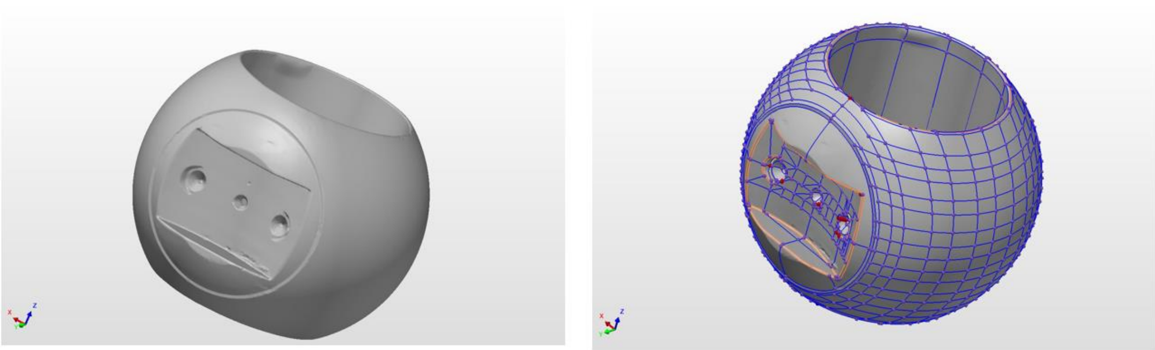

FIGURE 28: Adding curves to the mesh model to create NURBS patches

The surface geometries are recognized by the software after the curves have been added to the mesh model. The NURBS patches are then fitted to the mesh model with the use of fit nurbs patches feature in Polyworks Modeller.

This ensures that the NURBS patches follow the surface geometries of the mesh model.
After the patches are fitted to the mesh model, the patches are transformed into solid 3D model with the use of create solid 3D model feature in Polyworks Modeller as seen in Figure 29.

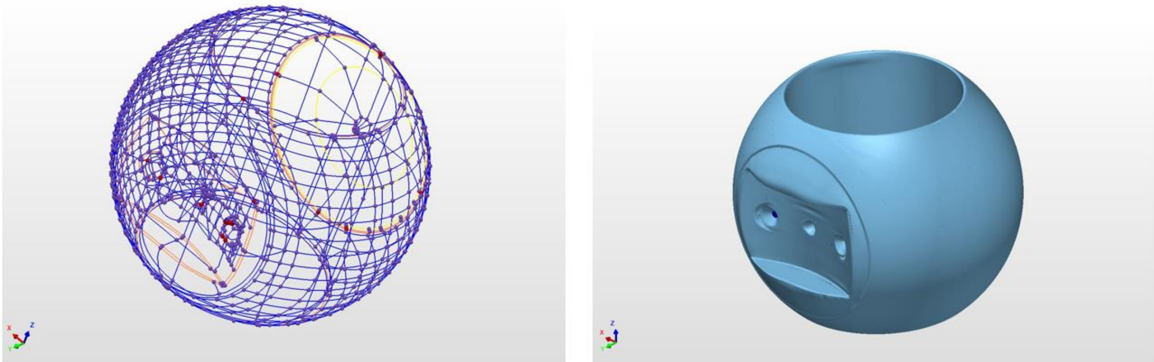

FIGURE 29: NURBS patches transformed into solid 3D model

The solid 3D model is in a format of STEP or IGES, which can be opened with any commercial CAD software.

8.2 XA04 H – Ball seat

8.2.1 Data acquisition

3D scanning of the ball seat begins by attaching the part to a solid surface and measuring the outer edges of the part with an absolute arm probe to enhance the accuracy of the measuring data. After the outer boundaries of the part are registered with the probe attachment the data points are set to the center of the coordinate system for the laser scanning.
Due to the high reflectivity of the material and for the better data acquisiton of the laser scanner, the 3D laser scanning was done twice.
The first laser scan was performed with just the part, which resulted in poor data point registration because of the shiny surfaces of the part produces unwanted reflections during the scanning session as seen in top Figure 21. In the second scanning session the part was covered with Bycotest D30plus developer before the 3D laser scanning to make the surface of the part less reflective.
This provides much more accurate point cloud data compared to the previous session.
To reduce the processing time, it takes to convert the point cloud data into a mesh model, the Polyworks Inspector presets were changed to automatically convert the collected point cloud data to a mesh model.

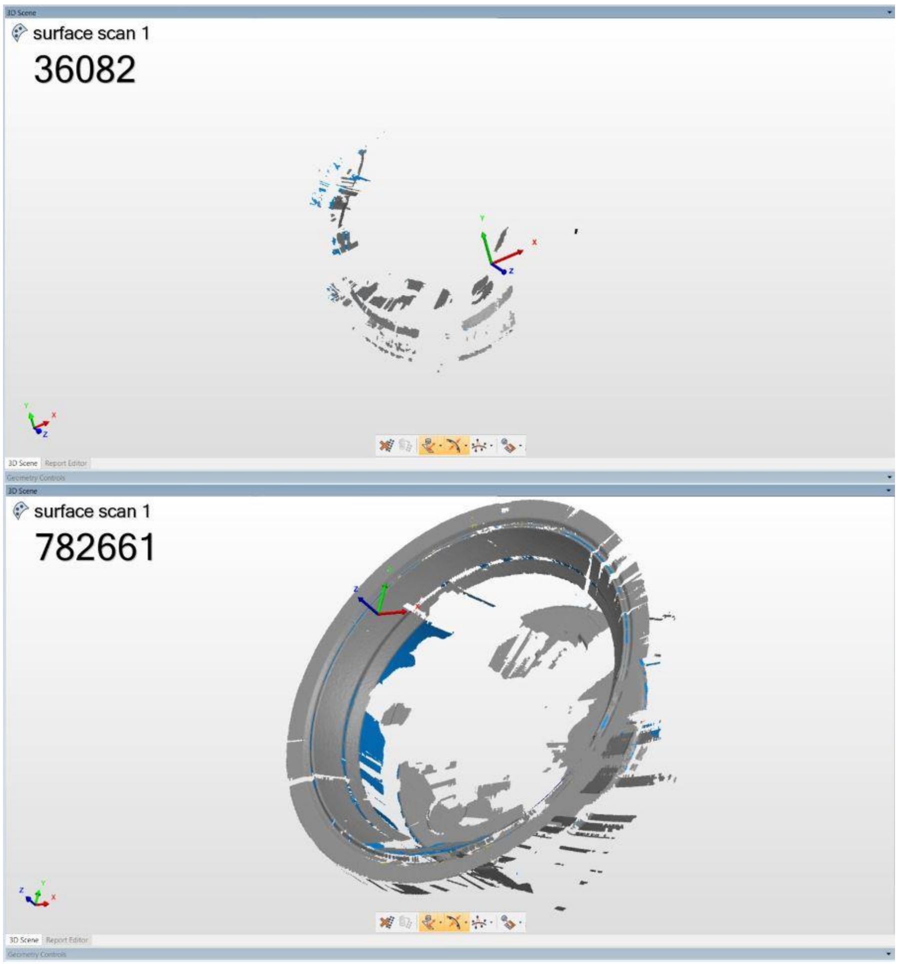

FIGURE 30: Scanning results from non-coated Ball seat (up) and coated ball seat (down) in Polyworks Inspector.

8.2.2 Processing of the scanned data

The mesh model of the ball seat as seen in Figure 30, still includes data points from the mounting bracket of the ball seat and data points caused from the unwanted reflectivity of the material. With the use of select elements tool in Polyworks Inspector, the unwanted data points can be removed from the mesh model. Once the mesh model is cleared of data points that are not needed for solid model construction, the cross section of the mesh model can be created by inserting a plane surface at the location of the part which has the most data points. With the cross section the outlines of the mesh model can be collected from the inserted planar surface.

The collected outlines of the mesh model are then exported from Polyworks Inspector to Solidworks 3D modeling software in a format of IGES or STEP.

8.2.3 Converting to solid 3D model

The cross-section method is the best method for parts that are symmetrical and require only the exterior of the part to be captured. This method uses the outlines of the cross section from the mesh model, which is revolved to make a solid 3D model.

The outline of the mesh model that is exported from the Polyworks Inspector is used as a template for the new sketch that is done over the outlines of the cross section of the ball seat in Solidworks. With the help of the measurement data from the probing system the outline accuracy can be further enhanced. The height and the width of the ball seat are determined from the probing measurement data and added to the sketch. The ball of the ball valve has been measured in previous processes so the width of the ball can be used as a reference line when making the sketch of the ball seat.

The outline of the mesh model is made with the use of the 3D laser scanner, but the exact dimensions of the ball seat are from measurements made with the probing system that was done before the 3D scanning of the ball seat. Once the dimensions are added to the outline of the mesh model, the rotation tool can be used in Solidworks. With the use of the rotation tool the sketch outline can be rotated around its set axis to create a solid 3D model, as seen in Figure 31.

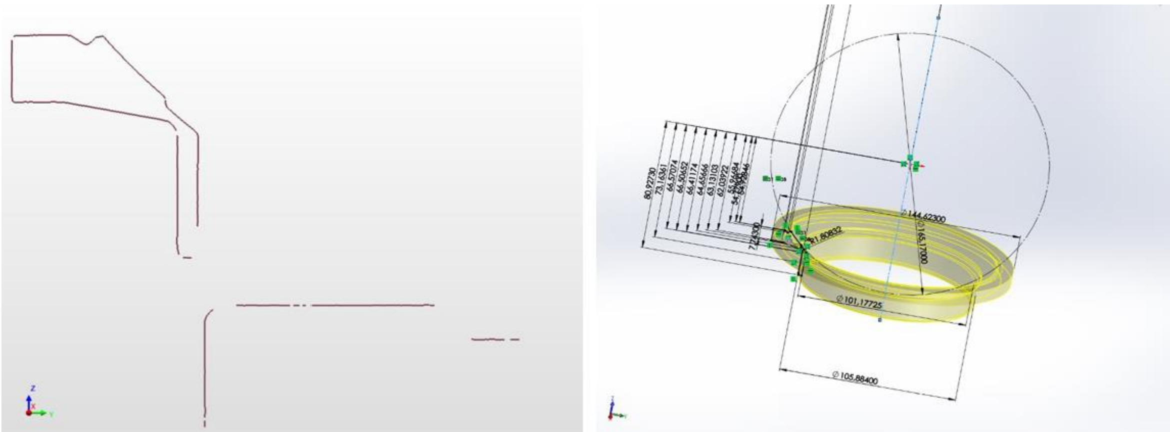

FIGURE 31: The sketch is rotated around its center axis to create a solid 3D model

The solid 3D model can be further customized with Solidworks or any commercial CAD modeling software features for more details.

9 RESULTS

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10 CONCLUSION

The results of this thesis illustrate the development points of the process of transforming the point cloud data to a solid 3D model. By improving these points of development, more detailed 3D models for simulations can be obtained. The correspondence between the models used in the simulation and the physical models makes it possible to detect and modify error points. The results obtained in the simulation are directly proportional to the physical object when the physical part and the solid 3D model are identical in dimensions and in detail. Based on the results, the model used in the simulation can be improved with changes. These changes can be made to the physical part after it has been shown to work.

The importance of scanning was recognized in the early stages of the process, especially how the scanning errors affected the end results of the process. Scanning provides a starting point for the whole process. Incomplete point cloud data which includes unwanted reflections, poor data point registration or too few data points does not produce a result that can be utilized in further research. In a perfect scenario the scanning should be done in one session to prevent any errors that may occur when the two-point clouds are combined. This was not possible in this project due the limitations of the equipment used for the 3D scanning. The process of combining different point clouds caused some accuracy errors for the point cloud. To prevent this, the point cloud should be scanned in single session into a single coordination system.

In order to obtain accurate information about the physical part, the mesh model formed from the point cloud should not be majorly filtered or processed in any way. Each process leaves room for accuracy errors, leading to poor results. Therefore, only mandatory processes should be used for creating the mesh model from the point cloud. If filtering or other processes are required to create the mesh model, it is recommended that the 3D scan of the part is done more thoroughly to prevent errors.

The transformation process was done in three different methods: surface recognition method, the NURBS method and the cross-section method. The results suggest that the NURBS method would be the best option for transforming the point cloud data to solid 3D model. Unlike other methods, NURBS has the advantage of providing a more realistic 3D model of the physical part. This is because the NURBS patches provide the exact geometry of the mesh model, so the model also contains flaws of the physical part. The drawback of the method is its dependence on the accuracy of the mesh model. NURBS curves are manually added to the surface of the mesh model, which results in the size of the NURBS patches becoming too large. This leads in a low-resolution mesh that does not contain enough information required about the surface of the mesh model. This could be prevented if the NURBS curves could be inserted to the surface of the mesh model automatically in the software. This would result in higher resolution NURBS patches, which would contain more realistic data of the surface of the mesh model.

To prevent inaccuracies in the point cloud data, one option would be to invest for better equipment for capturing the outer surface of the objects. This would give the possibility to create much more accurate solid 3D model that can be used for product simulations.

The 3D scanning can also be outsourced. If the measurements are made by external party, the measurement data must be in a format that can be used with the current systems. The measurement data should be presented in such way that the x, y, z coordinates of each data point can be determined in order to create the point cloud.

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