POLITECNICO DI TORINO

Laurea Magistrale in Ingegneria Meccanica

3D Scanner Inspection and Shape Correction of SLS Parts Through Reverse Engineering Compensation

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Contents

Chapter 1

Introduction

Additive manufacturing is conceived to be a fast production technology, with short lead time in between design process and production. For this reason, it is usually a good technology to produce prototypes or even final parts when small batches are required. The production process takes usually shorter compared to other technologies, not needing special tools for each shape, and makes it possible to achieve challenging shapes for other type of technologies (such as milling or casting), giving high design freedom and few constrains. A common problem is that other technologies, used to make the process possible, act as bottle neck, causing delays in the production or design loop.
In this thesis an important technology to ensure the quality of the part is trying to be implemented in order to reduce lead time and give an improved feedback from measurements, considering the complexity of the surfaces achievable with additive manufacturing.
Traditional measurements for quality are made through traditional CMM (Coordinate Measuring Machine), and they usually give very good results for more common shapes, but it requires programming time and time consumption if the surface is very complex, since it needs time to move to different points. In order to overcome this issue, 3D scanning technologies is scouted to give a complete shape feedback on the element.
It is very important to reduce and optimise the measuring time of an object. In fact, the design loop (Figure 1.1) of the creation of a new element is composed

by different iterations of design adjustment, production and measurement, in order to achieve the desired quality and tolerances. Many iterations can be necessary considering the complexity of the element and the quality of the feedback received by the metrology. Making the measurement process faster and more efficient in the feedback means to improve the quality of further adjustments. The iterative process can become much faster making the additive manufacturing even more competitive to other productions technologies.

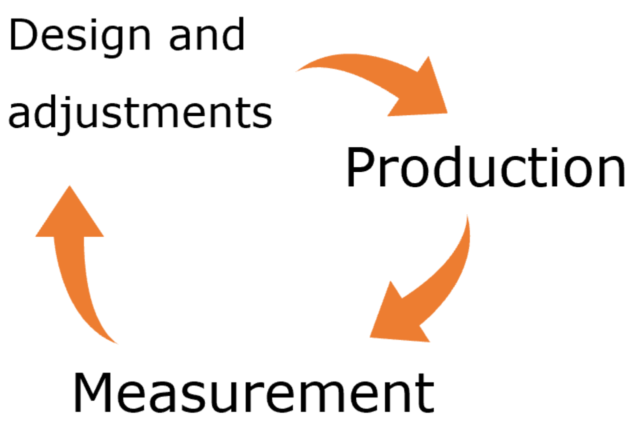


Figure 1.1: Design Loop for a new element produced in AM.

Chapter 2

Additive Manufacturing: SLS. Overview of the technology advantages and limits

One of the main technologies in the field of the Additive Manufacturing is the Selective Laser Sintering (SLS) [1]. It is commonly considered to be a “hot technology” since the temperature reached in the manufacturing chamber is higher than the room one, due to the heat generated by the laser and the preheat temperature obtained with electrical resistances.
The technology is based on a laser selectively melting layer of fine polymer powder of PA12 or PA11. The powder is displaced in a powder bed and different layers are added with a recoater. With the melting of different layers, it is possible to create the entire part desired. The laser moves as a result of lenses and mirrors.
When the laser impacts on the powder it causes melting, generating heat that produces dilatation and distortion on the powder bed, and so on the final part. This can break the part, make it collapse or cause important distortions. For this reason, the chamber is preheated in order to have a smaller temperature gap due to the laser and so less tensions in the final part, with temperature close to the melting point of the polymer. After the job is completed, a long cooling time of several hours is required to avoid poor results or cracks on the

part.

The time consumption (figure 2.1) in the machine is due to:

- Preheating of the chamber.
- Laser scanning time, the actual time used by the laser to run on the path to melt.
- Recoating time, the time used by the recoater to bring new powder for the next layer.
- Cooling time, to bring the temperature of the chamber close to room temperature.
- Post processing. It can run in parallel with a new job starting.

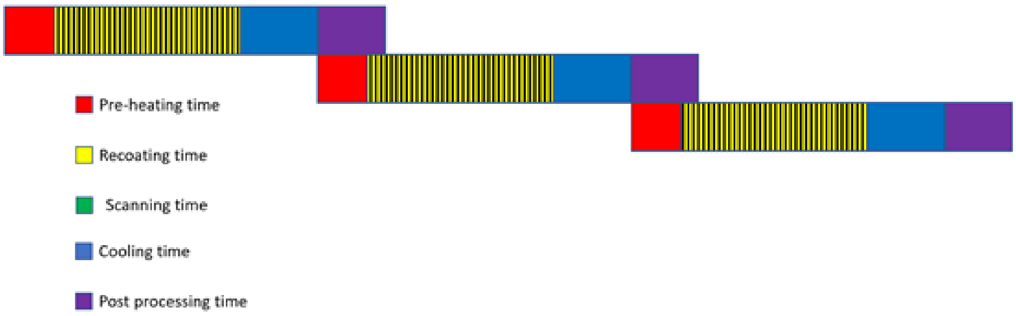


Figure 2.1: Time consuption by each operation of the process.

Regarding to this technology, there are several design rules to respect in order to obtain a good result. Firstly, is not possible to have details with wall thickness smaller than 3mm, but also massive sintered volumes carries to bad results due to massive distortion. If the distortion is big enough the part can bend up and collide with the recoater, making the full job abort with a consistent time and money waste. In order to slightly reduce the risk of collision between part and recoater it is considered to be a good practice to give sharp angles between the part and the recoater, so to have a progressive engagement of it on the surface, when preparing the job using, for example, software as

Materlialise Magics.

It is common to talk about support on the part when talking about additive manufacturing. Concerning SLS, supports are not required since the PA12 distortion in the chamber are very small and the powder bed is very compact. This allows to nest part on all the volume of the building chamber, increasing the number of parts produced in the same job and making this technology economically proficient. Another advantage of having no support is to have no support removal marks on the part, improving the surface quality, even if the orientation can still affect it. It is still important to remember that each part produced in the chamber alters the thermal map, creating distortions on close parts. Considering this factor, it is necessary to keep a reasonable distance between parts in order to achieve small tolerances.

One important design rule about SLS regards clearances and proportion of holes to allow a good cleanability, and at least 0.5 mm of clearance are necessary to have 2 different surfaces not soldered to each other in case of assemblies of moving parts (figure 2.2). [2]

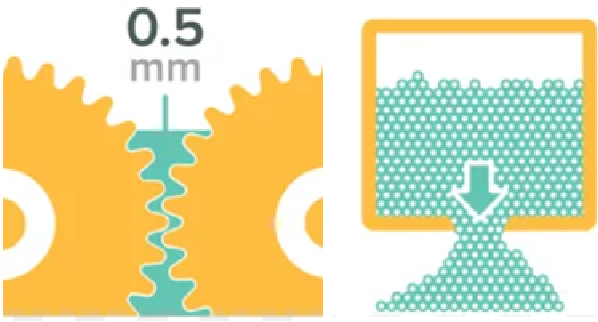


Figure 2.2: Example of design rules for SLS, with minimum cleareances and possibility to remove all the powder.

One important characteristic of SLS is the used material. In order to obtain a melting material, is must be thermoplastic. For this reason, all the parts are completely recyclable at the end of their life and have better mechanical properties. It is important to keep in mind that the sintered polymer is fully recyclable, but the powder waste must be stocked in a special way being microplastic waste.

To have finite part, after the cooling time, it is necessary to extract the build chamber and insert it in an unpacking station (figure 2.3), where it is possible to remove all the non-sintered powder. This powder can be recycled mixing it in 50-50 portion with virgin powder. This means that all the powder can be recycled only if the laser sinters at least 50% of the chamber volume, or a surplus of powder always is present. Is not possible to increase the percentage of recycled powder because the mechanical and chemical characteristic decreases due to aging of the polymer with the high temperature. This drives to the statement that high precision on part increases the price of it, because the parts need to be more distant and the volume usage in the chamber is less than 50%, producing not anymore usable powder to stock in a special, more expensive, way.
The unpacking station is composed of a plane to fit the chamber with a lifter and some sieving filters. A supplier for virgin powder to mix with the sieved recycled one is mounted on the top of it. When the cake of the job is mounted in the unpacking station it is possible to manually clean it, by pushing the powder into the sieve or vacuuming it, in case the intention is to not recycle it.

Figure 2.3: EOS Unpacking and sieving station station.

The parts do not need to be completely clean in the unpacking station

(Figure2.4), since the partially sintered powder is removed in the next steps. The part is treated after with blasting of powder, and finally with small glass particles, to obtain a smother surface (figure 2.5). Depending on the shape of the part it can require more time to clean, as well as more cleaning cycles.

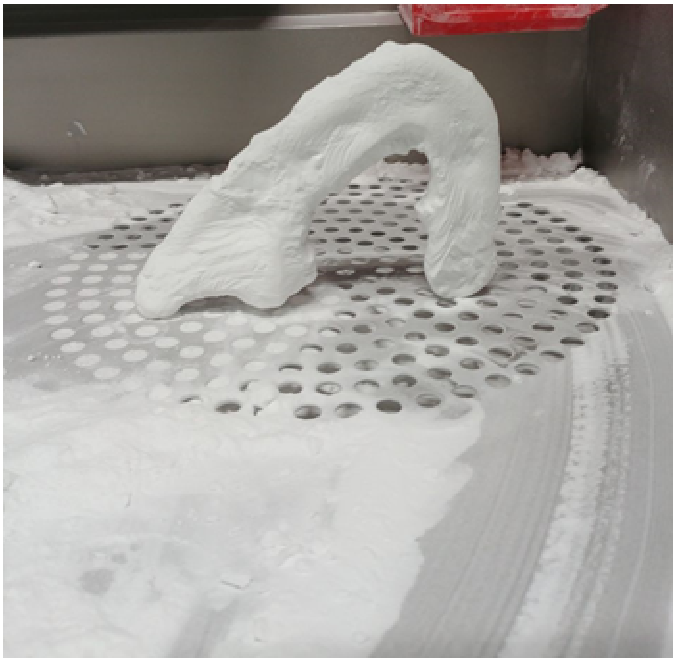


Figure 2.4: Partially cleaned part after the unpacking station work.

Figure 2.5: Cleaning step with powder or glass particle blasting in glovebox.

2.1 Deviations in SLS Parts

Experience demonstrated different distortion in the parts produced by SLS. It is possible to classify them in 4 different categories.

2.1.1 Shifting

Often the parts present all deviations in one direction (figure 2.6). On the analysis made on some parts it is possible to notice that all the feature at the same z-height present a common shifting. The way this shifting happen has been analysed with techniques explained later in the thesis, and this behaviour has been discovered to be usually almost linear, with zero shifting at the bottom layer and maximum shifting at the top layer, with a linear increment.

Figure 2.6: Rappresentation of shifting distortion *Gold* = Nominal shape *Grey* = Actual shape

The laser beam is theoretically circular and with a well-defined radius. More often, these conditions are not respected, and the laser beam follows some tolerances that makes it more oval, and with different radius. This creates distorted shapes, corners and mainly bigger or smaller features in all the part, because of the different diameter of the laser beam (Figure 2.7).
It is possible to set up a beam offset adjustment in the building program of the machine, if the real dimensions of the laser are known, to compensate

this behaviour. Usually this parameter is adjusted in the early prints of the machine, doing some calibration prints.

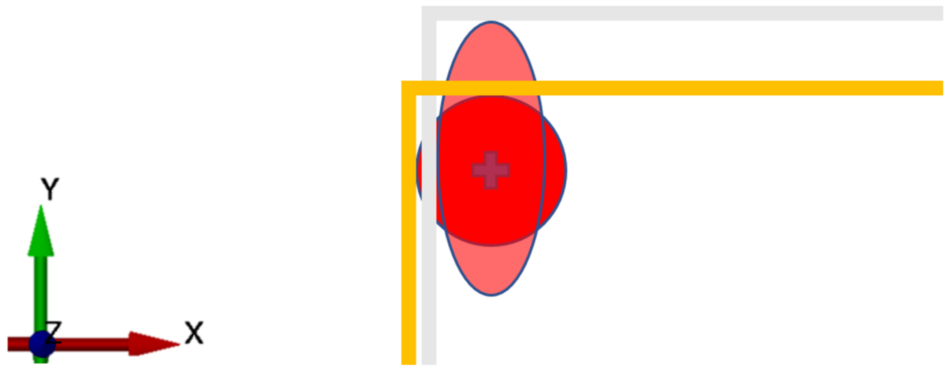


Figure 2.7: Rappresentation of the Beam offset error, with the laser beam of a different shape than nominal. *Gold* = Nominal contour *Grey* = Actual contour

2.1.2 Scaling

Due to the different temperature in the building chamber, the part suffers of effect of shrinkage (figure 2.8) between the part scanned with the laser and the cleaned part. It is possible to set scaling parameters to compensate this behaviour. Considering the material and the difference of temperature between the build chamber and room temperature it is possible to theoretically calculate a rough shrinkage coefficient (3,2% circa for PA12). If the required tolerance is quite small it is not possible to rely only on this rough solution and so a calculation of the shrinkage on the part itself need to be performed, since this effect is geometry specific, and keeps into account how massive the part is. It is needed to be aware that the scaling is not isotropic and so different calculations in different directions are needed and depending on the amount of material of each feature, it can be slightly different for massive or light shapes of local features. Usually an average of the scaling on the different features is considered to be an acceptable compromise, allowing us to apply an overall scaling factor (one for each direction) directly on the CAD program.

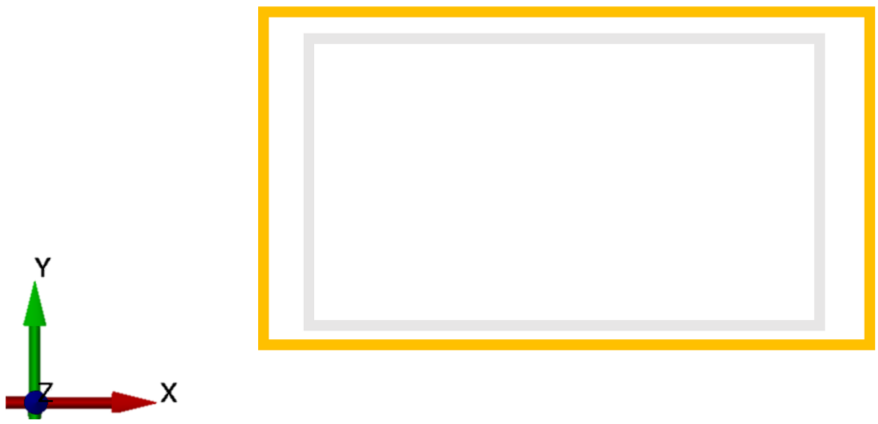


Figure 2.8: Rappresentation of scaling. The actual part (GREY) is smaller than the nominal one (GOLD). The shrinkage is anisothropic.

2.1.3 Error in Height - Overcuring

When printing the part, usually the result is taller of circa 150μm in Z. This is due to the way the laser works on the powder, and the error is known to be caused by what is called overcuring (figure 2.9). The laser is designed to melt the portion of powder in the desired layer and a small amount on the previous layer, so to ensure the complete attaching of the two. If the part is suspended and there is no support, a small amount of powder is sintered under the part itself, producing the overcuring effect.

Figure 2.9: Rappresentation of the Overcuring effect. *Gold* = Nominal part *Grey* = actual part

2.1.4 Other Errors and Sudden Shifting

Other small errors and imperfections are usually present on the part, and the reason can be an unknown combination of the previous factor and some random ones. Often these types of errors are considered acceptable for this technology, if in the tolerance.

The sudden shifting (figure 2.10) is something that happens only on some parts, but with high repeatability on jobs. It is hard to understand the reason of this type of deformation and to predict but is possible to see a layer completely out of place and misaligned with the rest of the part. This can be due to problem in the powder bed, the recoater or the thermal map of the chamber.

Not always the sudden shifting happens in the direction the recoater acts, and it usually occurs at similar layer heights on two identical print. It is possible to avoid it changing the complete nesting of the parts, or simply removing the parts affected by this defect when it happens from next prints.

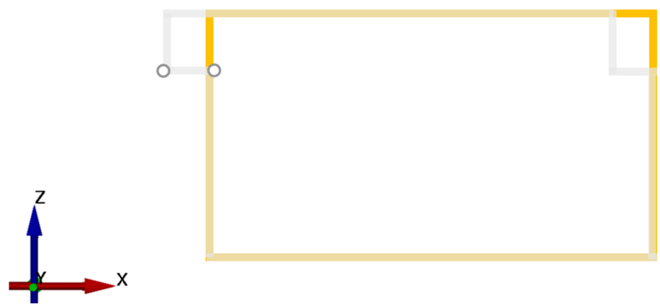


Figure 2.10: Rappresentation of the Sudden Shifting effect.

2.2 Strategy for Deviation Reduction

To achieve the ability to use printed part as equipment for real production or as finite product, it always is required by them to be into specified tolerances, which are commonly not respected with the first print job. At the current state, all kinds of deviations are corrected manually and separately changing the dimensions of the part on the CAD to compensate the deformation, relying on the fact that all the deviations corrected have high repeatability with same build parameters. Only the Beam Offset can be adjusted directly on the machine, calculating the size of the beam spot using some test samples.

2.2.1 Beam Offset

As said, this error is corrected directly on the machine, not requiring additional work on the CAD file. It is calculated measuring the size of some feature taking points with opposite normal vectors. Other errors also influence the measurement:

- Scaling. Measuring a small feature, the scaling is negligible in comparison to the beam offset error.
- Shifting. Taking measurement at the same layer height the shifting should be automatically compensated, being the same for every point at the same z-coordinate.

This makes it possible to reduce at minimum the influence of other types of errors. Comparing the size of the measurement to with the actual data it is possible to calculate the size of the beam and apply corrections on the machine parameters

2.2.2 Scaling

Knowing the dimensions of the actual and the nominal part it is possible to compare them to obtain a scaling factor. The scaling factor is often an average of different measurements, taking in consideration that different position in the chamber and shapes of the features can produce different scaling effects. Taking the measurements requires a preliminary study of the best point to isolate only the scaling factor behaviour. It is necessary to exclude all the other error such as shifting and beam offsets.

- Shifting: is necessary to take a difference between the position of two points on the same layer, since the shifting is compensated, being the same for both the point (the shifting is constant per layer, as seen before).
- Beam offset: is necessary to take into account two points laying on faces

with the same normal vector. This means that the beam offset error is in the same direction and, like the previous case, it is compensated.

At least two different scaling factors needs to be calculated, one per axis on the XY plane, because the shrinking behaviour of most parts is anisotropic. When starting the first iteration of a new part, a typical rough scaling factor of 3,2% is used for PA12 on the machine, and then minor adjustment of it comes with the real measurement on the actual part.

2.2.3 Shifting

The shifting is corrected translating the features of interest. Some measurements are taken between a fixed coordinate system (usually a feature created for the alignment of the part) and some points on the part itself. Every measurement is affected by scaling and beam offset. Knowing the value of the beam offset it is possible to eliminate it (since it has already been compensated with the calibration of the machine) and making an average of different points in different positions it is possible reduce the effect of the scaling.
For the correction it is possible to translate all the needed feature of the calculated value. If all the features to translate are at the same layer, the shifting is almost the same for all of them, and the distance between them is not affected by this. So, it is possible to move all of them together translating the pins or the features used for the alignment to place the part in the working environment.

2.2.4 Other Errors

Other types of error like sudden shifting are not corrected in the CAD file, because they are more commonly problem of the build job and it is necessary to find new parameters for the machine not directly related to the geometry. Small errors and distortion hard to connect with one of the previous reasons can be corrected too. Actually, there are some Reverse Engineering software that can make quite automatic adjustment on STL files through comparisons between the nominal data and the actual one. In this case single point measurement are not enough and a full geometry of the actual data is required. It is possible to get this geometry through CT scan or Optical 3D Scanner. A reverse engineering software is used for this purpose, and it is explained further.

It is roughly possible to state that all the type of error due to the SLS process can be adjusted through a reverse engineering software, but this is true only in the case the errors are small enough to allow the software to create new surfaces without logical errors due to the way it works. A better discussion about this is presented later.

Chapter 3

Different Technologies for Measurement: Advantages and Disadvanteges

3.1 Coordinate Measurement Machine CMM

Traditionally the measurement on 3D printed part are performed through CMM[3][4]. A CMM (figure 3.1) is a robot that, properly programmed, can measure the position of some points on surfaces. The measurement is made via a touch probe (figure 3.2) that physically goes in mechanical contact with the part. Principal advantages of this technology are the high repeatability of the measurement and a very high sensitivity. The robot needs a measurement program and qualified personal to use it, to define positions to measure and avoid any type of collisions. The environment around the part must be in control of temperature and humidity to not affect the part dimensions, and a calibration of the machine is needed before any series of measurements, usually using a calibrated sphere.

Sometimes it is challenging to measure point on undercut surfaces or position hard to reach with the touch probe. Particular attentions are necessary in case of sloped surfaces, since the probe has to reach the surface always along a normal vector.

With this technology every point is taken independently from the others and needs a certain amount of time to be measured, so some features can take long to measure if more than few points are needed. Geometrical tolerances are usually time consuming to verify with this type of technology since they require a high amount of points.

Figure 3.1: Example of a CMM manufactured by Zeiss.

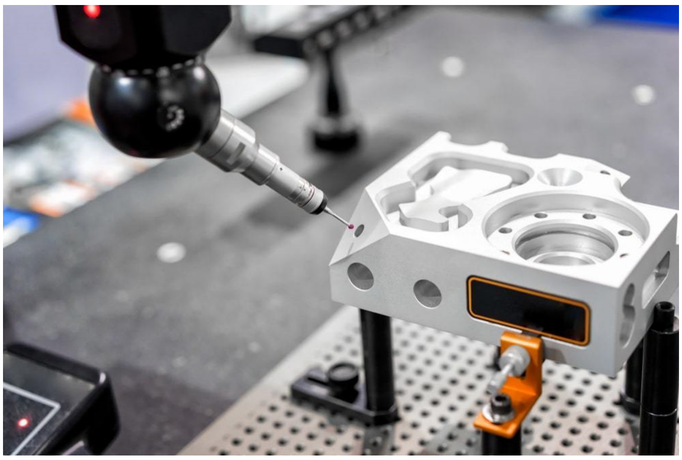


Figure 3.2: Example of a CMM touch probe during measurement.

3.2 3D Scanning

3D scanning [3] technology makes it possible to digitally recreate the full geometry of the part, commonly in an STL file (or other proprietary formats). This can be very useful in case the whole geometry is needed and, commonly, it is time-advantageous if the number of desired points is high enough to require long acquiring time on CMM machines. To obtain good data, most commonly a good alignment is required on the part, the same as for CMM, but recreated and edited after the measurement is taken. Two are the main technologies for 3D scanning:

3.2.1 Computerized Tomography (CT)

Computerized Tomography (CT) scan (figure). It works using radiations passing through the material of the part. The object rotates inside the scanning chamber (Figure 3.3) and all the detected images are combined to create the 3D object. Usually the main problem is that some materials (like gold, for jewellery) are not transparent to the waves, and it is not possible to measure them. Files can have lot of details and it is possible to see all the inner geometries, including undercuts, while files can become very big-sized. Usually it is a very expensive technology as initial investment.

Figure 3.3: Example of a CT Scanner provided by GOM

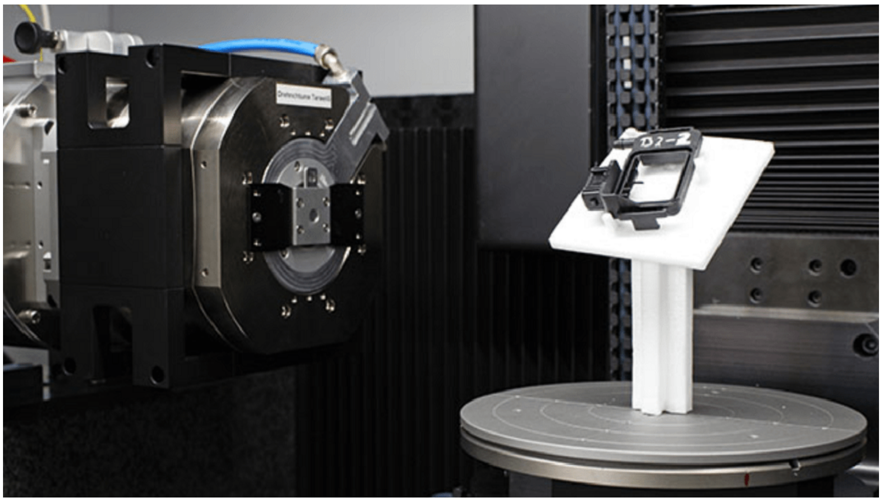


Figure 3.4: CT scanner working environment with rotating table and X-Ray source

3.2.2 Optical Scanner

Optical Scanner (figure 3.5). Images are collected using two different cameras (in order to have the stereoscopic effect). Many photograms are taken around the object. On the object some reference marks are placed in form of stickers and using these and the position of the scanner head itself (read through a close loop control) it is possible to merge all the photograms and recreate a 3D shape. The scanner always needs to capture at least three reference marks per photogram to merge them. Problem may occur in case most of the reference marks or the geometry are in an undercut or shadowed by the part itself. It is possible to adjust several parameters to have a better acquirement of surfaces and reference markers and filter them out in case on uncertain results. Commonly the more complex is the geometry, the more picture the scanner must take to ensure a complete and good calculation of the STL file. The part needs to be designed for the inspection, in order to have all the faces to measure well visible for the scanner.

Other problem may occur in case the surface is shiny. This can cause the non-acquirement of the points or very noisy surfaces. Programming software usually allows to set different exposure times for each photogram. Two or three photograms at different exposure time are taken for each position in the first tentative of acquisition. If the surface is underexposed (too dark) or overexposed (zebra lines) it is not possible to capture good data and create the final geometry with this photogram, that is excluded causing an incomplete geometry.

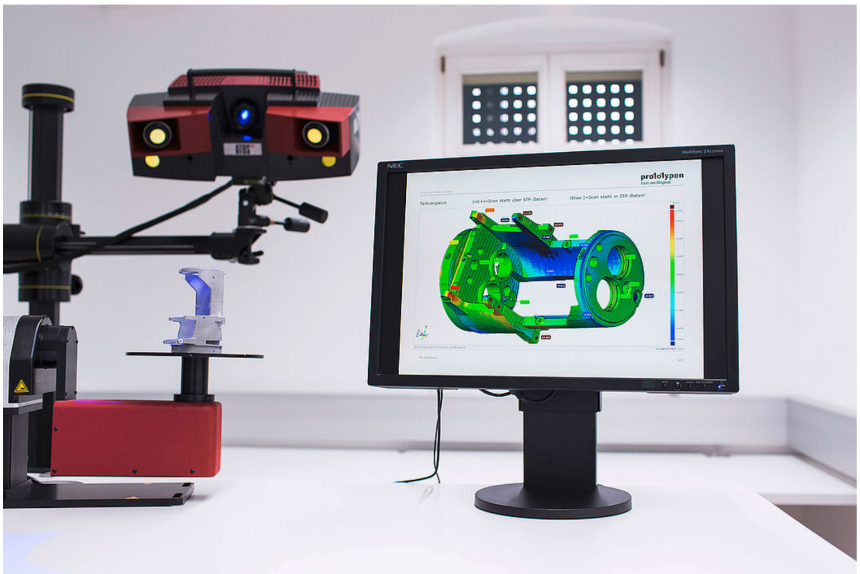


Figure 3.5: Example of an optical scanner setup

Chapter 4

Equipment

The main equipment used are an Optical Scanner by GOM and an SLS printing machine by EOS.

4.1 ATOS Scan Box

Outer Box This is a structure in which all the measuring equipment is contained. It insulates the equipment from wind, sudden temperature changes, and mounts several fans to keep the inner temperature constant. The temperature is measured via a sensor mounted behind the calibration element. The box has a door with sensors that stop the machine if open. On the external of the box, a light and two buttons are present. The first button is to give the machine a safety check for the door to be closed and confirm there is no one in the working area inside. The light is flickering if the safety button has not been pushed yet and is fixed on if the safety check has been given. The second one is the emergency stop button, and can be used in case of any issue, suddenly blocking any movement of the machine. (figure 4.1).

Robotic arm It is an anthropomorphic robot used to mount and move the camera. It allows many positions and has six degrees of freedom in the space, allowing any angle and coordinate (in respect of the available volume in the scan box.

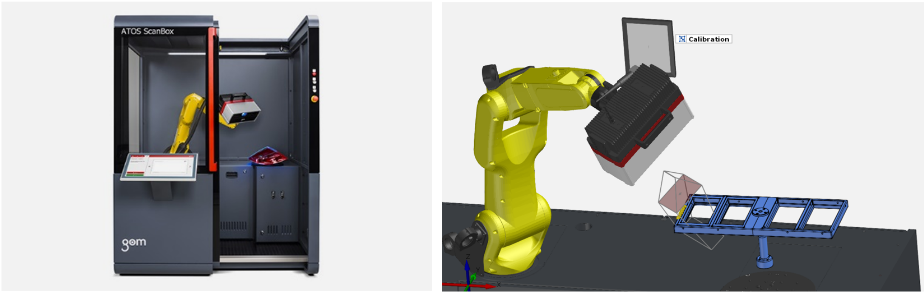


Figure 4.1: Complete setup of the ATOS Scan Box. It is possible to identify a frame mounted on the rotating table.

Computer It is used to control the robot arm and camera, storing all the data. Can be also used to postprocess data and perform analysis on them.

Rotating table The part is usually mounted on a rotating table. It allows to reach even more perspective for the camera. It is common to mount support structures on the rotating table as frames for the object to measure. This gives many advantages such as mounting more than one part at the same time and to place reference markers on the frame itself.

Calibration Frame It is a pattern of dots on white background. It is used to calibrate the sensor before each measurement. Behind the calibration frame a thermometer is mounted in order to consider the temperature in the box while performing the calibration.

Scanner sensor It is composed by two cameras, to have stereoscopic pictures, and a light working with Blue Light Technology to enlighten the part while scanning and creating some diffraction shapes to collect more and better data. The blue light is used to filter other type of light coming from the external environment and can also adjust to small changes in it, via compensating loops. Two are the sensors used in this thesis, both provided by GOM:

- ATOS Capsule (figure 4.2). Made for fine details and high definition. The acquisition area is small and needs many positions to capture the entire shape. This can also give some problems on the alignment of the different pictures if not enough reference points are present in each one. There are two versions, of 8 or 12Mp sensors.

- ATOS Q (figure 4.3). It is cheaper than the previous one, with definition of 8Mp (or 12Mp with a software upgrade). The scanning area is bigger so fine details are not always captured. It is much easier to use and program since fewer acquiring positions are needed. On the experience based on the measurement of some parts, it is possible to reduce the scanning time from 20 to 3 minutes).

Measuring Volumes	MV 70	MV 120	MV 200	MV 320
Measuring area [mm]	70 × 50	120 × 80	200 × 140	320 × 240
Working distance [mm]	290	290	290	290
Sensor types	8 or 12 million points per scan (pps)			
Dimensions [mm]	Approx. 310 × 220 × 150			
Weight	Approx. 7 kg			
Operating temperature	+5 °C to +35 °C (non-condensing)			
Housing	Dustproof, splashproof			

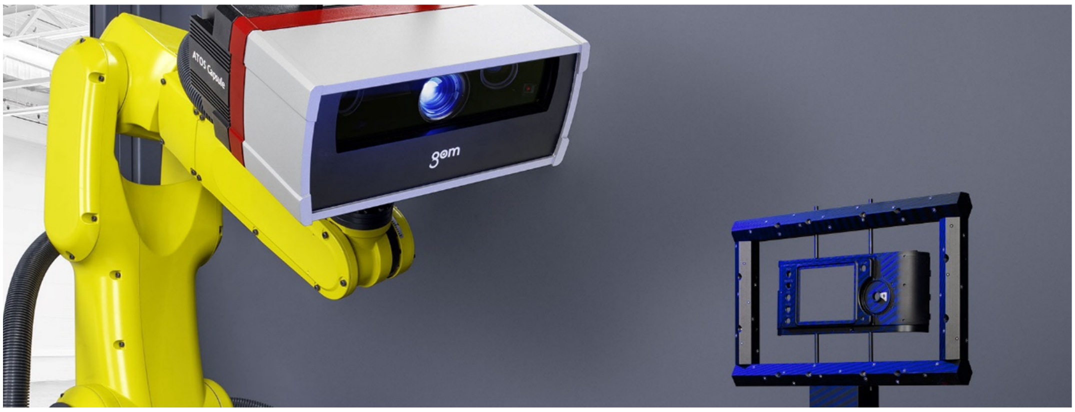


Figure 4.2: Atos Capsule and relative datasheet.

Touch screen It allows to control the machine, being the desktop of the computer. Commonly, a second screen is connected to a desk for a more comfortable desk use.

	ATOS Q 8M	ATOS Q 12M
Light source	LED	LED
Points per scan	8 million	12 million
Measuring area [mm^2]	100 × 70 – 500 × 370	100 × 70 – 500 × 370
Point distance [mm]	0.04 – 0.15	0.03 – 0.12
Working distance [mm]	490	490
Weight	approx. 4 kg	approx. 4 kg
Dimensions	approx. 340 mm x 240 mm x 83 mm	approx. 340 mm x 240 mm x 83 mm
Cable length	10 m fiber optic cable	10 m fiber optic cable
Operating system	Windows 10	Windows 10
Measuring volumes	100, 170, 270, 350, 500	100, 170, 270, 350, 500

Figure 4.3: Atos Q and relative datasheet.

4.2 EOS Formiga P110 Velocis

This is an SLS printer produced by EOS GmbH (Figure 4.4), World leading this technology. Working with 30W CO_2 laser on a build area of 200x250mm per 330mm height on Z, allows good production rate. It needs some external equipment to clean the build cake, as showed before. The machine is composed by (Figure 4.5):

CO_2 laser It is used to melt the powder layer per layer. It is fixed on the top pf the chamber

Mirrors They are used to focus, correct the shape and point the laser on the different position of the build chamber

Tanks of powder They release a small amount of powder for each layer, and they are positioned on the top of the machine. They are usually two but once per time is used, while the other is unlocked to allow refeeding.

Recoater It takes a small amount of powder from the side of the chamber, where the tank deposit it, and distributes it in the camber in order to fill a new layer. It mounts a blade, usually in steel. It is commonly necessary to check that the blade is clean before starting a new job. It is possible to dismount the blade by hand, since it is simply fixed with two springs on the sides and clean and inspect it during maintenance work.

Build plate It is a metal plate where the entire build cake is created. It is mounted on a lift, that moves it down to allow the creation of new layers during the build job, keeping the melting layer at constant distance to the laser source.

Window It is intended to inspect the working machine. There are some lights inside. The glass gives protection to the laser beam, that can cause eye hazards.

Touch screen It is used to control the machine parameters and launch the build job.

Figure 4.4: SLS machine provided by EOS.

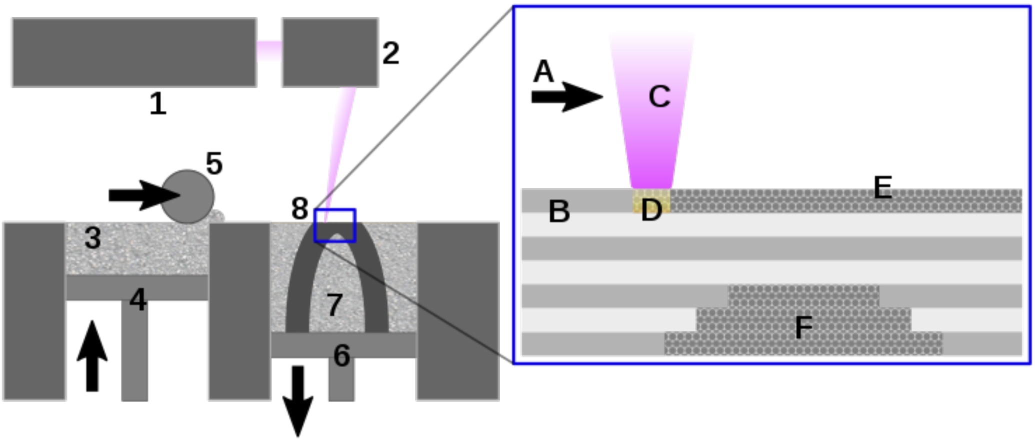


Figure 4.5: Scheme of SLS machine components and process.

Chapter 5

Inspection and Correction Software

5.1 Inspection

The data are acquired and inspected through the GOM Suite. It is composed by three different programs, well interfaced between them and with easy importation of data being part of the same suite.

5.1.1 ATOS

The ATOS software (figure 5.1) can communicate with the scanner and create a program for the measurement. A virtual measurement program consists in a series of position and parameters for the scanner head around the virtual object. These data is transformed and sent to the physical scanner to perform the real measurement. The most important editable parameters are:

- Position of the acquirement. It is composed by the coordinates and the direction of the camera when acquiring each photogram. The position can be reached with both rotation of the table on which the object is mounted and coordinates or the robot arm. Each photogram needs to include at least three different reference markers. The reference markers are enlightened in *green* if they are collected properly, *orange* if they are out of the acquisition field or slightly overexposed, or *red* if, even if recognised, the quality is not good enough to use them for their position, being out of the acceptance volume or focus.

- Depth of field. It is the acceptance range distance from the camera to the part. Closer points allow better precision. All the reference points need to be in the depth of field. Sometimes the software recognises the points even if they are not in the depth of field required, but they are excluded from the calculation of the 3D. This is a good indicator to take the decision to extend the dept of field.
- Angle of field. It is the angle used by cameras to capture images. A smaller angle allows better precision in the measurement, but requires more positions to get the complete geometry, since less area is collected with each photogram.
- Quality of the mesh result. It is possible to recreate the STL file changing the number of triangles. A high number of triangles makes the process slower, and captures more details, while a rougher mesh creates bigger triangles, with smaller size STL file and smoother surfaces. Sometimes, bigger triangles allow to eliminate all the noise that can be generated from not completely diffusive surfaces, increasing the quality of the data.
- Exposure time. It is possible to set how long the sensor capture each photogram, in milliseconds. The longer is the time for the acquirement, the more the image is bright. It is possible to set this parameter in automatic mode, but usually the better choice is to define it manually. Up to 3 different exposure time are allowed for each position of the camera. The goal is to have all the required element well enlightened but not overexposed. If the element is overexposed, it appears with zebra red lines in the photogram.

When a point cloud is collected by the scanner, it is necessary to perform a recalculation to align every reference point and polygonise the whole geometry into an STL file. This happens “offline”, which means that the scanner needs to be disconnected, and the whole computation power of the computer is used for the polygonization, not allowing to perform new scanning during this time.

Meanwhile the polygonization goes on it is still possible to open a new window of the ATOS software and run other measurements. After the first scanning is performed and the result is completely created, it is possible to extract a template of the program to run it with similar parts or import in the KIOSK program.

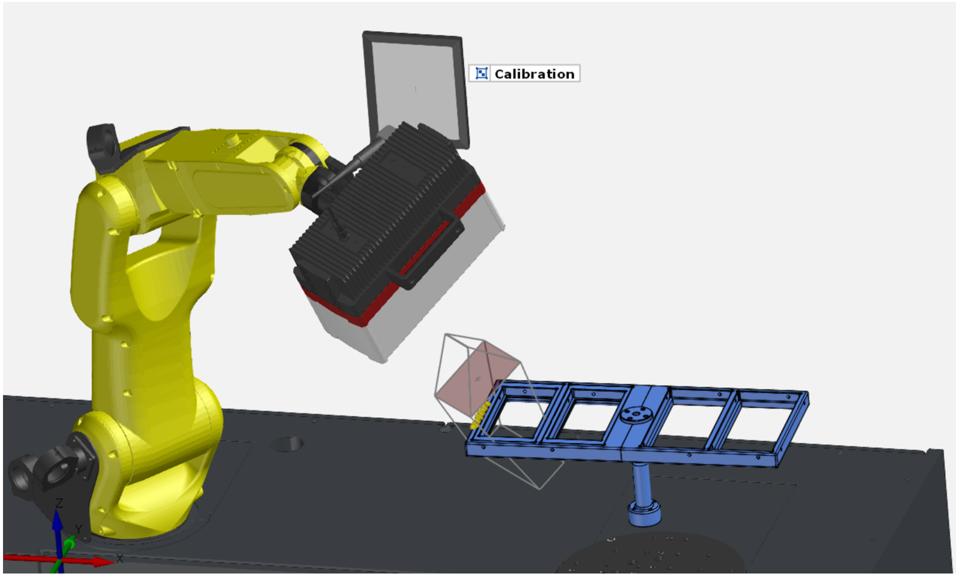


Figure 5.1: ATOS software virtual environment. It is possible to see the position of the robotic arm, rotating table, field of acquirement and calibration pattern.

5.1.2 KIOSK

It is the operator interface and it is used to collect data as well as the ATOS software, but works importing already made templates. The templates are the ones created and already validated in the ATOS. It is possible to choose the format of extraction of the file and the quality of the mesh, editing the template before, but no further changes are allowed in the KIOSK program. When launched, it is only possible to choose the template and the number of measurements required. The main advantage is the simplicity of use and that the polygonization is performed in background. This allows to avoid the disconnection to the scanner and keep using it for new acquirement while the

previous data are computed, optimizing the scanning time.
The way the program handle the data is, on the other hand, a bit less efficient than the ATOS interface, and in case of any error or bad acquired measurement, it stops the process with no possibilities to correct the acquired data (for example adding any new scanning position or changing any parameter), so all the acquiring time is wasted, and it is suggested to run this software only with very robust measuring templates.

5.1.3 GOM INSPECT Professional

This software, provided by the GOM company (figure 5.2), allows us to perform the analysis on the data acquired. It is possible to import a STEP file of the nominal data, that is converted into an STL file too, and the mesh of Actual data collected with the previous programs. The main feature is the comparison between the acquired data and a CAD file. A colour map is generated as result of the analysis. It is also possible to perform other analysis as single point position or *GD&T* measurement, that is illustrated further. To have good result from the software a good alignment between the feature you want to measure. A prealignment is automatically performed by the software minimising the average distances for all the points of the geometry (probably something close to multiple regression), but often some more steps with the imposition of more alignment criteria is necessary. To go through these steps, it is necessary to create some virtual geometries (cylinders, planes. . .) on both nominal and actual geometry to get a correct alignment. Detailed steps will be presented further.
After the creation of some dimensional measurements it is possible to create reports and export all of them in a .csv file to use them in different analysis software such as Microsoft Office Excel. The entire process will be shown further in details.

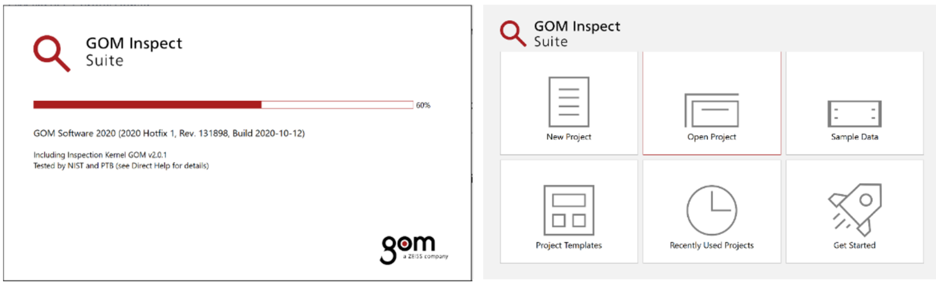


Figure 5.2: GOM Inspect Professional launching windows and Home Page.

5.2 Correction

5.2.1 Siemens NX

This is a CAD software developed by Siemens and allows the creation of geometries and shapes of part. In this thesis, it is used to adjust the CAD file directly and parametrically, editing the dimensions of a file manually. This is the most common way at the current state to apply corrections on a part.

Zeiss Reverse Engineering (ZRE) and GOM Inspect Professional
The software presented is the Zeiss Reverse Engineering (ZRE) software, but even more companies are developing similar solution, and something has been presented also in the last release of the GOM Inspect software.
ZRE implements some very close functions to the GOM Inspect Professional suite, such as alignment functions, creation of geometries and surface comparisons, but the main purpose of it is to automatically correct surfaces and shapes after a comparison of Actual and Nominal shapes and creating a new file.
The program works with meshes, point clouds or STL files as input and produces an STL file as output. The algorithm uses the difference between the position of nominal and actual point to create a new, mirrored surface to compensate distortions.
The first purpose of the software is the correction of injection moulding tools (Figure 5.3), for compensating the shrinkages after the extraction of the parts, so more function than the ones showed in this thesis are included.

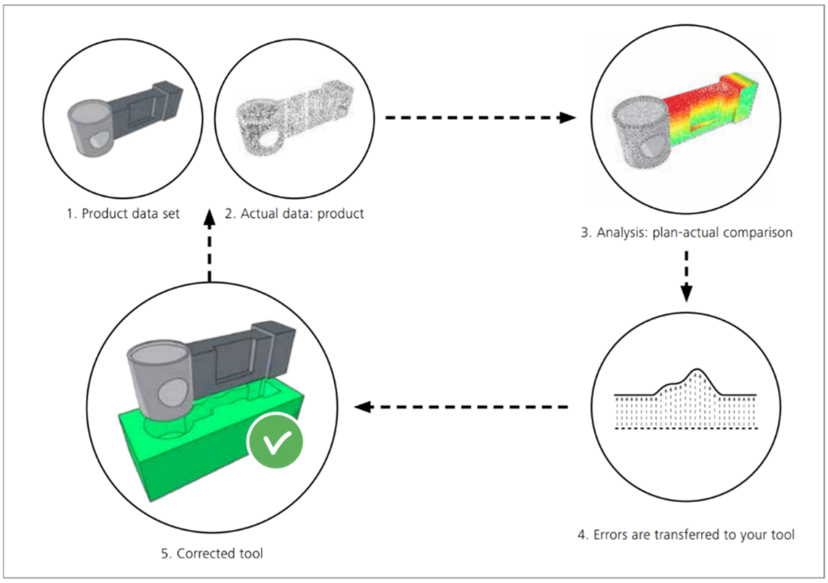


Figure 5.3: Proposed workflow for the correction of a mould tool with ZRE.

Chapter 6

Workflow

6.1 Preparation of the Scanner Setup

The scanning of one single part may usually take few minutes in a scanner, and this requires a high surveillance index, with an operator changing the part every time the scanner finishes and launching the new scanning process.
By creating a support for more than one part it is possible to scan them in the same setup, optimizing the manual work time. This allows a longer waiting time, implying less surveillance on the machine, and can also make the work more automatic, as explained further in case of needing of reference marks.
Based on this assumption, a support for 4 similar elements has been created (figure 6.1). The support keeps the part elevated, making it possible to the scanner to have a good perspective of all of them, and it is fixed on the rotation table.
The scanner can make different photos around the desired path but, in order to stick the pictures together, needs some reference points. For the used scanner there are two type of reference marks. They both are sticker appliable on the surfaces by hand, with the support of a tweezer:

Figure 6.1: Example of a frame used to measure four parts at the same time.

- Univocal reference marker (figure 6.2). These are all different than the others in the same package, and any sticker defines one and only one position in the structure. In addition, it also defines a direction, since it is not symmetric. The reference marker is composed by a circle divided into sectors (figure 6.3). A combination of different sectors gives an univocal marker. They are usually very expensive and a moderate use of them is suggested. They also are bigger than normal reference markers.

- Common reference mark (figure 6.4). It is a dot of small dimension. Different sizes are available (1.5, 3, 5 or 8mm). The 1.5 mm one has been used for the tests performed with this thesis. Usually much more common reference marks are required to define a position, since they need to define directions between them. It requires much more effort to apply them by hand, but the price of each mark is negligible if compared to the other type.

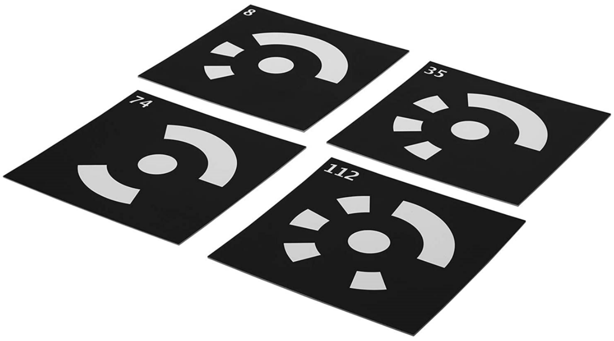


Figure 6.2: Univocal reference markers.

Figure 6.3: Logic of an univocal reference marker.

Figure 6.4: GOM reference markers sticker.

In order to have an optimized setup to perform more scan in less time, the whole frame is covered by sticker. This is done to avoid using stickers on any object you want to measure. Increasing the field depth and angle the scanner can capture several reference marks per each position, making it possible to

avoid the application of sticker on the part itself (and so creating a more robust way to measure too, bypassing human errors).
For this thesis purpose, in order to follow the purpose to create a generic support for different types of element, the housing in the holder have a generic shape, and some adapter is included to fit every type of different element in the future, so a Fixture is required for them (figure 6.5).
The design of the fixture is very important to define the quality of the scanning, and this requires also high precision tooling for this part, with very precise tolerances for the position of fixing and alignment holes.

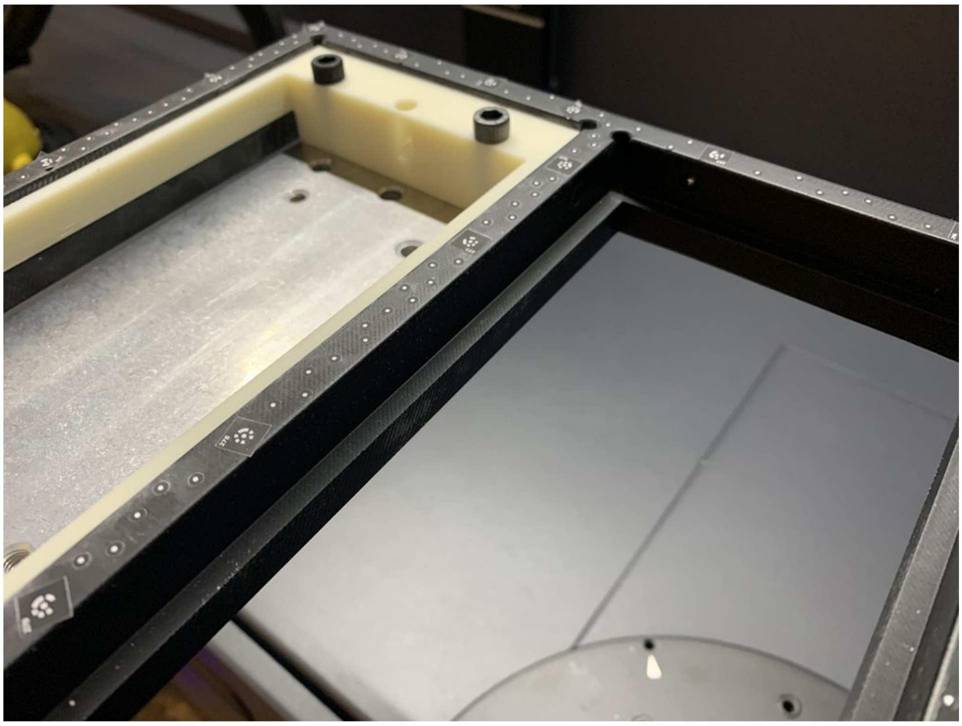


Figure 6.5: Detail of the frame for the scanner setup composed by the four housing holder, adapters and plates.

A big issue with the fixture is that, in order to achieve high precision, it is made in aluminium, which can reflect the light of the scanner. This can give error and bad surfaces on the scanner, which can be unable to detect all the details or have high accuracy. It is possible to make the surface more diffusive applying different type of treatment: sandblasting, coating or painting:

- The sandblasting is not the best solution since it changes the roughness of the surfaces, creating dependency error on the whole process.
- Colouring the surface with matte pigments requires very thin layer to not affect tolerances. Some PVD (Physical Vapor Deposition) treatment could be a good solution.
- Coating with a thin layer of “digitizing spray”. It is a very fine powder of Titanium Oxide that sticks on the surface. The surface results completely diffusive and is possible to get the higher resolution on the scanner acquirement. This layer can be easily wiped out with a soft cloth. This makes it very fast to remove but also not very durable in case you need a permanent coating, and is very easy to leave fingerprint on the coated surface

The results obtained further are performed with not threated surfaces, since the acquiring angles applied were not critical to reflectiveness. Some tests with digitalizing spray did not show any difference in the results.

6.2 Creation of the Scanner Program

For the creation of the scanner program, ATOS suite is used.

The first operation, in order to have good measurements, is to start a calibration of the sensor. The calibration is affected by the temperature in the scanning chamber. A sensor is built in the machine, just behind the calibration pattern, to collect the temperature, but is also possible to insert this data manually when launching the calibration.

It is necessary, in order to avoid collision and to allow the scanner to recognise better surfaces where to move the camera, to import a CAD file of the geometry to measure. Once it is imported in the program, it is possible to move it to the desired position in the workspace, trying to replicate the position to the physical part in the scanning chamber.

Using different function of the software it is possible to move the camera on the

desired position and view the area scanned on the computer connected with the scanner. The simpler way to do this is to simply click on the part of the CAD file we imported in the position we want to measure while clicking the CTRL button on the keyboard. The virtual scanner head moves to the normal position of the surface we selected, at a standard distance to avoid collisions. Adjustment can be done clicking on the scanner head or on the rotation table. A set of translation and rotation arrows (figure 6.6) appears and by dragging them it is possible to move the position of the camera or the rotating table. If while dragging the arrows some collisions are predicted, they are displayed in the software. To ensure to move the camera at the correct distance from the point we want to measure, a graphical area of the field of view with focus distances is displayed as well.
When the position seems to be reasonable for the point we want to measure, it is possible to move the real scanner head to the selected position by clicking the SPACE bar. The entire physical equipment moves to the desired position, and the coordinates saved and included in the scanner program while the output of the camera in the selected position is visualized (figure 6.7).

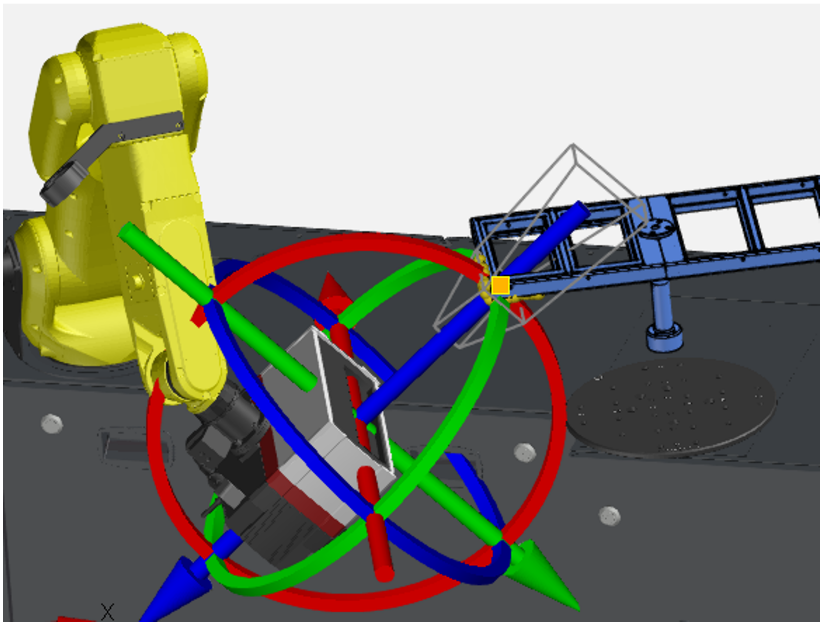


Figure 6.6: Setting of camera position with arrows for position adjustments and depth of field rappresentation.

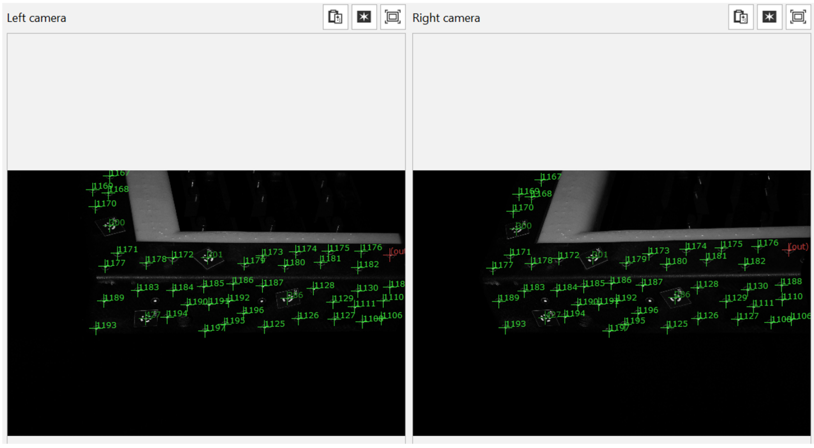


Figure 6.7: Real time result of the acquiring position selected.

By doing all this operation it is possible to ensure that enough reference points are present in the view and that the image is under the correct exposition. It is possible to change the exposition time from the automatic setting to a user defined one, defining 3 different time or exposition, in milliseconds. The result changes in real time.
For this thesis, the first part of the measurement program is built around the frame structure, in order to detect all the reference point and have a solid structure to stick all the next pictures. In fact, it is possible to set all the next measurement as dependant to this one, just ticking the specific cell in the properties (figure 6.8). In this way, all the next photograms is connected to the first, independent one. It needs to be only one independent series in a project if we want a single final mesh and we want to export it as a template and make it work in the KIOSK program.

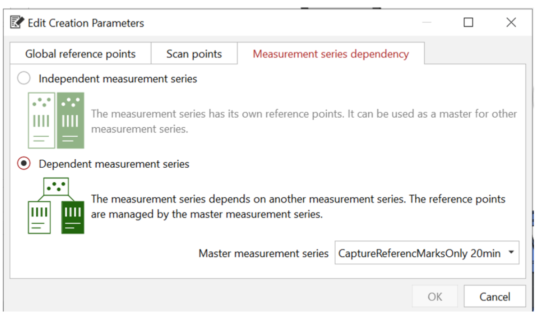


Figure 6.8: Measurement Series parameters window.

At this point, it is necessary to create all the point to ensure a complete measurement. Selecting each point by hand can be long and time consuming, since dozens of positions can be necessary to capture the entire geometry.
Useful instruments to create a measuring program are in the "Automation" tab (figure 6.9). With these it is possible to fast create copies of some measurement positions all around the part to measure. Copies can be made by translation along directions or rotation around axis. Axis or directions can be defined with the geometries of the CAD element we can create through some of the function that will be explained further. Another special type of replication is the one made with the rotating table. This one allows the creation of different measurement keeping the scanner sensor fixed and moving only the rotating table. It always is possible to decide the number of measurements you want to have and what distance each other, just following the guided function.

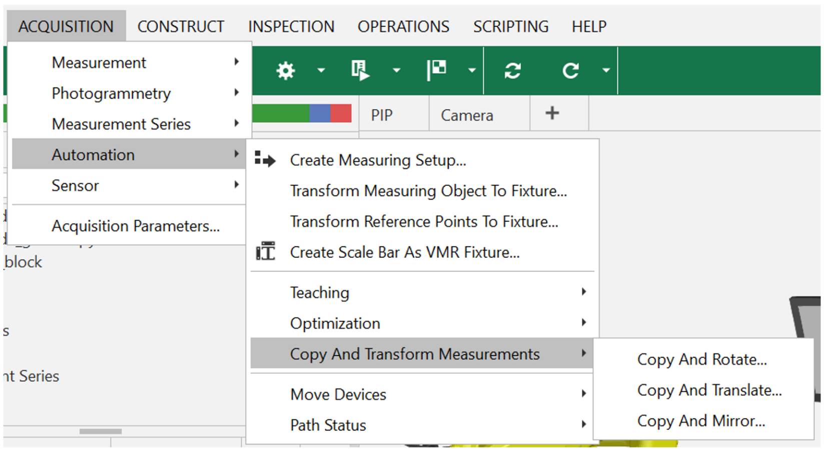


Figure 6.9: Automation tab for the creation of series of measurements.

The result of the whole program can be like the one showed in the picture (figure 6.10).
Often some parts of the geometry do not get stacked together ("*Cannot transform the measurement*" error) during the measurement, so is necessary to recalculate the project, to allow the program to make another iteration to compute the position of all the reference marks. A recalculation of the project always happens during the polygonization of the entire point clouds into a

mesh, so can be possible to proceed with this step directly.
Sometimes the measurement program still does not transform some measurement even after the recalculation of the project, and it is usually necessary to change the position of the camera to have more reference point or change the exposure time. A useful tool is provided by the software, to automatically optimize the position of the scanner head in order to have a better view of the part, but it is not possible to have the full control on what happens with this command. It creates a new measurement position close to the non-transformed one and sometimes it is enough to make the program working, in order to have a fast result for the scanner program.

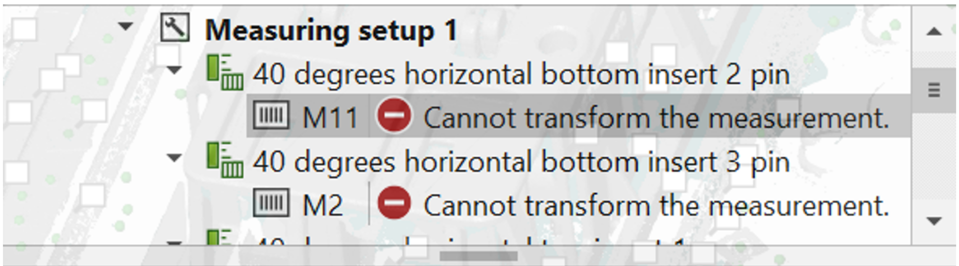


Figure 6.10: Example of a part of measuring program tree.

Once the measurement program is created it is common to optimize it once more with the "*re-sorting*" function. This type of optimization creates a new path for the scanner head changing the sequence of the measurement in order to reduce the overall time of scanning due to the movement of the robot.
Then, a validation of all the new, definitive path is required (figure 6.11). It is possible to run the validation alone or with scanning. If more than one scan is needed with this program, it is highly recommended to run the "validation only" so to reduce the surveillance time on the machine, cutting out the time for the scanning in the very first time the robot does the movements. In fact, the robot moves slower through all the positions to avoid serious damage in case of collision, and surveillance is needed to push the emergency button in case something goes wrong. Usually, if the CAD file in the program respect the dimension of the real part in the scanner, no collisions happens.

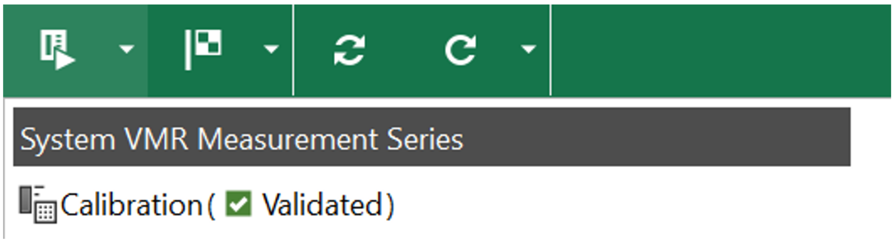


Figure 6.11: Example of validation of measuring series.

Once all the part has been captured in the different position, it is necessary to go through the polygonization stage (figure 6.12). It is possible to choose the quality of the desired mesh. Finer mesh produces bigger files, plenty of details. That also reproduces all the noises present on the surface, including errors due to shiny surfaces during the scanning. Low quality mesh creates smoother surfaces. In case of polymer, roughness is reduced during the working condition due to a small wearing of the surfaces and can be important to consider this. In this thesis the high-quality mesh is still used in order to have as more detail as possible, so to replicate the condition of measurement of the CMM.

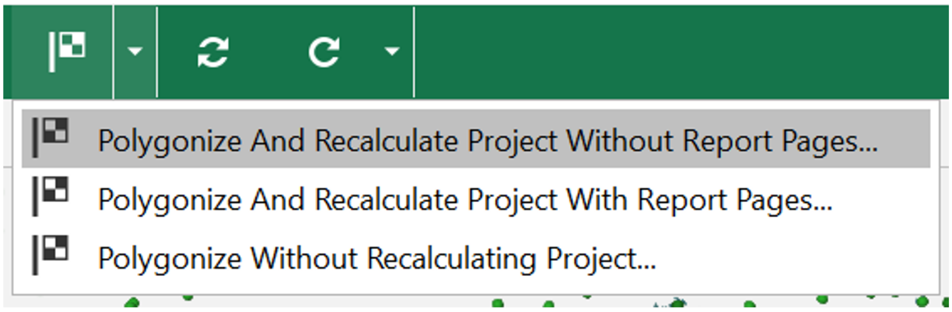


Figure 6.12: Poligonization tab window.

Once the mesh is calculated it is possible to export it. When exporting the file, the *.G3D* format is suggested if the mesh is used in a program from the GOM suite, since is use fewer storage data and it is a lossless format.
If the measurement program is complete and it has been tested to work properly, it is possible to export it as template.

For next measurements it is possible to start the scanning program directly from the KIOSK program (figure 6.13), importing the template. This optimizes the time of scanning, making all the process more fluid and faster because the polygonization and recalculation are computed in background in case more than one scan is performed next to the other.

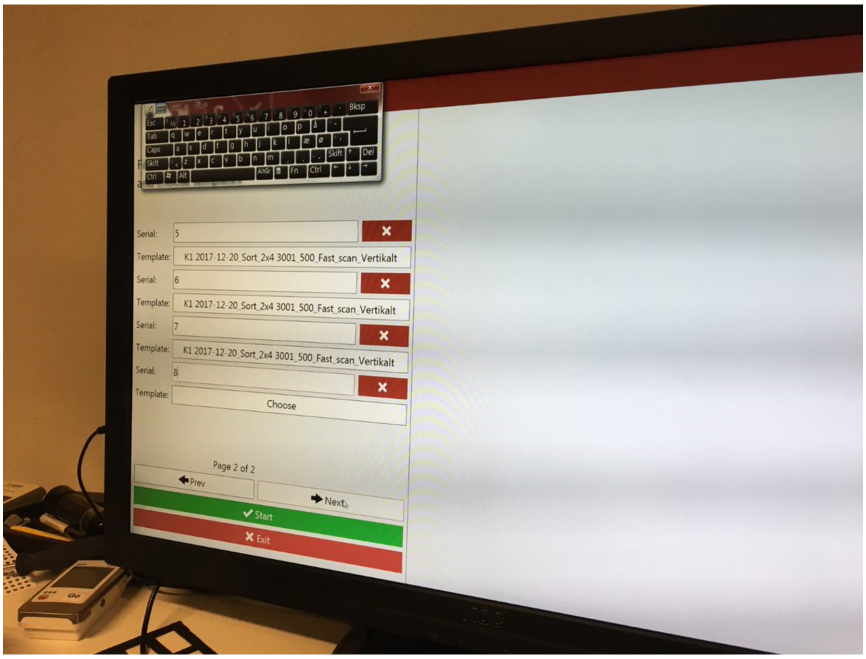


Figure 6.13: Example of KIOSK program setup measurement.

6.3 Data Analysis

6.3.1 Mesh Separation

Once the data are acquired it is possible to proceed in the analysis. To perform it, the GOM Inspect Professional suite is used. The first step is to separate the different elements mounted on the frame so to make it possible to analyse them separately. This step can be also done in the template, when saving the different files, but this time it is performed as post process on the data, as shown right further.

It is possible to do it making copies of the mesh and removing from each one not needed elements, and then save each element separately. For this operation, the command "*select through surface*" is used (figure 6.14). A good procedure is to select the part of the mesh we want to keep and then invert the selection, so to select all the points outside, and then delete the selection using the button combination "*CTRL+delete*".

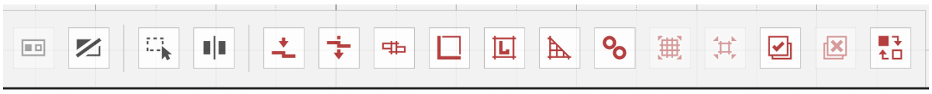


Figure 6.14: Bottom fast selection bar. Includes buttons for the mesh selection and editing.

This procedure requires some manual work for each mesh, when selecting the mesh manually, but the software gives the possibility to create some scripts for repeated commands. Into the tab "*Edit scripts*" (figure 6.15) it is possible to create new scripts. The script is written in Python, a very common, simple and versatile programming language. Using the "*record*" button (figure 6.16) it is possible to keep track in coded language of all the operations done right after. To stop the recording is simply possible to click again on the record button. Is then possible to manually edit the script including cycles, conditional operation and substituting the names of the used object with some variables so to create a generalized script for different files.
So, in this case it is possible to create a script that automatically divides and saves four different mesh, giving proper names for each element on the frame. The select and delete operation happens only the first time the operation is done, when creating the code, and it is based on coordinates. The coordinate points do not change for next measurements since the initial position of the scanner always is the same for the same template (figure 6.17). For next files it is just necessary to run the script.

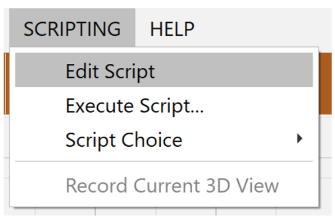


Figure 6.15: Edit Script tab.

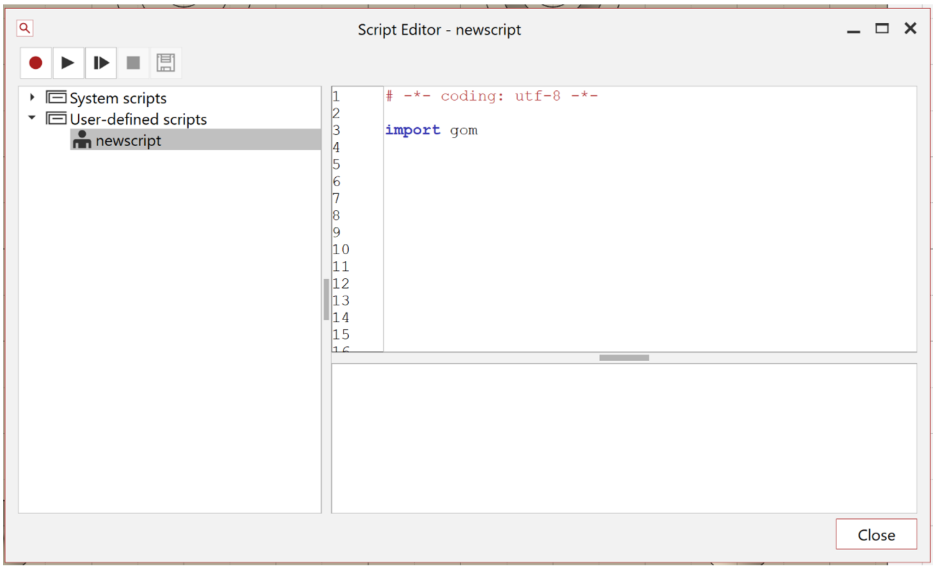


Figure 6.16: Script Editor window.

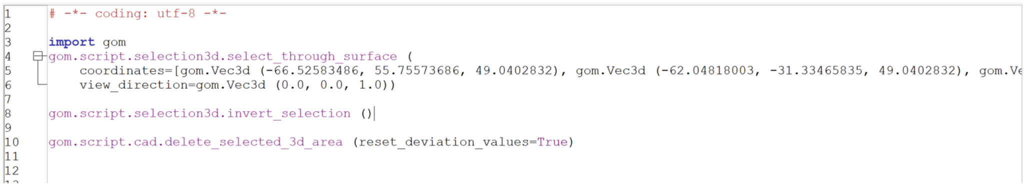


Figure 6.17: Example of mesh selection and editing script.

The result is now four different elements to study for each scanning, making it possible to perform separate analysis on them and making the entire process much faster than analysing single elements.

6.3.2 Alignment

It is necessary to import two files in the program to perform an analysis: CAD for the nominal data and the Actual mesh (the one separated before). The first operation in order to have a good analysis it is necessary to have a fine and precise alignment between them (figure 6.18).

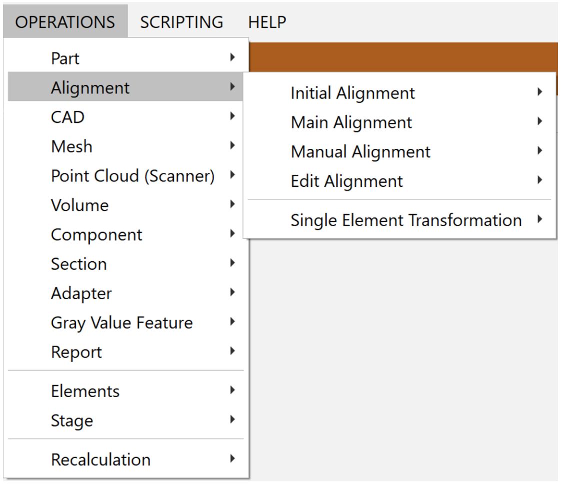


Figure 6.18: Alignments tab.

The first alignment is iteratively calculated by the program and it is called "*Prealignment*" (figure 6.19). It searches for a minimum in the average distance between points in the mesh and in the CAD geometries. You can choose between short, medium and long searching time, and it changes the number of iterations performed before the prealignment reached the target distance, that is smaller for longer searching times. Usually a longer prealignment time gives better results, if no computational error occurs. The prealignment result is very important since a bad prealignment badly affects the further fine alignments based on constructed elements.

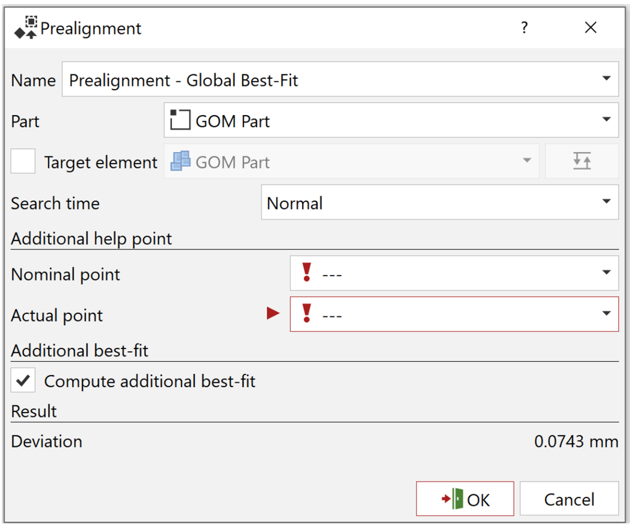


Figure 6.19: Prealignment window.

If the prealignment is not precise enough it is possible to use other alignments, using fitting regions. The more common is the "Local Best Fit" (figure 6.20). It works making some local alignment on small portions of the mesh, that can be selected with the "Select Surface" function used when separating the elements.

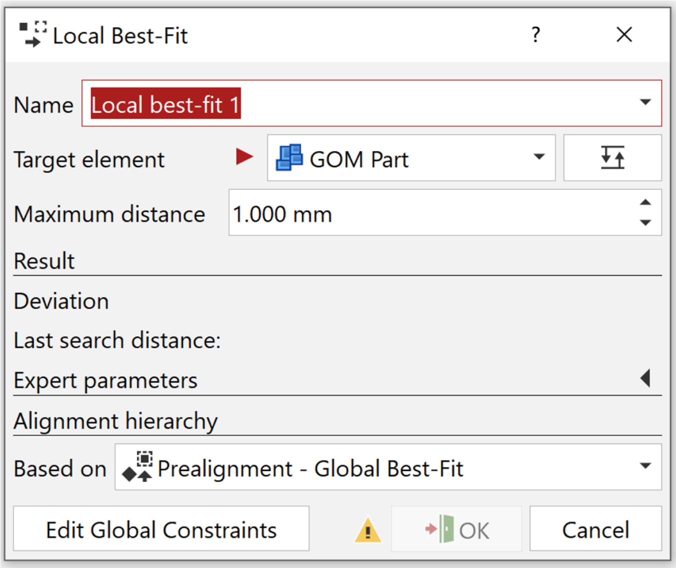


Figure 6.20: Local Best-Fit window.

When all the procedure of prealignment and intermediate alignments is done, a main alignment is still required.
It is important to think that any alignment (except the prealignment one) is based on a previous alignment, creating an alignment tree. It means that a bad prealignment or intermediate alignment of course creates very bad result on the main alignment.
Usually the main alignment is performed thinking of some geometrical constraints, similar to the working condition of the element (this is a concept similar to the datums when creating technical drawings). It is possible to create different geometries, like points, 2D geometries (line, circles. . .) or 3D (spheres, surfaces, cylinders. . .) along the element shapes (figure6.21).

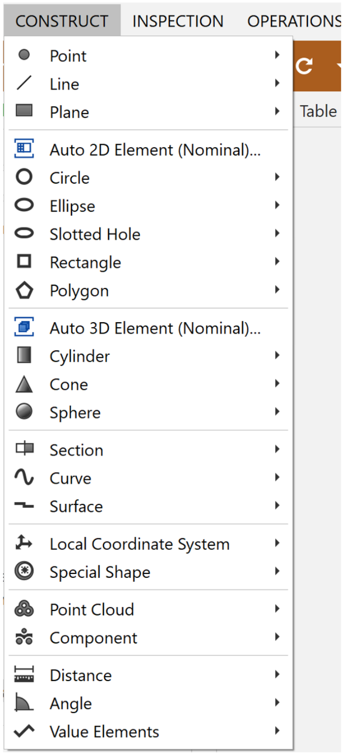


Figure 6.21: Geometry construction tab.

It is important to know how the different geometries used in this paper are defined in the program logics, before using them:

- *Point*. It is a set of three coordinates, based on one of the coordinate systems in the program.
- *Circle*. It is defined as a point and a vector for the radius.
- *Line*. It is defined as a vector.
- *Plane*. It is defined as a point and a normal vector.
- *Cylinder*. It is defined as a line and a vector for the radius.

It is possible to recreate these elements on the CAD geometry. Just by selecting the command and "*CTRL+click*" on the specific surface (figure 6.22), the element is calculated based on the program algorithm. It can be created on both the CAD and the Actual data. In case you need them for the alignment, it is highly suggested to create them on the CAD data and then calculate the correspondent one on the actuals. If some elements are needed in the ATOS software to create a proper scanning program with the automation function, it is possible to create them directly on the actual data.

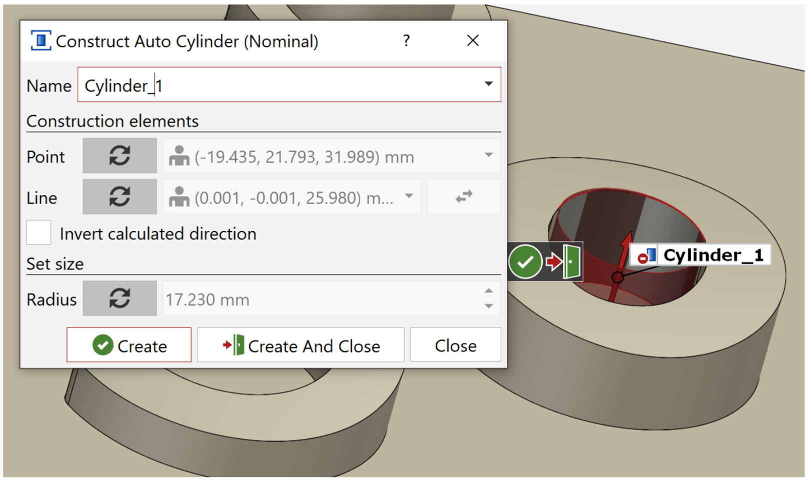


Figure 6.22: Example of the construction of a geometry on the CAD geometry.

When all the needed elements are created on the features for the alignment of the CAD part, it is necessary to calculate the same elements on the actual data. One way is to create them again and then create links between the CAD element and the Actual elements, but it can take long and can be used only in case the program is not working properly for some issues on the particular data set. The more common way to traduce each geometry on the actual data is to define an automatic "*Measuring principle*" by just right-clicking on the geometry and selecting the appropriate command. It is possible to define different types of measuring principles (figure 6.23), as following:

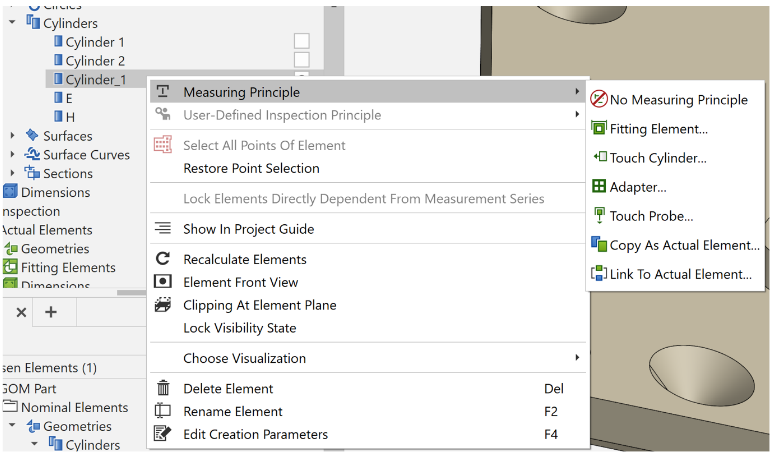


Figure 6.23: Measuring principle tab.

- *Fitting Geometry* (figure 6.24). The geometry is created through a gaussian interpolation of the points. It is possible to choose the sigma range of the point to use to recreate it (usually 3-sigma is recommended by default). It is possible to use some non-gaussian method too, such as Chebyshev approximation, if necessary. Only gaussian approximation are used in this paper, because of the high roughness of the surface the other methods can include or exclude some important crests of material.

- *Touch Disc* (figure 6.25). This function is valid only for points. The software creates a disc centred in the point, that approaches the surface along the normal vector of the surface, through a clearance defined by the user, and stops at the first contact. This is very similar to what happens working with a physical equipment with a touch probe in CMM. The clearance is defined based to the particular dimensions of the geometry and to the expected deviation. The dimension of the touch disc has to be defined taking into account that it has to represent the surface, and not a single crest or valley in the roughness, and be small enough to represent the point and no other positions (problems may occur in case of sloped surfaces, such as for CMM measurements). It has been observed, with tests made further, that for discs smaller than 50um the results remain constant for SLS parts.
- *Referred Geometry.* It is possible to create a geometry based on other elements already created (for example as intersection of them), but to apply some alignment it is necessary for it to be connected to one on the nominal CAD data. The element created before always respect a touch disc or fitting element principle, but the connection with the CAD data is given with the Referred geometry command, and it ensures that the new element is based on real measured data.
- *No Measuring Principle.* It is used in case the geometry is needed only to construct other geometries through intersections or other operations and does not need an equivalent on the actual part.

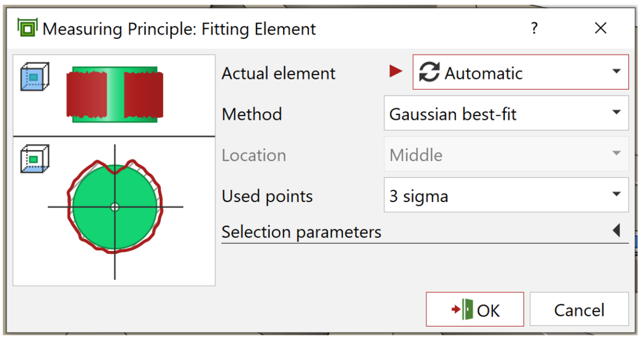


Figure 6.24: Example of the Fitting Element Measuring principle.

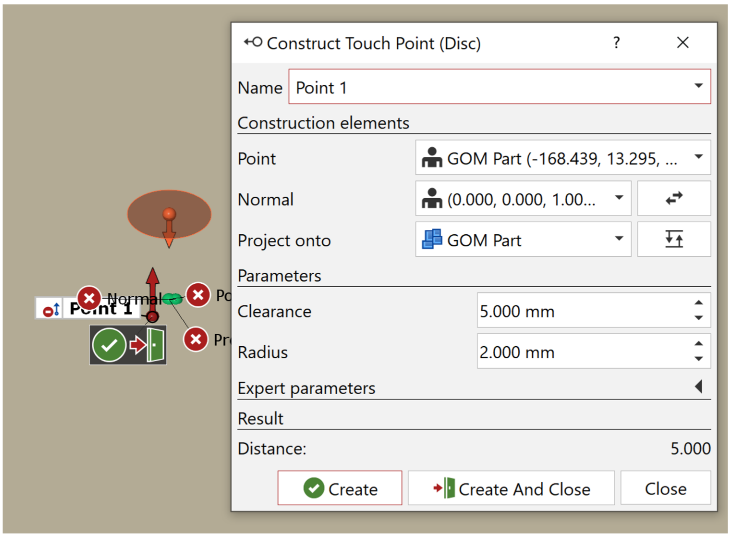


Figure 6.25: Example of Touch Point (Disc) Measuring Principle.

When all the necessary geometries have been created, it is necessary to proceed creating the proper alignment. There are mainly two alignment that can be used for the final alignment of a part:

- *Geometric Alignment* (figure 6.26). It tries to minimize distances between different selected geometric elements. The elements need to define the full position of the part and leave no degree of freedom. An example can be three perpendicular planes, or a plane-line-point system. It is important to remember that for example a cylinder is considered as a line in the software, and a circle as a point, as seen before. Three elements are needed to use this function and need to be created as seen before. It is also possible to choose combinations of these elements, as intersections, simply selecting two of them in the same selection. It is not possible to control exactly which direction each geometry is controlling.

- *Reference Point System* (RPS) Alignment (figure 6.27). It is based on points and gives the user the higher control of each degree of freedom and direction. It is possible to use only points for this type of alignment, so only circles or points are suitable. To define a plane, it is possible to select many touch points on the plane. When selecting each point, it is possible to define what direction it is controlling (X, Y, Z or a combination of them).

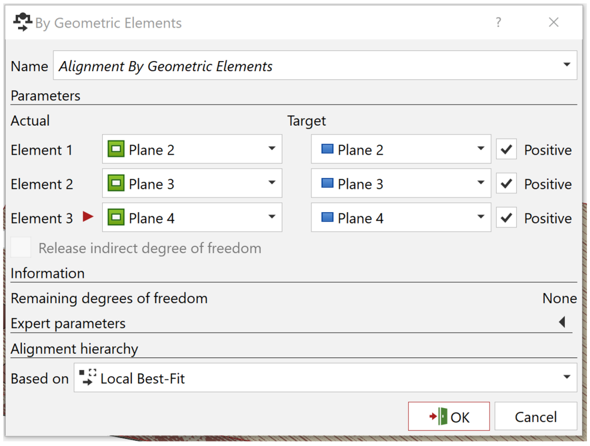


Figure 6.26: Alignment by Geometric Elements window.

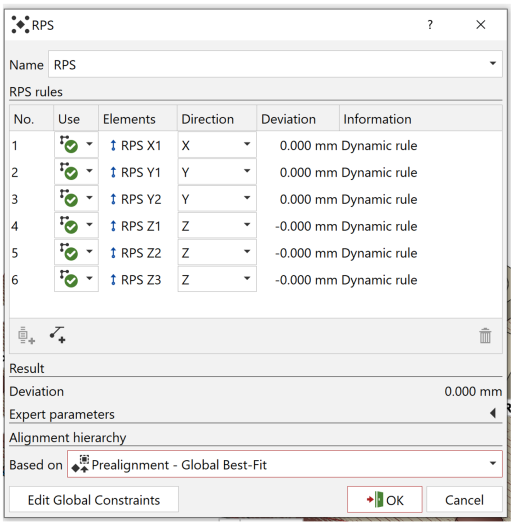


Figure 6.27: RPS Alignment windows example.

On the geometry used in this case, the alignment is based on the plane under

the element and on the centre of two cylinders, where the element is mounted. An RPS alignment has been chosen in order to have the best result and control on data.
It is necessary to set the number of iterations the program needs to minimize and optimise the distances between the actual and nominal points for the RPS the alignment. Usually three to five iteration are enough. An increment of this number takes longer computation time, but not relevant differences have been observed in the result.

6.3.3 Analysis of Different Elements

At this point, considering that more than one similar element is placed into the scanning platform, it is possible to include more than one element in the same project, in order to apply the same measurements to all of them without repeating the alignment and measurement process every time. This means that all the operation done on the first element is computed for each one of the others. It is particularly important to make sure that, specifically for the prealignment, it is set up as single stage transformation (figure 6.28), so it is calculated independently for each stage by the software. It is possible to check this parameter in the property of the prealignment (right click on it » "*properties*" or click + "*F4*").

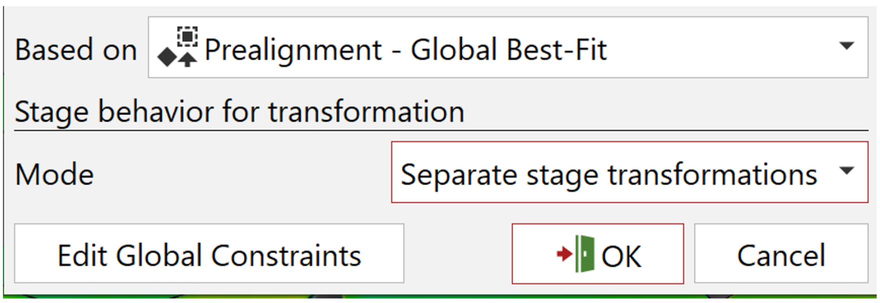


Figure 6.28: Single stage transformation mode in the Prealignment properties.

To import the other meshes it is necessary to import them as done for the first element and then select "*new stage*" (figure 6.29). The software opens new "*pages*" of project, creating automatically all the previous step and geometry, in order to use all the work already done on the first element.

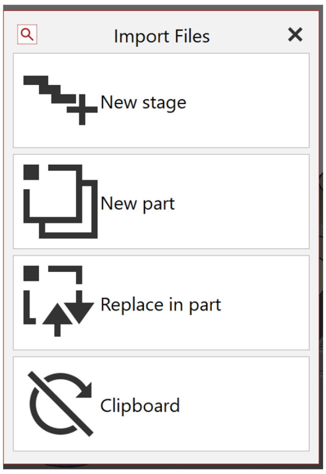


Figure 6.29: Import new file tab.

If the project contains too many stages (figure 6.30), it needs a considerable amount of RAM, and every small adjustment happen on all the stages. So is quite common to set the measurement on one single stage and then add all the others at the end and recalculate the project.

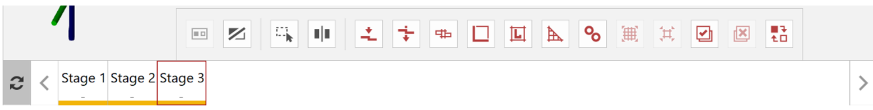


Figure 6.30: Stage bar.

It is also possible to deactivate and reactivate some stages in the Manage Stage window (figure 6.31), in order to make faster calculation in case of adjustment after importing all the other elements, and only as latest operation activate all the other stages and recalculate the project. It is possible to open this window with right click on the stage bar.

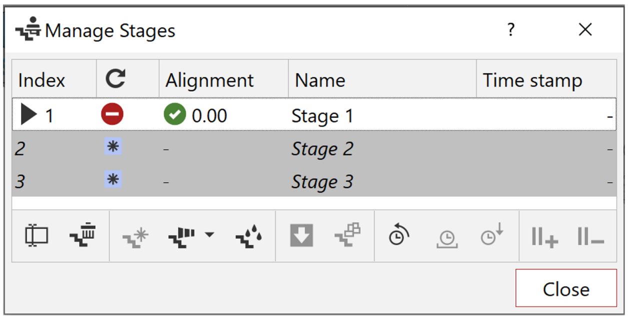


Figure 6.31: Manage Stages Window.

6.3.4 Type of Data Selections and Inspections

There are several ways to perform a selection and analysis of the data, considering the type of data required. It is possible to divide them into:

- Surface comparison.
- Analysis of punctual deviations.
- Analysis of entire surfaces with colourmaps.
- Analysis with *GD&T*

Surface comparison This is the simplest analysis to perform in the software. The software searches for the distance between each triangle of the actual mesh compared to the nominal one. It is possible to select the maximum distance to search in the calculation, and it needs to include the maximum expected distance. It is common to overestimate this number in order to not exclude any part from the calculation. Larger is the distance selected, longer is the time needed to finish the calculation and less accurate the result is. An example of the result is shown in (figure 6.32). The scale is by default in a three colours scale, with:

- *Red.* More material is on the actual part than the nominal one.
- *Blue.* Less material is on the actual part than the nominal one.
- *Green.* Same amount of material is on both parts (no deviations).

It can be very useful to modify the scale boundaries in order to visualize the data in the better way, simply by double clicking on the scale boundary to change. Furthermore, different types of suggested visualizations are possible (figure 6.33):

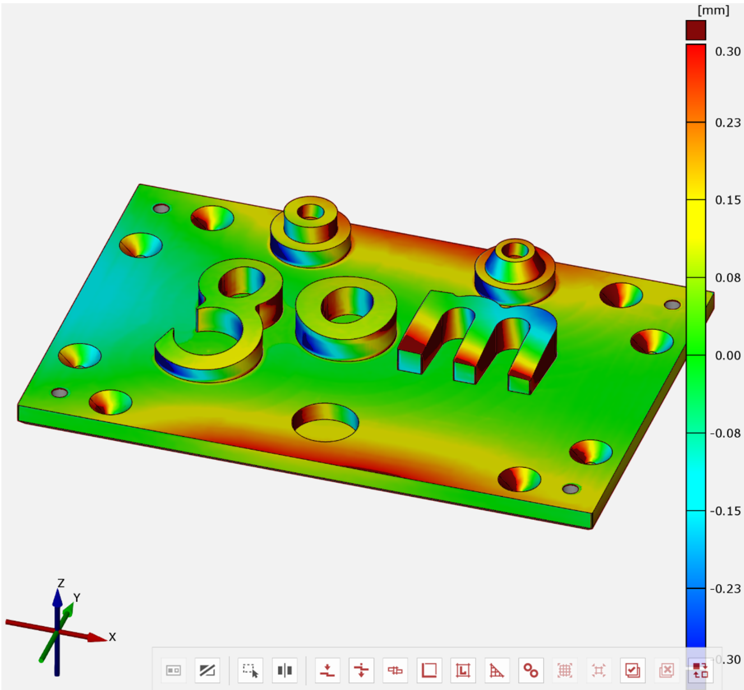


Figure 6.32: Example of surface comparison.

- Continuous scale. It provides a continue variation of the colour gradient on the scale.
- 3 or 8 colours. It divides the scale in discrete regions, 3 or 8 depending on the selected.
- Tolerance legend. It divides the result based on a user defined tolerance. In this case both regions with more material or less material is displayed in *red*, and the portion in tolerance in *green*.

Another useful tool provided by the software is the "*deviation label*" (figure 6.34). It is possible to apply a deviation label with the appropriate command and "*CTRL+ Right-Click*" on the surface of the analysis, in the desired point. A label with the deviation in the specific point is displayed.

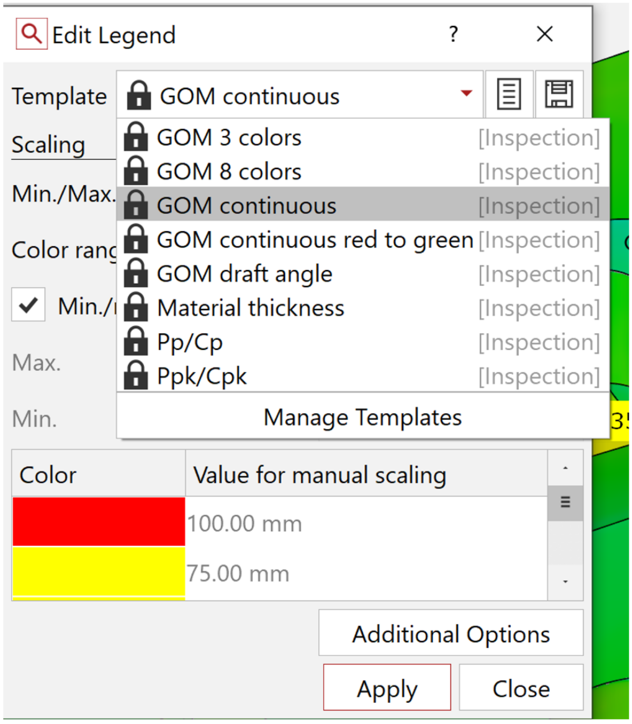


Figure 6.33: Legend Editor.

It is important to keep in mind that the deviation represented in the colour map or on the label is relative to the minimum distance to two point of the elements, not considering any direction. This means that it is not possible to make an analysis based on the distance on a certain direction, and it is usually useful to have a visual idea but not an exact number to apply adjustments.

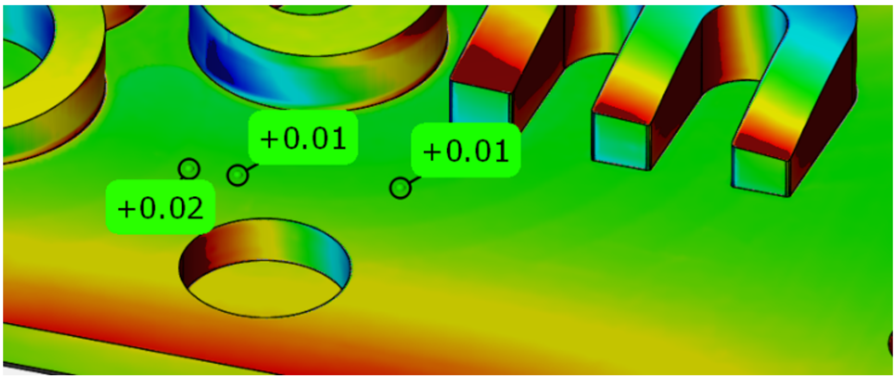


Figure 6.34: Example of Deviation Labels.

Analysis of punctual deviations To provide more accurate analysis it is possible to use the "*Inspection*" tab of the software in order to take deviations in some exact point, replicating the work obtained in the CMM machine. It is necessary to perform the following step:

1. Creation of a "*surface point*" (figure 6.35) on the surface of the nominal element. It is possible to create the point based on coordinates or clicking on the surface.
2. Creating a relative actual point using the tool "*touch point disc*" as measuring principle.
3. Construct some "projected point distance" (figure 6.36) between a coordinate system and a point or between two different point. This is an element that measures the distance between two points or a point and a coordinate system. It is necessary to define the direction when creating the element. A measuring principle as "*referred element*" is necessary for this element in order to create an actual one and make it possible to perform a real measurement.
4. Create the inspection element (figure 6.37) based on the distance elements

At this point it is possible to view all the result (Figure 6.38) on a table and export them in *Excel* format.

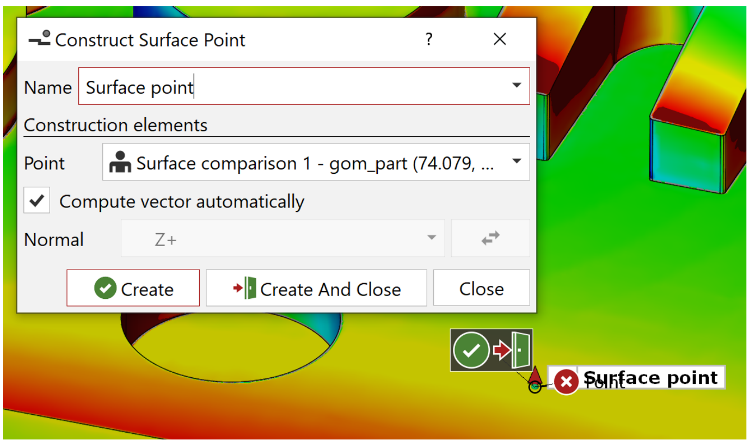


Figure 6.35: Construction of a Surface Point.

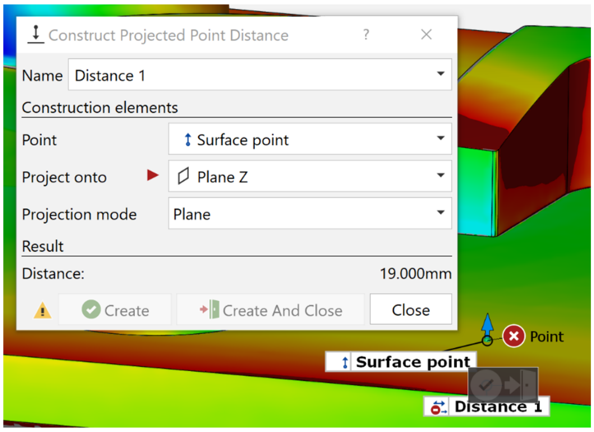


Figure 6.36: Construction of a Projected Point Distance.

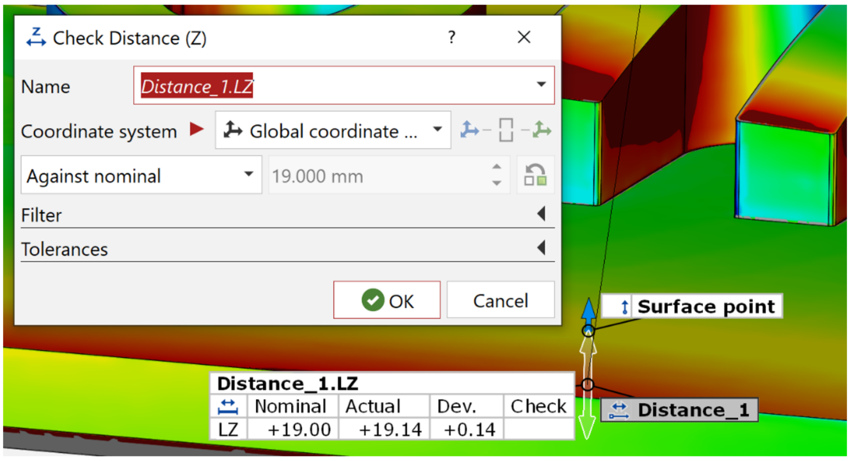


Figure 6.37: Inspection element for distance.

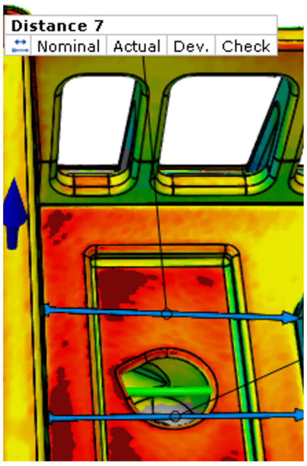
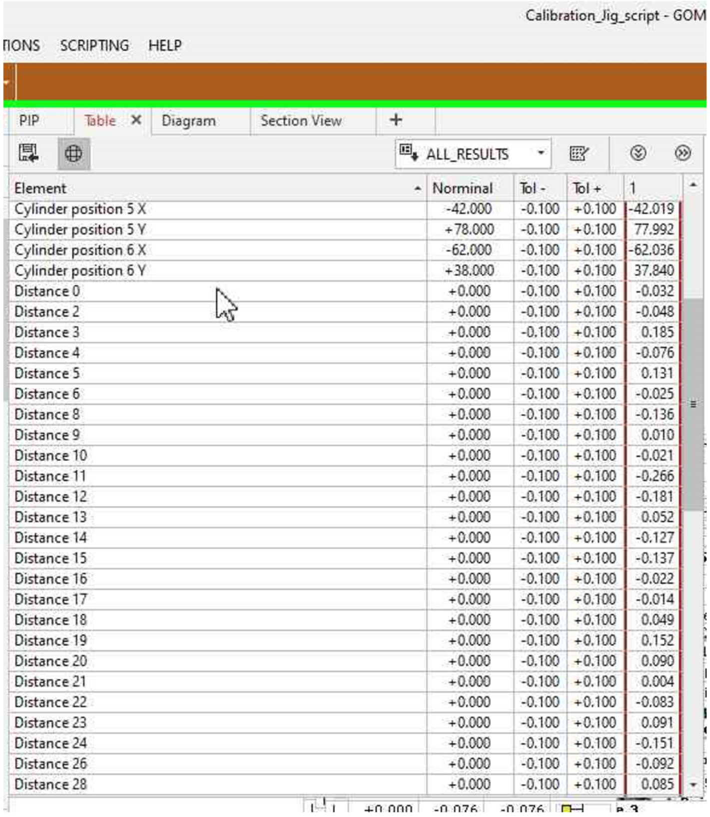


Figure 6.38: Example of distance element creation.

Since creating the different points and all the measuring program can be long by the point of view of the human work, it is possible in this case to create a small script and include all the operation to repeat for the creation of each point and distance element.
To make it possible for a script to detect and recognise each desired point, a good notation for them is required. It is possible to divide the points in the drawing for the measurement in a 3D grid of raw, columns and height (on *Z axis*). Columns and height can be, for example in this case, defined by letters or numbers. So, each point can be defined as a combination of these symbols. An example can be "*ABC*". This means that the point is on the first column (A), second raw (B) and third Z-level (C). This can be considered enough when thinking to a point, but since each touch point disc in the software is automatically referred to a direction (normal to the surface) when created by clicking, it is necessary to define also the vector of it. The vector can be defined, for example, as "*x+*", which means that it is parallel to the positive direction of the *X axis*. Based on this formal notation, the entire definition of a point is composed of five symbols, and the exact example showed is, in this case: "*ABCx+*". To make it possible for the software to have all the information about the 3D grid of points on the drawing, it is necessary to declare three different arrays with the coordinate for all the raw, column and height. A further array includes the name list of the points with the notation decided before. The script includes some loop instructions and automatically creates each measurement, making them appear in the export table (figure 6.39) just clicking the "*run*" button.



Element	Norminal	Tol -	Tol +	1
Cylinder position 5 X	-42.000	-0.100	+0.100	-42.019
Cylinder position 5 Y	+78.000	-0.100	+0.100	77.992
Cylinder position 6 X	-62.000	-0.100	+0.100	-62.036
Cylinder position 6 Y	+38.000	-0.100	+0.100	37.840
Distance 0	+0.000	-0.100	+0.100	-0.032
Distance 2	+0.000	-0.100	+0.100	-0.048
Distance 3	+0.000	-0.100	+0.100	0.185
Distance 4	+0.000	-0.100	+0.100	-0.076
Distance 5	+0.000	-0.100	+0.100	0.131
Distance 6	+0.000	-0.100	+0.100	-0.025
Distance 8	+0.000	-0.100	+0.100	-0.136
Distance 9	+0.000	-0.100	+0.100	0.010
Distance 10	+0.000	-0.100	+0.100	-0.021
Distance 11	+0.000	-0.100	+0.100	-0.266
Distance 12	+0.000	-0.100	+0.100	-0.181
Distance 13	+0.000	-0.100	+0.100	0.052
Distance 14	+0.000	-0.100	+0.100	-0.127
Distance 15	+0.000	-0.100	+0.100	-0.137
Distance 16	+0.000	-0.100	+0.100	-0.022
Distance 17	+0.000	-0.100	+0.100	-0.014
Distance 18	+0.000	-0.100	+0.100	0.049
Distance 19	+0.000	-0.100	+0.100	0.152
Distance 20	+0.000	-0.100	+0.100	0.090
Distance 21	+0.000	-0.100	+0.100	0.004
Distance 22	+0.000	-0.100	+0.100	-0.083
Distance 23	+0.000	-0.100	+0.100	0.091
Distance 24	+0.000	-0.100	+0.100	-0.151
Distance 26	+0.000	-0.100	+0.100	-0.092
Distance 28	+0.000	-0.100	+0.100	0.085

Figure 6.39: Table of measurements obtained with a script.

Analysis of entire surfaces deviations with colourmaps The GOM Inspect Professional makes it possible to create measurements based directly on surfaces. It is possible to select the surfaces directly from the CAD file, basing the selection on the colour of the surface (figure 6.40). The colour can be defined in the CAD program before exporting the file to make it suitable for the measurements. This allows us to keep in the CAD file all the data regarding the measurement process too.

It is necessary, when applying the measuring principle, to detect the distance between the two selected planes, to avoid selecting the more external part wince there can occur some rounding due to the technology of the laser or simply small errors of alignment. This is possible, when applying the measuring principle, to exclude a small portion of the external area in the expert parameters, decreasing the selection at borders (figure 6.41).

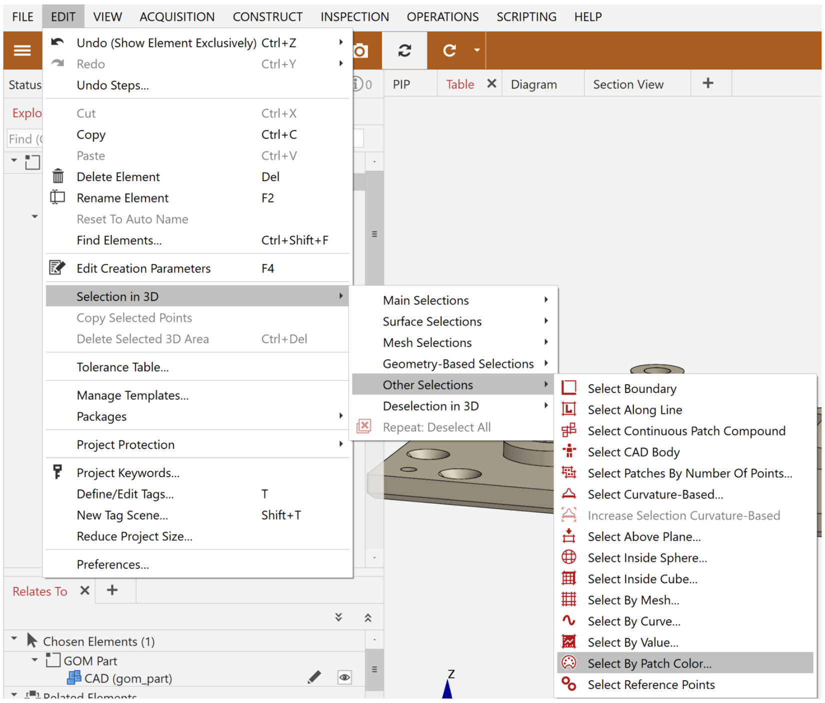


Figure 6.40: Select by patch color tab.

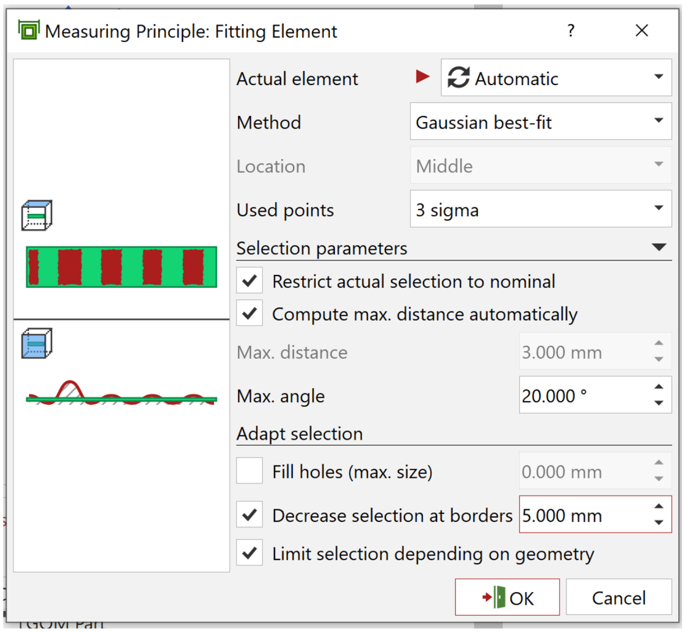


Figure 6.41: Decrease selection at borders example window.

At this point, when both actual and nominal surfaces have been created, it is possible to run the command "*Deviation from geometry*" (Figure 6.42). This performs an analysis in the direction of the normal to the nominal surface, making a projection of each triangle of mesh and at the end showing a colourmap like the one seen in the Surface Comparison feature.

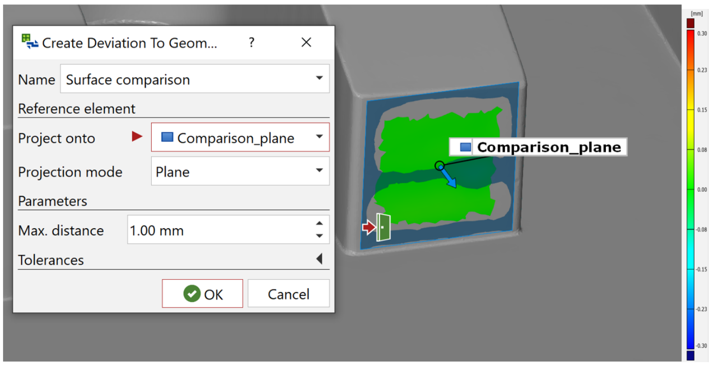


Figure 6.42: Creation of Deviation to Geometry inspection.

It is now possible, for each surface, to create some deviation labels. Selecting the surfaces, it is possible to apply special labels that is automatically located by the software in the desired position searching for the maximum, minimum or average distance, depending to the desired use of the measurement (figure 6.43).

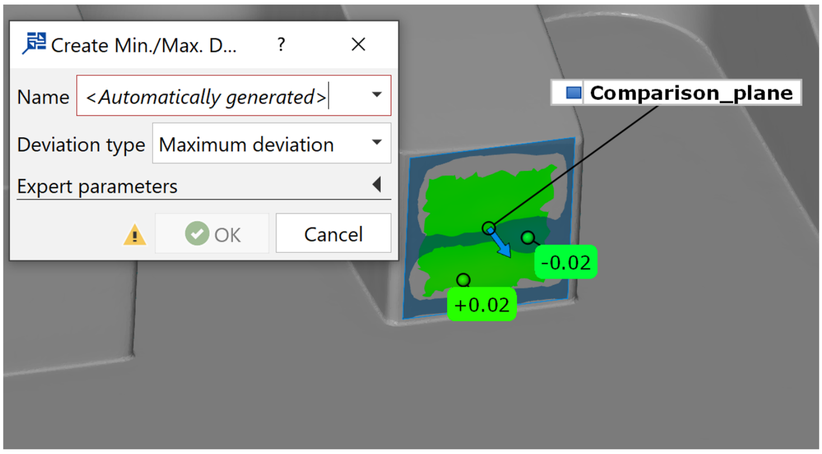


Figure 6.43: Creation of Deviation to Geometry inspection.

Analysis with *GD&T* The GOM Inspect Professional Suite allows the creation of *GD&T* tolerances. It is possible to create them in the program (Figure 6.44) or to import them with the CAD file, when they have been created in the CAD software with the use of *PMI* (Product Manufacturing Information) (Figure 6.45). By importing these instructions, the software automatically recognizes them and, applying the required measuring principle by hand, gives the result.

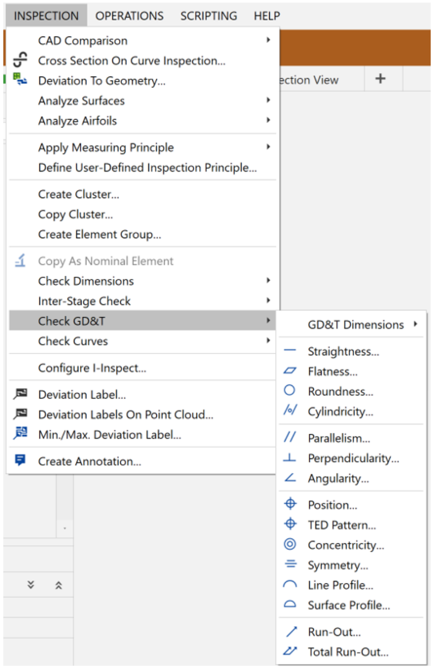


Figure 6.44: *GD&T* inspection tab in GOM Inspect.

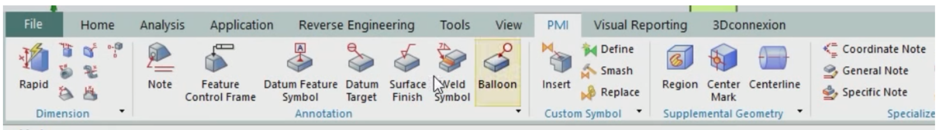


Figure 6.45: PMI creation tab in Siemens NX.

Most important *GD&T* (figure 6.46) (Figure 6.47) usable with this technology are the following ones, all included in the category of the "*form*" tolerances:

- Surface Profile. It describes the profile of a surface and controls size, form and orientation.
- Cylindricity. Controls form of an axis and shape.
- Flatness. Controls form of a median plane and shape.

They give an important feedback on the shape of the entire selected geometry and can strongly improve the quality of the final manufactured object. This aspect has not been studied further, considering the early state of the implementation of the technology.

TYPE OF TOLERANCE	CHARACTERISTIC	SYMBOL
FORM	STRAIGHTNESS	⏤
	FLATNESS	⏥
	CIRCULARITY	○
	CYLINDRICITY	⌭
PROFILE	PROFILE OF A LINE	⌒
	PROFILE OF A SURFACE	⌓
ORIENTATION	ANGULARITY	∠
	PERPENDICULARITY	⊥
	PARALLELISM	∥
LOCATION	POSITION	⌖
	CONCENTRICITY	◎
	SYMMETRY	⌯
RUNOUT	CIRCULAR RUNOUT	↗
	TOTAL RUNOUT	⌰

Figure 6.46: Table reporting the suitable *GD&T* to apply through PMI.

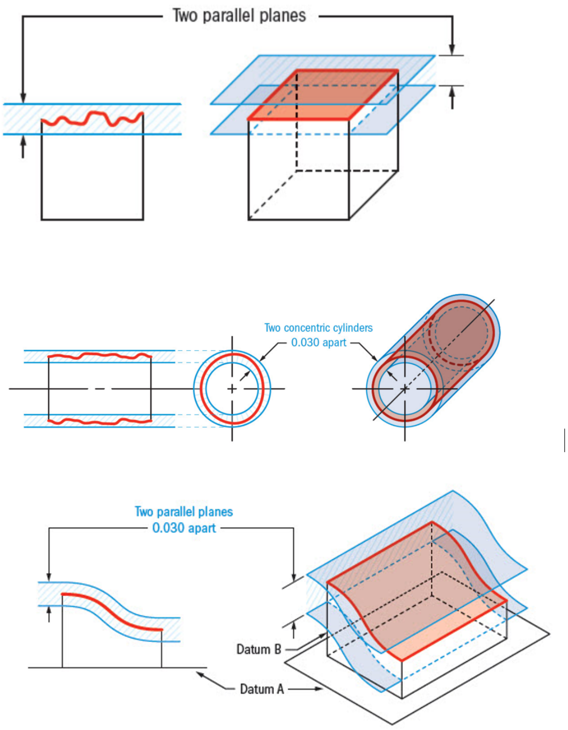


Figure 6.47: Rapresentation of tolerance zones for Flatness, Cilindricity and Profile Tolerances.

Comparison between the different methods of analysis All the different methods of analysis shown have some powerful features and can be combined between them to obtain a better overview of the result. The most immediate one in order to receive a fast-qualitative feedback of the shapes and deformation is for sure the surface comparison with colourmap. As shown in (figure 6.48), it is possible to immediately see a sudden shifting behaviour. Other methods are more advantageous in case quantitative results are needed, and the difference between them is defined in how deep the analysis should be (figure 6.49). A deeper dissertation will be presented in the conclusion chapter.

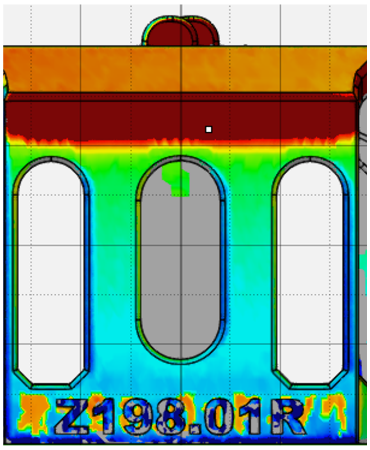


Figure 6.48: Example of qualitative analysis for the deviation with a colourmap, with evidence of sudden shifting.

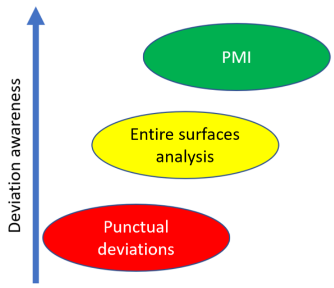


Figure 6.49: Rappresentation of the level of details given by different measuring methods.

6.4 Analysis of the Scanner Repeatability

Once the scanner setup is ready, it is possible to make some tests to verify the accuracy of the measurements and the repeatability of them, being a new tool used for this application.

In order to make this type of analysis, the KIOSK program is very useful since

it allows us to make several consecutive scanning without human surveillance. For this analysis, twenty consecutive different measurements have been performed on the same element. The setup is unchanged in the machine during the whole measurement.
This is intended to run a repeatability analysis on the entire setup. We are not interested in reproducibility since the entire setup to mount the part is the same as the CMM machine, and it is already proven to be stable enough and not give any issue on older applications.
Considering that each measurement takes 30 minutes, the advantage of using an automatic program to run twenty measurement allows you to have all the data in only one day, with completely not supervised machine.
When all the data are obtained, it is possible to follow all the step seen before, separating all the different elements in the mesh, performing the alignments, analysis and taking all the measurement points on each part.
In this case the twenty elements are imported as different stages. The computation time can take long, being many Gigabytes of files stored in the RAM, but only with this tool it is possible to have tables with all the statistics of the data, graphs and ranges, and be sure that all the same process is applied on each element.
A deep analysis of this data is performed to evidence what is the repeatability of the scanner in the same conditions.

6.4.1 Analysis of the Repeatability Data

Of the twenty measurements taken, the first one gave some problem on the reconstruction of the 3D mesh, so the analysis is performed on only nineteen of them. It was not possible to recover the mesh for the first measurement, since it is not possible to edit the measurement in the KIOSK program.
The data for all the measurements are exported in an *Excel* file, and at this point it is possible to start a good analysis of them. The export function has different parameters, and it is necessary to select the best way according to

your *Excel* setup. In this case the data are exported in semi-columns, with comma separation between integer and decimal part. The data have three relevant number after the comma, in order to measure the $1\mu m$ difference.
All the data have been normalized on the median value, in order to have the possibility to create a plot only with variations, not considering the measured dimension.
As showed in the plot (figure 6.50), which contains on the *y-axis* the deviation from the median value in millimetres and on the *x-axis* the different iteration for the measurement, all the points are in the range of [-20μm; +20μm]. It means that it is about $\frac{1}{5}$ of the entire tolerance range required, in this case, by the SLS final product, and it is considered acceptable for the purpose. It is possible to see an outlier point, on measurement 16, but it is considered not relevant. Other statistical studies with the data have been pursued by an expert, and the second analysis confirm the result of the first one(figure 6.51)

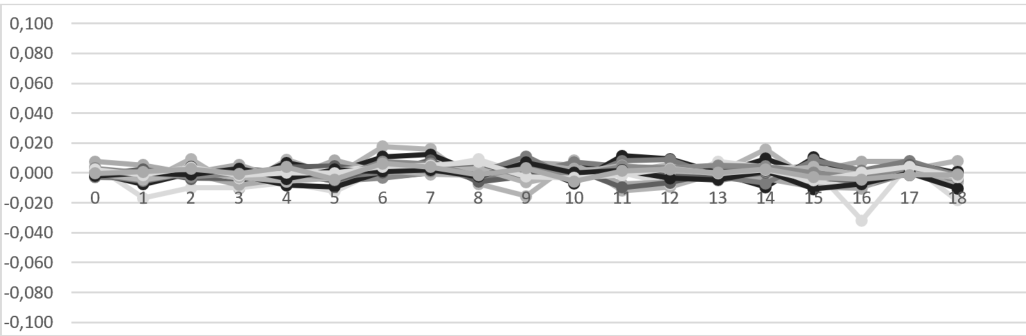


Figure 6.50: Plot of the Repeatability data.

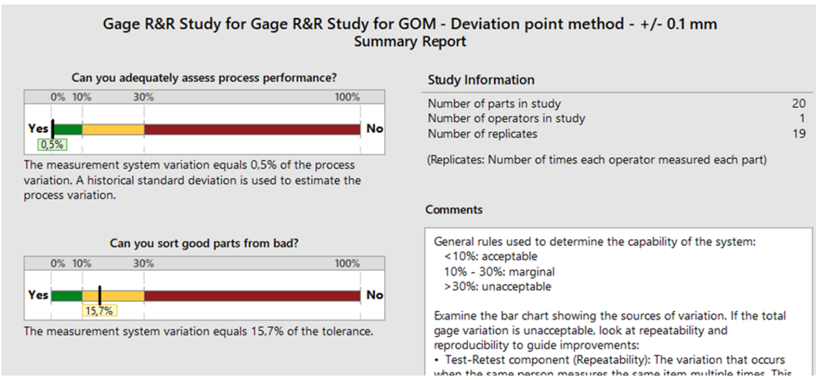


Figure 6.51: Repeatability & Reproducibility Study.

6.5 Correction of Shapes

6.5.1 Reverse Engineering with Zeiss

As told before, this software offers many functions similar to the one offered in the GOM Inspect suite, and it is possible to make alignments and pre-process most operations on the data. But, since it is not the main purpose of the software, all these operations are less refined than in the other software, and, considered the deeper experience developed on the other software and the possibility to control many more parameters, has been considered better to practice the alignment on the GOM Inspect Suite and then export the meshes to reimport them in ZRE. When exporting a mesh, it always has a position in the space, and the alignment is kept in the new importation. It is important to keep in mind that, in this case, meshes need to be exported in a neutral format such as STL, because the *.G3D* format is not readable for the ZRE software.
It is important to define a good alignment for the correction as well. The alignment can be different for the one used for the measurements, because maybe only the shape of some feature is needed to be adjusted, and so the alignment is locally applied to the feature.

6.5.2 Mesh editing

When the mesh is imported, as first step can be useful to remove all the defect in it, manipulating the mesh (Figure 6.52). The main functions presented are:

- *Smoothing/sharpening.* Meshes can be smoothed or sharpened by means of user-defined parameters. You can define the degree of smoothing or accentuation of surface edges by setting the parameters.
- *Denoising.* Meshes can be denoised using user-defined parameters.
- *Regularizing.* This function allows you to improve the quality of triangles in a mesh. Triangular meshes may locally contain triangles which differ significantly in form and size, although the surface can be represented in the mesh by largely uniform triangles. This function allows transforming

the mesh in such a way that an even triangular structure is created.

- *Decimating*. Meshes can be decimated using user-defined parameters. Editing a mesh may become time-consuming if a large number of triangles is involved. This function considerably simplifies such a structure, while producing only a small error. You can define an upper limit for this error, a maximum edge length, and a minimum number of triangles.
- *Removing islands* (Figure 6.53). This function allows you to remove islands from a mesh, based on a specified maximum number of triangles. An island is a contiguous component of triangles that are interconnected via edges.
- *Close holes*. It allows to close small holes in the element, with planes or curves shapes (according to the surrounding mesh).

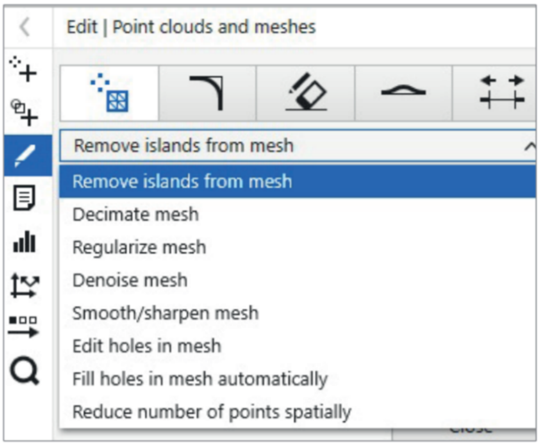


Figure 6.52: Mesh Editing Tab in ZRE.

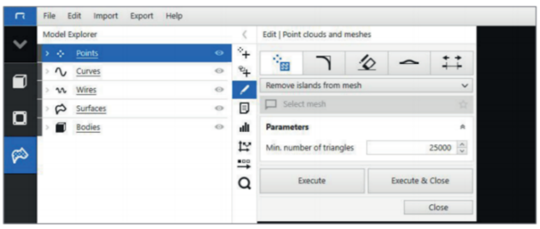


Figure 6.53: Example of the Remove Island function in the Mesh Editor.

6.5.3 Reverse Engineered Shapes Creation

The software can be basically used to reconstruct faces from elements acquired via a 3D scanner, starting from a mesh, entering in the appropriate tab (Figure 6.54). Based on this assumption, different types of shapes can be adapted to the structure, fitting different type of elements such as sheets or cylinders. Easier shapes are easy to recreate with basic function of the software, such are cylinders or planes, but the interesting part of it, since the aim of the thesis is to correct non-regular surfaces, is accomplished by some fitting freeform surfaces.

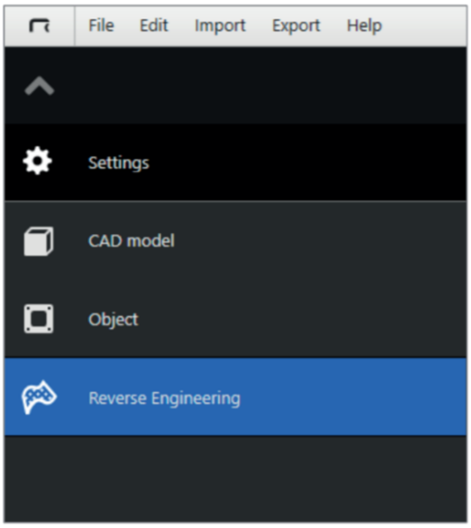


Figure 6.54: Reverse Engineering access tab.

Few examples are shown in the following figures, in order to give an idea of how the software recreates the surface. The software is very powerful in adapting these shapes, and at the end recreates a watertight element. The result is a freeform surface, not editable anymore. The starting shape fits the element according to some input given parameters (Figure 6.55).

- *Degree of freedom* (maximum amount always is three in each direction U or V).
- *Number of segments* in the grid of the surface. The higher is this number the more the shape is flexible and adapt better, even if a grid with a higher number of segments uses more computation power to execute.

- *Number of iterations* performed to fit the freeform surface to the acquired data minimising distances.

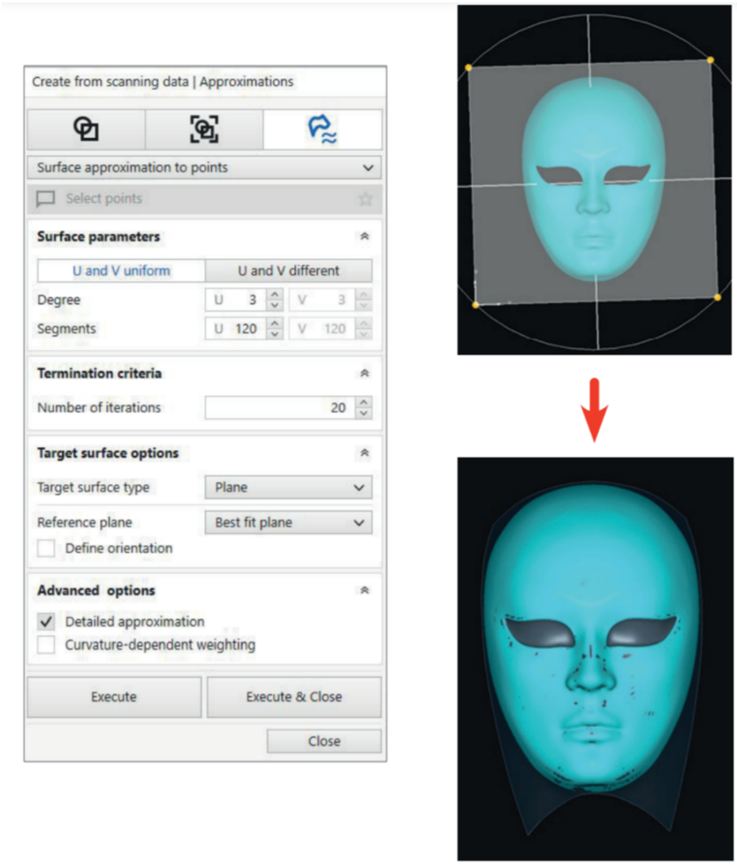


Figure 6.55: Creation of a freeform surface.

Shapes can be of different types (Figure 6.56), the more used are:

- *Sheet.* it is placed on the top of the element and fits it moving in a stated direction. An example can be the mask one.
- *Circle/Cylinder.* It is a circle that surrounds the element and reduces its dimension in order to fit the element, as in the example of the gear.
- *Spline.* It is the more complex element (such as a helix or just a planar spline), and creates a loop surrounding the element. It always is created by hand selecting a spline on the object and then applying an external offset to it, as in the example of the mould tool.

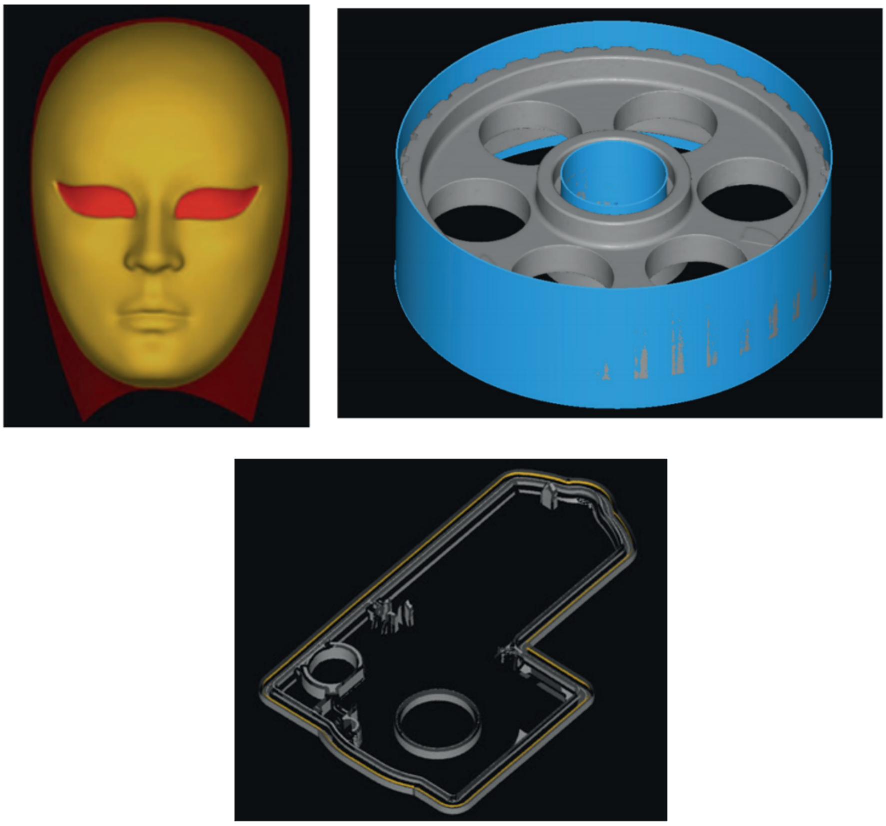


Figure 6.56: Example of creation of a freeform surface with a sheet, a cylinder or a spline.

Other functions are included in the software to create more complex shapes, but they are not discussed in order to keep the analysis easier to understand, being very specific functions.

6.5.4 Tool Correction

This is the main function for the correction of deviated shapes. It has been created with the purpose to correct shrinkages effects on mould tools (Figure 6.57) but, in this thesis it is adapted for the correction of 3D printed element shapes, since both workflows have in common the idea of compensation.
The software mirrors the deviations between actual and nominal element creating some points. It is possible to define the inversion factor for the correction. It is 100% by default, and it means that deviations is mirrored multiplied by a factor of 1 (Figure 6.58).

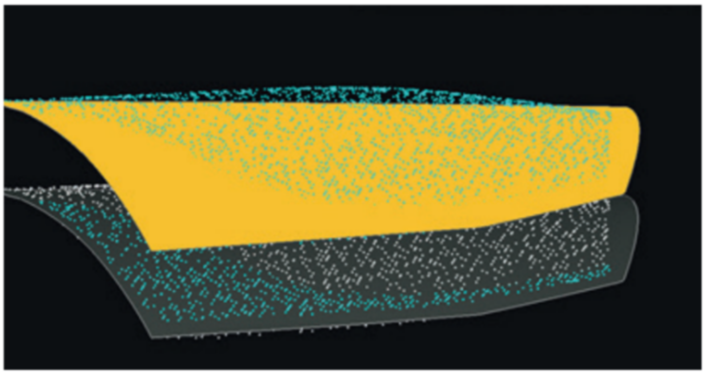


Figure 6.57: Example of the correction of an element with traslation of the deviation from the cad part, in grey, over the shape of the mould tool, in yellow.

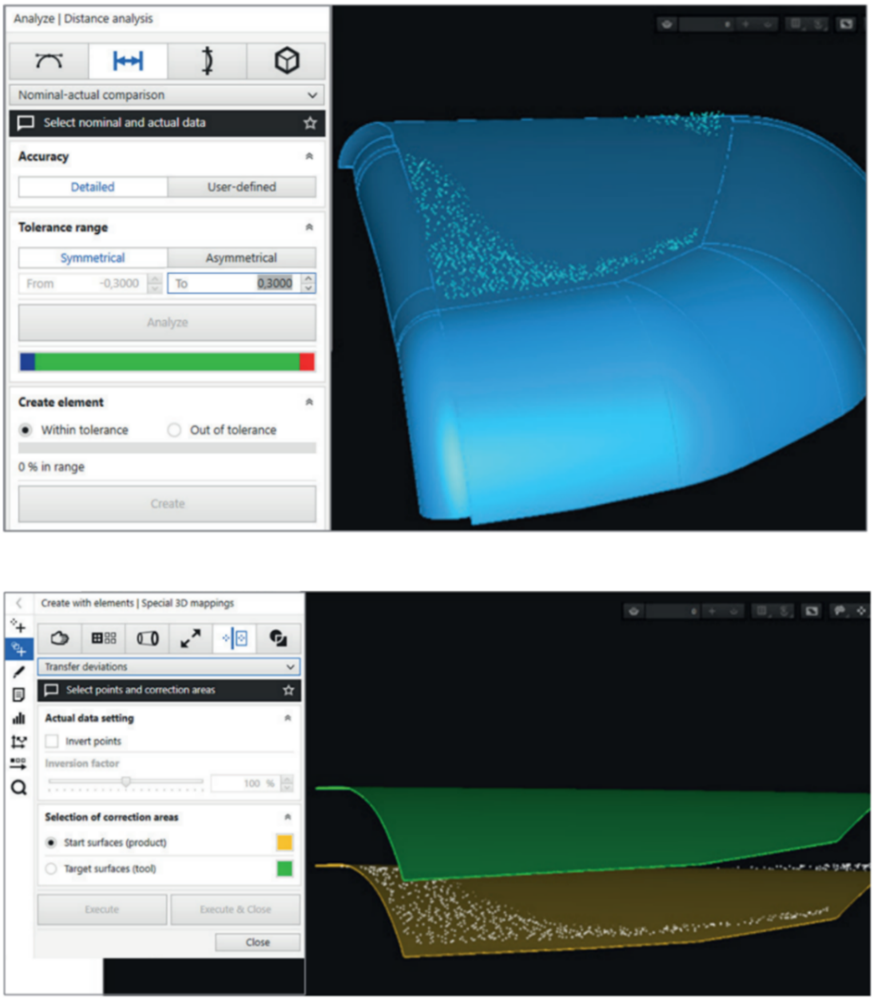


Figure 6.58: Example of the ZRE analysis of deviations and mirroring of deviation.

When the points have been created, it is necessary to run through the Reverse engineered shapes creation workflow to create the new freeform shape. It is the result and starting point for the new iteration of printing and measurements.

6.5.5 Observation on the software result

This software can be very powerful if there is no possibility to get the original CAD data, in order to recreate a shape, but it requires an important amount of manual work and adjustment to make the process feasible.
Another weakness point is that the created surface needs to be a freeform one and it is not possible to modify it in a design environment such as Siemens NX, losing several important dimensional information and the possibility to apply future design changes.
As anticipated before, deviations should be small compared to the shape of the geometry, since big deviations can produce important error (Figure 6.59) when running through the Tool Correction process. In fact the actual surface is mirrored to the closer nominal one, and in case of big deviations and specially close to the edges many errors can occur and it is necessary to remove all the bad created point by hand (even if it is possible keeping an acceptable shape for the future reconstruction).

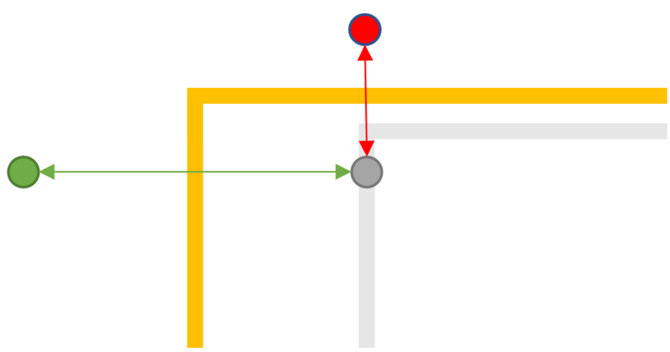


Figure 6.59: Rappresentation of correction logic of the ZRE software. The *grey* dot is mirrored to the *red* one, according to the closer Nominal surface (*gold*), but the correct point would be the *green* one.

Keeping into account all this consideration, the exploration of this software has been abandoned due to the high complexity of manual work and to bad results on the final shape due to compensations.

6.5.6 GOM Inspect Professional – Future Developing

As anticipated before, the new 2020 version of the GOM Inspect software has some function to allow shape correction. The creation of an editable mesh is performed remotely on GOM servers, but all the constraints and the adjustment is selected by the user.
It is possible to have more freedom selecting directions and faces to adjust. The result always is a freeform element, but with the advantage of high control on the transformation applied on elements and low computational power required. This has not been tested yet since all the work present in the thesis was done previous the release of the new version, and only a demonstration was given by the GOM company.

6.5.7 Siemens NX Adjustments

In order to keep all the element in a parametric file and keep track of all the adjustments performed on it, the most common way to act is to simply apply adjustments on the CAD file, through the same program used for the design itself, using the data obtained by the measurement technologies (CMM or Optical Scanner).

6.5.8 Manual Editing of Sketches and Surfaces

The first error editable with a CAD software is the shifting. The way to change some dimensions in an element is to simply change dimensions in the sketch of it (Figure 6.60), adjusting it according on compensation calculated using the data obtained from the measurements. So, moving an element, or changing a diameter is a fast operation.
Another operation often used is the “Move surface” (Figure 6.61), that allows to translate a surface of a defined distance. This allows small changes in

comparison with the dimensions of the overall feature, because bigger ones can affect rounding and make the program crash.

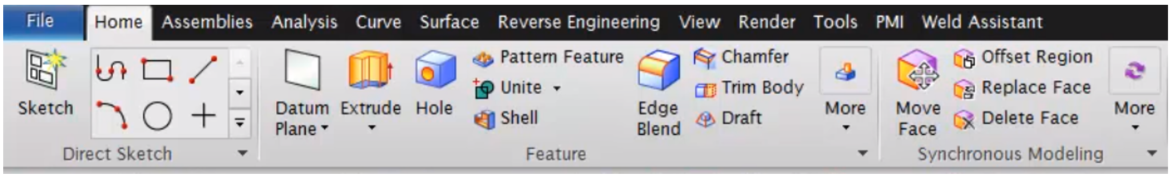


Figure 6.60: Sketch editor and "*Move Face*" button.

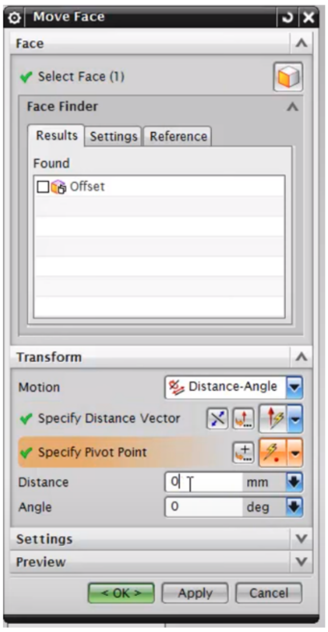


Figure 6.61: Move Face function tabn.

In case the problem is related to the scaling, it is possible to directly rescale the entire part in the three directions using the appropriate function included in the software. (Figure 6.62)

Figure 6.62: Scale body function tab.

Usually, the amounts calculated for the translations of surfaces, to change the sketch or to rescale the part are the result of the average of different points, and it is a good practice to take the more points as possible, and a technology as an Optical scanner makes the operation of taking much more points even easier and not more time consuming than taking single points.

6.5.9 Parametric Design

Another important function of the Siemens NX software (but many CAD software include it as well) is the possibility to link dimensions to an external file (typically an Excel book). This makes it possible to massively reduce the amount of manual work and clicks to change every single dimension by hand, even if some additional work is required to link every dimension when designing the element. A short workflow of the main operation to follow for the creation of parametric design dimensions is shown. When creating a dimension, it is necessary to select "*formula*" in the options (Figure 6.63a). Clicking on the f(X) button (Figure 6.63b) it is possible to access a new window where it is possible to select "spreadsheet" as input mode (Figure 6.63c). At this point it is just necessary to select the input file and select the cell containing the number (Figure 6.63d) The geometry needs to be designed for this purpose,

with the proper workflow for every dimension, and a particular attention and experience is needed on geometries like rounding or chamfers, that can be not very automatic adjustment-friendly and can cause the software crash.
In case of dimensional changes, it is possible, after changing them in the Excel file, to update the entire geometry with the "*Refresh*" button (Figure 6.64). The main advantage to link the dimension of the file with an excel file is that it is possible to create a template in the GOM Inspect Suite to export all the dimensions and make all the compensation process, when the calculation Excel books have been created, completely automatic for each iteration of the design loop.

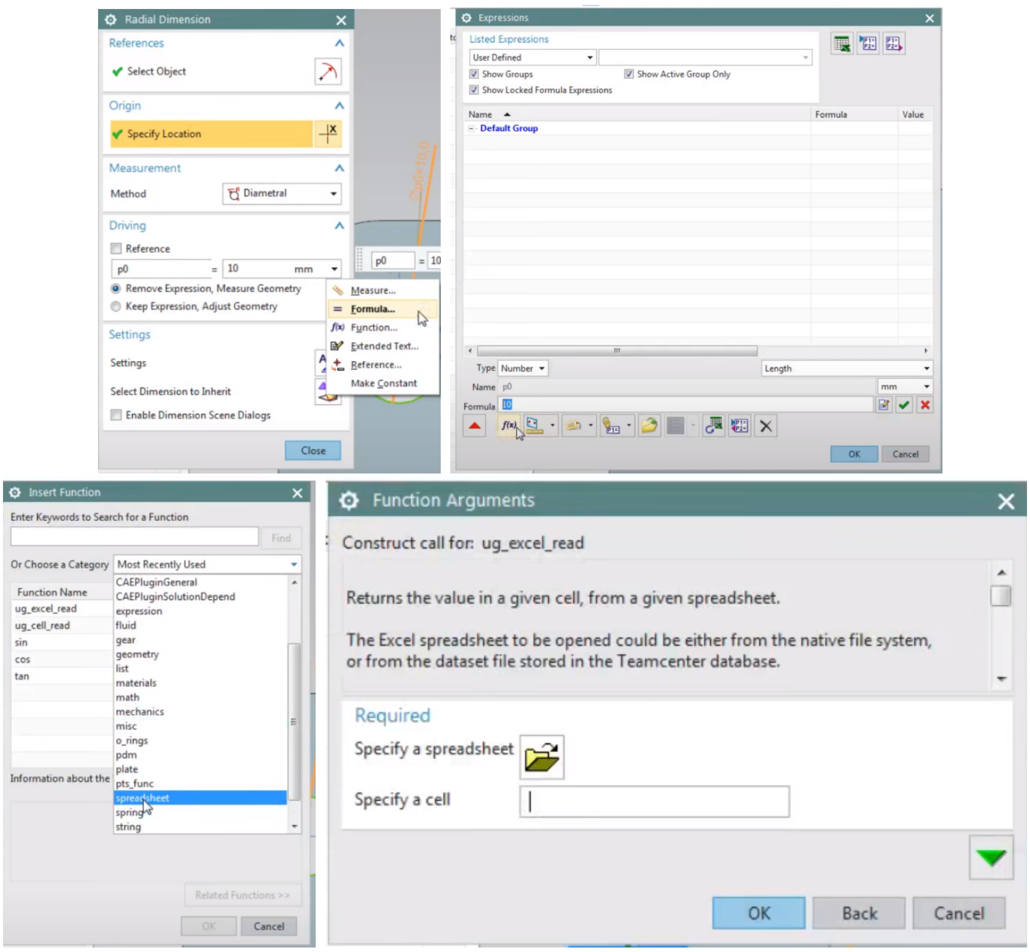


Figure 6.63: Parametric dimensioning workflow in Siemens NX.

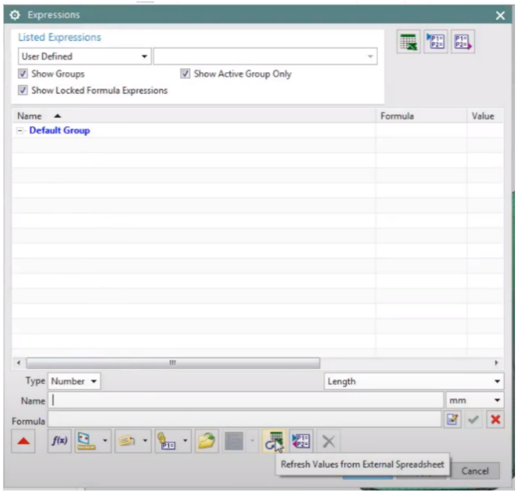


Figure 6.64: "*Refresh Value*" function button.

Chapter 7

Conclusions

At the current state of the scouting, the technology has been proved to be effective and to give, using the Optical Scanner technology, measurement in the desired tolerance range. On this basis, the measurements taken can be considered reliable and it is possible to perform adjustment based on the captured data. There are essentially three different ways to analyse the captured data, with both advantages and disadvantages:

- The creation of a Colourmap for the deviations is a good graphical way to have a visual feedback on the quality of the produced part, but the data are not directly usable to export data.
- The creation of points to define positions and deviations is similar to the work committed by a CMM touch probe. Loads of points can be needed to have a full statistical meaning of the surface. A faster way to work with this type of measurement is to use the coloured patches on the CAD file, to measure with labels as seen before (for maximum, minimum and average).
- The implementation of PMI directly in the CAD file to control the shape of the element and get the more precise feedback for the type of deviation and adjustment to apply. When all the measurements are taken, it is possible to adjust and correct the shape of the object mainly in 3 different ways:
- The correction via Reverse Engineering software, which is still too early-

state to be considered as a stable part of the process, since there are very few controls on the operation performed by the software. Therefore, an important amount of manual work is still required, and the final surface is not parametric.

- Manual correction via the CAD software. This is the most used way at the current state. It requires lot of manual work to apply all the adjustments but there is full control on the operations and on the quality of each correction.
- Parametric adjustments on CAD. It uses an Excel book as input for the measurement in the CAD software, making it possible to have a smart and fast way to edit the file. It is required for the CAD and Excel file to be created for this purpose and if the design contains small edges crashes can always happen.

This different measuring and correction methods can be combined in between them in order to complete the entire process of the iteration loop (Figure 7.1).

Data capturing methods / Correction tools	3D colourmap	Points positions and deviations	PMI & GD&T
3D freeform surface compensation	Not suitable at the current state of the software		
Manual adjustment on CAD		Same data quality and adjustment as for CMM method	Better control of shapes, manual work on adjustments
Parametric adjustment on CAD		Automatic adjustments, same quality of data from CMM	High control of position and shapes, automatic adjustments

Figure 7.1: Combination of the different measurement and correction methods.

The simple comparison of the two actual and nominal 3D element (entirely, or of a portion) can bring only to a correction via a Reverse Engineering software. The other methods of measurement and correction can bring to different combination for the workflow.

What has been tested in this thesis is the measurement of points or patches deviations to suit the manual correction or, in few cases, the parametric one. In conclusion, the advantages of using an Optical Scanner instead of a CMM machine brings to an easier way to collect a massive amount of data, in order to have a better control of the shape. It also makes it possible to take, when the data have been collected, new measurements offline, just working on the already collected geometry and avoiding the physical measurement process in the metrology area twice. Therefore, the possibility to implement *GD&T* measurement is no time-consuming on the machine and can bring to a big improvement of the quality of the part, and the possibility to visualise the deviations in colour maps is still a good advantage for the understanding of the designer or the process engineer on the SLS machine.

Chapter 8

Future Development and Implementation

At the current state the entire workflow is completely working with the use of single point measurement through the use of the Optical scanner and exportation of data in Excel format. The corrections are done singularly with the CAD software. Next step is to implement and validate the use of PMI and *GD&T* in the measuring workflow in order to improve the quality of the adjustment done and even reduce the number of iteration necessary to get the final product.

An important mention has to go to the Reverse Engineering correction software. They are still not suitable for the corrections considering the early state of their algorithm but would be important to pay attention to eventual updates or newer versions. Even more companies are trying to develop something usable for the purpose intended in this thesis, such as GOM itself, implementing new functions in the Inspect Professional software.

Bibliography

[1] M. Johnson, "A review on selective laser sintering," *United International Journal for Research & Technology (UIJRT)*, vol. 2, no. 1, pp. 19–21, 2020.

[2] Xometry, "Design guide: Selective laser sintering (sls)." `https://cdn2.hubspot.net/hubfs/340051/Design_Guides/Xometry_DesignGuide_SLS.pdf`.

[3] L. Iuliano, "Lecture notes from 'additive manufacturing technologies'."

[4] E. Atzeni, "Lecture notes from 'integrated production systems'."