Quality control in metal additive manufacturing

Pre- and postmanufacturing procedures and opportunities

Jakob Staffans

Bachelor’s Thesis

Mechanical and Production Engineering

Vasa 2021

BACHELOR'S THESIS

Author: Jakob Staffans
Degree Programme: Mechanical and Production Engineering
Specialization: Mechanical construction
Supervisors: Kenneth Ehrström and Masi Tammela

Title: Quality control in metal additive manufacturing

Date 19.3.2021 Number of pages 45

Abstract

Metal additive manufacturing is becoming increasingly more feasible as a manufacturing method for low volume series and prototypes. Due to the recent adoption of this manufacturing method, few standards exist. Manufacturers of 3D printers have, along with researchers, not yet fully understood the process of how to design printers that fully take into consideration all the possible ways the geometries of printed parts are affected by the printing process.

For this reason, fast and reliable quality control is required. As parts chosen to be printed naturally have complicated shapes, the process of measuring becomes very difficult. This study focuses on examining ways to measure metal 3D printed parts. 3D scanning quickly stood out as a prime candidate, and thus different 3D scanning systems were researched.

The findings showed that 3D scanning is the most versatile way of measuring, especially when evaluating overall form and shape changes. 3D scanning is not the most accurate, however, as the accuracy of a 3D scanner is twenty times lower than that of a coordinate-measuring machine. Hence, for the best all-round measuring capabilities, utilizing both systems is suggested.

Language: English Key words: 3D metal printing, scanning, Lillbacka, quality assurance, quality control, additive manufacturing

EXAMENSARBETE

Författare: Jakob Staffans
Utbildning och ort: Maskin- och produktionsteknik, Vasa
Inriktningsalternativ: Konstruktion
Handledare: Kenneth Ehrström och Masi Tammela

Titel: Kvalitetskontroll i additiv tillverkning i metall

Datum 19.3.2021 Sidantal 45

Abstrakt

Additiv tillverkning i metall blir allt mera rimligt som en tillverkningsmetod för små serier eller prototyper. På grund av det nya upptagandet av den här tillverkningsmetoden finns det endast få standarder. Tillverkare av 3D-skrivare för metall har, tillsammans med forskare, inte ännu helt förstått hur skrivare bör designas för att fullständigt ta i beaktande alla möjliga sätt som geometrierna i printade delar påverkas av den additiva tillverkningsprocessen.

Av den här orsaken krävs snabb och pålitlig kvalitetskontroll. Eftersom delar som väljs att bli utskrivna av naturen har komplicerade former blir även mätningen mödosam. Det här arbetet fokuserar på att utvärdera olika sätt att mäta 3D-utskrivna delar. 3D-skanning skiljde sig snabbt från mängden som en av de främsta kandidaterna och därför studerades olika 3D-skanningssystem ingående.

Resultatet visar att 3D-skanning är det mest mångsidiga mätningssättet, speciellt när formändringar utvärderas. 3D-skanning är inte det noggrannaste, emedan noggrannheten hos en 3D-skanner är tjugo gånger svagare än med en koordinatmätmaskin. Därför föreslås att båda systemen utnyttjas för den mest allsidiga mätningsförmågan.

Språk: engelska Nyckelord: 3D-skrivare för metall, skanning, Lillbacka,
kvalitetskontroll, kvalitetsförsäkran, additiv tillverkning

OPINNÄYTETYÖ

Tekijä: Jakob Staffans
Koulutus ja paikkakunta: Kone- ja tuotantotekniikka, Vaasa
Suuntautumisvaihtoehto: Koneensuunnittelu
Ohjaajat: Kenneth Ehrström ja Masi Tammela

Nimike: Metallin lisäävän valmistuksen laadunvalvonta

Päivämäärä 19.3.2021 Sivumäärä 45

Tiivistelmä

Metallin 3D-tulostuksen käyttö valmistusmenetelmänä on yleistynyt toteuttamiskelpoisena vaihtoehtona pienten sarjojen ja prototyyppien valmistuksessa. Tämän viimeaikaisen käyttöönoton vuoksi ei ole vielä monta standardia saatavissa. Metallin 3D-tulostimien valmistajat sekä tutkijat eivät ole vielä ymmärtäneet metallin lisäävän valmistuksen prosessia niin hyvin, että he voivat valmistaa tulostimia, jotka ottavat huomioon kaikki eri tavat, joilla tulostetun kappaleen geometria muuttuu tulostuksessa.

Tämän vuoksi nopeaa ja luotettavaa laadunvalvontaa vaaditaan. Koska tulostukseen valituilla osilla luonnollisesti on monimutkaisia muotoja, myös mitoitus muuttuu vaikeaksi. Tämä tutkimus keskittyy erilaisiin 3D-tulostettujen kappaleiden mitoitustapoihin. 3D-skannaus ilmestyi heti ensisijaisena ehdokkaana.

Tulokset näyttivät, että 3D-skannaus todella on monipuolisin tapa mitata, erityisesti kun evaluoidaan yleismuodonmuutoksia. 3D-skannaus ei silti ole tarkin, koska 3D-skannauksen tarkkuus on 20 kertaa heikompi kuin koordinaattimittauskoneen. Seurauksena, laaja-alaisimman mittaamiskyvyn saavuttaakseen, molempien systeemien käyttöä ehdotetaan.

Kieli: englanti Avainsanat: metallin 3D-tulostus, skannaus, Lillbacka, metallin lisäävä valmistus, laadunvalvonta, laadunvarmennus

---

Preface

Future technologies have always interested me. So, when I first learned about metal additive manufacturing, I was instantly drawn to it and wanted to explore it. I went to a 3D printing event organized at the university and that is where I met the supervisor of this thesis, Masi Tammela, who worked with metal additive manufacturing in the nearby town of Alahärmä.

I want to thank Masi for providing me with the opportunity to write my bachelor's thesis for Lillbacka Powerco Oy. Also, I want to thank him for continuous feedback and support regarding the thesis, and for all the information he so freely shared.

Additionally, I want to thank Mika Luopajärvi and Esko Kallionpää for believing in this project and approving of arranging the measuring solution offer round. In addition to that, I want to thank Masi and Mika for continuous support in planning the content and execution of this thesis.

Furthermore, I want to thank Kenneth Ehrström and Novia University of Applied Sciences for the great learning opportunity, and for the work that Novia did in bringing this thesis to light. Not to mention, all the excellent courses that both supported this thesis and my future career.

Finally, I want to thank my girlfriend Sonja Broo for support and understanding during late night school sessions. Likewise, I want to thank my family for believing in me going back to school to change career path.

Table of contents

Units

[mm]	millimeter, length
[µm]	micrometer, length
[kg]	kilogram, mass
[*Ra*]	Profile roughness parameter for a surface. The arithmetic average of surface heights measured across a surface.
[°C]	degree Celsius, temperature
[wt%]	percentage by weight

Abbreviations

AM: Additive Manufacturing

CAD: Computer Aided Design

CAM: Computer Aided Manufacturing

CMM: Coordinate Measuring Machine

CNC: Computer Numerical Control

DMLS: Direct Metal Laser Sintering

LCD: Liquid Crystal Display

LPBF: Laser Powder Bed Fusion

1 Introduction

Metal additive manufacturing (AM) has over the last decade slowly become more affordable for the general manufacturing industries. Printers have become smaller, and material cheaper. Knowledge is still not widely available but is growing, and examples of successful metal AM implementation is showing up more and more. (Markforged, 2020)

1.1 Purpose

The purpose of this work was to be a pre-study for the company Lillbacka Powerco Oy regarding what quality control system would be the most applicable for additively manufactured parts. A way of inspecting that the printed parts are within tolerance was sought.

1.2 Goal

The goal of this work was to evaluate methods of measuring the differences in geometry of 3D printed metal products compared to the original CAD model. Additionally, the usability of 3D scanning as a tool to analyze the dimensional tolerances was to be determined.

2 Metal additive manufacturing

2.1 Lillbacka Powerco Oy

Lillbacka Powerco Oy, later referred to as Lillbacka, is a Finnish family-owned company in Alahärmä, Finland. The brand Finn-Power, formed in 1969, manufactures portable, benchtop and production model hydraulic hose crimping and cutting machines, as well as hose cutting and nut crimping machines. Thanks to an international distributor network Lillbacka exports approximately 95 % of its production to more than 60 countries.

The metal 3D printer Lillbacka operates is a 3DSystems ProX DMP 300, shown in Figure 1. It is a high-quality, highly automated machine with tight tolerances, high resolution and surface quality. It uses laser powder-bed fusion technology to bind the metal together. It has an automated recycling system for the unused powder and for material loading. The build volume is 250 x 250 x 330 mm. Like other printers, more than one part can be printed at a time, as long as they all fit inside the build volume. This can often be used in batch production to lower costs of single components. (3D Systems Inc., 2021b)

Figure 1 3DSystems ProX DMP 300 metal additive printer. (3D Systems Inc., 2021b)

The software Lillbacka uses along with this printer is 3DXpert. The software is used to prepare designs for additive manufacturing. It is also used for optimizing design structures to achieve lighter weights. This is done by geometry optimization and by creating shell and lattice structures.

Often, especially with bulky designs, shell and lattice designs are a fast and efficient way to reduce the mass manufactured. Decreasing the manufacturing time reduces the cost of manufacturing significantly. (Tammela, 2021)

The steel used is known as maraging steel, a martensitic steel with an extended heat-treatment process. It is an ultra-high-strength steel with 17 to 19 wt% nickel as the principal alloying element. Other alloying elements consist of chromium, zinc, manganese, molybdenum and titanium. (3D Systems Inc., 2021a)

2.2 Laser Powder Bed Fusion

Metal printing is achieved by many different methods. Laser Powder Bed Fusion (LPBF), also known as Direct Metal Laser Sintering (DMLS), presented in Figure 1, is currently the most common. In this method the work area is filled with a metal powder. A selective laser sinters the metal one layer at a time. In between each laser sintering, powder is added and a roller rolls over the workpiece spreading and evening out the metal powder. Then the laser sinters the powder selectively according to the dimensions of the CAD model, and then the process starts over. In the end the powder is removed, and a finished metal 3D printed component is achieved. In case of hollow components, a hole in the outer shell of the component must be included in order to drain out the powder. (3DEO, 2018a)

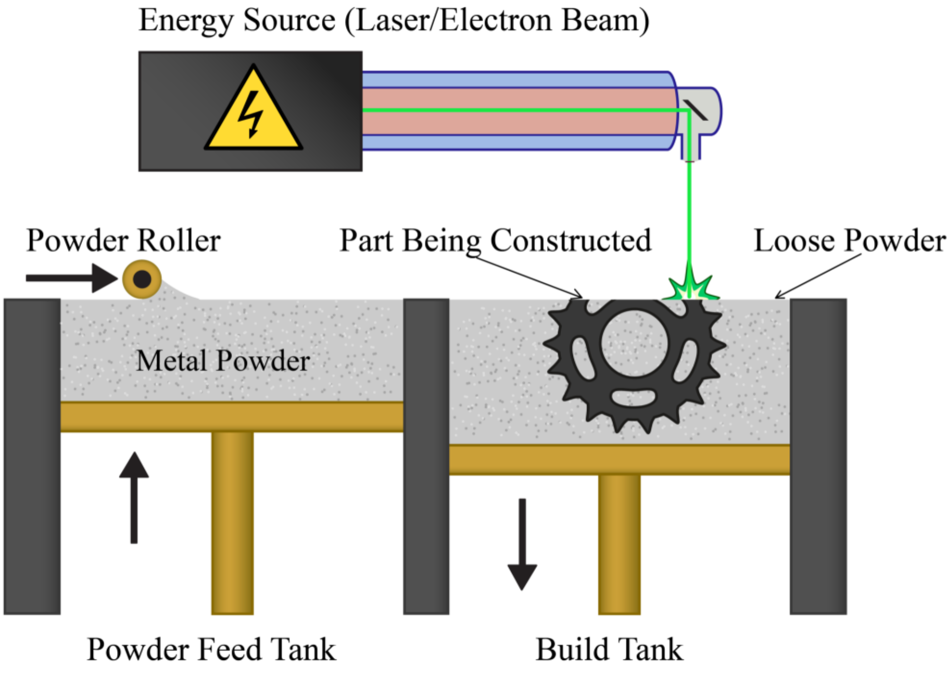


Figure 2 Overview of LPBF metal 3D printing. (3DEO, 2018a)

2.3 Use cases of metal AM

The potential use cases for metal AM are almost as wide as the whole field of metal manufacturing. While metal AM has yet to be fully embraced by the whole manufacturing industry, it has already made headway. The first use cases for metal AM are niche markets where the versatility and low lead time of metal AM is utilized to the maximum. Such cases include rapid prototyping, printed spare parts, personalized medical devices, weight reduction in parts for transport sectors, and part consolidation, where many small parts are combined into one. Over the next decade one can expect the use cases of metal AM to diversify even further. (MAN, 2020)

2.4 Post-processing of metal AM parts

One of the drawbacks to metal AM parts is the surface roughness of parts straight out of the printer. An example is shown in Figure 2. For printed parts to be able to be used in an integrated system with other traditionally machined parts, surface finish on the contact surfaces is often crucial. In dynamic systems where friction and wear are dominant forces, a highly smooth surface will last longer.

It comes as a major set-back, then, that surface finish for metal AM typically ranges from 5 – 20 *Ra* µm, which makes it hard for designers to know what to expect from printed parts and, by extension, how to integrate it. Lillbacka's printer manages 5 – 8 *Ra* µm. New printing techniques are bringing the surface roughness further down in the coming years. Factors that affect the surface roughness are the specific type of printer, part complexity and materials. (3DEO, 2018b)

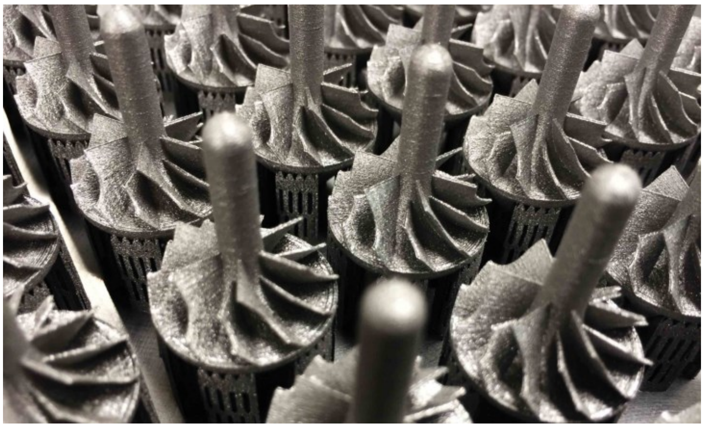


Figure 3 Surfaces of metal 3D printed components often need post-processing. (Valve Magazine, 2018)

As a remedy, surface finishing methods for metal AM are almost always used. Some of these methods are listed below:

- Centrifugal disc and barrel finishing

  The first type is an open barrel which is filled with printed parts and an abrasive medium and then spun with 5 to 10 G-force to grind the parts. The second one is a closed barrel spun with 5 to 30 G-force. (Fuges, 2017)

- Bead blasting

  Bead blasting shoots a stream of air injected with beads onto the surface of the part. The media type, speed, size and direction of impact all affect the surface finish. Bead blasting is an option for hard to reach areas in complex geometries. (3DEO, 2020)

- Black nitride

  A thermochemical process that diffuses nitrogen and carbon into the surface of a ferrous part. It enhances the part's resistance to corrosion, wear and chemicals. This process does not affect the dimensions of the component. (3DEO, 2020)

- Polished finish

  Polishing is done with abrasives, removing material to smoothen the surface. Polishing removes oxidation, corrosion or other contaminants that affect the appearance and how the part will accept a protective coating. (3DEO, 2020)

- Electropolishing

  Electropolishing uses a rectified current and a chemical electrolyte bath to remove the outermost layer of a metal part. Electropolishing enhances corrosion resistance by removing the outermost layer of metal that contains embedded contaminants and other surface impurities. (ABLE, 2021)

Lillbacka has invested in an automated surface finishing machine called RADOR, manufactured by PostProcess Technologies, Figure 4. It uses a technique they invented and call “Suspended Rotational Force (SRF)”. Essentially, it is a container filled with an abrasive media and a chemical detergent. The detergent optimizes the abrasive energy and washes away broken-down media.

Figure 4 RADOR, an automated surface finishing machine. (PostProcess, 2020)

Through the software the user can alter the friction force that is applied to each batch, along with tank levels and cycle times, enabling companies to plan the results ahead. The rotational aspect of the name comes from the motors introducing a vibratory motion that moves the media/part-mixture in a circular motion along the Y-axis. This motion ensures uniform exposure of the part to the abrasive media. (PostProcess, 2020)

2.5 Challenges of the metal AM manufacturing method

Several challenges arise in metal additive manufacturing. One of those are distortions from thermal stresses. Shrinkage, oversizing, warping, and curling are typical distortions. When the printing process goes from a small cross section to a large one, the newly laser-fused layers of the part can become distorted due to thermal stresses. This can also cause delamination between the layers. For this reason, such parts are printed at an angle to reduce the cross section being printed at any one time. Thermal stresses are concentrated in sharp corners and thus radii are used wherever possible. (Masi Tammela, personal communication, 30.10.2020)

Metal printing is a new technology. There are not yet solutions readily available for how to verify the reliability of the printer and in turn the printed parts. Traditional CNC-machines rely on the robustness of the x, y and z axis of the machine and the machined parts thereby have matching tolerances. Machined parts are not subject to significant thermal stresses and thus no warping occurs. Metal printed parts, however, always have thermal stresses. Overall, there is a lack of standards regarding all aspects of metal 3D printing. (SIS, 2020)

A practical solution for inspecting the printer would be to print benchmark parts that are designed to test the limits of the printer. Such parts would be thick and thin sections, overhangs, small details, etcetera. However, knowing how to adjust the printer would still be uncertain. (Terran Data Corporation, 2021)

Another problem with metal AM is the relative porosity of printed parts, see Figure 5. Porosity is undesirable for parts under fatigue loads since porosity could lead to premature fatigue failure. Parts produced for use in aerospace are subjected to hot isostatic pressing (HIP), meaning the pressure on the part acts in all directions, leading to densification. HIP is used to eliminate voids and pores by placing the part in a gas tight capsule and pressuring a gas to 1000 bar. (Ahlfors & Hjärne, 2015)

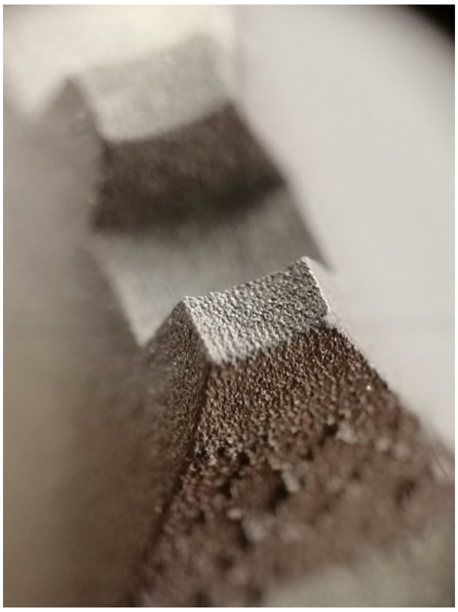


Figure 5 Close-up of a crimping die by Lillbacka. Printed parts are very slightly porous.

2.6 3D measuring of metal AM parts

Two key uses for 3D measuring methods in metal AM is reverse engineering and quality control. Quality control is a large application for 3D measuring. It is done to assure that the produced part follows the required dimensional tolerances. If a part straight out of the printer is the final product, then many companies require a Dimensions Measurement Report.

It can also be done to improve on the production process, especially now in the early years of metal 3D printing. A part would then be measured in different stages of the process and the dimensional changes in each stage would be monitored. There is no other way of knowing if a printed part meets the tolerances. (Siitonen, 2011)

2.6.1 Coordinate measuring machines

Coordinate measuring machines (CCM), Figure 6, measure the geometries of objects by sensing them with a probe. These machines measure points relative to a reference point in a three-dimensional coordinate system. Factors that affect the tolerances is the build quality of the machine as in straightness and squareness.

CCMs are used in conjunction with CAD-models and thus automatization of measurement tasks is easily achieved using software. Software for these machines are continuously being updated for usability and accuracy. (UNIMETRO Precision Machinery Co., 2020)

Figure 6 Coordinate measuring machine. (UNIMETRO Precision Machinery Co., 2020)

Figure 7 Portable coordinate measuring machine. (RPS Metrology, 2020)

Portable coordinate measuring machines, Figure 7, have the advantage that they can easily be transported to the job site and they are more flexible and have more freedom of movement. These measurement arms use embedded encoders in each axis which calculate the position of the probe through software. Because of their portability and flexibility these machines can increase productivity and decrease inspection bottlenecks. (FARO Technologies, 2020)

2.6.2 Optical 3D scanners

Optical scanners, Figure 8, have many advantages over CCMs. When conventional coordinate measuring machines collect one data point at a time, optical scanners collect tens of thousands of datapoints per second. Optical scanners enable reverse engineering of objects with odd shapes such as propellers, organic or very complex shapes in a fracture of the time. Optical scanners do not need to touch the object to measure it. This enables scanning of soft materials like textiles and thin-walled constructions. Special scanners can scan extremely large objects like buildings and ships. Optical scanners use mainly one of two technologies for small to medium objects: laser triangulation and structured light. Because of how laser triangulation works, it is impossible to measure small to medium sized holes, because the laser is blocked by the edges of the hole. (Kuusela, 2019)

Figure 8 Artec Eva handheld 3D scanner uses artificial intelligence to track its position relative to the work object. (Artec Europe, 2020)

Laser triangulation

Laser triangulation, Figure 9, uses trigonometric triangulation in form of a laser and a sensor to measure distance. The angle of the light reflected into the sensor is dependent upon distance and is used to calculate the distance to the object. Laser scanners are more affordable, and accurate on the order of tens of micrometers. However, they do not work very well on shiny or transparent surfaces. (3Dnatives, 2020)

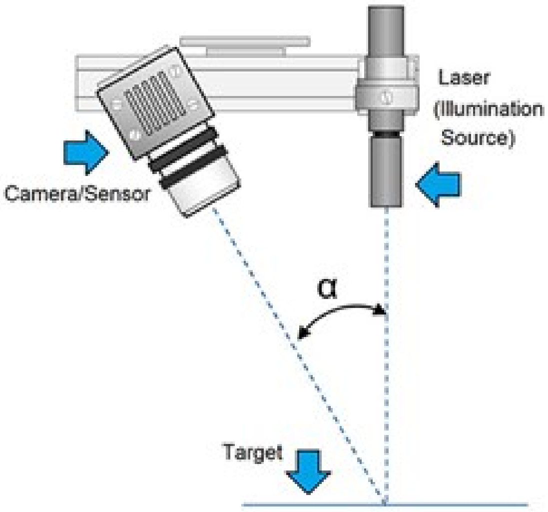


Figure 9 Laser scanning. (3Dnatives, 2020)

Structured light

Structured light scanning, Figure 10, is a term that includes all colors of light but generally refers to blue or white light. Structured light also works with trigonometric triangulation but instead of using a laser it uses a liquid crystal display (LCD) projector to project a light pattern on the object and then uses cameras slightly offset to the projector to read the angle. From the angle it calculates the distance to the object. Structured light scanners are extremely fast, a scan be done in two seconds and the scanning area is quite large. Structured light scanners work best indoors because they are sensitive to external light. (3Dnatives, 2020)

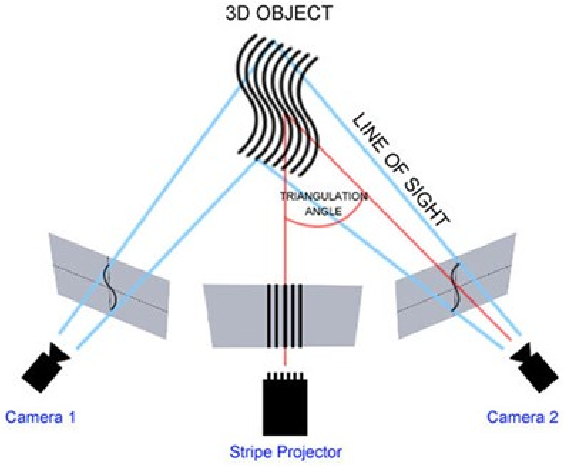


Figure 10 Structured light scanning. (3Dnatives, 2020)

2.7 Reverse Engineering

Reverse engineering is the process of recreating a CAD-model from measured data. If no 3D model exists for an existing component that is to be manufactured, then instead of drawing a possibly complicated CAD-model, a 3D scan of the same object can be done. This is done in the following way. First, a scan is conducted on the object and the resulting point cloud data is opened in the reverse engineering software. Then, for example, if the scanned point cloud model has an apparent flat surface, the software can find this plane and the user can then place a new plane-element on the surface. The new plane will position itself so that as many points in the uneven scan data is above the surface as there are below, approximating where the plane should be. By placing elements like this on all surfaces of the part, a new CAD-model can be created. Further on the planes must be trimmed where they intersect, then the planes must be stitched together, and often some planes are aligned exactly 90 ° in relation to each other. At this point the CAD-model is complete and can be manipulated or corrected further as needed. (Formlabs, n.d.)

Applications for reverse engineering often include reproducing spare parts which do not have a CAD-model. Such spare parts are often old and therefore do not have a 3D model, or the 3D model has been lost. Another application example is in die presses for sheet metal. The dies that are planned and manufactured over many months do not always work perfectly on the first try, and hence the dies are customized with grinders to make the die shape the sheet metal as it should. The problem is that after the customization, the CAD-model is not up to date anymore for reproduction of the die. Now the die would be moved to a CCM for measuring. With a 3D scanner, the modifications would be reverse engineered and transferred to the CAD-model. (Dan Brokstad, personal communication, 11.3.2021)

In a case study by Artec3D it was shown that a company saved weeks of work by using reverse engineering to measure large machine parts. Before, they would measure the parts in the traditional way, and some elements of the parts were hard to measure accurately. Afterwards, it would take weeks to draw the parts. Using 3D scanning and reverse engineering they reduced they total time needed to just a few days. (Artec Europe, 2021)

3 Case study: Inspection of metal 3D printed crimping dies

The case study is done for the Finnish company Lillbacka Powerco Oy. Lillbacka is a producer of hydraulic crimping machines and the case study will revolve around the inspection and quality control of the metal 3D printed crimping dies. The study will evaluate using 3D scanning as a tool for measuring the dies quicker and more precisely than before.

The two important questions this study aims to answer are:

- How can the data acquired from the point-cloud-dataset effectively be used to evaluate the die?
- Is 3D scanning a viable option for Lillbacka's quality control process?

This chapter includes a description of Lillbacka, their current method of quality control, potential scanners, a definition of requirements, and possible metal 3D printed benchmark parts.

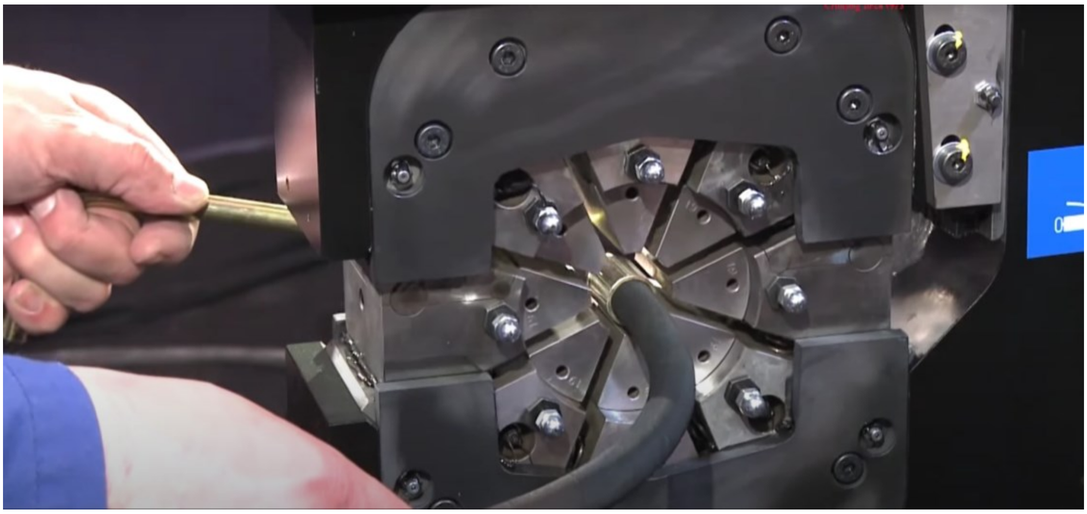


Figure 11 The crimping dies are subject to great pressure when crimping fittings onto hoses. (Lillbacka Powerco Oy, 2021)

3.1 Method of approach

The method of approach for the case study was to evaluate the current method of quality control, define requirements for the problem, hypothesize a solution – 3D scanning, and then compare the 3D scanning systems for suitability at Lillbacka. The scanned results and reports were to be evaluated. Finally, a workstation for quality control was defined.

3.2 Current method of quality control

The quality control process currently at Lillbacka is manual hands-on measuring. The most important dimensions of the printed parts are measured right after they have been removed from the build-plate. Surface roughness is also measured. After the measurements have been made the part is polished by glass bead blasting. The supporting surfaces are grinded to a smooth finish. At this point the dies are sent to heat treatment. Finally, the dies are inspected, the mounting-knob is inserted and then they are packaged.

Doing measurements by hand always carries the risk of measurement errors. The measurements can vary slightly from measurement to measurement even on the same piece, from person to person and simply from human impreciseness. This can result in a greater variance in the dies than accepted. (Zilling, 1973)

One reason for the current difficulties of measuring is also due to the shape of the dies. For example, the dies have two parallel round surfaces, see Figure 12. To precisely measure the distance in-between would require the caliper to be close to in perfect alignment on both the bottom and top of the curved surfaces. This is not achievable by human hands and as a result only an approximate measurement can be made. This is known as Random Error. Similar challenges are present in all dies. (Zilling, 1973)

Figure 12 Metal AM manufactured crimping die.

Precise dimensions of the dies are important because the dies in turn decide the final dimensions of the crimped hydraulic connection. The general tolerances for the dies are 0,1 mm. Even the surface roughness plays a part in the dimensions of the die since metal 3D printing produces such rough surfaces. Precise, quick, and easy measuring of the dies would be a major tool in the quality control process. Aside from the dies, Lillbacka uses suppliers for some components. Some are plastic, some metal, and when parts are faulty then inspection is done to find the root problem. This is where a tool for quick quality control would come in handy.

Figure 13 Zeiss Prismo 9/12/9 coordinate measuring machine at Lillbacka.

There is a Zeiss Prismo 9/12/9 at Lillbacka already, Figure 13. This machine has an accuracy of 2 µm. The measuring range is 900 mm in X axis, 1200 mm in Y axis and 900 mm in Z axis. The reason it is not being used regularly is that there is currently no designated operator or otherwise trained worker who could use the machine. Another reason is that the software is old and obsolete and would have to run on a Windows 95 computer. The machine could, however, very precisely measure most parts if the software were up to date and it had a skilled operator.

3.3 Definition of requirements

The study begun by using first principles – as in finding out which parts are to be inspected and what resolution is needed. The current focus is on the printed dies but scanning larger parts is also a requirement. Therefore, the measuring device will need to be able to scan parts with sizes varying from the smallest dies, 40 mm in length, to medium sized parts, for example flanges, cylinders or pistons. Possibly even the frame of the largest presses, 1500 mm in height, would be scanned. Custom dies are often sold as one-off series, so quick of measuring is advantageous.

In the future Lillbacka plans to grow the amount of complex AM parts manufactured, such as mass- and topology optimized parts. The geometries of these are nearly impossible to measure with manual measuring devices or CCMs. Therefore, the measuring solution would need to manage this, too.

The 3D metal printer prints in layers of 40 µm, which calls for a measuring resolution of ± 20 µm if that high a resolution is needed. Seeing the different layers may not be the most important requirement, but high resolution could show shrinkage, warping or waviness in printed parts, especially those printed with internal lattices.

Surface roughness, shown in Figure 14, is measured using a dedicated roughness testing device. Therefore, a scanner does not need to perform that function. The amplitude of surface roughness valleys and peaks is also on an order of magnitude below what most scanners are capable of. A scanner would then only need a resolution of just below 20 µm.

Another requirement is accuracy. That is how accurately in space the point is measured. This measurement is useful when scanning for waviness, Figure 15, or warping in very small parts. Again, an accuracy of about the same resolution as a printed layer would suffice.

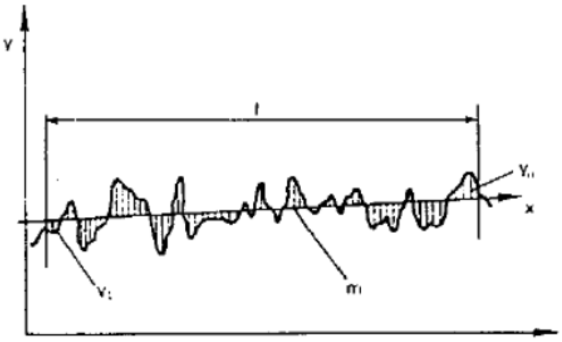


Figure 14 Illustrative picture of surface roughness. (Järvinen, 2014)

Figure 15 Waviness on a surface. (Järvinen, 2014)

Figure 16 Wavy surfaces can happen to parts printed using internal lattices. (Tammela, 2021)

As different sets of dies have different demands, they may be printed with internal lattices to save on manufacturing cost. That is when waviness easily happens. By using thicker outer walls, it can be minimized. Measuring waviness is impossible to do with calipers and requires more complicated surface measuring tools unless a scanner can do it.

In case a scanning device would not be the chosen solution, and instead, for example, a coordinate measuring arm was chosen, then some sort of fixture would be needed for small objects. This fixture would need every part to be placed inside it the exact same way every time. At the same time, the measuring should not be obstructed. A possible solution to this would be to use the six-point method, Figure 17.

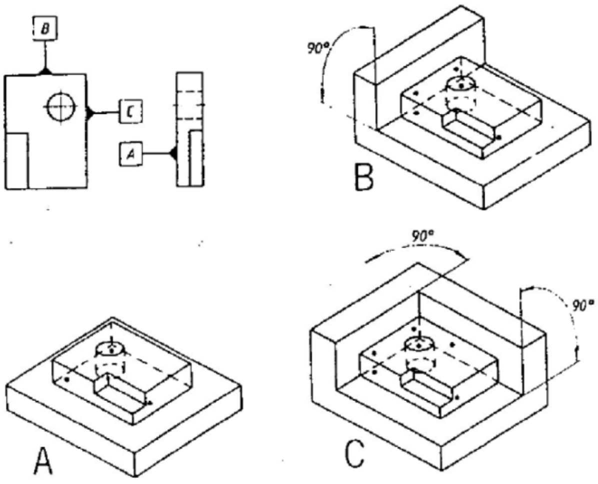


Figure 17 Six-point-method setup. (Järvinen, 2014)

In the six-point method the part is first placed on a surface, which theoretically needs only three contact points. Then it would be pushed against two points that stop it and act as a wall. Lastly it would be pushed against another stopper, the final sixth point. This locks the part in space. Obviously, this obstructs the part heavily, but inspiration can be drawn from it to create some type of fixture. The dies have mounting holes that could be placed on a cone to center the die exactly, for example.

3.4 Testing the current quality control process

Three 20 mm test cubes were printed in different configurations to test the current quality control process, Figure 18. Different configurations of the printing process were used to get a general picture of the metal 3D printer's performance.

One cube was compensated by the 3DXpert software. This means its X and Y dimensions were adjusted before being sent to the printer to try to correct dimensional changes, which is a known phenomenon in 3D printers. The second cube was not compensated. The third cube was also not compensated but was printed on a 30-degree angle with a support structure under it.

Figure 18 The test 20 mm test cubes.

The main purpose of the testing was to test the measuring instrument and review the accuracy and process. The measuring instrument was a Mitutoyo digital caliper with 0,01 mm accuracy.

Table 1 Measurement results, 20 mm cube. Print direction is Z.

Dimension	Compensated	Not compensated	Not compensated, 30 °
X	20,01	19,97	20,05
Y	20,01	19,97	20,00
Z	20,22	20,24	20,09

Conclusion

The cube with compensated print settings achieved very accurate X and Y dimensions. The cube that was not compensated achieved the worst dimensions. The third cube which was printed on an angle achieved satisfactory dimensions. Printing parts at an angle reduces thermal stresses and distortions. The results show that the real-world dimensions are not extremely close to nominal, or to precise machining standards. Surface roughness also plays a part. Quality control is thus important to include when printing as a service.

Even easy shapes such as the test cubes take a while to measure. Handling the measuring instrument with care, taking care not to place calipers on odd protrusions in the surface roughness, resetting the calipers for every measurement. Additionally, the measurement result on the caliper-display were misread multiple times. The calipers are a good option for general measures such as length, width and height but they do require careful conduct and patience, in other words a great deal of time.

3.5 3D measuring system demos over Microsoft Teams

3D scanning was chosen as the measurement method because of its speed, resolution and versatility. Conventional measuring tools like calipers, coordinate measuring machines, or even coordinate measurement arms using touch probes all measure single points which are then compared to the nominal. Conventional methods were considered too slow compared to 3D scanning which records data on the order of two million points per second, and impractical because of the sometimes-complicated shapes of dies.

Three companies were chosen as potential suppliers of 3D scanning measurement systems: MLT Machine & Laser Technology Oy (MLT), Carl Zeiss AG (ZEISS) and Hexagon Manufacturing Intelligence (Hexagon MI).

A set of dies and one piston were sent to each of the companies. Remote demonstrations were then arranged with each company over Microsoft Teams. The companies measured the parts in real-time while a few engineers from Lillbacka Oy and the writer of this document watched. The scans produced point clouds (sets of data points in space) that were inspected using each company’s software.

4 Results

4.1 MLT

MLT Oy is the Finnish retailer of 3D scanning equipment and software made by the Canadian company Creaform Inc. (MLT Oy, 2021a)

Figure 19 The MLT logo. (MLT Oy, 2021a)

The 3D scanner Eetu Siivonen at MLT suggested was the handheld model HandyScan Black Elite which is recommended to be used for parts that are between 50 to 4000 mm in size. For parts measuring 310 mm by 350 mm the scanner has an ISO-certified accuracy of 25 micrometers due to its blue laser technology. However, the mesh that is created from the point cloud has a resolution of 0.1 mm. When scanning larger parts, the accuracy drops to 0,02 mm + 0,04 mm/m. It records around 1.3 million measurements per second and has an operating temperature of 5 to 40 °C. It weighs around 1 kg, is 288 mm in height and with a portable external battery an operator can scan constantly for up to six hours. (MLT Oy, 2021a)

Figure 20 HandyScan Black Elite. (MLT Oy, 2021a)

Data is collected in relation to an internal coordinate system and therefore to be able to collect data the position of the scanner must be determined. The way this is done with the HandyScan is with adhesive reflective tabs. If the part is small, then the tabs can be placed permanently on the worktable where the scanning takes place. If a large part is to be scanned, then tabs will have to be placed directly on the part with circa 10 cm spacing, and on the surface beside it. If the work object is largely flat, more tabs are needed and the tabs need to be placed even closer to each other. (MLT Oy, 2021b)

The scanning software is called VXscan and is part of the VXelements 3D software platform. VXscan produces an .stl file that must be inspected in another application, VXinspect. For inspection of the scanned results MLT also offers the application Polyworks Inspector.

Other compatible third-party software for inspection is Geomagic and Metrolog. Because 3D scanning often needs some post-treatment afterwards, for example to fill in gaps in the 3D model, another software is used – VXmodel finalizes the 3D scan data for use in 3D printing or CAD software. (MLT Oy, 2021a)

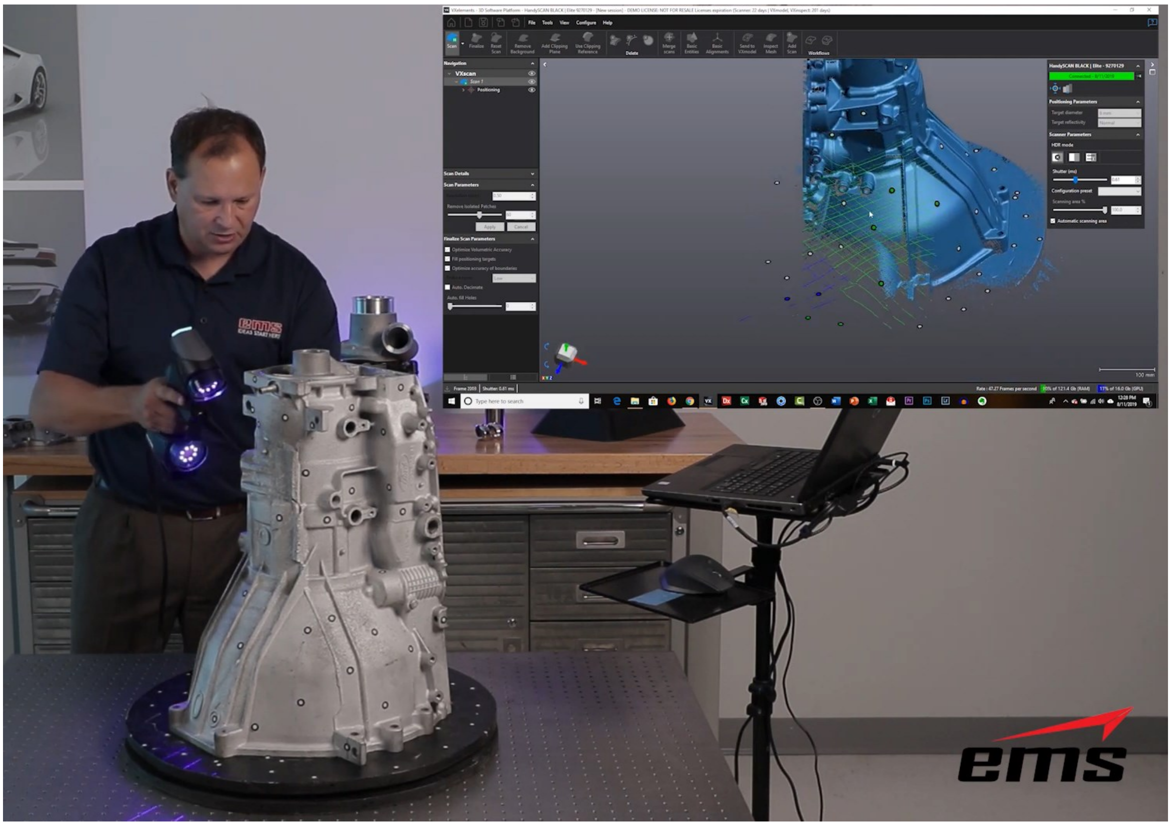
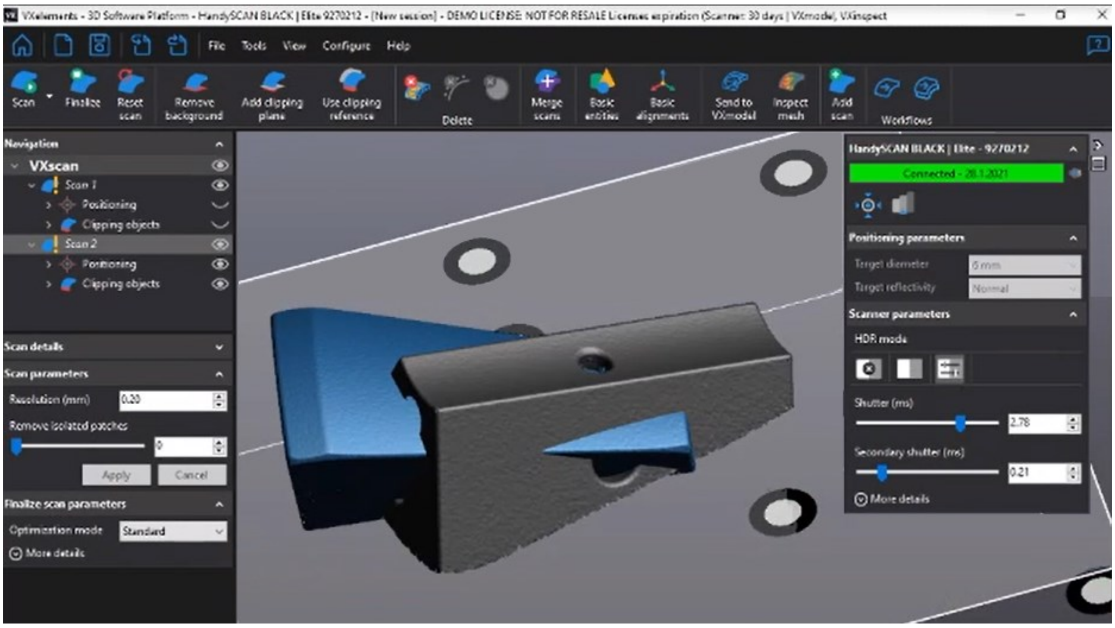


Figure 21 Scanning demonstration of a transmission housing. Also seen are the reflective tabs. (EMS, 2021)

Figure 21 shows the process of scanning a transmission housing. On the housing can be seen the reflective tabs that are manually put on before scanning. The housing sits on a rotating table for easy access to the whole part. The rotating table is not a must, as the reflective tabs is how the scanner knows where it is in relation to the part. Hence, one can also simply walk around the table, but the scanner must always see the tabs or else it will lose track. (EMS, 2021)

Also shown is the scanning software producing the point cloud model in real time. The result of the scan is an .stl file that can be opened in the inspecting software for analysis or in the modeling software for reverse engineering a CAD-file. The raw scan data is full of real-world features like rounded edges, texture in the steel from production, imperfections, rough dimensions. When generating a CAD-model, one wants exact dimensions, perfect planes, sharp corners and so on. That is achieved in the modeling software. (EMS, 2021)



Resolution (mm) 0.20

Remove isolated patches 0

Optimization mode Standard

Target diameter 6 mm

Target reflectivity Normal

Shutter (ms) 2.78

Secondary shutter (ms) 0.21

Figure 22 VXelements. Two scans have been done and will be combined. (MLT Oy, 2021b)

Figure 22 shows the demo by Siitonen. He had placed reflective tabs on the worktable and placed the master die of a crimping machine on the table. The die cannot be turned during the scanning, and thus a separate scan must be done to get the underside. The scans were combined into a finished scanning result. This resulting file can then be inspected versus a CAD-model in software like VXinspect or PolyWorks Inspector, Figure 23. (MLT Oy, 2021b)

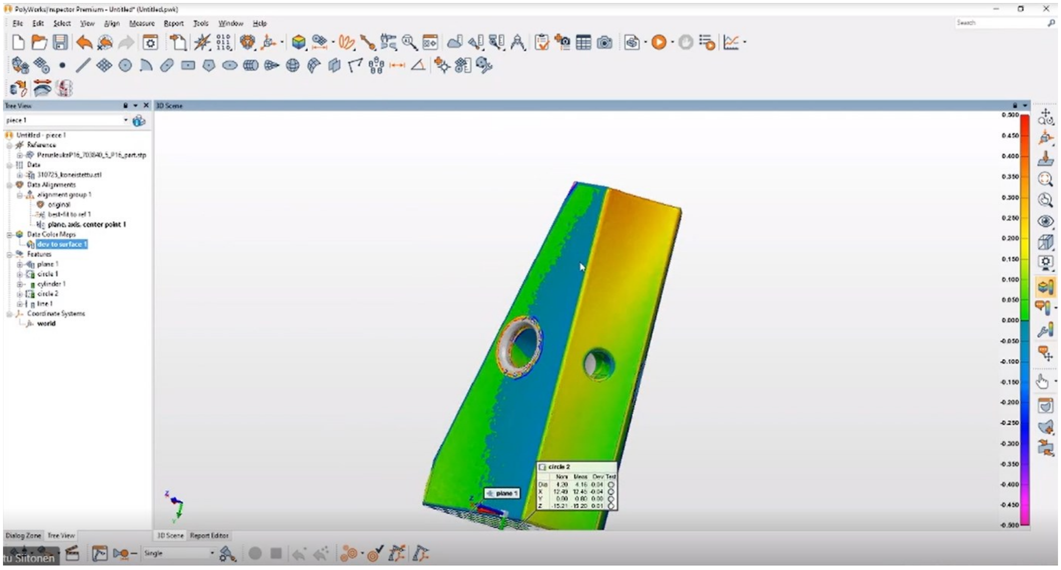


Figure 23 Inspecting a scan versus a CAD model in PolyWorks Inspector. (MLT Oy, 2021b)

4.2 ZEISS

The German company ZEISS has developed their own 3D scanners and acquired GOM in 2019 which is a leading provider of hardware and software for automated 3D-coordinate measuring technology. (Carl Zeiss AG, 2021a)

Figure 24 The ZEISS logo. (Carl Zeiss AG, 2021)

The scanner that Mikko Kähäri at ZEISS showed was the T-Scan 10, which scans objects up to 10 cubic meters in size. The scanner has an ISO 13600 certified accuracy of 40 µm + 40 µm x L/1000, and the recommended working distance is 150 mm. The weight is 1100 grams, and the dimensions are 300 x 170 x 150 mm. The data rate is 210 000 points/second. (Carl Zeiss AG, 2021a)

Figure 25 T-Scan. A handheld 3D scanner. (Carl Zeiss AG, 2021)

Cooperatively with the handheld scanner is a tracking device called the T-Track and a control box. The way the tracking is done with the T-Scan is that a separate device is set up on a tripod to overlook the part to be scanned. The T-Track uses a laser tracker to determine the position of the scanner and it uses cameras to determine its orientation. (Carl Zeiss AG, 2021a)

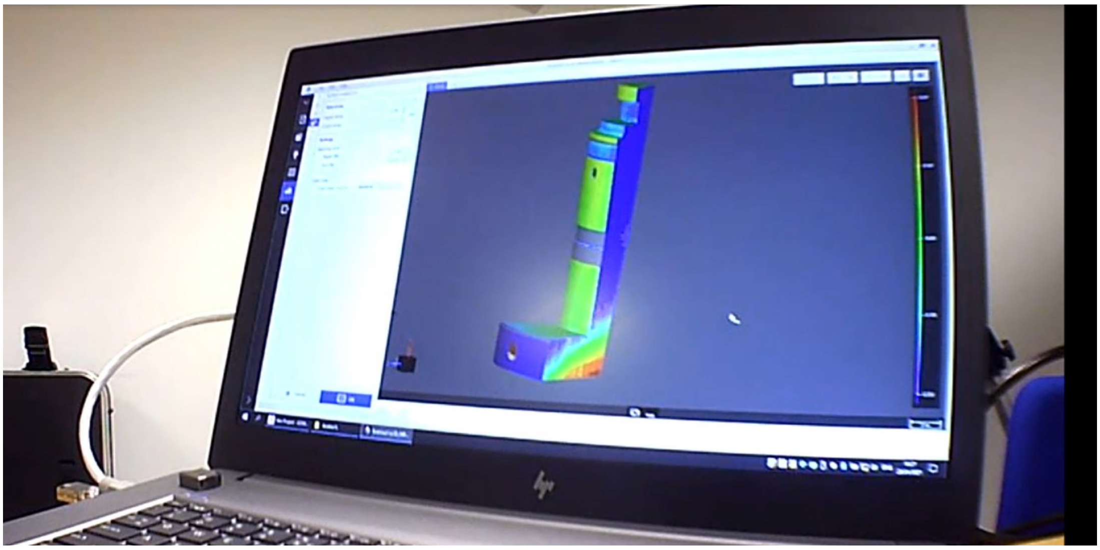


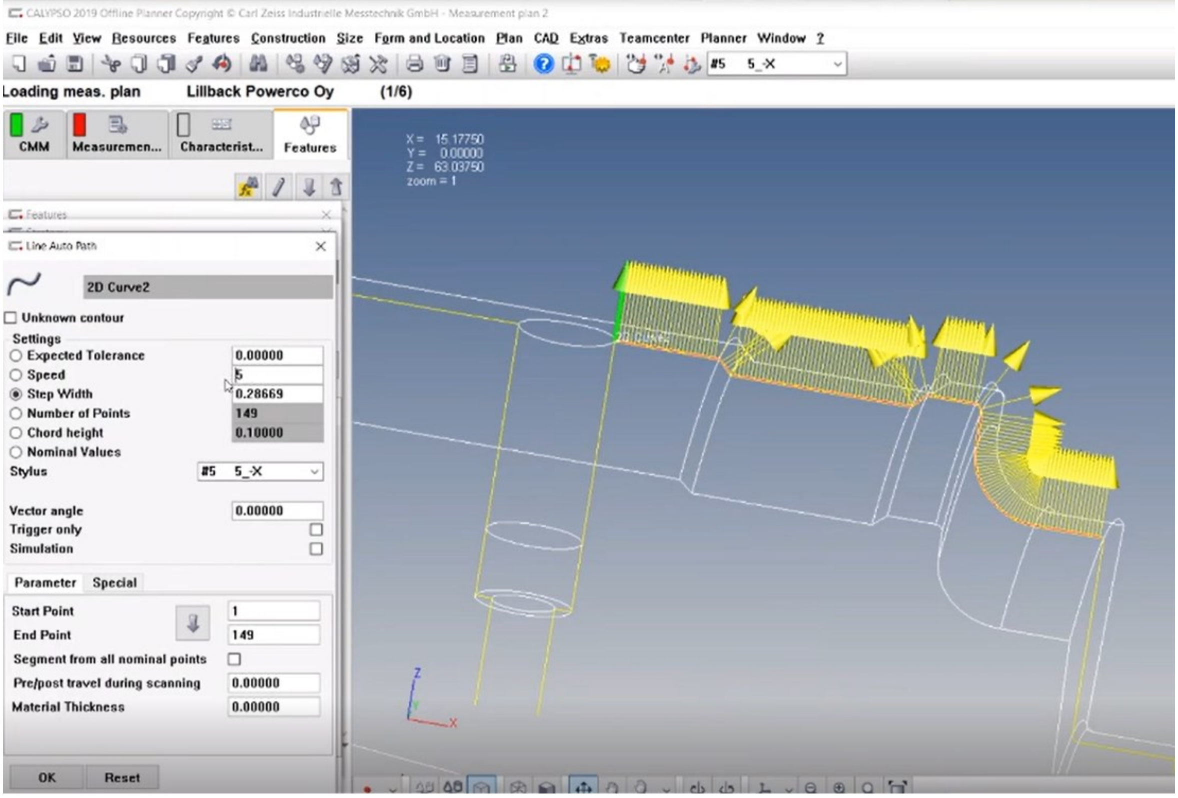
Figure 26 Screenshot of the demo with Kähäri. Colin3D demonstrated. (Carl Zeiss AG, 2021a)

The T-Scan operates with Colin3D which is a solution for both scanning and inspecting. The software is parametric, in other words the steps are traceable if one would want to go back to a certain step and continue again onwards from there. Figure 26 shows Colin3D in use. A scan has been done and is compared to the CAD-model. The green color shows areas that are within tolerance. The yellow and red areas are above tolerance, and the blue and light blue are under nominal. In this way one can easily get an understanding of the way the part is out of shape or form. The software has the same working principles as VXelements by MLT. For more extensive inspection of, for example, surface roughness or squareness the software Calypso is used. (Carl Zeiss AG, 2021a)

Figure 27 Example of the scanning process. The T-track tracks the T-Scan. (Carl Zeiss AG, 2021a)

Figure 27 shows the scanning process on a factory floor. The cable supplied is 10 meters long which enables scanning of large parts. The scanning system is portable but does require some time for setup. What is not shown on the picture is the control box and laptop. The control box can be thought of as a connection hub which puts all the data together and sends it to a computer over an Ethernet cable, while also powering the system. Therefore, the control box needs a power supply. (Carl Zeiss AG, 2021a)

According to Kähäri, Lillbacka could also use their conventional coordinate measuring machine if only the software on it would be updated. The machine is made by ZEISS in 2003 and is still not outdated in any form except software. This machine has an accuracy of 2 micrometers, which is much more accurate than a 3D scanner that is accurate to on average about 50 micrometers. Hence, for extreme accuracy of measurements a conventional coordinate measuring machine would be the most appropriate. Figure 28 shows the CMM software Calypso being demonstrated by Kähäri on the same die as shown in Figure 26. He used the symmetries of the piece to create a centerline. By using this line one can quickly program a CMM to move along the cross-sectional profile and take measurements. For the jig he suggested using magnets to keep the die in place. (Carl Zeiss AG, 2021b)



Loading meas. plan Lillback Powerco Oy (1/6)

X = 15.17750
Y = 0.00000
Z = 63.03750
zoom = 1

2D Curve2

☐ Unknown contour

Settings
○ Expected Tolerance 0.00000
○ Speed 5
● Step Width 0.28669
○ Number of Points 149
○ Chord height 0.10000
○ Nominal Values
Stylus #5 5_X

Vector angle 0.00000
Trigger only ☐
Simulation ☐

Start Point 1
End Point 149
Segment from all nominal points ☐
Pre/post travel during scanning 0.00000
Material Thickness 0.00000

Figure 28 Centerline to be measured. (Carl Zeiss AG, 2021b)

4.3 Hexagon MI

Hexagon MI is a Swedish metrology company that aside from its own products have acquired metrology companies such as CE Johansson and Brown and Sharpe, among many more. (Hexagon MI, 2021)

HEXAGON
MANUFACTURING INTELLIGENCE

Figure 29 The Hexagon MI logo. (Hexagon MI, 2021)

The scanner Dan Brokstad at Hexagon MI recommended was the model RS6, a 3D scanner connected to a separate 7-axis portable measuring arm, the Absolute Arm 8525-7. Like the HandyScan, data is collected in relation to an internal coordinate system, but the position of the scanner is determined using the measuring arm, Figure 30. No references like reflective tabs are needed, nor a laser tracker. Such a scanning solution can be very exact because the arm has encoders in every joint which tell the software exactly where the scanner is. That way the accuracy of the whole system, scanner and measuring arm, gets down as low as 47 micrometers. The mesh has a minimum point distance of 26 microns, same as the accuracy for the scanner head. (Hexagon MI, 2020)

Figure 30 A 3D scanner connected to a portable measuring arm. (Hexagon MI, 2021)

The RS6 scanner, Figure 31, uses blue laser technology like the HandyScan. The scan line is wide, 150 mm which enables fast scanning. The accuracy of the whole system is dependent upon which series and size measuring arm is used. With the 85 series, 7-axis, 2,5 meters long arm suggested by Dan Brokstad – model 8525-7, the accuracy of the whole system would be 47 micrometers. The weight of the arm is 9,3 kg and the scanner 400 grams. With a technique they call "Zero-G counterbalance" the light-weight carbon-fiber arm balances itself and moves effortlessly with barely any friction in the joints. The scanner has an OLED display for feedback and access to settings and data. (Hexagon MI, 2020)

Figure 31 The RS6 scanner by Hexagon. (Hexagon MI, 2021)

Unique to the RS6 scanner is the built-in exchangeable touch probe, Figure 32. For holes and cavities, a probe may work better. The probes can be changed whenever needed without any recalibration. Likewise, the scanner head can be removed along with the grips for better access when probing. This, too, without recalibration.

Figure 32 Accessories. Three different sized grips and touch probes. (Hexagon MI, 2021)

Noteworthy is that the arm with a touch probe is more accurate than the scanner, with an accuracy of 12 microns. That is why, when scanning, one first uses the touch probe on reference areas like flat surfaces and then scans the rest. This way the best results are achieved. (Dan Brokstad, personal communication, 11.3.2021)

Hexagon MI uses the software PC-DMIS for all their metrology products. It is a very clean application that is made to be easy to use. Basic understanding was achieved in just an hour when Brokstad was in contact with the writer of this study using Team Viewer. Brokstad also demonstrated how to use it during the Teams demonstration for Lillbacka. Figure 33 is a screen capture of the demo and here he showed the variations in the dimensions of a metal AM crimping die that was sent to Hexagon MI and scanned.

The tolerances have been set to ± 0,1 mm. Most of the surface of the part is shown as green, which means it is close to ± 0,025 mm from nominal, according to the software. The yellow spots are 0,05 mm above nominal. In this way hills or valleys are seen. Colors, tolerances, standard deviation and more can be adjusted.

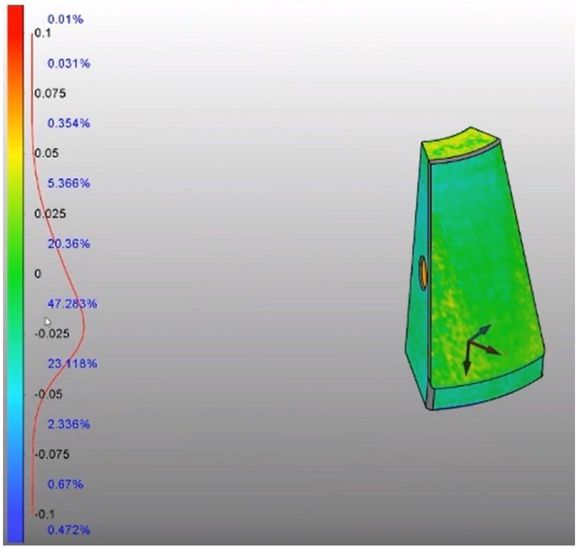


Figure 33 Examination of a crimping die in PCDMIS. (Dan Brokstad, personal communication, 11.3.2021)

Brokstad also showed how to measure the cone of the die, Figure 34. It is done by creating elements along features in the part. Two circles were created along edges on the die. A surface can be created between them to measure the angle of the surface compared to a plane approximated on the bottom of the die, and so on. The features are approximated for the best fit. (Dan Brokstad, personal communication, 11.3.2021)

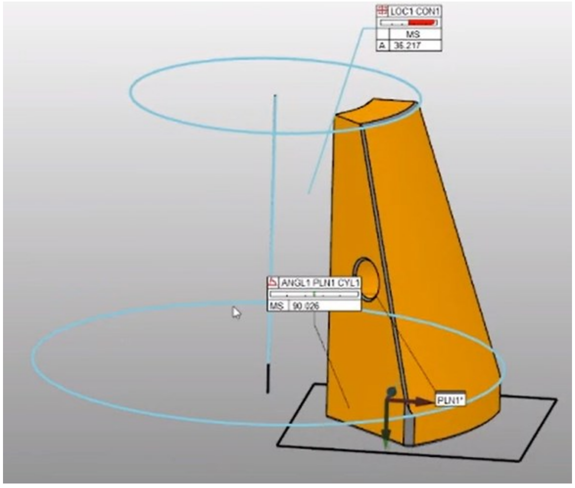


Figure 34 Measuring of the cone surface. (Dan Brokstad, personal communication, 11.3.2021)

According to Dan Brokstad at Hexagon, (personal communication, 11.3.2021), coordinate measuring machines and measuring arms with probes or scanners are the industry norms. The reflective tabs that handheld scanners require result in too much downtime. Institutions like museums use handheld scanners mainly because their scanning frequency is so low, so the downtime does not matter. Another point Brokstad made was that, according to his knowledge, different scanning companies that use reflective tabs and still say they are ISO-certified are bending the rules. The companies do their best to meet the requirements, but the accuracy is not the same as that of CCMs or measuring arm scanners.

5 Analysis

The analysis will focus on the two questions posed in chapter three:

- How can the data acquired from the point-cloud-dataset effectively be used to evaluate the die?
- Is 3D scanning a viable option for Lillbacka's quality control process?

First principles thinking is applied to the second question – which parts are going to be measured, where, how often, by whom? For Lillbacka, the smallest dies are 40 mm long, and the largest part that could be measured is the frame of the biggest press, 1500 mm in height. If both can be measured with the same device, it would be a great advantage. The measuring of dies would likely happen in the building with the metal 3D printer. The measuring of frames would happen in a separate building on the factory floor. Therefore, portability would be an advantage. The scanning was planned to be handled by a production machine operator. It is reasonable to assume that some measuring would happen every week. The three scanning systems will be evaluated against these considerations.

5.1 MLT

Scanning small and large parts

The HandyScan Black Elite can scan parts between 0,05 and 4000 mm. This is sufficient for both small dies and the largest frames. For small parts, reflective tabs can be permanently put on a worktable, which would work well on a permanent scanning setup near the metal 3D printer and would be very convenient. For larger kinds of scanning, the tabs would have to be placed on the work object and then taken off every time.

Portability

This scanning system is the most portable among the three: it is a single handheld scanner and a laptop. Both can be carried on one trip. This is useful for moving around the factory doing regular quality control of varying parts provided by suppliers. A benefit of handheld scanners is that it is easy to travel with a small scanner in the luggage. If the quality control technician travels a lot, then a HandyScan is convenient.

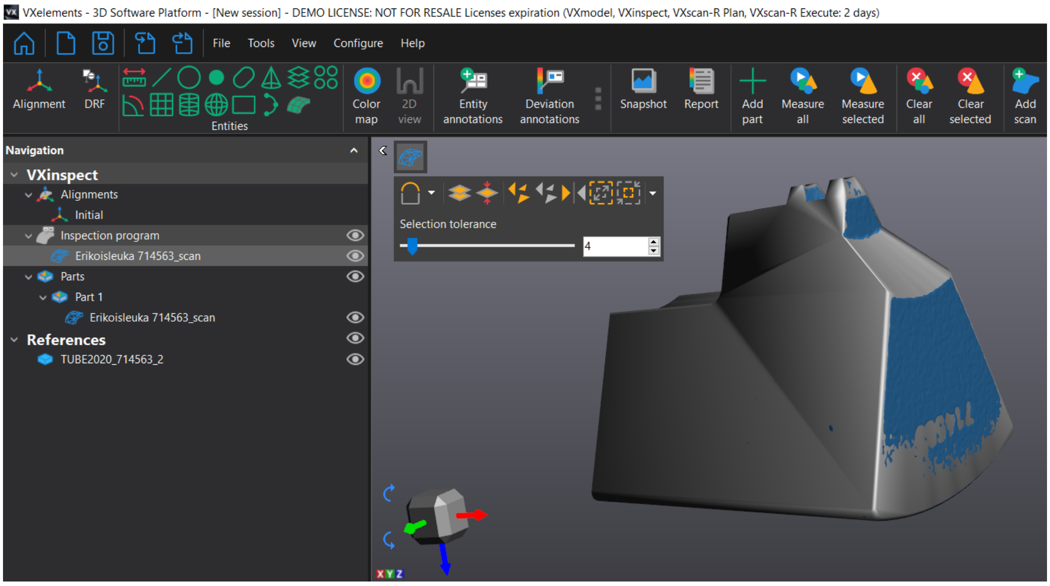
Setup time

The scanning system is simple with barely any setup time for the scanner. It consists of only a handheld scanner and a laptop. The tracking system requires more setup time, however. Possibly three hundred tabs would need to be placed and taken off if the part is as large as a frame. Even medium sized objects would need some 20 to 50 tabs.

User friendly

The scanning process is easy. After the setup is done, the scanner is immediately ready to scan. The scanned result is shown in real time on the laptop, thus any holes in the point cloud can be spotted and filled. The scanner glows red if it is moved too close or too far from the object which is convenient.

The software, however, does require training. It is a CAD-type application, which is not an everyday tool for machine operators. On Figure 35 is shown a screenshot of a first try using VXinspect with a CAD-model superimposed on raw scan data. The data used is the same point cloud data as before, provided by MLT. The blue area shows where the scan data sticks out of the CAD-model, which means the part is larger in that dimension. However, measuring the differences was not achieved on this try.



VXelements - 3D Software Platform - [New session] - DEMO LICENSE: NOT FOR RESALE Licenses expiration (VXmodel, VXinspect, VXscan-R Plan, VXscan-R Execute: 2 days)

Selection tolerance: 4

Figure 35 VXinspect in use comparing a CAD-model to raw scanned data.

The problem does not lie in the application, though. VXelements can measure all that is needed for inspecting parts. A very useful feature of 3D scanning is showing warps and bends. Siitonen demonstrated this during the demo, Figure 36. A plane was placed on the side of the die and balanced by the software to be evenly situated between the low and high spots. A valley appeared in the side of the die, along with uneven surface texture. The valley is a perfect example of geometric changes not easily noticed otherwise.

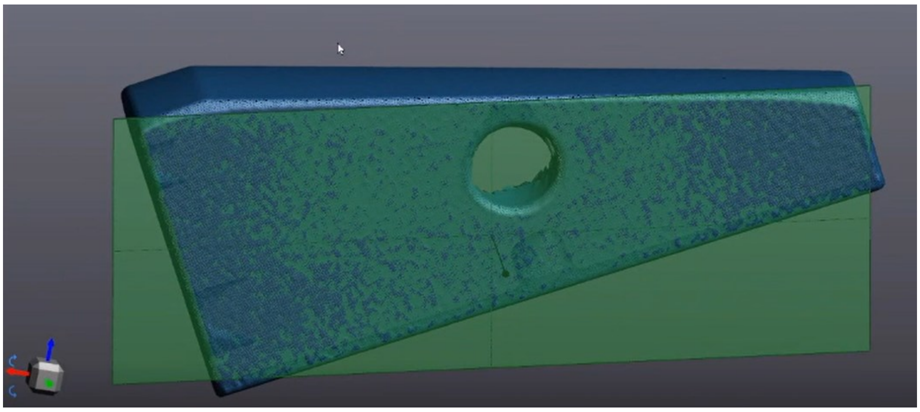


Figure 36 Planar variations in the die.

Furthermore, Siitonen demonstrated PolyWorks Inspector. On this software he produced a section view of the die along the midline. He took measurements along the profile of the deviations from nominal. The blue flags show where the measurement is under nominal and the yellow and green where it is above. This is also what a report looks like.

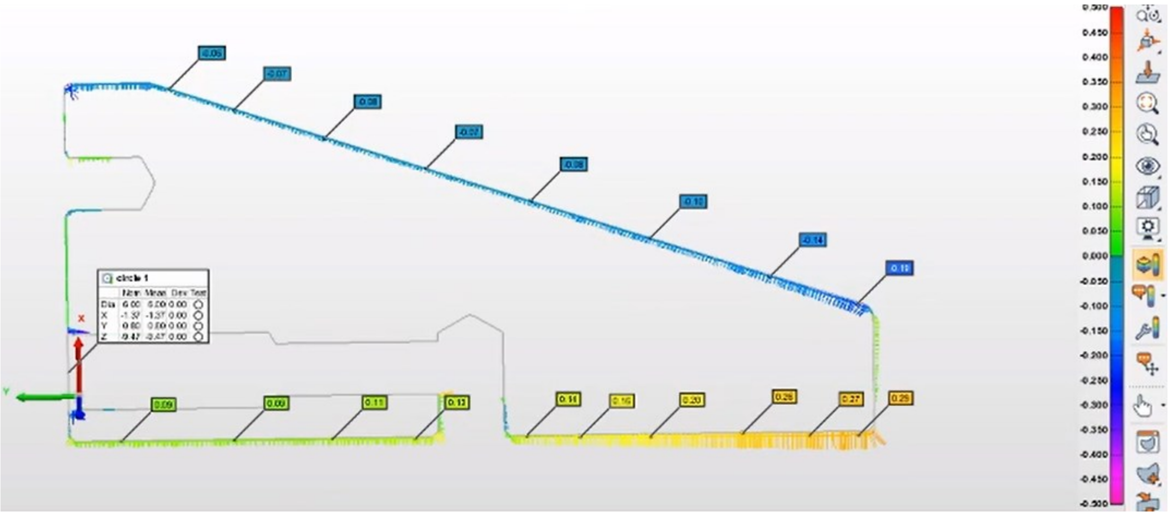


Figure 37 Section view of the die in PolyWorks.

5.2 ZEISS

Scanning small and large parts

Ten cubic meters is the largest scan volume possible with the T-Scan 10 and T-Track. This is easily enough for the largest press frames that Lillbacka produces. The smallest resolution the scanner manages is 0,075 millimeters, so small dies are no problem.

Portability

The ZEISS scanning setup is considerably larger than the one by MLT. Aside from the handheld scanner is the T-Track placed on top of a tripod, a control box and a laptop. A power supply is also needed. The system comes in transport boxes similar in size to briefcases and suitcases. It is not hard to move the setup, but it does take a while, as it is not supposed to be a portable system.

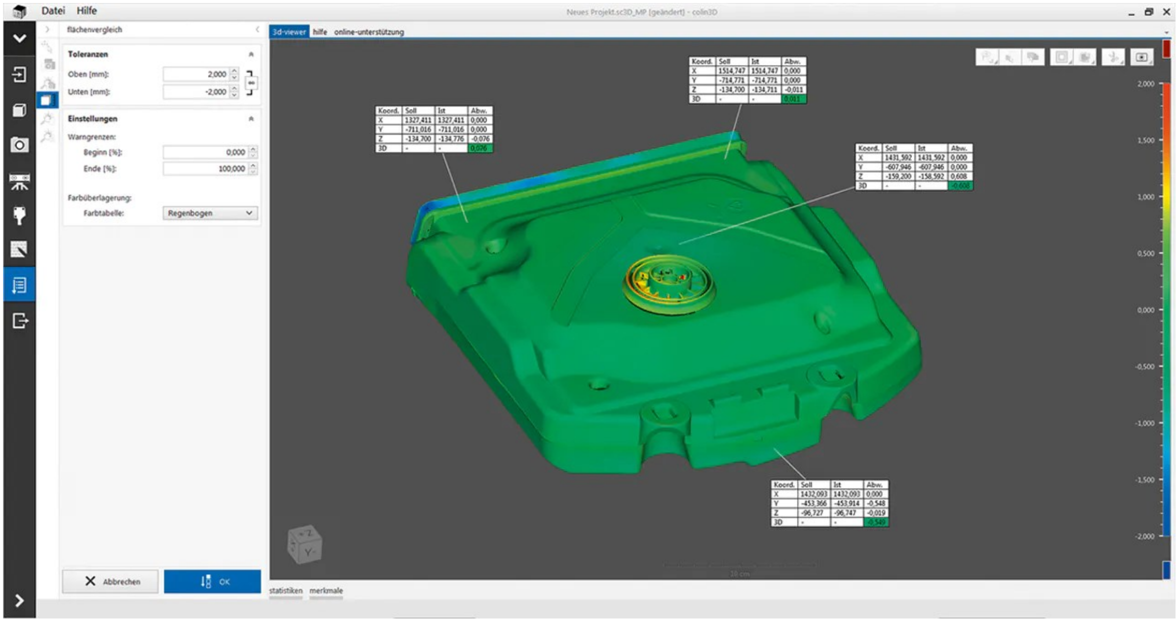
Setup time

The setup time after transport is perhaps slightly better than for the HandyScan by MLT. All the components need time to be set up but can still be up in a few minutes. The tripod with the T-track needs about two meters distance to the work object. All the components must be handled with care because it is an expensive system.

User friendly

The scanning process is easy. Once everything is set up one only needs to press the trigger and scan. Thanks to the T-tracker the part can even move around or vibrate, and the result will still be accurate. The point cloud is shown being created in real time in the software so eventual gaps in the model can easily be seen and filled.

The software Colin3D does require some training. It is also a CAD-based program with lots and lots of features, options and settings.



Toleranzen

Oben [mm]: 2,000
Unten [mm]: -2,000

Einstellungen

Warngrenzen:
Beginn [%]: 0,000
Ende [%]: 100,000

Farbüberlagerung:
Farbtabelle: Regenbogen

Koord.	Soll	Ist	Abw.
X	1327,411	1327,411	0,000
Y	-711,016	-711,016	0,000
Z	-134,700	-134,776	-0,076
3D	-	-	0,076

Koord.	Soll	Ist	Abw.
X	1514,747	1514,747	0,000
Y	-714,771	-714,771	0,000
Z	-134,700	-134,711	-0,011
3D	-	-	0,011

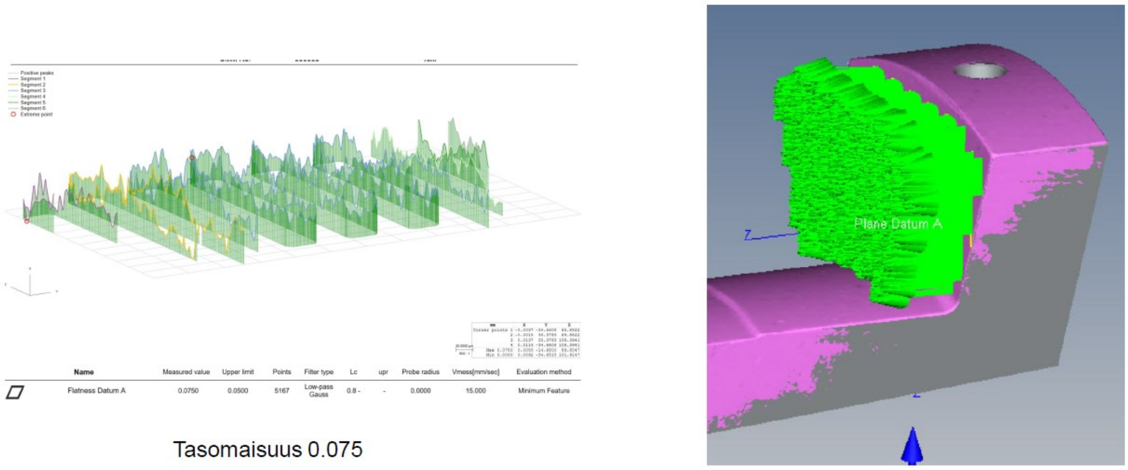
Koord.	Soll	Ist	Abw.
X	1431,592	1431,592	0,000
Y	-607,946	-607,946	0,000
Z	-159,200	-158,592	0,608
3D	-	-	-0,608

Koord.	Soll	Ist	Abw.
X	1432,093	1432,093	0,000
Y	-453,366	-453,914	-0,548
Z	-96,727	-96,747	-0,019
3D	-	-	-0,549

Figure 38 Example of the Colin3D software. A color map is used to find deviations in the dimensions of the part. (Carl Zeiss AG, 2021a)

Still, quick and simple evaluation of the data is possible in just a few minutes. The point cloud is created or imported, it is meshed, and then the CAD-file is imported and aligned with it. When this is done the color map can be achieved. Figure 38 shows an example of the color map. The green color is where the part is within tolerance, the red and blue areas show where there is too much or too little material.

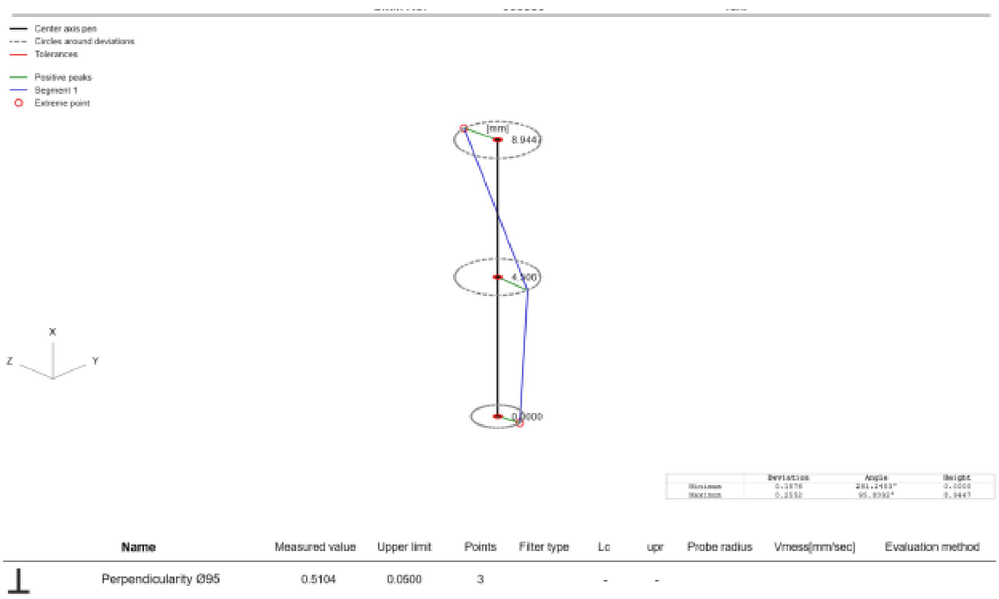
For more extensive measuring, a software called Calypso is used, shown in Figure 39. With this software all types of measurements can be made – surface roughness, orthogonality, parallelism, roundness etcetera. (Carl Zeiss AG, 2021b)



	Name	Measured value	Upper limit	Points	Filter type	Lc	upr	Probe radius	Vmess[mm/sec]	Evaluation method
⏥	Flatness Datum A	0.0750	0.0500	5167	Low-pass Gauss	0.8 -	-	0.0000	15.000	Minimum Feature

Figure 39 An example of the measurements in the measuring report by ZEISS. (Carl Zeiss AG, 2021a)

Figure 40 shows yet another example of what is possible with Calypso and 3D scanning. It shows a measurement of orthogonality, in other words perpendicularity, of the vertical surface in Figure 39 compared to the horizontal adjacent.



	Name	Measured value	Upper limit	Points	Filter type	Lc	upr	Probe radius	Vmess[mm/sec]	Evaluation method
⊥	Perpendicularity Ø95	0.5104	0.0500	3		-	-			

Figure 40 Example of Calypso measuring abilities, orthogonality = 0,5104.

5.3 Hexagon MI

Scanning small and large parts

All small parts can be measured with the scanner. The minimum point spacing is 0,026 mm so even the smallest details on dies can be scanned. The largest parts that can be scanned depend on the size of the measuring arm. A measuring arm by Hexagon that is rated for a range of 2500 mm actually has a range of 2980 mm and has a measurement volume of a sphere nearly 6 meters in diameter. Placing the arm on beside a 1500 millimeters tall frame would thereby be well enough, even double the range needed.

Portability

The arm and tripod are light and can be carried around without problem, but a portable base station would be the most convenient, Figure 41. The arm can be fastened directly on top of a portable base station for the best portability. Thanks to this the arm is not limited by a tripod but can be rolled up to the part to be measured. The scanner and arm can be powered by batteries and thus the system is completely portable.

Figure 41 Portable base station. Small part fixtures are included in the boxes. (Hexagon MI, 2021)

Setup time

There is no setup time after transport within the factory. The system rolls up to the part and is ready to scan. Only when transporting between buildings is where there is some setup time when the arm is lifted out of the transporting box.

User friendly

After setting up, the system is ready to use by simply turning on the measuring arm and starting a scan. Like the other systems the point cloud is shown in real-time on a laptop.

Also like the other systems, the software requires training. The basic functionality can be achieved in just a few minutes with a little training. This is how a machine operator can easily do simple measurement tasks like producing the colormap or checking deviations in known problem areas. As soon as specific detail or adjustment is needed, much more familiarity with the application is needed.

Brokstad guided the writer of this study through a basic use of Hexagon MI's software PC-DMIS. The result shown in Figure 42 was achieved after just a few minutes. The red curve has its high point approximately at -0,035 mm and 44 %, meaning that approximately 44 % of the part dimensions are under nominal. The software is extremely versatile, however, as Hexagon uses the same software for all of its metrology products. It has all the features needed for industrial metrology.

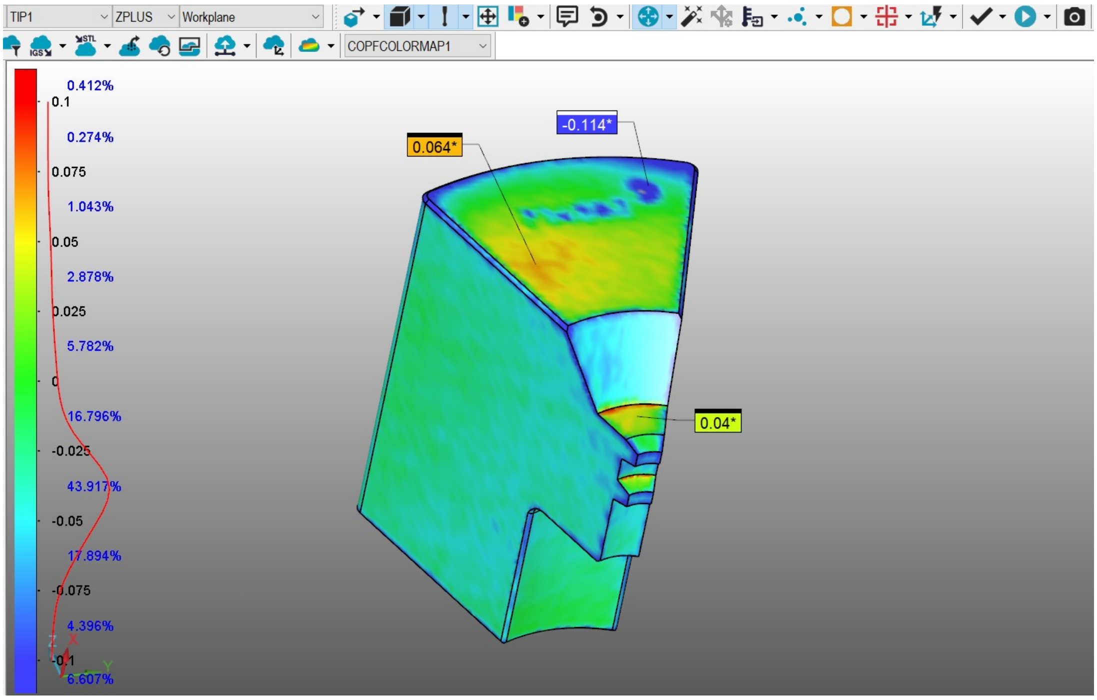


Figure 42 The result within three minutes of opening the software.

The RS6 scanner produces millions of points and thus requires a lot of computing power. Around a two- to three thousand euros worth of computer is needed, most of the price going towards a powerful graphics card to deal with the point cloud. Such a cloud is shown after having been meshed in Figure 43. The meshing is done by the user – either basic or more advanced custom settings. The edges of the crimping die have a mesh that is much tighter than, for example, the flat surfaces. This is because a very small minimum triangle size and deviation error were allowed, 0,005 mm and 0,002 mm, respectively. Features like these is what makes the software powerful but also why it requires training.

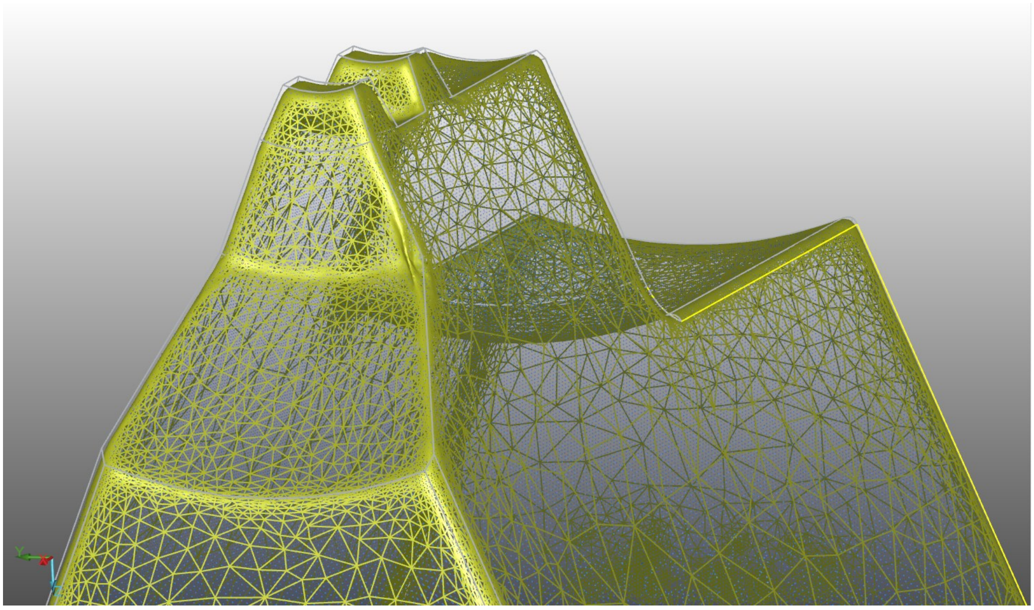
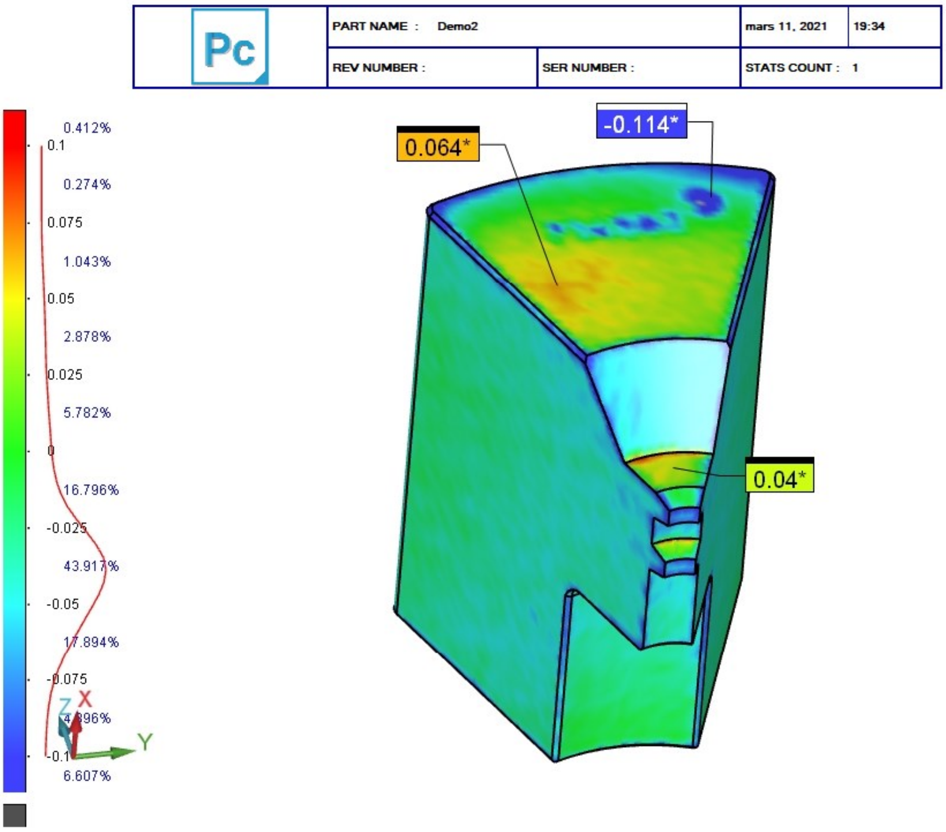


Figure 43 Mesh of a point cloud. Larger mesh on the flat surfaces.

Measurement reports are made instantly by pressing the report button, see Figure 44. More report designs exist. Annotation labels can be placed on areas of interest as in high and low spots. (Dan Brokstad, personal communication, 29.1.2021)



Pc	PART NAME : Demo2		mars 11, 2021	19:34
	REV NUMBER :	SER NUMBER :	STATS COUNT : 1	

Figure 44 Example of a measurement report.

5.4 Comparison of the scanning systems

Essentially, the scanning process for all scanning systems is as follows:

- Physically set up the scanner as needed.
- Open the scanning software and start scanning without many settings.
- Mesh the point cloud that is generated.
- Import the original CAD-model.
- Align the mesh on top of the CAD-model.
- Perform measurements such as color maps and annotation points to show values.
- Produce a report.

Software

There are no significant differences in the software between the different scanning solutions for general scanning and measuring of basic dimensions and relations. All of them would work well for Lillbacka. The applications are different, but the working principles are the same. All of them produce points clouds that are meshed and aligned with the CAD-model. All of them use colormaps with editable tolerances and colors and produce clear reports.

Mechanicals

The HandyScan is by far the smallest and most portable system of them all. This would be a deciding factor if the scanning technician would travel a lot for quality inspection. For Lillbacka that is not needed. The big drawback are the reflective tabs that must be set up.

The T-track by ZEISS is best as a stationary set up to which parts are brought to be scanned, but if needed it is easy but not quick to move around.

The measuring arm with a probe or scanner head by Hexagon MI is what is regularly used in heavy industry. Rolling the arm to the part and beginning the scan takes no time at all, as the arm is already set up on the portable base station. This system is not easy to transport between buildings, however. That is why a tripod could be used at the stationary workstation and the portable base station could be kept near the large frames.

Accuracy

The most accurate system is the measuring arm by Hexagon MI – the touch probe connected to the measuring arm is at best 12 µm accurate. The scanner connected to the arm achieves 47 µm accuracy with 26 µm point spacing. The scanner by itself achieves 26 µm accuracy but the positioning error of the arm reduces the overall accuracy to 47 µm.

MLT claims accuracy to 25 µm and has a point spacing of 100 µm. However, when scanning larger objects, the accuracy is 20 µm + 40 µm/m. For example, 20 µm + 40 µm = 60 µm for a one-meter-long object. It is still unclear if the HandyScan is the most accurate scanner for small objects, as Dan Brokstad suggested that such scanning manufacturers might interpret the standards too loosely.

The ZEISS T-scan has an accuracy 40 µm + 40 µm x L/1000, with a mean point spacing of 0,075 µm. For example, 40 µm + 40 µm x 1000/1000 = 80 µm for a one-meter-long object.

In any case, Lillbacka must weigh the necessity for extreme precision. Scanning systems are best at quick assessment of the general form of a part or to check if it is within tolerances and thus passes quality control. Coordinate measuring machines are accurate to 1 or 2 microns and are more useful for accuracy than scanners. With this in mind, paying large amounts for higher accuracy is perhaps redundant.

Price

MLT has the most affordable scanner. ZEISS comes second, and the most expensive is Hexagon MI whose product is about double the price compared to the HandyScan. Price is one of the most important factors. When only looking at value then HandyScan gives the most value for the lowest price. This is debatable, of course, but HandyScan managed to do the task it was given and that is what matters. If Lillbacka decides a full-time technician should be hired for quality control, then ZEISS or Hexagon MI make more sense. Both are systems without any downtime as long as the workstation is stationary. At Lillbacka some portability is required, but not all the time.

Conclusion

To get an overview of how the systems compare, a table was made where each system is given points in different categories. The points correspond as follows:

- 1 point: Considerable drawbacks.
- 2 points: Satisfactory.
- 3 points: Good but has some drawbacks.
- 4 points: Excellent.

Table 2 Overview of the systems.

Factor	MLT	ZEISS	Hexagon MI
Software	4	4	4
Setup time between scans	2	4	4
Portability	4	2	3
Accuracy	3	2	4
Price	4	3	1
Bonus points			
Same software as Lillbacka's CCM, better workflow		1	
Economic gain of the same software, less training needed		1	
Rotary table support	1	1	1
Sum	18	18	17

As seen from Table 2, all the systems have advantages and disadvantages, while all are very capable. Consequently, the role of selecting the scanning system falls entirely on Lillbacka:

- MLT is portable and cheap but has a long setup time.
- ZEISS is somewhat portable, but fast at scanning.
- Hexagon MI is portable, fast at scanning, accurate, but expensive.

The question Lillbacka needs to answer is – what is most important? Price? No setup time between scans? Mobility? Only then can a tailored choice be made.

5.5 Comparison to original CAD-model

The comparison of the scanned data to the CAD-model is where the benefit lies in 3D scanning. In a few minutes one can get a general sense of the whole part, where it fails or if it passes the tolerances. Figure 45 shows how the scanned data does not touch the CAD-model-contour, suggesting material is missing. A better way to show this is with color maps, as shown in Figure 45. The colormap makes it obvious where the deviations are. All sharp edges on the part have become rounded. This is because the surface finishing operations that are abrasive in nature gets the best hold of the material in the edges and removes it. The red area is where there is too much material. Too much material could make the part not work as well as it should, and this is again one such area that is bothersome to measure manually.

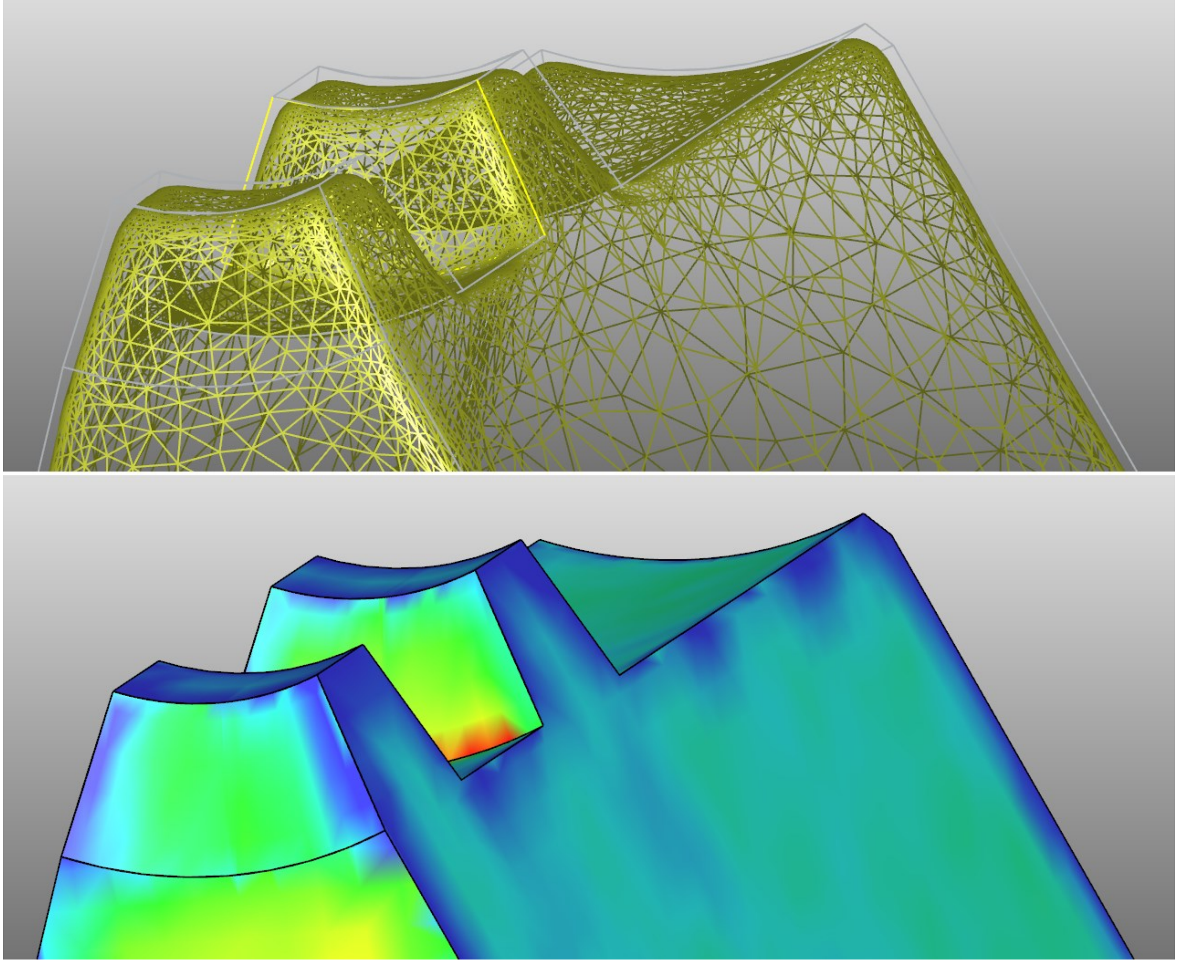


Figure 45 The blue areas are where material is missing.

5.6 Reverse engineering

All companies spoke of reverse engineering and can provide software for this purpose. Hexagon MI was the only company that took the time to show this process during the demos. Hexagon MI has its own reverse engineering software called Recreate. The process was fast, even though Brokstad was unfamiliar with the software. This goes to show that the reverse engineering process is quick.

The drawing of the model from scratch in reverse engineering software does take some time, but the big advantage is that all the measurements take barely any time to achieve with 3D scanning compared to traditional measuring. Also, when drawing, plenty of properties such as angle, exact position of surfaces, arcs and more, end up in the right places as they are semi-automatically created.

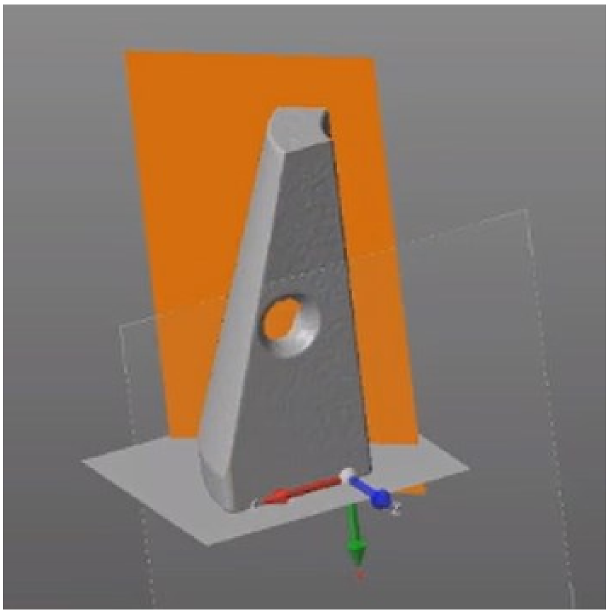


Figure 46 Elements are created.

Reverse engineering has compounding effects that make it both more accurate and saves time. Being an instant supplier of reverse engineered spare parts would definitely be a niche market that Lillbacka could exploit. Many potential use cases are not even known yet, ergo the demand will grow still.

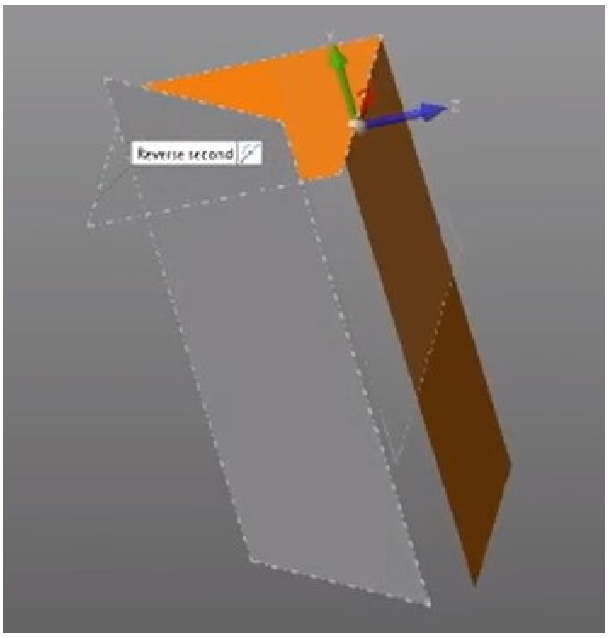


Figure 47 Surfaces are trimmed.

5.7 Setup for 3D scanning

Regardless of which scanning system is chosen, a dedicated workstation is needed. This is in line with the 5S methodology, as in every tool that is part of the 3D scanning technician’s job would be found here. This is assuming the technician would have considerable work load every week, as opposed to only scanning a few parts occasionally. If the workload is small then the workstation can be considerably simpler, for example using temporary setups and upgrading the occasional scanning technician’s laptop to one that is powerful enough. This is not advised, as it leads to downtime when having to set up the temporary scanning workstation.

In any case there must be a dedicated and very powerful laptop in the two- to three-thousand-euro range. The point clouds require extremely powerful and therefore expensive graphic cards. A large monitor and an external keyboard and mouse are recommended for comfort and ergonomics.

Along with a laptop a worktable is needed. The best choice would be a welding table that is full of holes for clamps and fixtures. This enables repeatable, easy and safe positioning of components. It also keeps parts from falling off the table or on the operator. The scanning systems are designed for industrial use, but nonetheless they would benefit from being kept away from dust, in a separate room. Temperature control is generally not needed if the scanning systems are kept indoors. The operating temperatures are 5 – 40 °C and condensation should be avoided. Temperature control may however affect the measured part, so any temperature-controlled room should be kept at +20 °C and parts that are to be measured should be brought into the room 24 hours before measuring.

The MLT scanning system would do best with a large table on which the part would be placed. On top of this a rotary table could be placed. The table/rotary table would be permanently covered in the reflective tabs needed for the HandyScan.

The ZEISS scanning system would also do best with a large table to place the part on, and a rotary table, as the T-track cannot track the scanner if it is blocked by the measured part. Additional room space is needed for the T-track to overlook the part placed on the table.

The Hexagon MI scanning system also would do well with a worktable and a rotary table. The arm can be placed permanently on the table, on a tripod, or a cart. The Hexagon scanner can also be used with a rotary table, but a little differently: the rotary table needs to be locked while the part is scanned, then it would be rotated and locked again. Doing it this way, one gets multiple scans that would be combined into one in the software. Another way of doing it would be to measure three reference points, perform a scan, rotate the table, measure three reference points again, and resume scanning. In other words, a rotary table is possible to use, but only when locked.

In personal communication with Dan Brokstad, 30.3.2021, he stated that using a rotary table, or performing two scans that are combined, lowers the accuracy for any scanner by a factor of 1.4. For example, an accuracy of 47 micrometers becomes 1,4 × 47 micrometers = 65,8 micrometers. For combining three scans, the factor is 1,7.

5.8 Limitations

Repeatability and consistency

The scanners are not sensitive to the person doing the measuring, which means the scanned results are perfectly repeatable. The same can be said for consistency. As it is an electronic device that is not even sensitive to the distance to the scanned object, the results will always be consistent and repeatable.

Reliability

The scanners need to be calibrated once a year to be perfectly reliable. Other than that, they do not change. They will always work if treated with care.

Accuracy

The scanners are accurate enough for metrology. Their measuring accuracies are under 0,075 mm which should be enough for product inspection and R&D. However, if measurements on the order of a few micrometers are needed, then a CCM must be used.

6 Conclusion

A 3D scanning system would definitely be a valuable asset and provide enormous advantages for Lillbacka. An overview of parts can be achieved quickly and effectively during the product development phase. Complex customized dies and tools are often made as one-off series. When measuring these is where scanning would save hours of work. The alternative would be to program toolpaths or manually measure using a coordinate measuring machine. Also, certain AM parts with complex shapes perhaps are only possible to measure using a scanning system. Quality control of parts made by third parties could easily and quickly be done in the assembly area with a 3D scanning system. For example, large steel frames could be scanned to see if they have enough material to be machined. Not to forget is that many companies need a measurement report on additively manufactured parts. Being able to measure all kinds of parts is critical.

Evaluating the data from the point clouds is a relatively easy process, and the software, while powerful and full of settings, can be learned well in a few days. Hence, the skill can be transferred from worker to worker easily and flexibility in the company is achieved. 3D scanning can also be used for reverse engineering, which means it could even directly earn a return on the investment.

Regarding which scanning system to choose, Lillbacka must consider its intentions regarding quality control. These scanning systems are expensive and require a technician to do the scanning and inspecting. Is Lillbacka going to invest heavily in quality control and continuous improvement? Or shall Lillbacka save money on this end and focus on another area of development? What is the budget, and is portability of the system essential?

3D scanning has proven that it provides great value. Looking into the future, technology companies must continue investing to remain relevant. Parts are machined to greater and greater tolerances, which means quality control will always remain important. Coordinate measuring machines are limited by the measuring volume, a least some of Lillbacka's parts do not fit into the current CMM. Moving parts to a CMM and setting them up leads to a lot of downtime. Scanning systems are fast, flexible and accurate. Investing in a good system will reap many benefits, but perhaps even more could be gained if Lillbacka employed a full-time dedicated measuring technician or engineer.

Bibliography

3D Systems Inc. (2021a). *LaserForm Maraging Steel (B)*. https://www.3dsystems.com/materials/maraging-steel

3D Systems Inc. (2021b). *ProX DMP 300*. https://www.3dsystems.com/3d-printers/prox-dmp-300

3DEO. (2018a). *Intro to Metal 3D Printing Processes – Powder Bed Fusion*. https://www.3deo.co/manufacturing/intro-to-metal-3d-printing-processes-powder-bed-fusion-dmls-sls-slm-lmf-dmp-ebm/

3DEO. (2018b). *Understanding Surface Finish in Metal 3D Printing*. https://www.3deo.co/metal-3d-printing/understanding-surface-finish-in-metal-3d-printing/

3DEO. (2020). *What are Your Options for Improved Surface Finishes After 3D Printing?* https://www.3deo.co/metal-3d-printing/what-are-your-options-for-improved-surface-finishes-after-3d-printing/

3Dnatives. (2020). *Laser Scanner vs Structured Light Scanner: which should you choose?* https://www.3dnatives.com/en/laser-3d-scanner-vs-structured-light-3d-scanner-080820194/#!

ABLE. (2021). *Electropolishing. The Final Step in Prototyping*. http://www.ableelectropolishing.com/wp-content/uploads/2014/07/AbleElectropolishing-TheBenefitsOfElectropolishingForPrototyping-WebOnly.pdf

Ahlfors, M., & Hjärne, J. (2015). Hot Isostatic Pressing: Improving quality and performance in AM parts production. *Metal AM Vol. 1 No. 4*. https://www.metal-am.com/articles/hot-isostatic-pressing-improving-quality-and-performance-in-3d-printing/

Artec Europe. (2020). *Portable 3D Scanners*. https://www.artec3d.com/portable-3d-scanners

Artec Europe. (2021). *Reverse engineering huge machine parts in difficult locations with Artec Eva and Geomagic Design X*. https://www.artec3d.com/cases/reverse-engineering-parts-of-construction-machine-in-geomagic-design-x

Carl Zeiss AG. (2021a). *ZEISS Industrial Metrology*. https://www.zeiss.fi/metrology/home.html

Carl Zeiss AG. (2021b). *ZEISS Teams Demonstration*.

EMS. (2021). *Creaform HandySCAN Black Detailed Demonstration*. https://youtu.be/RhKfOYl4u3Q

FARO Technologies, I. (2020). *Understanding Portable Measurement Arms*. https://insights.faro.com/blog-articles/understanding-portable-measurement-arms#:~:text=Portable measurement arms determine and,or joint) in the arm.

Formlabs. (n.d.). *How to use 3D scanning and 3D printing for reverse engineering*. https://formlabs.com/eu/blog/how-to-use-3d-scanning-and-3d-printing-for-reverse-engineering/

Fuges, C. M. (2017). 3D Printing with Postprocessing in Mind. *Additive Manufacturing*. https://www.additivemanufacturing.media/blog/post/3d-printing-with-postprocessing-in-mind

Hexagon MI. (2020). *RS6 Laser Scanner*. https://www.hexagonmi.com/products/3d-laser-scanners/rs6-laser-scanner

Hexagon MI. (2021). *About Hexagon Manufacturing Intelligence*. https://www.hexagonmi.com/about-us/about-hexagon-manufacturing-intelligence

Järvinen, M. (2014). *Mittaustekniikka*.

Kuusela, V. (2019). *3D-SKANNAUS JA SEN HYÖDYNTÄMINEN 3D-*.

Lillbacka Powerco Oy. (2021). *Side feed machines*. https://powerco.lillbacka.com/products/side-feed-machines

MAN. (2020). *Here's 5 Metal 3D Printing Success Stories*. http://www.modernapplicationsnews.com/cms/man/opens/article-view-man.php?nid=2&bid=815&et=featurearticle&pn=01

Markforged. (2020). *Address More Manufacturing Challenges with Composite and Metal*

3D Printing.

MLT Oy. (2021a). *MLT Finland*. https://www.mltfinland.fi/

MLT Oy. (2021b). *MLT Teams Demonstration*.

PostProcess. (2020). *RADOR Surface Finish*. https://www.postprocess.com/product/rador-surface-finishing/

RPS Metrology. (2020). *RPS Metrology*. http://www.rpsmetrology.com/en/

Siitonen, E. (2011). *3D – skannaamisen ja fotogrammetrian hyödyntäminen suunnittelutyössä*.

SIS. (2020). *Brist på standarder för additiv tillverkning i metall*. https://www.sis.se/nyheter-och-press/pressmeddelanden/brist-pa-standarder-for-additiv-tillverkning-i-metall/

Tammela, M. (2021). *General discussions*.

Terran Data Corporation. (2021). *3D Printer Benchmark Announced*. https://www.fabbaloo.com/blog/2010/7/24/3d-printer-benchmark-announced-html

UNIMETRO Precision Machinery Co., L. (2020). *Miracle-P series High precision 3D coordinate measuring machine*. https://www.visionmeasurementmachine.com/sale-8198602-high-accuracy-3d-coordinate-measuring-machines-1-5-um-coordinate-measuring-system.html

Valve Magazine. (2018). *Understanding surface finishig in Metal 3D printing of valves*. https://www.valvemagazine.com/web-only/categories/technical-topics/9430-understanding-surface-finish-in-metal-3d-printing-of-valves.html

Zilling, F. (1973). *Mekanisk mätteknik*.