AUTOMATION AND INVESTMENT IN METROLOGY

Lappeenranta–Lahti University of Technology LUT

Degree Programme of Mechanical Engineering

Master's Thesis

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Hamza Taher

Examiners: Professor Juha Varis

Mikael Ollikainen, D. Sc. (Tech.)

ABSTRACT

Lappeenranta–Lahti University of Technology LUT
LUT School of Energy Systems
Mechanical Engineering

Hamza Taher

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Automation level in industry has been rising strongly in last decades. With the rise of production levels, also rises the need for inspection actions. That puts more pressure to invest in more automated metrology devices. Robotics has made huge leaps in the metrology field to make the inspection process more efficient. Collaborative robos or COBOTs are a relatively new implementation in the metrology field and the feasibility of these kind of systems have been under speculation.

In this thesis two levels of metrology automation were studied. The other studied system was *Absolute Arm* articulating arm with *AS1*-laser scanner, and the other system was *Primescan* structured light scanner that was attached to a COBOT. The quantitative and economical differences of these systems were compared. The test results that this work yielded show that the inspection process can be made significantly more efficient with more automated metrology systems.

TIIVISTELMÄ

Lappeenrannan–Lahden teknillinen yliopisto LUT
LUT Energiajärjestelmät
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Hamza Taher

Automaatio ja Investointi Metrologiassa

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Teollisuuden automaatiotaso on noussut voimakkaasti viime vuosikymmeninä. Tuotantotason nousun myötä myös tarkastustoimenpiteiden tarve on lisääntynyt. Tämä lisää painetta investoida automatisoituihin metrologialaitteisiin. Robotiikka on tehnyt suuria harppauksia metrologian alalla tarkastusprosessin tehostamiseksi. Kollaboratiiviset robotit tai COBOTit ovat suhteellisen uusi sovellus metrologian alalla, ja tällaisten järjestelmien toteutettavuutta on spekuloitu.

Tässä opinnäytetyössä tutkittiin kahta metrologian automaatiotasoa. Toinen tutkittu järjestelmä oli *Absolute Arm* nivelvarsimittalaite varustettuna *AS1*-laserskannerilla, ja toinen järjestelmä oli *Primescan*-rakenteisen valon skanneri, joka oli kiinnitetty COBOTiin. Näiden järjestelmien kvantitatiivisia ja taloudellisia eroja vertailtiin. Tämän työn tuottamat testitulokset osoittavat, että tarkastusprosessia voidaan tehostaa merkittävästi automatisoiduilla metrologisilla järjestelmillä.

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SYMBOLS AND ABBREVIATIONS

Abbreviations

3D	Three Dimensional
ADM	Absolute Distance Metering
AIFM	Absolute Interferometer
CAD	Computer Aided Design
CCD	charge-coupled device
CMM	Coordinate Measuring Machine
COBOT	Collaborative Robot
IFM	Interferometry
ISO	International Organization for Standardization
MPE	Maximum Permissible Error
PCMM	Portable Coordinate Measuring Machine
PSD	Position Sensing Device
RDS	Romer Data Software
ROI	Return On Investment
SHINE	Systematic High Intelligence Noise Elimination
SLS	Structured Light Scanning

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Abstract

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Symbols and abbreviations

1. Introduction

In this everchanging world the need for automation is arising. Cost of labour and constant drive for increased efficiency causes the level of automation in production increase. As the efficiency demand increases, also increases the need for tighter tolerances. To be able to verify tight dimensional tolerances of products the need for metrology actions is increased as a by-product.

Investing in more automated systems in metrology can bring huge efficiency gains to the production. With automation investment the inspection process will take less work hours and thus the operating costs are usually lot less compared to manual inspection methods. In change the initial investment of automation systems is usually very large compared to more manual inspection methods. When investing in automation in metrology a company needs to invest large amounts of money in equipment and setting up the automation systems. Also, the operating personnel needs to have required skill level and training to be able to operate and monitor the automation systems. The problem of investing in metrology automation as in any automation is to understand when it is economically viable to make the investment. The investor must understand the cost difference between different levels of metrology automation. The return on investment (ROI) estimation of metrology automation systems is usually a little bit more difficult than estimating the return on investment of a production machine such as machining centre. With metrology investments the company is always losing money if the product meets its tolerances, then the measurement stage is seen as completely unnecessary extra step in the manufacturing line. The gains of metrology investment usually come with lower number of reclamations and better reputation amongst customers. Metrology division in an industrial company is usually there to avoid future failure. Due to the probabilistic nature of these future failure events, it is often hard for financial management to justify metrology automation investments. [34]

The need to verify the dimensions of a product is partly affected by company internal quality control and partly by demand from customers. Company that is producing a product that is assembled from multiple different parts usually uses subcontractors that make some or all the parts that are assembled into the end product. To be able to monitor the quality of the different parts, the end company usually demands the subcontractors to show a measurement report from the delivered parts to approve them into the product assembly line.

Company internal quality control is important when producing high volumes or when parts are very expensive. It is important to know if the part is meeting set tolerances before the part is finished. If the produced part fails to meet set tolerances at the end of production line it probably ends up scrabbed and the losses to company are huge. For this reason, it is important to inspect the product in between or in some cases during a production stage. This way companies can achieve savings in cost.

In past few years metrology has made huge leaps towards more automated systems. Traditional measurement methods in production consists of manual handheld measuring equipment such as calipers and micro metres and various gauges. These devices rely on the skill of the user to take reliable and comparable measurements. Also, the documentation of these results is all up to the skill of the user and margin for error is quite large compared to newer metrology devices.

Portable CMMs or PCMMs were developed to meet the need to provide easy to use measurement devices to the production floor. In this work PCMMs are going to be the main devices that will be focused on. Portable CMMs consist mainly of articulating arms, laser trackers and photogrammetry devices. PCMMs are very easy to carry and handle in the production floor. The setup of PCMMs is easy and fast and can be done with only one user without any special tools.

Articulating arm is one type of PCMM with usually 6 or 7 joints that are connected to solid shafts. The assembly of joints and shafts looks and moves like human arm. The arm can be attached to worktable or the measured piece itself or it can be setup on a tripod near the measured object. In the other end of the arm there is a measuring probe head or other type of sensor like laser scanner. Each joint has encoder that calculates the angle between the two shafts that are connected to that joint. With the data from the angle encoders and the knowledge of the shafts lengths the machine then calculates the x, y and z positions of the probing head or scanner in relation to the base of the measuring arm. These types of PCMMs were developed in the early 1970´s. One of the developers of these kind of machines was *Homer Eaton* the co-founder of *Romer*. *Eaton* patented the articulating measuring arm in 1974. [12]

In the early days of PCMMs they were used to measure pipes with accuracy of just under 1 mm. Modern PCMMs can reach the accuracy of under 0.01 mm and can gather geometrical data from almost any physical part. Below in figure 1 a modern articulating arm can be seen. The arm has contact probing head and laser scanner both attached to it. User can change between contact and contactless measurement with a flick of a switch while staying in the same coordinate system.

Figure 1. Modern articulating arm PCMM with 7-axles. Featuring contact probing head and laser scanner. User holds the device from the pistol grip and takes measurements using the trigger. In the base of the arm there is a handle to make it easier to carry the device around. [13]

Articulating arms have been used in the manufacturing industry for decades now and they have taken their place as fast and easy way of taking measurements. Especially laser scanning has brought a sense of automation to businesses with limited resources for metrology automation. With articulating arm and laser scanner it is possible to raise the level of inspection department automation level. Even changing from hand measurement tools such as calipers and micrometres to probing articulating arm the speed and efficiency of inspection will grow. The articulating arm makes it faster and easier to do complicated measurements.

When comparing the articulating arm probing and laser scanning methods from automation perspective, it can be said that laser scanning is clearly distinguishable as automation step in the inspection process. Laser scanning can be seen in metrology as semi-automatic way of inspecting geometrical features. When using laser scanning, it is not necessary to fix the measured object into the measurement table because laser scanning is contactless measurement style. This saves time and effort from the measurement process. With laser scanning it is possible to gather hundreds of thousands of points per second from a large area. Comparing that to contact probing where user can only take single points from one place at a time. This point acquiring speed difference brings huge benefits for laser scanner users in inspection.

One other type of PCMM is laser tracker. Laser tracker is a device that has two moving axles with encoders and a distance measuring device that is based on laser. With the data from the encoders and distance measurement from laser a x, y, z position can be calculated to a corner cube reflector in relation to the base of the tracker. New generation laser trackers are usually equipped with Absolute Interferometer (AIFM). AIFM uses both interferometry (IFM) and absolute distance metering (ADM) technologies to determine the position of a reflector in relation to the tracker. IFM is largely used method of calculating the change in distance. ADM is also based on laser but can determine the position of reflector despite the change in distance. Both methods use the characteristics of laser light as means to determine the outcome. [14]

In figure 2 a modern laser tracker is seen. The tracker part in the name laser tracker comes from the fact that the device can track or follow a reflector that it is locked into. The laser tracker has a position sensing device (PSD) that sends signal to the laser trackers motors which then turn the device to point in the direction of the reflector. The laser beam that is reflected to the instrument causes a displacement when the reflector is moved. The displaced beam generates a signal on the PSD which is used to reposition the tracker and keep it on target. [16]

Figure 2. Modern laser tracker on a tripod. Attached to the centre pole of the tripod are controller for the tracker (left) and battery (right). Laser trackers can measure distances even up to 300 meters with few millimetres' accuracy. [17]

In addition to the AIFM modern laser trackers can also have digital camera system. This is a camera that focuses on a handheld device for probing or scanning seen in figure 3 and figure 4. The camera detects infra-red led lights placed on the handheld device. With the pattern produced by the led lights the system can calculate the pitch, yaw, and rotation of the handheld device. The x, y, z location of the handheld device is calculated by the encoders and AIFM as previously described in this introduction. The handheld device has corner cube reflectors positioned on all sides of the device. The tracker can lock onto these reflectors however the user decides to twist the handheld device on his hand.

Figure 3. Handheld probing device with repeatable quick clamping probe mount. In the centre of the device there is larger round object, that is the reflector. The other smaller round objects and the objects on the ends of the prongs covered by red material are the infra-red led lights. [19]

Figure 4. Handheld scanning device. The round objects on the end of the prongs are led lights that emit infra-red light. The larger cylindrical objects mounted on the sides, top and rear end of the scanner are reflectors that the laser tracker locks into. [18]

With laser tracker equipped with digital camera system it is possible to track a laser scanner that is attached to a robot arm. With this kind of setup, it is possible to run a measurement cell fully automatically with minimum human operator involvement. Modern laser trackers can keep up with rapidly accelerating targets and can thus be used with robots. Laser trackers PSD and strong motors give the tracker ability to track reflector or scanner that is mounted to a robotic arm. In this way modern laser tracker can be used in a partly or fully automated measurement cell.

A third type of PCMM is structured light scanner or SLS. SLS device is based on photogrammetry. Photogrammetry is contactless style of measurement which uses sensors like cameras to find the dimensions of the measured object. Photogrammetry 3D-measurement depends on two cameras fixed in relation to each other that look the same area from different positions for stereo view. [22] Photogrammetry has two different main techniques. In the other technique reference objects like stickers or reference blocks are used to get a reference of the dimensions of the measured object. The other main technique of photogrammetry is SLS. SLS uses structured light patterns projected on the surface of the measured object. The light reflects from the surface and the cameras capture the reflections.

The light structure is distorted by the measured surface and from the distortion the surface dimensions can be calculated. [23]

In figure 5 a modern SLS PCMM can be seen. The device is very light and can be mounted to a robotic arm or on a tripod. A turntable can be used with the scanner to increase the automation level of the system. That way most objects can be scanned without human intervention.

Figure 5. Modern structured light scanner or SLS. SLS devices can capture the whole surface of the measured object that is facing the measurement device. A turntable can be used to rotate the object so that the whole object can be digitized. Also, the opposite can be done so that the object stays in one place and the scanner itself is moved around the measured object for example with a robotic arm. [24]

One way to further rise the degree of automation from turntable is to invest in a collaborative robot (COBOT). COBOTs are lighter form of robotics. COBOTs are designed to work in an environment with human intervention. They have sensors and systems that can detect if human touches the robot, and they make the robot arm stop before any harm is done to the human. This way they don’t need safety fence around them, and they can operate in collaboration with human workers. The loading and unloading of parts and change of trajectory can be done by human worker without the need to stop the whole system from running. Modern COBOT can be seen in figure 6. On the metrology field there have been development for this kind of partly automated measurement systems with COBOT that can be used with SLS devices or laser scanners with laser trackers. Although they have been developed, they still are quite new concept in the field of metrology.

Figure 6. COBOT with contact stop functionality. When encountering human or other contact, the COBOT will stop automatically and will not hurt the human. The COBOT trajectory can be taught by human hand manually moving the COBOT through the moves it is wanted to do. [26]

Because of the nature of the usage of COBOTs their structure is quite light compared to full-size industrial robots with strong motors capable of high accelerations and high loads. Robotic arms with long reach and high load capacity are structurally stronger and heavier and thus more dangerous when they are moving in high speeds. To be able to stop this kind of heavy machinery it takes a lot of effort as the inertia build up on these kinds of systems is huge. Therefore, full-size industrial robots need a safety system around them. Usually, the safety system consists of cage around the working parameter of the robot. There are also safety sensors on the cage door to prevent intrusion inside the parameter when the robot is working. In figure 7 a fully caged robot measuring system can be seen.

Figure 7. Industrial robot measuring system inside safety cage. The operating computer is placed outside of the parameter of the robot’s working area. There is shutdown switch on the outside of the cage to turn the robot off for human intervention inside the working parameter. Without the safety systems there is a risk of serious injury or even death if human gets crushed or hit by the moving robot. [27]

1.1 Typical uses for PCMMs

To be able to better understand what the PCMMs are used for, there will be introduction to the most typical uses of this type of measuring devices in this chapter. As said earlier, PCMMs come mostly in three different categories: articulating arms, laser trackers and photogrammetry devices. Basically, they all do the same thing. They measure 3D-dimensions. However, the size, shape and tolerance of the measured part changes a lot, and it is impossible to measure all different kind of parts with only one measurement device.

The most typical use for articulating arm is measuring welded and machined metal parts with lot of different features such as holes and fittings. The size of the measured part varies typically from 0.1 m to 5 m in terms of length. Articulating arm measurement volume is typically 1 m – 5 m. Articulating arms are used to measure for example the dimensions of forklift frame. There are many threaded and unthreaded holes and different features in the forklift frame to mount all the other parts that make the forklift and all of them need to be in their right place. The articulating arm is used to measure the position of these features in relation to each other and make sure they are in spec. The measurement uncertainty of articulating arms is dependent on their measurement volume. The measurement uncertainty grows with the length of the arm. Typically, the accuracy of articulating arms is in the range of 0.01 mm to 0.1 mm. In figure 8 an articulating arm can be seen measuring a metal part with complicated form. As mentioned earlier, laser scanning can be used to make the articulating arm system semi-automatic way of measuring objects. Laser scanning will bring huge benefits especially in the inspection of parts with multiple features. With laser scanning it is easy and fast to measure all the features in one go.

Figure 8. Articulating arm laser scanning metal part with complex shapes. [31]

Laser trackers typically start their work where articulating arms measurement volume is not enough. Laser trackers are typically used to measure objects that are over 5 m in length and can measure up to 300 m long distances. Laser trackers can be used for example to measure the dimension of a train cart. When attaching a laser scanner to a robot and using laser tracker to track the scanner, the system can be used in automation cell. One application to laser tracker is measuring the dimensions of a car body. One of laser tracker automation applications is inspecting the flush and gap of car body panels. In figure 9 a laser scanner attached to a robotic arm can be seen scanning the panel gap of a car body.

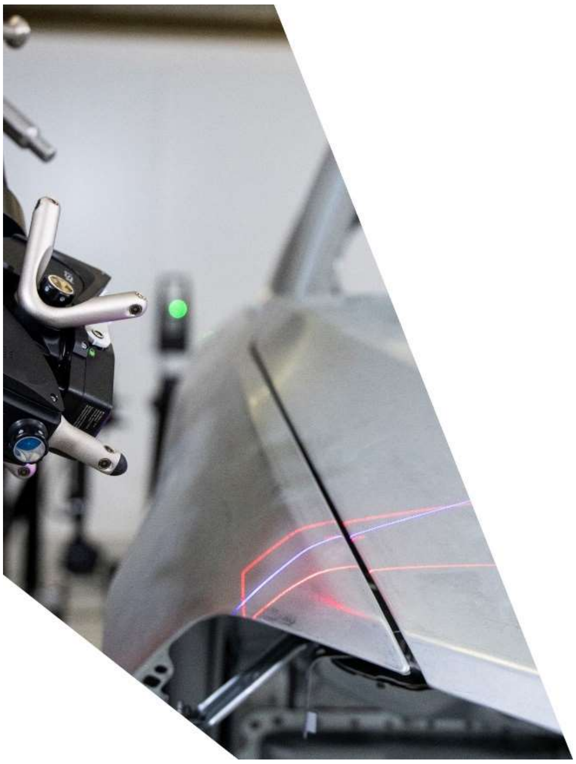


Figure 9. Robotic inspection of a car body panels gap and flus. Laser tracker is tracking a laser scanner attached to a robotic arm. [32]

The laser scanner produces a digitised model of the panels surface. The digitised model can then be inspected in application software. A cross section can be made from the digitised model where the panel gap and flush can be inspected in detail. In figure 10 the flush and gap inspection is taking place inside an application software.

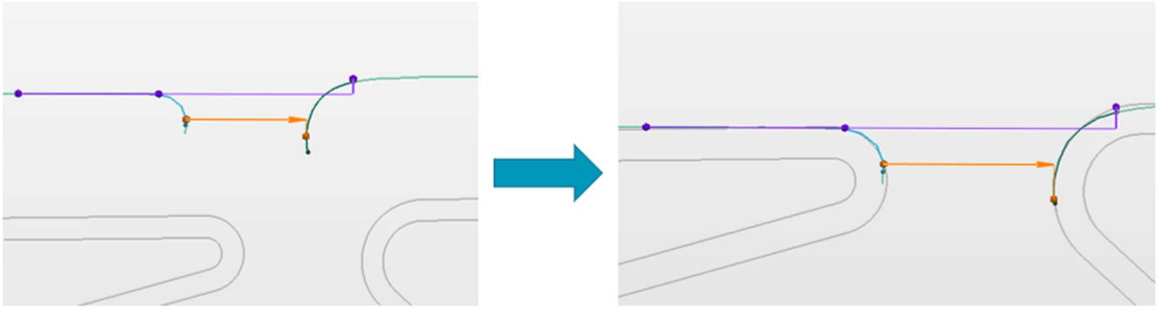


Figure 10. The digitised panel surface is fitted over CAD-model by using best fit alignment. In the cross section of the panel gap it is easy to inspect the panel gap and the panel flush. [32]

Photogrammetry solutions are used typically to inspect large-scale objects. With photogrammetry it is fast and easy to inspect the whole surface of a large-scale object such as plastic moulded vehicle panels. Photogrammetry is also often used in high volume industries such as pipe manufacturing or other line of manufacturing where the production volumes are high, and the inspection process needs to be quick and consistent. In figure 11 a photogrammetry inspection system can be seen scanning trucks engine cover.

Figure 11. Plastic moulded truck engine cover panel inspected by photogrammetry device. With photogrammetry devices it is fast and easy to digitise the whole surface of a large-scale object. [33]

1.2 Research Problem

The research problem of this work is to find out what is the quantitative and the economical difference between two different automation levels in 3D-measurement of solid part with different features. The differences that will be compared between the two systems are cost and measurement results. There is not much research to be found that clearly compare the economical and quantitative differences between different automation levels in metrology. In this work the focus will be on PCMMs. Laser scanner and photogrammetry devices will be the main methods of data collecting that will be used in this work.

1.3 Research questions

The research questions are divided into two categories. First is cost and second is measurement results. The cost differences will be shown in this work as percentages because of the nature of the data. The raw pricing data will be appended to this work and will be available for the inspectors. Below a list where the research questions can be seen.

Cost research questions

- What is the initial investment difference between the two different levels of automation?
- What is the operating costs difference between the two different levels of automation?

Measurement results research questions

- What is the difference between measurement time between the two different levels of automation?
- What is the difference in measurement deviations between the two different levels of automation?

1.4 Research objective

The objective of this research is to make a simplified presentation of costs and measurement results of portable metrology automation for companies that are looking for automation in metrology. The purpose of this research is to get a clear understanding of the costs and measurement results involved in two different levels of automated portable metrology.

1.5 Research confinement

Because of the nature of the research the systems used in this research are limited to products made and sold by Hexagon Manufacturing Intelligence. This research will not involve any other brands because that would require so much more work and effort that it would exceed the resources available to this work. In this research only portable CMMs are studied although traditional CMMs can also be used in highly automated systems.

2. Methods

The methods used in this research are quantitative. Two types of portable CMMs are used to collect data on the surface of the demo part. Laser scanning and photogrammetry will be the two main methods used to digitize the surface of the demo part. To set a baseline for the measurement results a PCMM with probing head will be used to measure the features of the demo part using contact probing method. With PCMM contact probing the features can be inspected in the micrometre level of accuracy. The data gathered with other ways will be compared to the probed data.

In this research the goal is to get understanding between the economical and quantitative differences between measuring with two different levels of portable automation. The levels of automation will be divided into two groups. First group will be manual measurement with laser scanner that is part of articulating arm. Second group will be structured light scanner that is mounted to COBOT.

The differences of initial investment between these two groups will be compared. Also, the operating costs between the two groups will be compared. In the quantitative part of this research both systems will perform series of measurements to demo part. The demo part seen in figure 12 has holes, planes and other geometrical features that will test the systems capabilities in versatile way. The same part will be measured with both systems and the results will be compared.

Following chapters will explain the methods used in this work more in depth. There are two method related chapters: Cost and Measurement. Cost related research methods will be reviewed in chapter Cost and measurement related research methods will be reviewed in chapter Measurement.

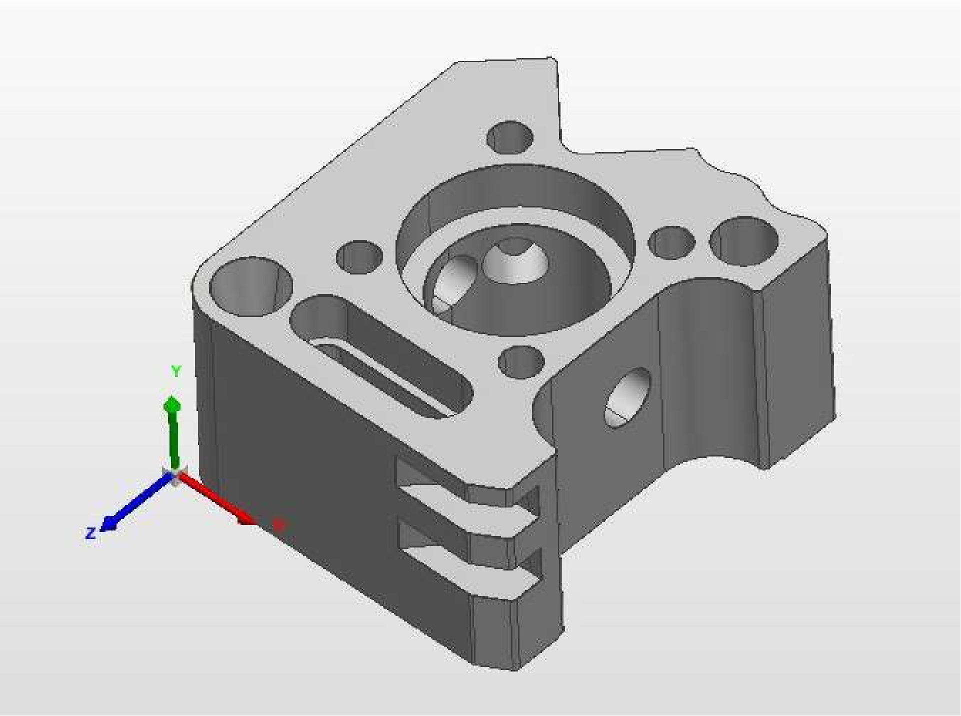


Figure 12. *Hexagon* demo part has many different geometrical features. With scanning devices these features can be measured very quickly. [25]

2.1 Cost methods

The costs of initial investment for each system can be quite easily calculated using prices provided by *Hexagon*. Because in this work the focus will be on *Hexagon* made products therefore the prices are easily attainable. The raw data of the prices will be gathered to appendix file that will be available to the examiners of this work. The prices will be referred to in this work with percentages so that the differences between each system can be viewed.

The operating costs will be calculated using the time data from the measurement part of this research and multiplying that with the human work hourly cost. The operating costs of inspection line are divided into many different aspects. The largest cost operating a production inspection line is the work force costs. There are also energy costs, property costs, material costs, maintenance, and repair costs. However, the largest cost that is needed for operating an inspection line for solid part is the labour cost. To simplify the comparison between different automation levels, only the work force costs will be considered in this work. This way only one variable is changing and the comparison between different automation levels is easier.

The operating costs will be compared by means of cost per measured unit. The total time that human worker must do work on the measurement process will be documented. The total time used by human worker on the measurement process will be divided by the total number of measured parts.

2.2 Measurement methods

Methods used to get measurement data include a baseline measurement with contact probing method. The baseline data will be gathered by probing the demo part with high accuracy PCMM. The part will be mounted during the contact probing with robust fittings. The mounting will be reviewed later in this work. The mounting will be done so that the probing head can access all features without turning the part upside down. The part will be fixed in one place during all the measurement runs when gathering the base line data. Series of measurements will be done to the demo part with the contact probing method.

The measurement data that is used to compare both automation levels will be gathered by laser scanning and by structured light scanning. Series of measurements will be done to the demo part with both scanning systems. The part will be mounted in the working field of the system so that the system can see all the features that need to be measured without turning the part upside down. In between every measurement run the part will be detached and mounted again to the jig to simulate a real-life situation where the operator needs to change the part after each measurement run.

The software used to gather the measurement data is *Inspire*. *Inspire* is software made by *Hexagon*. It is designed to work with portable CMMs. In figure 13 the main view of *Inspire* can be seen.

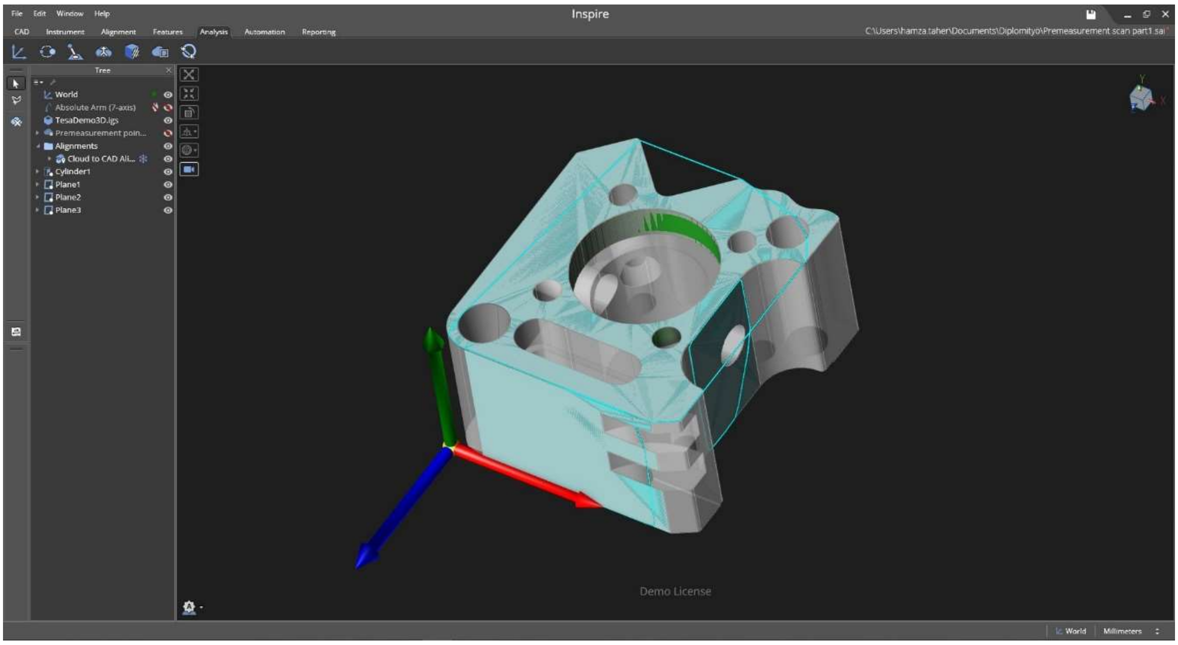
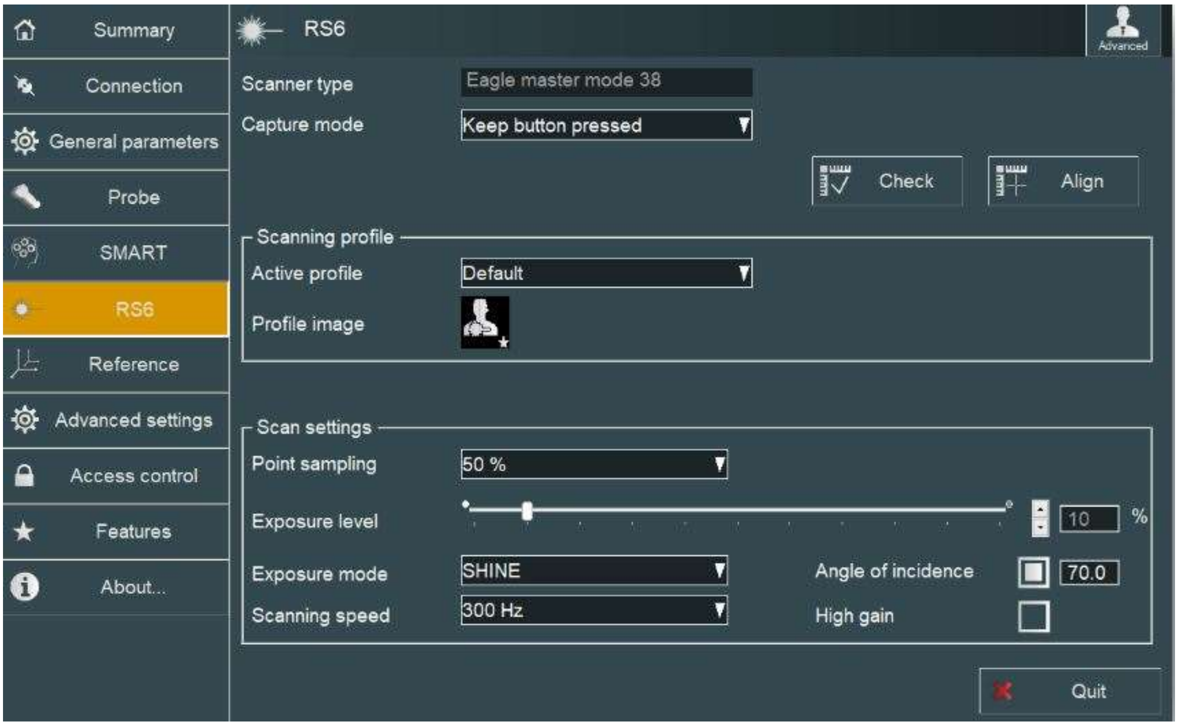


Figure 13. The main view in *Inspire*. To the left a list of features created from computer aided design or CAD-model. In the centre imported CAD-model of the demo part. [25]

The measurement instrument that is used to gather data from the measured object is connected to computer via ethernet cable or wireless network. The data gathered by the instrument is sent to the computer and analysed by the application software. Inside the application software the data is used to create a point cloud. When scanning with laser scanner or SLS systems the instrument collects points from any solid surface that is in the scanner field of view. It is possible to set a virtual plane on the software under which the points are not used to form the point cloud. This can be done after the instrument is aligned with the measured part. Creating this kind of cut-out plane does not have impact on the measurement results. It is done only to limit the number of points that the software must deal with. The number of points affects the calculation speed of the computer. With the number of points increasing, also increases the calculation time of the computer. Therefore, the unwanted points are filtered out if possible.

In addition to the cut-out plane there are more filtering options to use when gathering scanned data. When scanning with the laser scanner there are few settings that need to be specified in *RDS* (*Romer Data Software*). *RDS* is an interface software between the articulating arm and computer. In *RDS* the settings for laser scanner can be specified. The laser scanner used in this work uses scanning filter called SHINE (Systematic High Intelligence Noise Elimination). SHINE adjusts the laser power of the scanner automatically depending on the surface reflectivity. In glossy areas with strong reflection of the laser light SHINE will adjust the laser power to be lower and in areas with low reflectivity the laser power will be increased to get enough reflected laser light back from the surface. During this research the SHINE setting will be on.

Other settings to specify in laser scanning are gain, point sampling, scanning speed and angle of incidence. High gain is set to be off on all the measurements. High gain is meant for surfaces with very dark and glossy finish. Point sampling will be set to 50% on all the measurements. Point sampling has two settings 50% and 100%. If set to 100% there will be twice the number of points gathered by interpolating point between every gathered point. This setting is used when the surface features are very small and detailed. Scanning speed will be set to 300Hz on all the measurements. 300Hz is the highest speed available and it will make the scanning process as fast as possible. Angle of incidence is set to 70% by standard and this will be used on all the measurements. The angle of incidence filters the points taken based on the angle between the scanning laser and the measured surface. The best situation for laser scanner is to take points perpendicular to the measured surface. When approaching the scanned surface from low angles the light that reflects is not sufficient and the data will not be as good as possible. In figure 14 the *RDS* settings page for laser scanner can be seen.



Scanner type: Eagle master mode 38
Capture mode: Keep button pressed

Scanning profile
Active profile: Default
Profile image

Scan settings
Point sampling: 50 %
Exposure level: 10 %
Exposure mode: SHINE
Scanning speed: 300 Hz
Angle of incidence: ☑ 70.0
High gain: ☐

Figure 14. Screen shot of laser scanner settings page from *RDS*. These settings are the standard settings for this type of laser scanner. They work very well in most applications and surface finishes. [25]

2.3 Test equipment

The main equipment on this research are 3D-measuring devices made by *Hexagon MI*. Robots and accessories and mounting solutions might be from other manufacturers. The two main systems used in this research are: 1. Articulating arm *Absolute Arm 8525* 7-axis with *AS1* laser scanner. 2. SLS scanner *Aicon PrimeScan R5 Field of view 200* mounted on *Fanuc CRX-10iA/L* cobot.

The *Absolute Arm* 7-axis articulating arm has probing head with repeatable quick clamp and quick release scanner mount both seen in figure 15. The arm does not need calibration if scanner or probe are changed. *Absolute Arm* is calibrated according to International Organization for Standardization or ISO standards 10360-8 and 10360-12. User can switch between scanning and probing during measurement without realignment. The standard-length probing head and scanner can be mounted to the wrist simultaneously without interference. If longer probing head is used it will interfere with the laser line and should be removed during scanning. The weight of the arm is approximately 10 kg depending on the probe and scanner that are connected to it.

Figure 15. *Absolute Arm* 7-axis articulating arm wrist. Operator holds the device from the pistol grip and takes measurements using the red trigger. Scanner and probing head are both removable with repeatable mounting surface. The calibration certificate of the arm is valid for 12 months. [29]

The *PrimeScan* structured light scanner seen in figure 16 is equipped with powerful projector which enables glossy or dark surfaces to be scanned without pre-treatment. The scanner has laser pointers to show the operator where the field of view of the scanner is. This helps to position the measured object. The *PrimeScan* weights 3.8 kg. It is equipped with Monochrome CCD (charge-coupled device) camera.

Figure 16. *PrimeScan* SLS scanner. It can be mounted to fixed stand or to moving object like robot. In the centre there is light projector and, on the sides, the angled cameras that catch the light pattern on the measured object surface. [30]

3. Measurement planning and premeasurements

The measurement planning is important to give realistic proportions for the number of measurements to be taken. In book *Tutkimusmetodiikan perusteet* by *Eskelinen* and *Karsikas* the basics of research methodology are reviewed. In the book it is said that for the measurements to be reliable the number of measurements needs to be sufficient. What is sufficient is controversial and is greatly dependent on the research itself and only common thought amongst researchers is that when number of measurements increase also increases the reliability. [28]

The number of measurements in this work is limited by the resources available to this research. The measurement machines that are studied in this work are used to do customer demos and contract inspection in daily work, so it is not possible to hold a system for months on end only for the purpose of this work. The number of measurements will be defined by getting enough measurements to be able use simple equations on reliability analysis and the time that is available to make measurements. According to *Eskelinen* and *Karsikas* if the number of measurements (n) is more than 30 (n>30), simple equations can be used during the reliability analysis. [28]

Before the actual measurements a premeasurement is done to get an idea for the feasibility of the test setup and number of measurements. This will be done with the articulating arm and laser scanner because it is the most flexible system to perform different kinds of measurements and experiment with different approaches.

The *Hexagon Absolute Arm 8525* with *AS1* laser scanner was used in the premeasurements to gather data from the demo part. The arm has measurement uncertainty of 0.047 mm according to ISO 10360-8 when using the *AS1* laser scanner.

The arm is held by user by the pistol grip and moved near the measured part so that the blue laser line covers the surface of the part. In figure 17 the handling of the arm can be seen. The laser scanner gathers data with a rate of up to 1.2 million points/second. The data gathering is controlled by holding down the red trigger in the arms pistol grip. When the trigger is released the data gathering is stopped. This way the operator can avoid scanning something that is not meant to be measured.

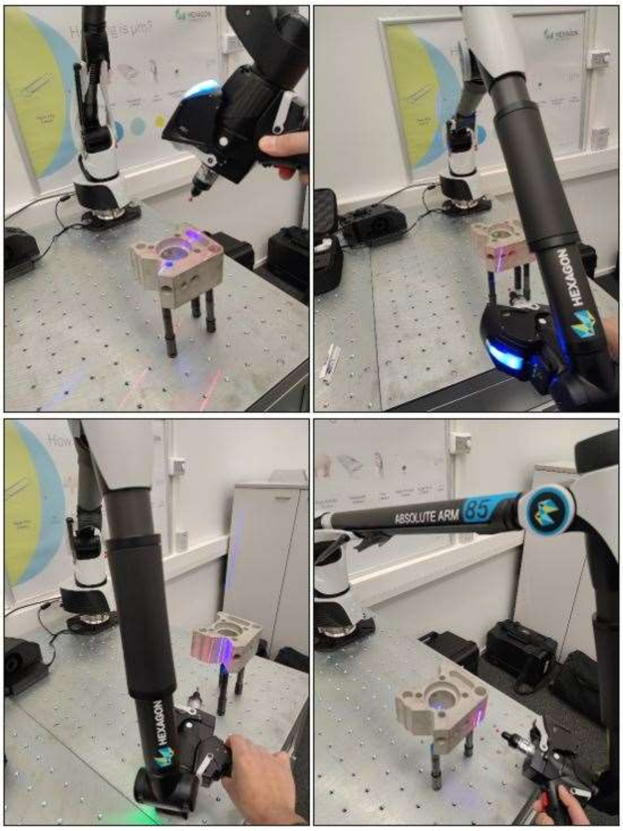


Figure 17**.** A blue laser line is projected on to the surface of the part. The red laser lines seen in the picture are there to guide the operator to hold the scanner in optimal orientation. Operator controls the path of the scanner and is responsible that all the surfaces that need to be measured are covered by the laser line. The arm articulates in different positions so that the whole surface of the part can be digitized to point cloud. [25]

The premeasurement was done on a measurement cart with steel plated top. The steel plated top has threaded holes drilled into it for easy attachment of measuring device and measured part. Figure 18 shows the premeasurement setup. The critical thing to note during measurements with articulating arm is to have the relationship between the arm mounting point and the measured part as rigid as possible. The articulating arm accuracy assumes that the measured part does not move in relation to the arms coordinate system during measurement.

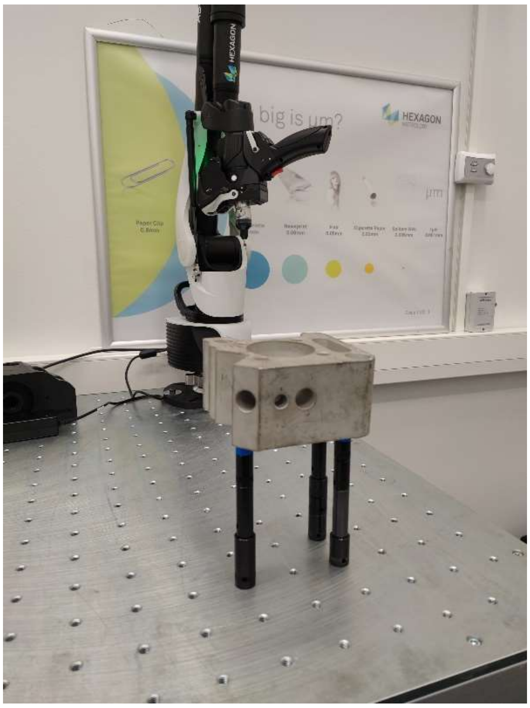


Figure 18. Premeasurement setup with the demo object suspended over three pegs. The articulating arm is fastened to the same threaded plate. The part was only held in place by gravity as laser scanning is contactless measurement type so there is no need to hold down the part during measurement. [25]

After setting up the system and doing first scan with the arm it was noted that the part was not suspended high enough for the scanner to be able to gather points underneath the part. After the first scan the pegs were lengthened from 94 mm to 144 mm so that the scanner could get data from underneath also without turning the part over.

The part was measured a total of 10 times during the premeasurements. The part was picked up from the pegs and put back on in a slightly different orientation after each measurement routine to simulate a part change. When placing the part on to the pegs again after each measurement the relationship between the articulating arm and the part changes. This means that the measurement software must calculate the alignment of the part again in every measurement event. It was noticed after putting the part back on the pegs in very different orientation from the original measurement program that the alignment was not able to be calculated in some instances or the alignment was very poor. The alignment result greatly affects the measurement results.

At each measurement time a total of 34 features were measured from the demo block. It was quickly noticed after starting to process the data that this was way too many features to process with the time available for this work. After re-evaluating the number of processed features, only 1 feature was selected to be recorded from each measurement and processed. The selected feature can be seen in figure 19. The measurement results were exported to excel, and the deviations were calculated. In table 1 the diameter for cylinder 1 from each premeasurement can be seen. Chart 1 shows the plotted measurements results. Chart 2 shows the normal distribution of the measurement results from the scanning.

Table1. Diameter for cylinder 1 from each measurement with the *AS1* laser scanner. At the bottom of the table the average diameter and standard deviation can be seen.

Measurement number	Feature	Measured diameter (mm)
1	Cylinder 1	64.006
2	Cylinder 1	64.014
3	Cylinder 1	64.021
4	Cylinder 1	64.005
5	Cylinder 1	63.997
6	Cylinder 1	63.980
7	Cylinder 1	64.019
8	Cylinder 1	64.010
9	Cylinder 1	64.023
10	Cylinder 1	64.019
Average		**64.009**
Standard Deviation		**0.0125**

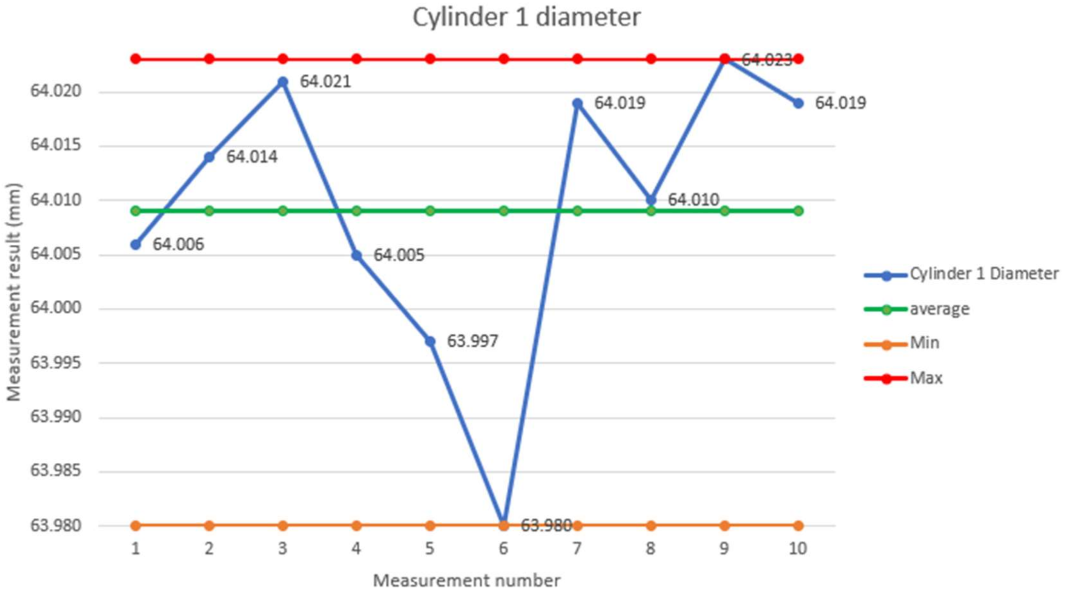


Chart 1. The measurement results from the premeasurement scanning can be seen in this chart.

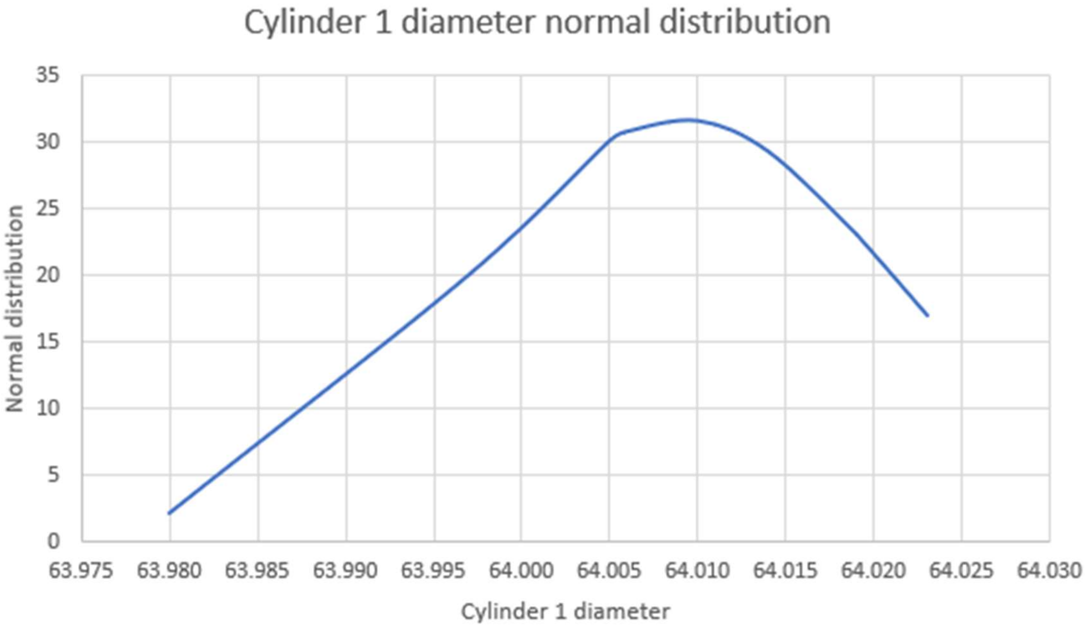


Chart 2. Normal distribution of cylinder 1 diameter from premeasurement scanning.

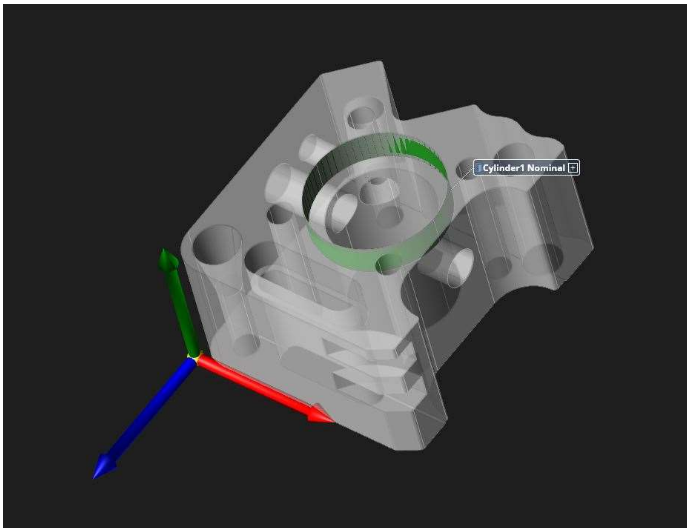


Figure 19. Cylinder 1 highlighted in green. Nominal diameter for this cylinder is 64 mm. [25]

In addition to scanning, cylinder 1 was also measured with contact probing method using *Hexagon Compact arm 7512*. The contact probing method was done to get finer estimate of what the actual diameter for this cylinder is. *Compact arm* is the smallest version in *Hexagon* line-up of articulating arms. It has 6 axles and contact probing head. The *Compact arm* has measurement uncertainty of 0.006 mm when probing according to ISO 10360-2 standard. The Compact arm has measurement volume of 1.2 m. In figure 20 the *Compact arm* can be seen.

Figure 20. *Compact Arm* in the right and *Absolute Arm 8525* in the left. The size difference between the two articulating arms is noticeable. Shorter shafts and fewer joints of the *Compact Arm* means higher measurement accuracy compared to the larger *8525* with longer shafts and extra joint, 7 axles versus 6 axles in the *Compact Arm*. [25]

In table 2 the measurement results can be seen for the diameter of cylinder 1 when measuring it with the *Compact Arm*. The diameter of cylinder 1 was also measured with caliper and the result was 63.98 mm.

Table 2. The measurement results after measuring cylinder 1 by contact probing.

Measurement number	Feature	Measured diameter (mm)
1	Cylinder 1	63.976
2	Cylinder 1	63.978
3	Cylinder 1	63.978
4	Cylinder 1	63.978
5	Cylinder 1	63.978
6	Cylinder 1	63.980
7	Cylinder 1	63.981
8	Cylinder 1	63.984
9	Cylinder 1	63.981
10	Cylinder 1	63.978
Average		**63.979**
Standard Deviation		**0.002**

The premeasurement results for the diameter of cylinder 1 from scanning and probing were compared and it was found that the standard deviation of the measurement results when scanning was quite high compared to contact probing with the *Compact Arm*. Clearly contact probing is the more reliable way of measuring the diameter of a machined hole. In table 3 the difference between the scanned diameter and the probed diameter is seen.

Table 3. The table shows difference between scanned and probed diameter in the premeasurements. The average deviation between scanned and probed diameter for cylinder 1 is 0.030 mm. This is within the specs of the *8525 Absolute arm* with *AS1* scanner. The maximum permissible error (MPE) of the device is 0.047 mm.

Measurement number	Feature	Scanned diameter mm	Probed diameter average mm	Difference between scanned and probed mm
1	Cylinder 1	64.006	63.979	0.027
2	Cylinder 1	64.014	63.979	0.035
3	Cylinder 1	64.021	63.979	0.042
4	Cylinder 1	64.005	63.979	0.026
5	Cylinder 1	63.997	63.979	0.018
6	Cylinder 1	63.980	63.979	0.001
7	Cylinder 1	64.019	63.979	0.040
8	Cylinder 1	64.010	63.979	0.031
9	Cylinder 1	64.023	63.979	0.044
10	Cylinder 1	64.019	63.979	0.040
Average		**64.009**	**63.979**	**0.030**

The measurement process begins with importing the CAD-model to the measurement software. After the CAD-model is imported, features can be extracted from the model by using the Extract from CAD operation in the measurement software. When using this operation user can choose different features like circles, cylinders, and planes from the model by hovering mouse pointer over the wanted CAD-surface and clicking the left mouse button. The feature under the mouse pointer highlights yellow to indicate which feature is chosen. In figure 21 the Extract from CAD operation can be seen.

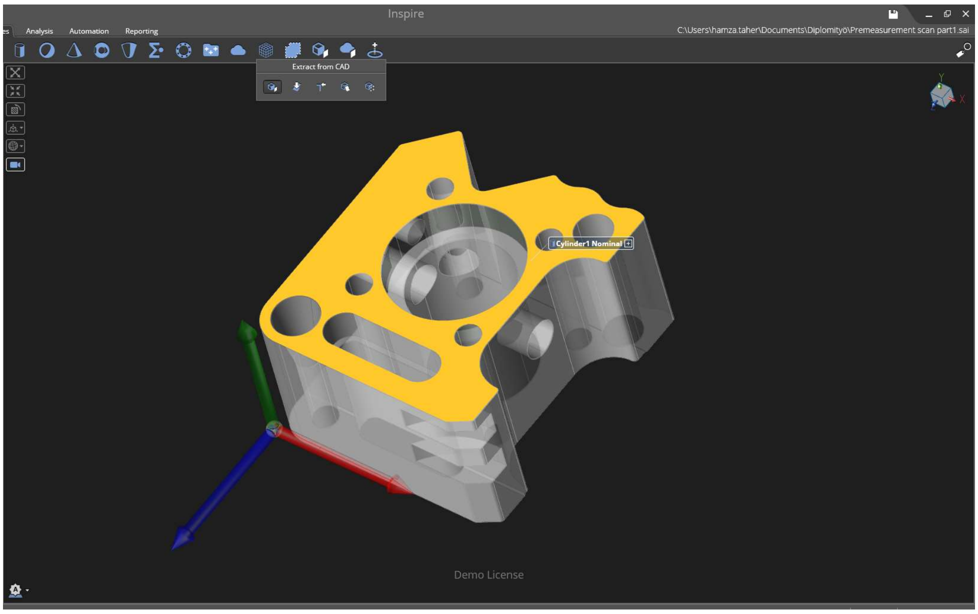


Figure 21. In the Extract from CAD operation user can choose different features from the CAD-model. In this figure the top plane of the part is highlighted in yellow to indicate to the user that this feature is selected. User can confirm the selection by pressing Enter on the keyboard. [25]

After the wanted features are chosen, the next step is to get the data from the actual part by scanning it with the laser scanner. During scanning a point cloud of the surface of the part is being created. Operator can see from the point cloud which areas are fully covered and if some areas need more data. In figure 22 a point cloud of demo object can be seen.

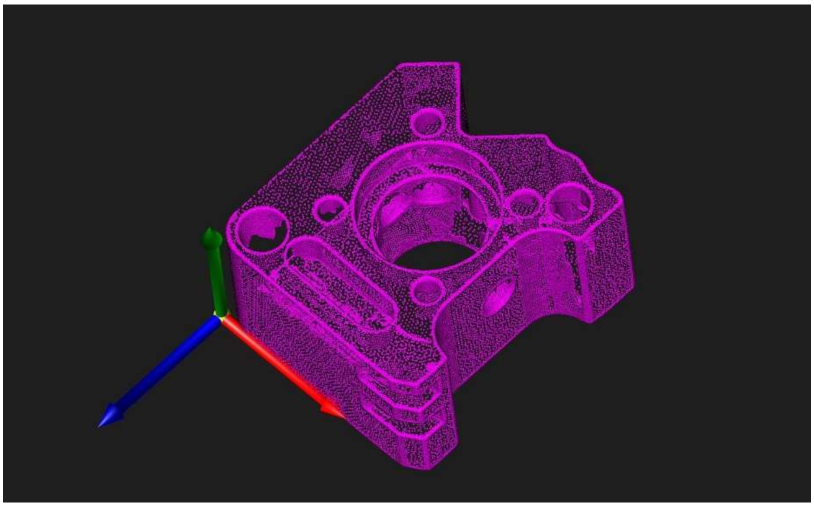


Figure 22. When scanning the part with the laser scanner the operator can see the part surface digitised in the measurement software as point cloud. [25]

After the part surface is digitised into the measurement software as point cloud, an alignment can be done. With the Alignment tool pack different kind of alignments can be done. First to get the point cloud and the CAD-model roughly aligned a cloud to CAD alignment was done. This operation aligns the point cloud to match the CAD-model as closely as possible. In the measurement software the operation can be found under the button named Create Cloud to CAD/Mesh Alignment. In figure 23 the CAD-model and point cloud are aligned.

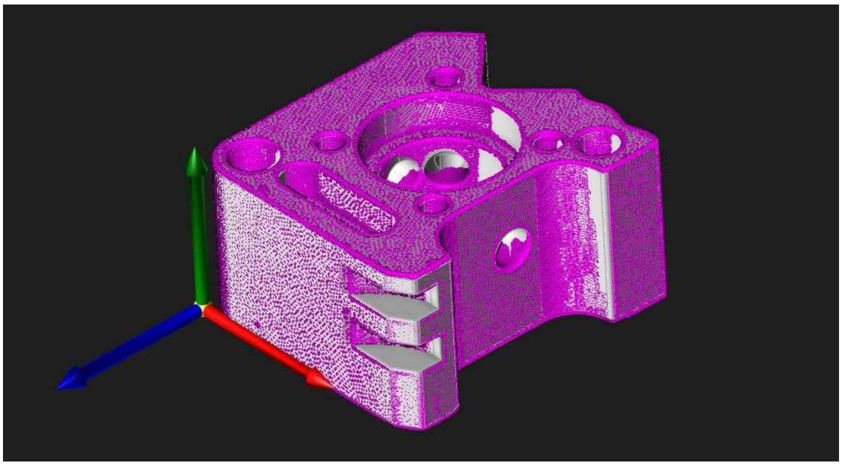
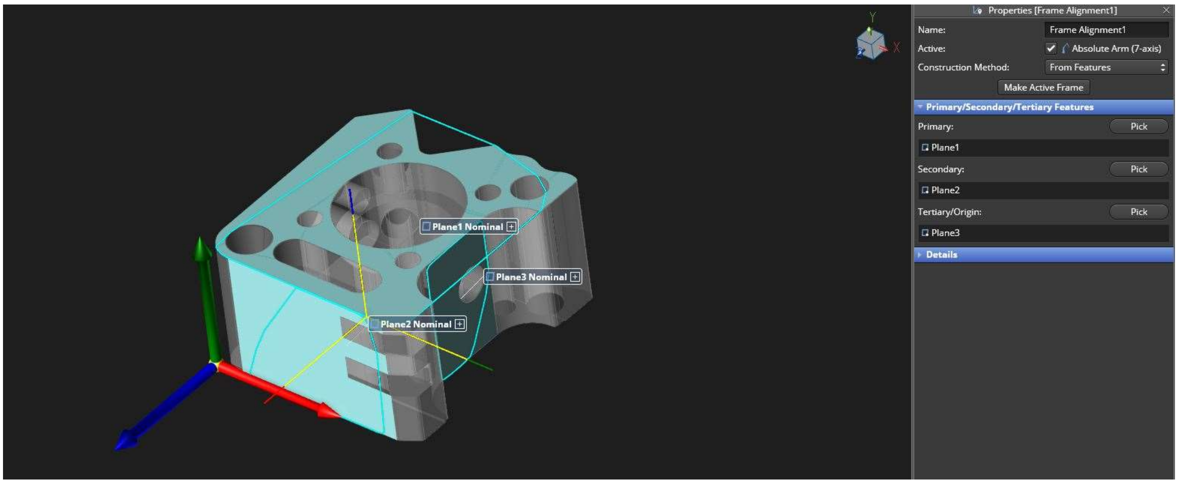


Figure 23. After Cloud to CAD alignment the CAD-model and point cloud are as closely matched as possible. This alignment considers every point on the cloud equally and tries to minimise the distance between each point and the CAD-model. [25]

After the cloud to CAD alignment the software can extract data from the cloud to the features that were selected from the CAD-model. This extraction is done automatically when the software has data objects near enough the nominal feature. After the cloud to CAD alignment a more refined alignment can be done using three planes. This operation can be started by pressing the Create Frame Alignment button in the measurement software. After starting the frame alignment, the software asks the user to select primary, secondary and tertiary feature for the alignment. In figure 24 the picked features can be seen.



Properties [Frame Alignment1]

Name: Frame Alignment1

Active: ☑ Absolute Arm (7-axis)

Construction Method: From Features

Primary/Secondary/Tertiary Features

Primary: Plane1

Secondary: Plane2

Tertiary/Origin: Plane3

Figure 24. The three planes that were used to create the frame alignment can be seen in this picture highlighted in green. Plane 1 is the top surface of the part. Plane 2 is the surface facing left and Plane 3 is the surface facing right. [25]

Based on the premeasurements it was noticed that the number of measured features should be in a realistic level in relation to the available resources. It was also noted that the placement of the measured part should be done in a controlled manner so that the measurement device is able to take all the measurements without the need to rotate the part during measurement. Also, the placement of the part should be as repeatable as possible. A more controlled jigging for the part is advisable to construct for the upcoming measurements.

The measurement time average for premeasurements was 3 minutes. The minimum measurement time was 2 minutes 14 seconds. Maximum measurement time was 3 minutes

51 seconds. The measurement time includes part change. The setup time and setup modification times were not documented separately. It took approximately one working day to perform the premeasurements. The temperature inside the measuring room was steady 21℃ during the premeasurements.

4. Main measurements

In this chapter the setup and results for the main measurements are reviewed.

The main measurement with articulating arm and *AS1* laser scanner was done 30 times. The part was placed to the measurement stand again after each measurement run to simulate the part change as in real life measurement situation. The setup for main measurements with laser scanner was different from premeasurements so that the demo part was placed directly on to the metal surface of the measurement table. To make sure the part was positioned similarly on each measurement run, a jig was made on to the threaded measurement table to position the demo part. The position of the demo part was marked clearly with marker to make sure it was placed correctly on the jig. In figure 25 and figure 26 the positioning of the demo part and the jig can be seen.

The laser scanning settings in *RDS* were the same as in premeasurements. Also, the alignment used in main measurement was the same that was made in the premeasurement stage. The room temperature during the main measurements was steady 21°C.

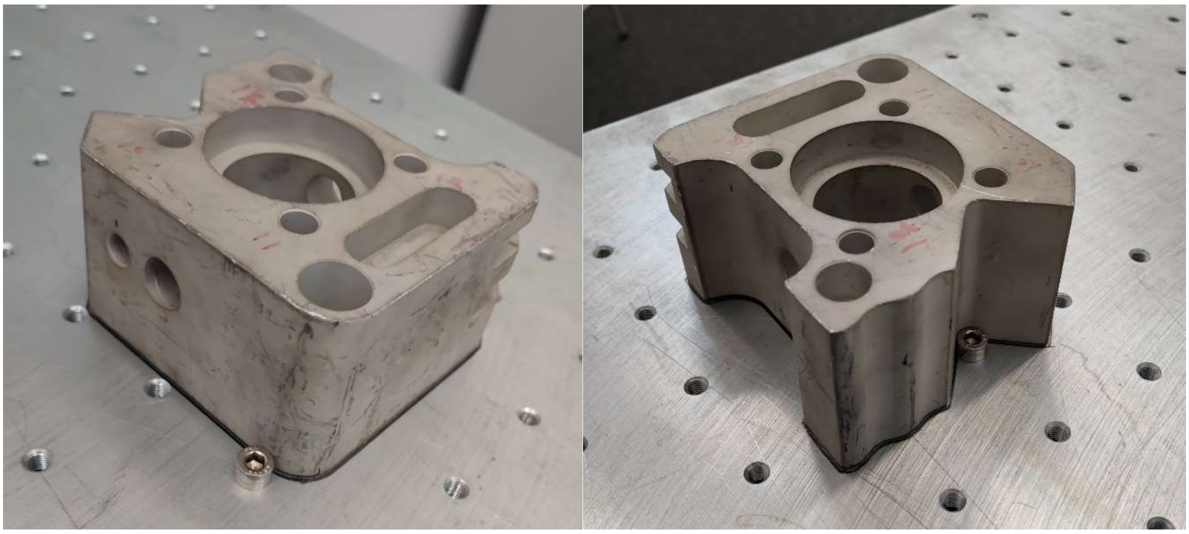


Figure 25. The positioning of the demo part was done with simple jig. The outline of the part was drawn to the measurement table and two screws were screwed to the table to guide the part to the same position after each measurement run. [25]

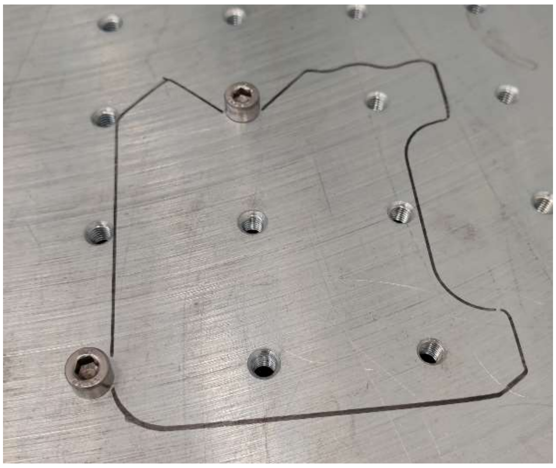


Figure 26. The outline and the screws can be clearly seen in this picture. The jig helps user to position the part very similarly in each measurement run. [25]

The positioning of the part in relation to the articulating arm and laser scanner was like the premeasurements. Using the articulating arm, the measured part is placed so that the operator can reach all necessary surfaces of the measured part easily with the measuring device. In figure 27 the positioning of the demo part in relation to the articulating arm during main measurements can be seen.

Figure 27. The positioning of the demo part in relation to the arm is like the premeasurement setup even though the support for demo part has been changed a little bit. The part is placed so that the laser scanner can reach all necessary surfaces of the demo part without the need to rotate the demo part. [25]

The total time it took to make the main measurements with laser scanning was 1 hour 3 minutes and 19 seconds. This gives average time per measurement run of 2 minutes and 7 seconds. The measurement results for the main measurement with laser scanner can be seen in table 4.

Table 4. The measurement results for laser scanning can be seen in this table. The feature that was measured is cylinder 1. The diameter of cylinder 1 is presented in this table. In the bottom of the table the Average, Standard Deviation, Min, and Max values for the diameter can be seen.

Measurement number	Measured feature	Diameter (mm)
1	Cylinder 1	63.992
2	Cylinder 1	63.998
3	Cylinder 1	63.994
4	Cylinder 1	63.998
5	Cylinder 1	64.003
6	Cylinder 1	63.994
7	Cylinder 1	63.999
8	Cylinder 1	64.004
9	Cylinder 1	64.006
10	Cylinder 1	64.009
11	Cylinder 1	64.012
12	Cylinder 1	64.010
13	Cylinder 1	64.011
14	Cylinder 1	64.010
15	Cylinder 1	64.007
16	Cylinder 1	64.006
17	Cylinder 1	64.007
18	Cylinder 1	64.005
19	Cylinder 1	64.014
20	Cylinder 1	64.008
21	Cylinder 1	64.008
22	Cylinder 1	64.007
23	Cylinder 1	64.012
24	Cylinder 1	64.004
25	Cylinder 1	64.015

26	Cylinder 1	64.019
27	Cylinder 1	64.025
28	Cylinder 1	64.017
29	Cylinder 1	64.023
30	Cylinder 1	64.028
Average		**64.008**
Standard Deviation		**0.009**
Max		**64.028**
Min		**63.992**

In chart 3 the measurement results for laser scanning can be seen. From the chart it is easy to see how the measurement result changes during the series of measurements.

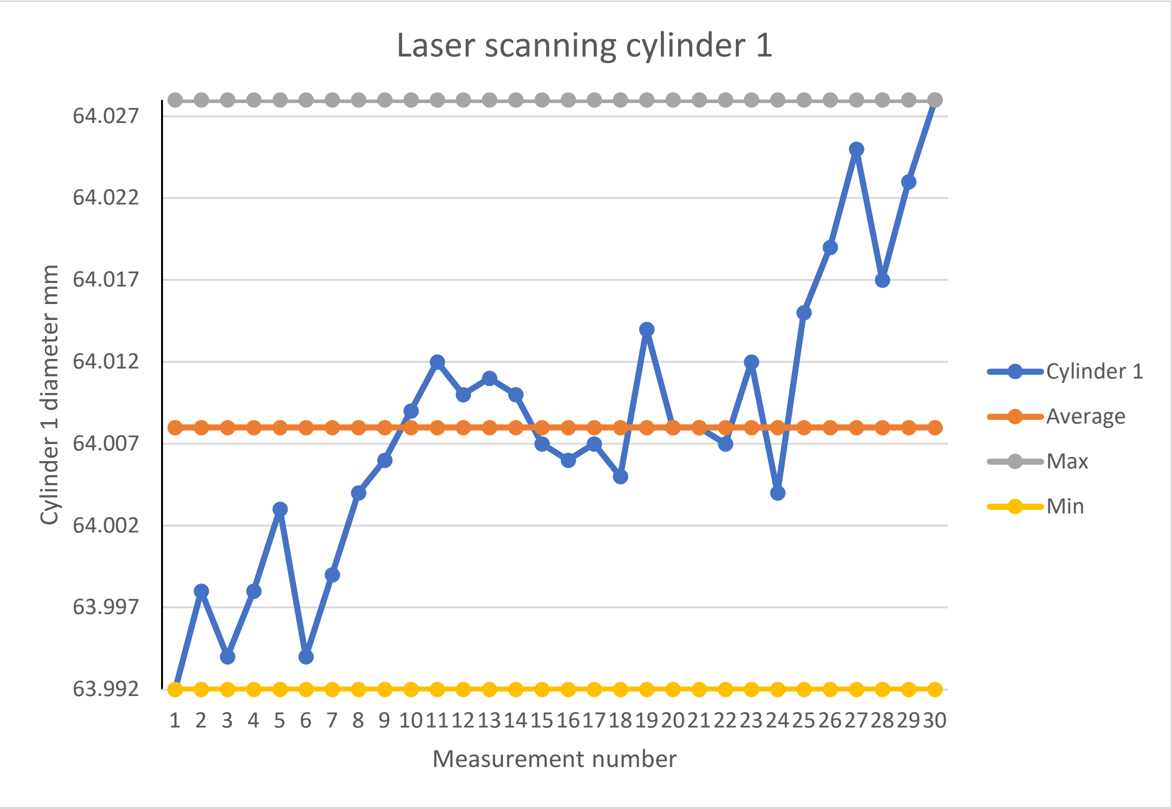


Chart 3. The measurement results from main measurement with laser scanner can be seen in this chart. The horizontal axis is the measurement number, and the vertical axis is the cylinder 1 diameter.

In chart 4 the normal distribution of the cylinder 1 diameter can be seen. From normal distribution chart it is easy to see which result is most probable when using the laser scanner to measure the diameter for cylinder 1.

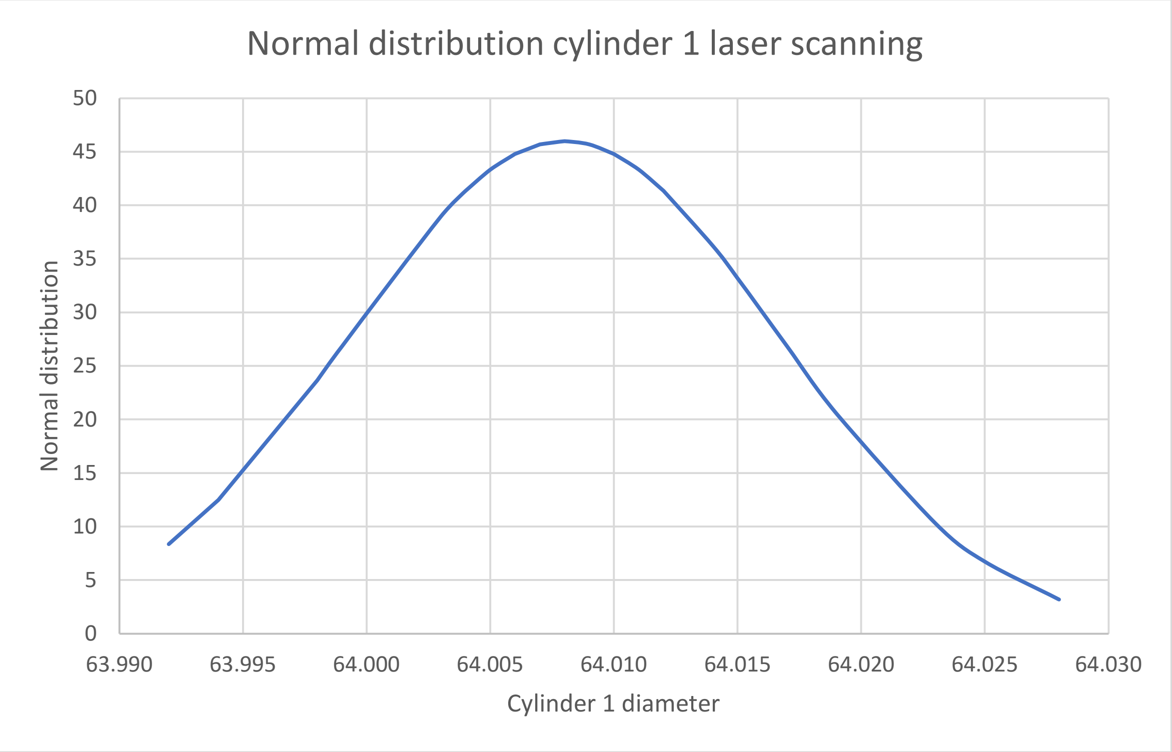


Chart 4. In this chart the normal distribution for cylinder 1 diameter can be seen. The horizontal axis is the cylinder 1 diameter and vertical axis is the normal distribution value.

In figure 28 the measurement setup for the COBOT + *Primescan* system can be seen. The COBOT was fixed to a measurement cart table with screws. The demo part was placed on a stand that was fixed to the same table as the COBOT. The *Primescan* SLS scanner was fixed to the COBOT.

The COBOT + *Primescan* measurements produced digitized surface of the part as did the laser scanning method. The processing of the produced digitized surface was same to the COBOT + *Primescan* system as for the laser scanning system. The digitized surface was first aligned roughly to the CAD-model with best fit alignment and after that aligned with finer frame alignment. Cylinder 1 was extracted from the cloud after alignments. Results from the COBOT + *Primescan* measurements can be seen in table 5.

Figure 28. The COBOT + *Primescan* system measurement setup. A similar cart was used with the laser scanner setup also. The threaded tabletop is handy when setting up different kind of measurement situations.

Table 5. COBOT + *Primescan* measurement results. Diameter for cylinder 1 in the right column. Average, Standard Deviation, Min, and Max values at the bottom.

Measurement number	Measured feature	Cylinder 1 diameter
1	Cylinder 1	63.972
2	Cylinder 1	63.969
3	Cylinder 1	63.968
4	Cylinder 1	63.968
5	Cylinder 1	63.970
6	Cylinder 1	63.968
7	Cylinder 1	63.968
8	Cylinder 1	63.968
9	Cylinder 1	63.967
10	Cylinder 1	63.966
11	Cylinder 1	63.966
12	Cylinder 1	63.967
13	Cylinder 1	63.967
14	Cylinder 1	63.970
15	Cylinder 1	63.969
16	Cylinder 1	63.969
17	Cylinder 1	63.967
18	Cylinder 1	63.966
19	Cylinder 1	63.967
20	Cylinder 1	63.971
21	Cylinder 1	63.966
22	Cylinder 1	63.968
23	Cylinder 1	63.969
24	Cylinder 1	63.968
25	Cylinder 1	63.967
26	Cylinder 1	63.969
27	Cylinder 1	63.970
28	Cylinder 1	63.967
29	Cylinder 1	63.968
30	Cylinder 1	63.968
Average		**63.968**
Standard Deviation		**0.001**
Min		**63.966**
Max		**63.972**

In chart 5 the measurement results for COBOT + *Primescan* system can be seen graphically.

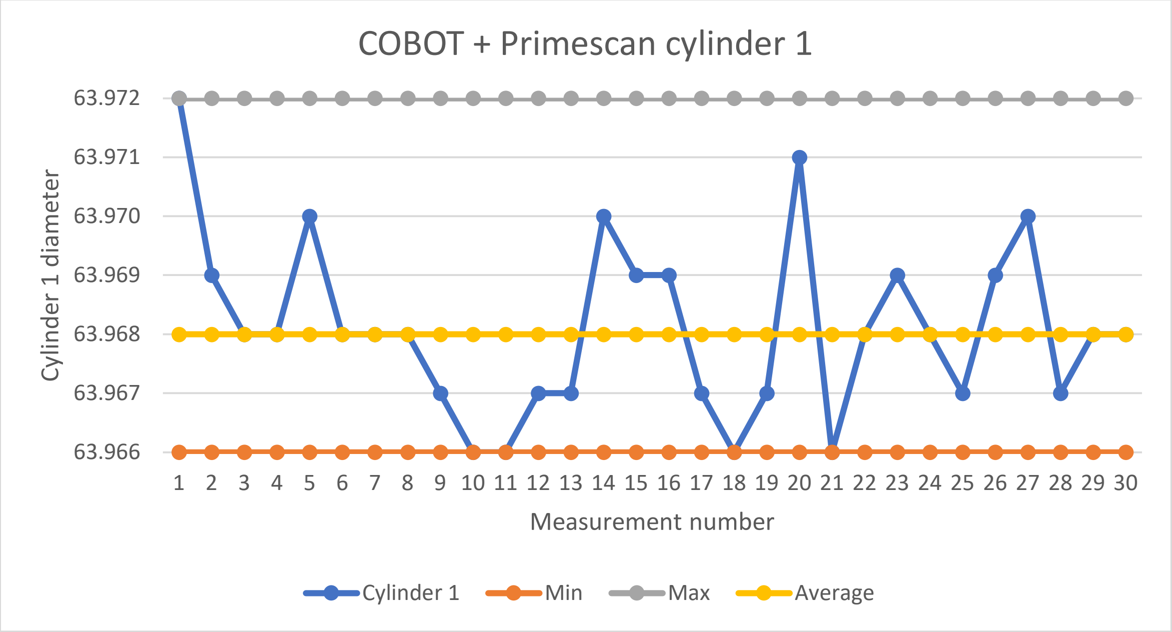


Chart 5. Graph of cylinder 1 diameter from COBOT + *Primescan* measurements. Vertical axis is the cylinder 1 diameter and horizontal axis is the measurement number.

The normal distribution graph of COBOT + *Primescan* system measurements can be seen in chart 6.

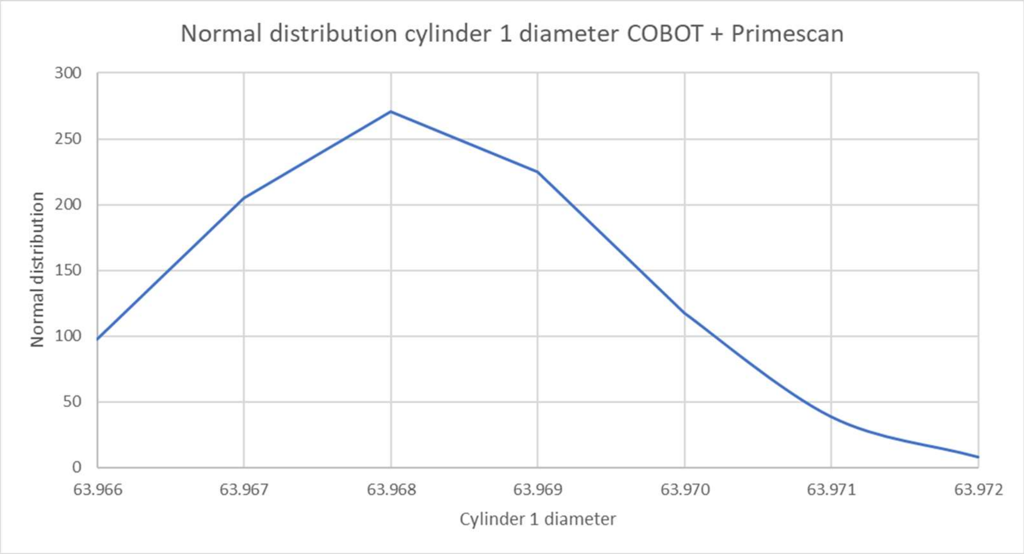


Chart 6. Normal distribution of cylinder 1 diameter from the COBOT + *Primescan* measurements. Vertical axis is the Normal distribution and horizontal axis is the cylinder 1 diameter.

The COBOT was programmed to move the *Primescan* to 12 different positions where the COBOT would stop and the *Primescan* would scan the demo part. Each measurement run lasted approximately 4 minutes. Between each measurement run the operator would process the data, place the part again to the stand and start the measurement again. The processing of the data and replacing the demo part took approximately 1 minutes and 20 seconds. The measurement with COBOT + *Primescan* system took approximately 2 hours and 40 minutes in total. The data acquiring was done using software called *Scan Control* and the data processing was done with *Inspire*.

There were some settings in *Scan Control* software that were specified during the tests with the COBOT + *Primescan* measurement. First and most crucial setting was the first position where the COBOT stopped. A 45-degree angle in relation to the part was specified for the *Primescan*. In figure 29 the first position of the scanner can be seen. The first position was specified so that the *Primescan* would have as good coverage as possible of the part.

Figure 29. The first measuring position of the COBOT + *Primescan* system. The projected white light patterns can be seen on the demo part and at the wall behind the part.

The rest 11 positions that the system stopped at were too from approximately 45-degree angle so that the part was covered all around. At this measurement the bottom of the part was neglected because there were not any features that needed to be measured. The other main settings in *Scan Control* were mesh setting which was set to Standard fast. Part complexity setting was set to simple and part glossiness setting was set to bright.

5. Analysis and economical differences

The measurement results from the laser scanning main measurement revealed that the diameter of cylinder 1 grew as the testing proceeded. The diameter seemed to stay relatively similar at the beginning of the testing during the first 8 measurements. With the 9th and 10th measurement time the diameter jumped to around the average value of the diameter. In the middle of the testing the diameter hovered around the average mark from the 10th to 25th measurement time. At the end of the measurements the 26th to 30th measurement time the diameter shot up quite steeply. The maximum diameter was recorder at the 30th measurement time. The maximum diameter for cylinder 1 was 64.028 mm.

When noting that the diameter that was acquired with contact probing method for the cylinder 1 was 63.979 mm, the laser scanning result of main measurement can be compared to the contact probing result. The scanning result of main measurement stayed within the specifications for the laser scanner system almost throughout the whole measurement. The maximum permissible error for the *AS1* laser scanning system + articulating arm used in this work is 0.047 mm. So, keeping in mind the measurement uncertainty of the used measurement device, the results were as expected. One exception was the last measurement time. At the 30th measurement time the diameter of cylinder 1 was 64.028 mm which is 0.049 mm larger that the probed diameter.

It would be interesting to see what would have happened if the measurements would have continued for a longer time but the resources available to this work are limited. The results are noted and will be analysed internally at *Hexagon* to see if there is something to further investigate the diameter growth.

The main measurements with COBOT + *Primescan* system showed that the cylinder 1 diameter was very steady throughout the measurement. The average diameter for cylinder 1 was 63.968 mm which is only 0.011 mm smaller that the diameter acquired with contact probing method. The standard deviation for the cylinder 1 diameter from COBOT +

Primescan system measurements was 0.001 mm which tells just how repeatable the measurements with robotic system can be. The maximum diameter for cylinder 1 in COBOT + *Primescan* measurements was 63.972 mm, and the minimum diameter was 63.966 mm. There is only 0.006 mm between the minimum and maximum values. The *Primescan* model that is attached to the COBOT is R5 Field of view 200. For this model the measurement uncertainty is specified by manufacturer to be 24 micrometres. So, looking at the specified uncertainty of the system and the results that the test yielded, it can be said that the system was performing as it should be.

After getting data from both systems, it is possible to do some comparisons between the two systems. As it was said in the Introduction section, these systems will be compared from the quantitative point of view and from the economical point of view. Below the research questions can be seen that were stated in the introduction chapter.

Cost research questions

- What is the initial investment difference between the two different levels of automation?
- What is the operating costs difference between the two different levels of automation?

Measurement results research questions

- What is the difference between measurement time between the two different levels of automation?
- What is the difference in measurement deviations between the two different levels of automation?

The first research question was related to cost and the initial investment difference between the two systems. The price information is sensitive and will be available to the inspectors of this thesis.

The laser scanning system with articulating arm will be called system A and the COBOT + *Primescan* system will be called system B. System B is approximately 1.7 times the price of the A system. The price for the COBOT + *Primescan* system is still an approximation because it is still in development state as a system. The system purchase prices usually include the necessary training that is needed for the operators of the system to be able to confidently operate the system on their own. The purchase price also includes all necessary hardware and software for the system to be completely functional.

When comparing the two systems it is important to also compare the cost of use for both systems. To get a simplified idea of what the cost of use would be for both systems, the measurement times of both systems from main measurements will be compared. The measurement time will tell in a simplistic way how much the operator must do work when measuring the same exact part.

Measurement time for system A was approximately 1 hour and 3 minutes. For system B the measurement time was approximately 2 hours and 40 minutes. The time it took to complete the measurements with system B was approximately 2.5 times the time that it took system A to perform the measurements. This comparison doesn't take in consideration the human operator involvement. When looking at the human operator involvement in the measurement process, the system A measurement time required constant human operator involvement. System B involved human operator involvement only in between the measurement runs changing the part and processing the data and initiating the system measurement process again. The human operator involvement time was approximately 40 minutes during the whole measurement with system B.

The cost of use difference can be approximated by comparing the human operator involvement times for both systems. It is assumed that the operator for both systems is costing the same amount of money for the company. When looking at the differences only between the human operator involvement times, system B required approximately 37 % less human operator involvement than system A. Taking in consideration that the demo part used in this test was quite small when comparing to the measurement volume of both systems, a larger difference in human operator involvement can be predicted with larger measurement objects.

To be able to decide for investing in more automated system, investors need to have idea what the return on investment will be for that particular investment. ROI calculation can be simplified as follows

$$ROI = \frac{Benefit}{Investment} \tag{1}$$

where benefit is the return that the investment gives to the investor. In this case it is the savings in labour cost because of the smaller human operator involvement time. Investment is the initial investment of the system that in this case is the COBOT + *Primescan* system higher price in relation to the articulating arm + laser scanner system. By investing more initially, investor can get savings in the longer run. To be able to exactly know how long it would take for the investment to payback, the investor needs to know what is the yearly salary that the company pays for its measurement personnel, what is the volume of measurements needed to perform on a yearly basis and what is the initial investment made.

With only the knowledge of the initial investments and the difference in time involving human operator for both systems there is not enough data to be able to make any ROI calculations. It can only be presented how the investors can use the data gathered from this work to perform ROI calculations on their own.

The measurement result comparison between the two systems shows that with more automated system, the results are more repeatable. With articulating arm + laser scanner the standard deviation was 0.009 mm and with the COBOT + *Primescan* system the standard deviation was 0.001 mm. The COBOT + *Primescan* system being a new concept and in experimental phase during this thesis, it was confirmed that the system can function as intended. With more automation the workload of human worker can be reduced, and efficiency can be increased. When measuring bigger parts that take longer to scan, the difference between articulating arm + laser scanning system and COBOT + *Primescan* system would likely become even more pronounced. One further testing suggestion is for larger parts that take longer to scan. That would really pronounce the benefits of the more automated system.

One additional aspect of comparison that was not discussed at the Introduction chapter is user comfort. In an inspection situation like the tests in this work with many similar parts being inspected in great numbers, the more user involving articulating arm becomes somewhat tiresome to use and the user becomes fatigued quite easily. In this type of situation with many similar parts needing to be inspected, the COBOT + *Primescan* system will be the more user-friendly system where the operator doesn’t have to move the measurement device at all. It is valuable to know that when needed, the articulating arm + laser scanner system can perform in this type of heavy loaded measurement environment also.

The articulating arm + laser scanner system took only a little over 1 hour to perform the 30 measurements and the COBOT + *Primescan* system took 2 hours and 40 minutes. That shows just how flexible to use the articulating arm system is, and it is possible to do a lot of work with it in short time if needed. This flexibility comes in favour when the inspection need consists mainly of larger complex objects. When starting a new objects measurement with the articulating arm system there is no need to reprogram any equipment or reconstruct complicated measurement software that fits the measured object. The user can move the measurement device in any way that is needed to acquire the needed data. The more automated COBOT + *Primescan* system takes more planning and preparation to start measure a completely new object.

6. Discussion

The results from laser scanning main measurement showed that the diameter of cylinder 1 was growing during the measurements. Although the results were mostly inside the specified measurement uncertainty of the articulating arm + laser scanner system, its interesting behaviour and needs to be noted. There could be multiple possible reasons for this behaviour. Those reasons are speculated in this chapter.

One possible reason for the cylinder 1 diameter growth during laser scanning measurements is heat transfer from operator hand to the demo part. The demo part was picked up from the jig and put back in after each measurement time. The part was handled by bare hands and the body heat from operators' hand could transfer into the demo part. This heat can cause heat expansion which could result to the diameter growth. The demo part material is not known specifically. It is metal and possibly some kind of aluminium alloy based on the weight of the part. It can be estimated if heat expansion could be the reason for the diameter growth by approximating the heat needed to expand the diameter by the amount it expanded during the measurement.

During the main measurement with laser scanner, the result for cylinder 1 diameter grew for 0.036 mm. The minimum value was 63.992 mm, and the maximum value was 64.028 mm. By calculating the heat needed to expand the diameter from min to max value it can be approximated if the heat expansion can be the reason for the diameter growth. Thermal expansion of hole in metal can be approximated as follows

$$\frac{\Delta A}{A_{initial}} = \propto_A \Delta T \tag{2}$$

, where ΔA is the change of area of the hole, $A_{initial}$ is the initial area of the hole, $\propto_A$ is the coefficient of thermal expansion for the material and ΔT is the temperature difference. The temperature difference is what is wanted. The temperature difference can be calculated as follows

$$\Delta T = \frac{\Delta A}{(\propto_A * A_{initial})} \tag{3}$$

The coefficient of thermal expansion for aluminium is approximately $24*10^{-6}$ m/ (m °C). The areas for initial hole and expanded hole are calculated as follows

$$A_{initial} = \pi \left(\frac{63.992\ mm}{2}\right)^2 = 3216\ mm^2 \tag{4}$$

$$A_{expanded} = \pi \left(\frac{64.028\ mm}{2}\right)^2 = 3220\ mm^2 \tag{5}$$

Now the temperature difference can be calculated as follows

$$\Delta T = \frac{0.00322\ m^2 - 0.003216\ m^2}{24*10^{-6} \frac{m}{m°C} * 0.003216\ m^2} = 50°C \tag{6}$$

This calculation shows that for the cylinder diameter to grow from 63.992 mm to 64.028 mm only due to thermal expansion of the demo part, it would take a temperature change of approximately 50°C to do that. When taking in consideration that the part was already at around 21°C when the measurements started, it would have been approximately 70°C at the end of the measurements. That is well above human body temperature and would have been quite painful to handle. During the measurements, the part did not feel any warmer to the touch and certainly not too hot to touch. This said it still is possible that thermal expansion can have some part in the diameter growth although very minor. The temperature of the demo part was not monitored during the measurements. That is something that will be done if further testing will be done.

Other possible reason for the growth of cylinder 1 diameter in laser scanning is form error of the cylinder. A perfect cylinder is perfectly round and perfectly straight but in the real-world errors from the manufacturing process result the machined cylinder to have imperfections. These imperfections are registered by the measurement device that is used to measure the cylinder dimensions. In this case the cylinder 1 was measured with laser scanning. The laser scanning device projects laser light at the cylinder wall and the scanner sensor registers the returning reflection of the laser light. The reflection is used to create a digitised copy of the cylinder wall. The digitized copy of the cylinder wall is created in the measurement software as point cloud. This point cloud is then used to create a cylinder feature inside the measurement software. The measurement software creates the cylinder feature by best fitting the points to form a cylinder. It is possible that the cylinder has some form error that causes the measurement software to calculate the best fit of the cylinder a little bit differently each time it is measured thus resulting in changing diameter. During the measurements done in this work, the form error of the cylinder was not considered. In future testing it is suggested to use a measurement object with known form error. There is a certified sphere provided with the laser scanning system to perform checks and adjustments if needed. This sphere has certification from the manufacturer that describes the form error and diameter of the object in great accuracy. It is advisable to use this measurement object if further test will be done to find out the reason for the diameter of the cylinder 1 diameter growing during main measurements with laser scanner.

It can also be speculated if the reason for the cylinder 1 diameter growth had something to do with the laser scanner internal factors. The articulating arm + laser scanner system is electronic device that has many different heat producing components inside. As we know, heat causes materials to expand and thus result in internal error in any measurement device. Knowing this the articulating arm has temperature sensors build into the device and the temperature information is used to compensate the measurement results so that the device can maintain the specified accuracy level. The specified operating temperature for the

Absolute Arm is from 5 to 45°C. Noting that the measurement room temperature was steady 21°C throughout the whole main measurement, the arm was operating within its specified operating temperature range. It is possible that the heavy constant use of the laser scanner caused the thermodynamic stability of the device to go beyond the threshold designed for the device. Further testing will be done internally at *Hexagon* to find out if the device used was in designed operating condition. As mentioned before the diameter of cylinder 1 stayed mostly within the specified measurement uncertainty of the used device. If the testing would have been continued further, it is possible that the diameter growth would have stopped and maybe started to shrink with further measurements.

Reading this work, it is important to understand that the articulating arm + laser scanner device used in this work is designed to measure large volume objects with multiple features. The cylinder measurement performed in main measurements was a way to get a clear understanding of the differences in the different measurement systems. The benefit of laser scanning with articulating arm is the flexibility of the system. It can be used in various inspection tasks and brings efficiency to the inspection process. As mentioned in introduction chapter, the articulating arm + laser scanner system can be used to perform semi-automatic measurements. With laser scanning, the inspection process can be performed in a way that the operator doesn't need to know a lot about metrology. A measurement program can be created for different products before or after the measurement process takes place. The measurement device operator's job is only to cover enough surface of the measurement object so that the measurement software can extract all wanted features from the data. When the first measurement program for a particular part is created, the same program can be used to measure same parts repeatedly. This is perfect for companies that make big batches. With laser scanning the measurement process is not dependant on the skill level of the operator because the measurement process does not involve contact measurements. Laser scanning is a non-contact measurement style. By not contacting the measured object there is low possibility for the object to move accidentally during the measurement process. By not contacting the measurement object it is also very improbable that the user does something that causes measurement error. With hand measurement devices and with contact probing, the operator skill level is very important when taking measurements. With laser scanning there is very little possibilities for the operator to make any mistakes. Either the measurement software has enough data, or it doesn’t. During the laser scanning process, the operator sees the covered area on the computer screen, and it is very easy to see which areas need more coverage.

It is very important to understand the basics of choosing the right measurement device for the job in hand. When measuring the length of a wooden board that will be installed in the outside wall of a house, the tolerance requirement is usually from few millimetres to a centimetre. In that case the board cutter can use a cheap and handy tape measure that has a measurement uncertainty of a millimetre. The rule of thumb for choosing the right measurement device for the job is to choose a device that has measurement uncertainty of 10 % of the tolerance requirement. So, if the tolerance for a board length is 1 cm, then the measurement device should have measurement uncertainty of 1 mm. When the tolerance requirement gets tighter, it becomes increasingly difficult to fulfil the 10 % rule of thumb and it is usually acceptable to use a measurement device with 20 % measurement uncertainty of the required tolerance. [35, 36]

This becomes important for example when there is a need to do axle and hole fittings. Let’s say there is a hole that is 125 mm in diameter and an axle must be fitted inside that hole with a clearance fit. According to SFS2232 standard the clearance fit tolerance for 125 mm diameter axle would be from -25 micrometre to 0 micrometre, and hole tolerance would be from 0 micrometres to 40 micrometres. To be able to verify the diameter with these tolerance requirements, the measurement device should have a maximum measurement uncertainty of 5 micrometres according to the 20 % rule of thumb introduced earlier. This means that for example the articulating arm + *AS1* scanner used in this work would be the wrong choice to measure these types of tolerances because it has a measurement uncertainty of 47 micrometres. A right choice for axle and hole fittings measurement would be a traditional coordinate measuring machine.

As mentioned in the Introduction chapter, manual handheld measurement devices such as micro metres and calipers are the traditional way of measuring dimensions such as hole diameter and part thickness. Step up from the manual handheld measurement tools is coordinate measuring machine or in short CMM. CMM is a machine that has moving axles and a probing head that gathers points from the surface of physical object. CMMs come in many different forms and sizes. Traditionally CMMs have been known to have Cartesian axles that move linearly in x, y and z directions. The movement of the axles is controlled manually or by computer. Usually, the measuring probe is equipped with force sensing touch probe which takes points consistently when the probe is brought in contact with the measured surface. CMMs can also be equipped with optical, laser or white light sensors instead of mechanical probe. Modern CMM shown in figure 30. CMMs usually have 3 axles x, y and z which move in a straight line. The axles position is monitored with a scale or an encoder. CMMs have usually heavy stone base on which the axles move. This stone base weighs hundreds or even thousands of kilograms and is very hard to move around. Usually, these type of CMMs also have a room build around them. The room usually has monitored air quality and vibrations control to achieve high accuracy. Bringing parts inside this type of environment sets some challenges to the measurement process.

Figure 30. Modern CMMs in work. Modern CMMs are computer controlled. The operator is used to program the CMM trajectory and change the measured part when the CMM has finished measuring. [20]

In the early days CMMs were controlled manually by levers or joystick to guide the contact probing head in different locations of the measured part. Nowadays CMMs are computer controlled meaning that the operator can produce a measurement program on a computer. The CMM then operates using the instructions given to it by the measurement program. The contact probing head is moved with electric motors. This provides increase in automation level and frees the operator to do other tasks as the machine is measuring a part. After one part is measured, the operator changes the part and starts the automated measurement process.

The automation level can be even further increased with CMMs when introducing automatic part feeding system. By using a robot to change the part to the CMM, the operator is only used to monitor the system. Of course, these systems occasionally need operator intervention when a new part is introduced to the system. The operator needs to create a measurement program for the new part and teach the part feeding robots to set the new part to the CMM. Also, a fastening system for the part into the CMM needs to be modified to fit new parts.

6.1 Additional articulating arm test

Due to the measurement results got from this work, an additional measurement was initiated to find out if the articulating arm + laser scanner diameter growth could be replicated with other similar system. In the additional test the measured object was a certified sphere with known diameter and form. The goal of this additional test was to see if the growing of the diameter could be replicated with other similar system. Below the results from the additional test can be seen in chart 7.

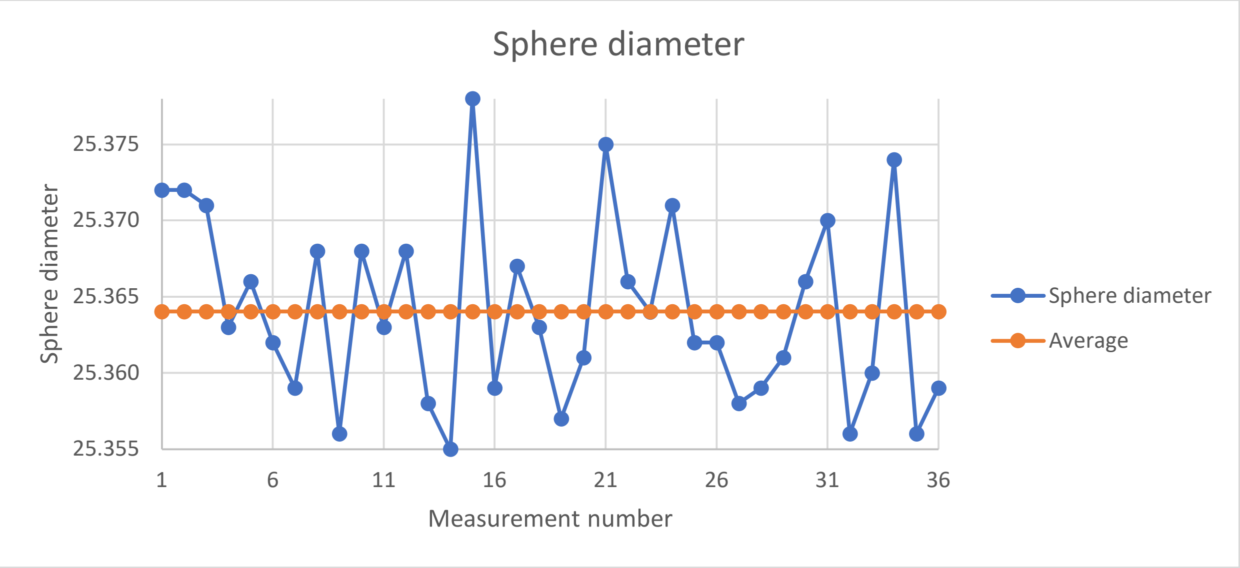


Chart 7. Measurement results from articulating arm + laser scanner measurement with a certified sphere object. The diameter of the sphere is hovering nicely around the average value. No growing or shrinking of the diameter is recognized.

As seen in above chart, the certified sphere diameter was fluctuating around the average diameter throughout the whole test. This indicates that there was something unknown happening in the tests performed with articulating arm + laser scanner system in the main measurement phase of this work. The measurement number in the additional test was raised to 36 measurements to be sure that the measurement time would be sufficient to see if thermodynamic stability of the system would drift. The additional test took approximately 1 hour and 20 minutes.

6.2 Further coming research questions

As the additional testing showed that the diameter growing could not be replicated with other similar system and a known measured artefact, it leaves the question of what happened in the main measurement phase with articulating arm + laser scanner system. As mentioned in the discussion chapter, the form error of cylinder 1 could have a part in the growing of the diameter. This will be one of the further coming research questions. If the form error is not significant, then it can be speculated if the growing was a result of some user related or environment related matter that was not noticed during the testing.

Further coming research questions

- What is the form error of cylinder 1 when measured with accurate contact probing method?

- Will the growing of the cylinder 1 repeat if different user repeats the test done in main measurement with the same articulating arm + laser scanner system?

- Will the growing of the cylinder 1 repeat if the testing is done in a different location than in the main measurement phase originally?

7. Conclusion

In this work two different levels of metrology automation were compared. First system that was studied was *Absolute Arm* articulating arm with *AS1*-laser scanner. The second system was *Primescan* structured light scanner attached to a *Fanuc* COBOT. Series of measurements were carried out with both systems. The measured object for both systems was the same machined metal part with different features like holes and planes. One feature was chosen from the measured part to be inspected with both systems. As result from the measurements a diameter for cylinder 1 and a measurement time were obtained.

With the results it was possible to make comparisons about the speed and accuracy of both systems. It was noticed that the more flexible articulating arm managed to complete the measurements in a shorter time than the COBOT system. The COBOT system human worker involvement time instead was lower than the articulating arm system by 37%. This tells that by investing in more automated metrology system, company can save in work costs in long run.

The standard deviation of cylinder 1 diameter with the more automated COBOT system was 0.001 mm where the articulating arm + laser scanner system managed to reach standard deviation of 0.009 mm which tells that the more automated system is more repeatable. The measurement results from main measurement for both automation systems can be seen in chart 8.

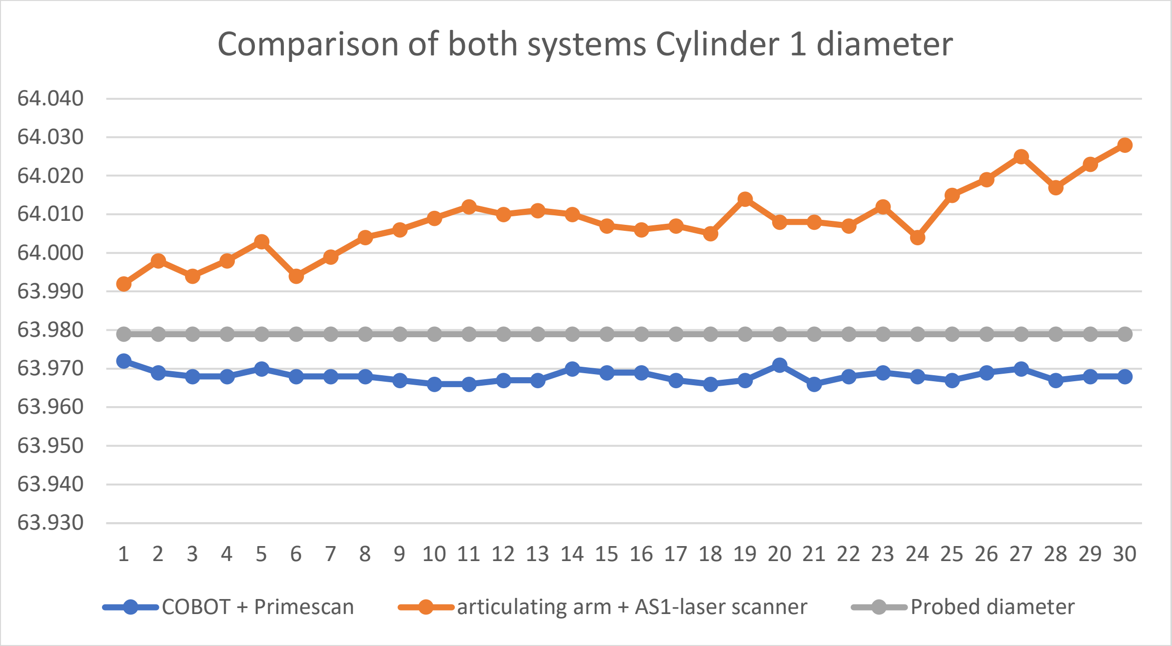


Chart 8. Comparison chart with both automation systems measurement results from main measurements on the same chart. In this chart it can be seen that both systems did relatively well in measuring the diameter of cylinder 1. The more repeatable nature of the more automated COBOT + *Primescan* system can be noticed from the graph. The result does not fluctuate as much as the articulating arm + AS1-laser scanner systems result.

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