Good practice guide for generating high-density 3D point-cloud data sets of complex freeform machined surfaces using optical scanning techniques positioned directly on the machine tool.

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1 Scope

This good practice procedure guide is intended to act as a set of guidelines for those using optical 3D scanning systems as an aid in determining the dimensional uncertainty of machine tools. The reader should be aware that the material artefact being measured may be fitted to the machine tool system or independent of it.

This document includes worked examples relating to the set-up, measurement and analysis of data for various artefacts. This document does not replace the need for formal training using the various pieces of scanning equipment and analysis software. It is designed to give the user a good practice guide which can be applied to the wide range of hardware and software available.

1.1 3D optical scanning systems

There are various 3D optical scanning systems available to the user and it is important that the correct system is selected to best match the circumstances in which the artefact is due to be measured.

Currently there are several different types of scanning systems in existence that are typically based on structured light (fringe) projection or laser line scanning with new systems continuing to be developed in the future. This guide is designed to be applicable to all currently available systems but should be able to be extended to any systems developed in the future.

Selecting the correct system will depend on what is required to be measured and careful consideration must be given to the strengths and weakness of available systems when deciding which type to use.

1.2 Post processing software

As with scanning systems, there are various different producers of software for carrying out analysis of information captured by 3D scanning systems. Some 3D optical scanning systems come with their own software to capture and analyse data, while others may rely on using 3rd party software to capture and analyse data. The procedures described in this guide are designed to be independent of software used, as they are of scanning system used, to allow the user to apply the procedure to as wide a range of software packages as possible.

2 Terms, definitions, abbreviations and symbols

Some key terms are defined here to assist the user of 3D scanning systems in understanding 3D scanning, metrology tasks and engineering processes.

3D SCANNING SYSTEM

A system designed to allow an operator to create a virtual 3D model of a physical object.

ALIGNMENT

ALIGNMENT refers to the act of “lining up” a scanned image with a CAD MODEL. ALIGNMENT is usually the first action carried out once the object to be inspected has been scanned in and polygonised.

ARTEFACT

An object to be scanned is often referred to as an ARTEFACT.

CAD MODEL

A CAD MODEL is a 3D model produced using a Computer Aided Design software package. There are many file formats available but commonly *.step and *.iges files are used as they are non- proprietary.

DEGREES OF FREEDOM

Ways in which an object can move in free space; typically referring to translation in an X, Y and Z direction and rotation about those axes, equivalent to the pitch, roll and yaw of an aeroplane.

INSPECTION

The act of checking whether a manufactured product has been created within the tolerances specified in the engineering drawings. Usually carried out at the end of the production cycle but can also refer to process carried out during manufacture. Traditionally carried out using equipment such as callipers and micrometers but can also be carried out using 3D SCANNING SYSTEMS.

LASER LINE SACNNER

A type of 3D SCANNING SYSTEM that uses a projected laser line to measure an object. Usually mounted on the end of an articulated arm, the laser line is projected onto the surface of the object to be measured. The line is viewed by a camera mounted in a known location, adjacent to the laser which projects the line. By measuring the deformation of the line the scanner can calculate the shape of the underlying surface.

MACHINE TOOL

The generic name given to a machine found in a workshop to produce finished parts. Could refer to a milling machine, a lathe, a 5-axis CNC machine or any other similar machine.

POINT CLOUD

A collection of points that define the surface of an object or artefact. In general, each point will be assigned co-ordinates, *x*, *y*, *z*, and its direction vector, *i*, *j*, *k*.

POLYGONISATION

The act of generating a mesh of triangles from the available POINT CLOUD. In general, the size of the triangles is an indication of the curvature of the surface, large flat areas increase the area of the defined triangle, thus reducing the amount of data required to define the surface. The smallest triangle generated can only be as small as the area defined by the three closest points from the POINT CLOUD.

REFERENCE ARTEFACT

An ARTEFACT of known dimensions that can be used to check a 3D SCANNING SYSTEM is performing correctly. Can sometimes be used in conjunction with a calibration process but can also be used to see whether a 3D SCANNING SYSTEM needs to be recalibrated.

STRUCTURED LIGHT SYSTEM

A type of 3D SCANNING SYSTEM that uses projected shadows to measure an object. Usually, but not always, the projected shadows appear like a barcode on the surface of the object to be measured. These systems consist of a projector and one or two cameras in a known fixed relative orientation. The cameras view the projected shadows upon the surface and by measuring the deformation of the shadows on the surface can calculate the shape of the underlying surface.

TARGET MARKERS / TARGET STICKERS

Small, usually circular, markers that allow the 3D scanning software to align progressive scans together. They can be attached to the surface of the object being scanned or to a framework surrounding the object being scanned.

VERIFICATION

The act of checking how a measurement tool performs against a known standard and correcting, where necessary, for any inaccuracies. In the case of 3D SCANNING SYSTEMS, they are usually provided with a CALIBRATION ARTEFACT of known size and form, which can be measured by the scanner to assess their accuracy. These artefacts can be either 2D or 3D, depending on the manufacturer. Also often referred to by the manufacturers as a calibration.

3 Preparation of artefact and scanning environment

Before the artefact can be measured there are several conditions that must be considered to avoid producing poor data and hence inaccurate data.

3.1 Temperature

Temperature has a significant impact on the ability of an operator to measure an artefact correctly. Metrology inspection should be carried out, where possible, at the international standard temperature of 20 °C. This temperature should apply to not only the environment but also the artefact. Inspection of the artefact should, where possible, be carried out in a climate controlled inspection area of uniform temperature distribution free from moving air currents.

The target artefact should also be allowed to reach 20 °C before being measured. Thermal expansion or contraction of the artefact will affect the measured data and care should be taken to ensure the artefact is as close to 20 °C as possible before being measured. Soaking the artefact by placing it on a large steel block or surface table at ambient temperature can assist with this process. Typical soaking times could be two hours for small objects in good thermal contact with a flat surface such as a soaking table. Anything weighing more than 1 kg should be left at least four hours to soak and preferably overnight.[1]

It is however appreciated that it is not always possible to carry out inspection of artefacts in ideal conditions. Large parts may not fit in a climate controlled metrology room or deadlines may not allow for the time required to cool a part to 20 °C. For any number of reasons it may be necessary to inspect the artefact in the machine workshop while moving it between machines or even while still mounted in the machine being used to produce it. In these circumstances, it is still possible to perform an inspection of the artefact using 3D scanners, but consideration must be given to any effect on accuracy carrying out the inspection in non-ideal conditions may have.

If not carrying out inspection in a climate controlled environment it is important that the temperature of the room is recorded. Where possible the temperature of the artefact being measured should also be measured as the temperature of the artefact is not necessarily the same as the room. Before carrying out any inspection of the part it must be determined how much of an effect the temperature of the room is having on the inspection process. This can be assessed by inspecting a reference artefact in the area where inspection is going to occur. A reference artefact made of a material with a very low expansion coefficient, for example invar, will allow the user to assess the effect of the temperature in the inspection environment on the performance of the 3D scanner. If the 3D scanner is shown to produce sensible results when inspecting the reference artefact then it should be suitable for use for inspection of the part. If however the 3D scanner does not produce sensible results when inspecting the reference artefact then a re-calibration of the scanner may help increase the systems accuracy.

If the ideal temperature of 20 °C cannot be achieved, then it should still be possible to carry out inspection in the workshop, provided the temperature remains stable. If the temperature in the room can drift rapidly, moving of the order of a few degrees over the course of the inspection, then meaningful results may not be achievable. If the temperature suddenly drops considerably, caused by someone opening a large door to outside for example, then the temperature of the artefact and scanning system may change rapidly, causing it to possibly change in size and give inaccurate results. Care needs to be taken to ensure the temperature within the workshop remains as constant as possible during inspection. It is also important to remember that the temperature of the artefact, and scanner used, will not change at the same rate as the surrounding room. The transfer of heat into or out of the artefact will take differing amounts of time depending on the composite material. For this reason, where possible, recording the

[1] NPL Good Practice Guide No. 80. “Fundamental Good Practice in Dimensional Metrology”. David Flack and John Hannaford. October 2012.

temperature of the artefact as well as the ambient temperature of the room may help give the inspector a better idea of how temperature may have affected the inspection process.

Table 1 shows a selection of linear expansion coefficients for various common materials. The values in the table give the expansion, in microns per meter, of a material for each 1 degree Kelvin increase in temperature. It can easily be seen how susceptible materials like aluminium and copper are to changes in temperature and the comparison between these materials and other more temperature invariant materials such as Invar and Pyrex.

Material	Linear expansion coefficient α at 20 °C / 10^{-6} K^{-1}
Aluminium	23.1
Brass (67 Cu + 33 Zn)	17.5
Carbon Steel	10.7
Copper	16.5
Glass (Pyrex)	2.8
Gold	14.2
Invar	0.13
Iron	11.8
Nickel	13.4
Stainless Steel (304)	14.1
Titanium	8.6
Zerodur	<0.1

Table 1. A selection of linear expansion coefficients of common materials[2]

3.2 Vibration

Optical 3D scanning systems, like most metrology systems, are sensitive to vibration. However, unlike contact systems, there can be instances where the vibration of the 3D scanner and the artefact are vibrating at different frequencies or amplitudes and this can have a detrimental effect on the quality of the data captured. Care should be taken to isolate the 3D scanner and artefact to be measured as much as possible. Vibration isolating surfaces may be used where available but it is important to remember that not isolating both parts of the system, the artefact to be scanned and the scanner itself may increase the uncertainty in the measurements.

It may not always be possible to move the part to be scanned to an isolating surface. A 20 tonne object is difficult to move and is bigger than most available isolation platforms. Similarly, as with temperature

[2] Tables of Physical & Chemical Constants. 2.3.5 Thermal Expansion. Kaye & Laby Online. Version 1.1 (2010) www.kayelaby.npl.co.uk

measurements, it simply may not be possible to spend the time removing the part from the machine to be inspected. In these instances it is possible to still perform an inspection, but care should be taken to minimise the vibration as much as possible.

Vibration can be introduced from a wide range of sources, from forklifts driving past to CNC machines cutting, friction welding machines to people walking past. In a busy workshop it may be almost impossible to prevent all sources of vibration but taking steps to avoid times when certain machines will be running is preferable. If the part being measured is still held in the jaws of the machine, isolating the machine from the mains may prevent vibration that could be introduced by the alternating mains current running through coils. Isolating the machine from the mains will also insure any cutting/cooling fluid pumps will stop running, further reducing vibration of the part.

3.3 Surface finish

Optical 3D scanning systems operate in the visible section of the electromagnetic spectrum. As such they can be susceptible to errors caused by various surface finishes that may need to be measured. The ideal surface to be measured is a diffuse, specular reflective surface, like a white sheet of paper, but it is appreciated that most objects to be measured are not of this form. Most machined metal surfaces are usually highly reflective and as such are more difficult to scan. Careful consideration must be given to the angle between the scanner and target artefact to avoid reflections directly back down the system lens.

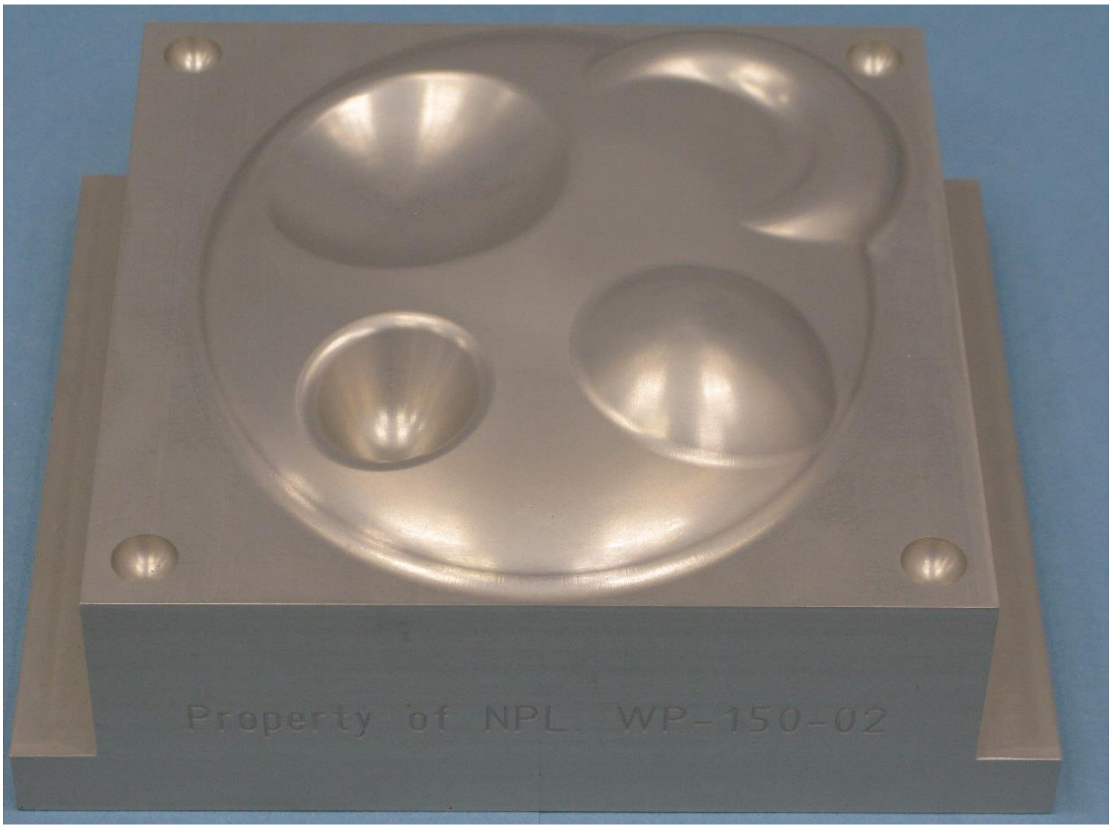

Figure 1. The NPL Freeform Artefact

Figure 1 shows the NPL Freeform Artefact which has been machined from aluminium and then treated. Treatments can include anodising or acid etching, amongst others. Despite it having a shiny surface, it is still possible to scan in using a 3D scanner.

Dirt, dust and greasy marks left on a surface to be scanned can all cause inaccuracies and care should be taken to ensure the surfaces are clean before measurements are carried out. Where inspection is being carried out in a workshop environment, it is important to remember to clean off any cutting/cooling fluid residue that may be left on the surface and ensure that any cleaning products used are also washed away, in accordance with local health and safety guidelines. Some system manufacturers claim that their systems perform well against polished shiny surfaces but in the authors experience they are generally difficult to measure using 3D optical scanning systems without treatment. A white titanium dioxide spray, or crack testing developer white, can be used to coat a shiny surface and give it a specular reflective appearance but this will have a detrimental effect on the precision of the system. Depending on the type of spray used, the target surface, the skill of the user applying the spray and the finish achieved with the spray, the precision of the 3D scanner can be affected in the order of tens of microns.

3.4 Ambient lighting

Many 3D scanners are susceptible to errors induced from ambient lighting in the inspection area. Care should be taken to ensure uniform light is used to illuminate the surface to be measured. Fringe projection systems are much more sensitive to non-uniform lighting, for example, shadows cast across the surface from people walking past, or natural light can interfere with the projected fringes. For laser line scanners, care should be taken to avoid light with a wavelength similar to that of the laser used to avoid inaccurate data being acquired.

3.5 Artefact movement

The accuracy of 3D scanners can be affected by the relative movement of the measurement system and the target artefact. As mentioned in section 3.2, vibration will have a detrimental effect on the accuracy of the measurement system but translation of the artefact can also reduce the resolution of the system.

Laser line type scanners require the artefact to remain in in the same co-ordinate system as the laser scanner. Should the artefact move from its original position the software may be able to align different scans together but this does introduce an error in the measurement, from the necessity to align two differing frames of reference, and should be avoided if possible. If there is a risk of movement, the artefact can be glued in place before being measured. A hot glue gun can be used to fix the artefact in place quickly and can also be easily removed from the workbench and artefact after measurement has been carried out.

Fringe projection systems vary depending on the manufacturer but most can align data sets using some form of contour alignment or target markers. Contour alignment can perform in one of two ways; the software either automatically looks for similar features and initially aligns multiple scans together or may require the user to select matching points in several scans for an initial alignment to take place. Once an initial alignment has been performed the software will then attempt to align the multiple scans together, by analysing similar features across multiple scans and matching them together. Some software packages allow the user to define parameters such as a target convergence value or a maximum distance to look around a specific point for other similar points. These parameters should be adjusted in line with the manufacturer's guidelines. The user should be aware that if set incorrectly, these parameters can cause the software to incorrectly align scans together so care needs to be taken when adjusting these values. For some scanners to achieve their best results it is recommended by the scanner manufacturer to attach target markers to the object being measured, to allow the software to align the various scans. The size of target marker used may vary depending on the scanner used, with some scanners able to accept a variety of sizes, so ensure the correct sized markers are used. Target markers should be stuck on flat surfaces on the artefact. It is important to remember that any target markers used will obscure the artefact below so should be used sparingly but sufficient should be used to allow the 3D scanner to “see” at least 5 in each scan to allow any captured images to be stitched together.

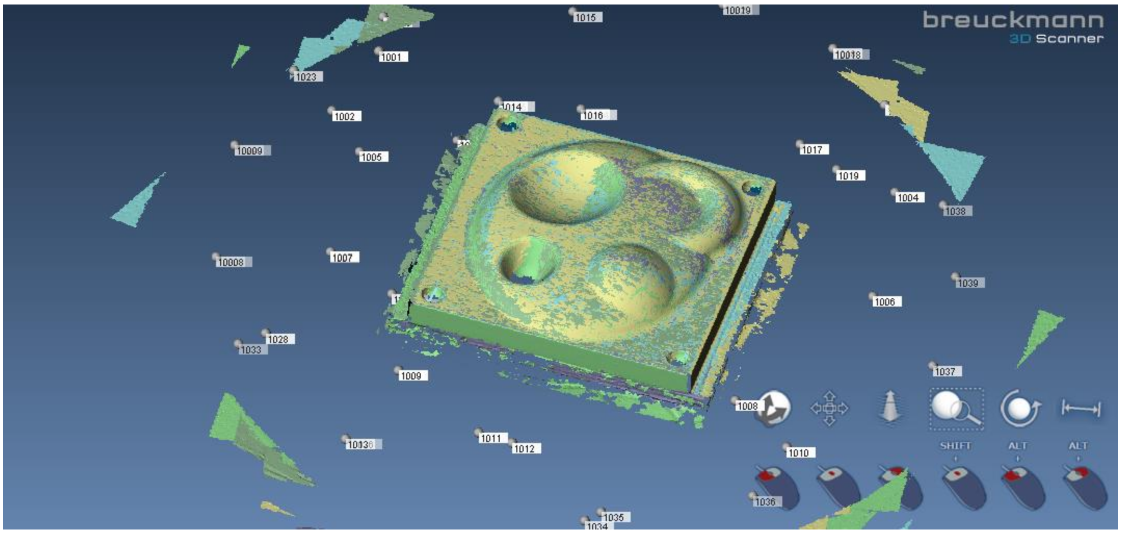

Figure 2. Artefact scanned in using reference markers for alignment. Images captured from Optocat, using a Breuckmann fringe projection system

It certain circumstances it may not be possible to stick reference markers directly to the artefact being measured, if it contains no locally flat surfaces for example or one that can’t be contaminated by having reference markers stuck on it. In these instances a reference frame should be constructed. A reference frame should enclose the artefact to be measured and have reference markers attached to it. The artefact should then be attached to the reference frame and fixed in place. Now, the reference points on the reference frame can be used to align the scanned data from the artefact and then the reference frame can be removed in post processing.

If the inspection is being carried out with the part still mounted in a machine, it may be possible to use the machine itself as a reference frame. Parts held in a chuck could have reference markers on the chuck itself. This would mean that the part can be rotated within the chuck, moving relative to the fringe projector but not relative to the reference markers. Alternatively, if may be possible to attach reference markers around the part while it is held in place, either on an inspection table or a moving surface within a CNC machine.

4 Laser line scanning

4.1 Preparing the part

As discussed in section 3, care must be taken to ensure the artefact and environment are ready for measurement, with particular care being taken to ensure the artefact is clean from dirt and debris and fixed in position. Place the laser line scanner arm base within range of the part to be measured and ensure that there is full free movement of the arm around the artefact. It is important to remember that many angles of scan may be needed to fully capture the part being inspected. For this reason, there should be as much room to move around the object as is possible.

4.2 Preparing the scanner

Ensure that any power outage is the same as that required by the measuring device and associated equipment, and confirm that the scanner is correctly connected to any accompanying computer. In accordance with the manufactures instructions begin the setup process of turning on the scanner and computer and allow the scanner to warm up to scanning temperature as advised. It is important to ensure the scanner is at the correct operating temperature to avoid any inaccuracies that may be introduced by thermal expansion or contraction. While the artefact is sensitive to variation in size due to temperature change so is the scanner and care needs to be taken to ensure the scanner is at a temperature used in an environment with a stable ambient temperature. As described in section 3.1, when it is not possible to perform an inspection in a temperature controlled room, recording the ambient temperature of the room and temperature of the artefact being measured can help determine whether an accurate inspection can be carried out or not and whether any compensation needs to be applied.

4.3 Scanning the artefact

Scan the artefact using the laser following the manufacturers' instructions. When choosing a location for the scanner consideration should be given to its position. The encoders in the articulated arm are most accurate when the joint is near 90° as the encoders have the largest angle to distance moved ratio. To maximise the accuracy of the scanning arm, take the scanning arm and move the "elbow" of the arm to 90° to the vertical axis from the base, which will leave it parallel to and just above the measuring surface. A line projecting directly down from the elbow of the arm to the measurement surface gives the ideal location for the placing of the object to be inspected. This position should give the maximum range of movement of the arm relative to the artefact being inspected and also keep the elbow as close to 90° as possible for maximum resolution in the encoder.

Figure 3. Image showing best practice positioning of artefact to be scanned with laser line scanner

While scanning, it is important to pay particular attention to any indicators that may warn the user if the scanner is too far away or too close to the artefact, keeping the scanner at the optimal distance from the part wherever possible. With regards to angle of scanner, it is important to keep the scanner at an angle as close to perpendicular to the surface being scanned as possible. Care should also be taken to avoid “painting” the object, where the user moves the scanner up and down the same path on the same scan run. The scanner should be moved in one direction, at a slow steady speed, pausing the scan to change direction or to negotiate around features. With respect to angled surfaces, the user should scan each surface separately. To fully scan any edges the user should run the scanner along the length of each surface defining the edge and also the edge, along the plane that bisects the normal of both surfaces forming the edge. This process is shown in Figure 4, where the arrow represents the angle of the beam and the photographs show the resultant projected laser lines.

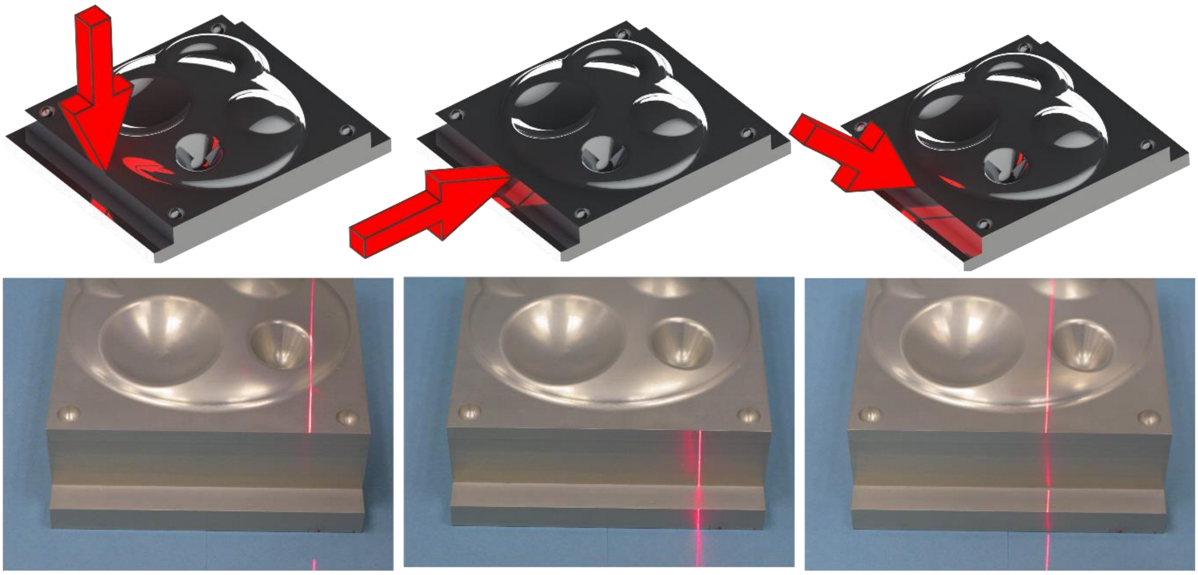

Figure 4 Diagram showing the scanning of an external corner

Other areas that may present a problem are internal corners, where light reflecting off one surface and reflects off the other face and return to the scanner, giving a false reflection and the creation of phantom points in the scan. To avoid this ‘cat’s eye’ effect, the user should take care to minimise pointing the scanner directly at the internal corner where possible. Should spurious points appear in the scan, it is possible to edit these erroneous points as most scanning software packages allow the user to select and delete these points to improve the quality of the scanned data.

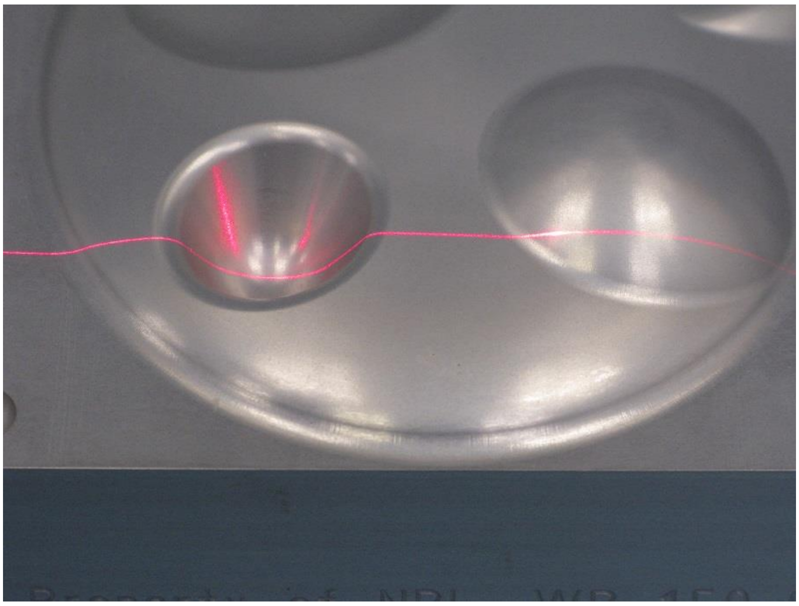

Figure 5. Internal reflections, commonly seen when scanning an internal corner or feature

Where available, software that gives an indication of the quality of the data acquired should be adhered to. Measurements should be taken to fill in all gaps in the surface, to get as complete a representation of the scanned surface as possible. Once all the data has been acquired it should be converted from a point cloud into a meshed surface, using the correct method for the software being used. A meshed surface is a surface that is created from the point cloud collected by the scanner, to represent the surface that has been scanned. This meshing process consists of triangles, known as polygons, being created between the scanned points. There polygons vary in size and shape but give the best approximation for the surface that has been scanned. It is worth noting that the user should be aware of the settings used to create the mesh and consider the effect of: smoothing factors, outlying point exclusion and averaging of repeat points may have on the resultant mesh. The created mesh can now be save ready for analysis.

5 Fringe projection scanner

5.1 Preparing the part

As discussed in section 3, care must be taken to ensure the artefact and environment are ready for measurement, with particular care being taken to ensure the artefact is clean from dirt and debris. If using reference points, ensure they are stuck down firmly on the target artefact. If using a reference frame, ensure the artefact is attached to the frame in such a way that it can't move independently of the reference points. Unlike the laser scanner, the relationship in position between the artefact being measured and the scanner is not critical. For this reason it is not necessary to firmly hold the artefact or artefact and reference frame assembly in position. In fact, it is usually easier to move the artefact relative to the scanner than the other way round, due to the large size of the fringe projection scanner.

5.2 Preparing the scanner

Ensure that any power outage is the same as that required by the measuring device and associated equipment, and confirm that the scanner is correctly connected to any accompanying computer. In accordance with the manufactures instructions begin the setup process of turning on the scanner and computer and allow the scanner to warm up to scanning temperature as advised. It is important to ensure the scanner is at the correct operating temperature to avoid any inaccuracies that may be introduced by thermal expansion or contraction. While the artefact is sensitive to variation in size due to temperature change, so is the scanner, and care needs to be taken to ensure the scanner is at a temperature as close to its operating temperature as possible. As mentioned previously, if it is not possible to achieve the ideal temperature in the location the inspection is due to be carried out; testing the performance of the scanner against an artefact with a low thermal expansion co-efficient or recalibrating may help improve the results achievable.

5.3 Scanning the artefact

Scan the artefact in accordance with the manufacturers' instructions. It is important to pay particular attention to any notifications or warnings given to the user by the software. There may be warnings advising of movement of the artefact or scanner, warnings relating to the under/over exposure of the artefact being scanned or warnings about the number of reference points in vision at that time, amongst others. It is only through familiarity using each system that the user will know how to deal with the different error messages.

As with laser line scanners, particular care needs to be taken when scanning edges. Placing the scanner at an angle, which bisects the normal from each surface, projecting the fringes across both surfaces gives the best resolution of the edge itself. Similarly, the "cat's eye" effect can occur when scanning internal corners so care should be taken to avoid pointing the scanner directly into the corner. When spurious points do appear, the user should be able to remove them to improve the quality of the scanned data.

Measurements should be taken to fill in all gaps in the surface, to get as complete a representation of the scanned surface as possible. To achieve this it may be necessary to move both the artefact being scanned and the scanner itself. The use of a rotary table can assist with the measurement of some artefacts. For other artefacts a rotary table may be unsuitable, due to either their size or mass or that the part to be inspected cannot be removed i.e. from the chuck of the machine being used to manufacture it. Where large objects are to be scanned, the fringe projection scanner can be moved around the object. If the object is being held in the chuck of the machine, it may be possible to use this to the operator's advantage, by using the machine to rotate the target object. However, it should be recalled that vibration needs to be kept to a minimum in order to achieve accurate results, so this should be considered if turning on the machine.

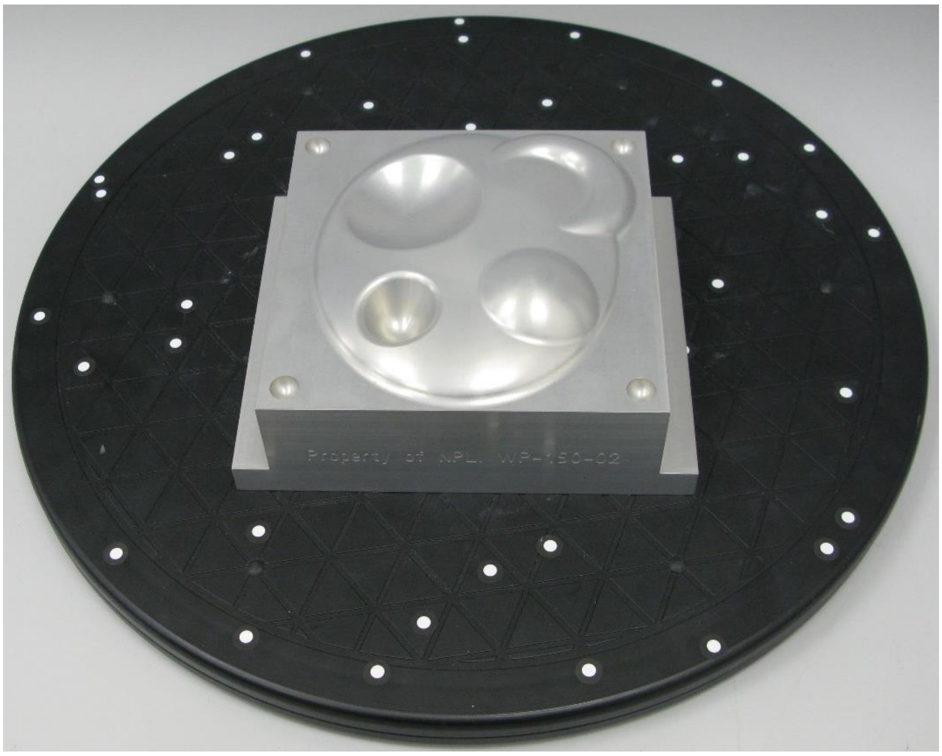

Figure 6. NPL Freeform Artefact mounted on a rotary table with reference markers

Once all the data has been acquired it should be converted from a point cloud into a meshed surface, using the correct method for the software being used. This will involve the polygonisation of the point cloud and then a mesh created from the polygons although often the software will include this in the meshing process. It is worth noting that the user should be aware of the settings used to create the mesh and consider the effect any smoothing factors, outlying point exclusion and averaging of repeat points may have on the resultant mesh. The created mesh can now be saved ready for analysis.

6 Analysis of data

To analyse the data collected by either type of optical scanner it is possible to compare the scanned data with a CAD model of the part, as it was intended to be manufactured. This allows the user to make a direct comparison between the part scanned from the manufactured artefact and the “perfect” CAD model and check for deviations. It is then possible to add tolerances to the CAD model and scan comparison to allow the user to check the produced part against a drawing but also to measure the uncertainty of the machine tools used to create the scanned artefact.

6.1 CAD data

Various CAD model file formats are supported by the different brands of analysis software, guidance on which are supported by each particular piece of software should be available from the manufacturer. It is important to ensure that the CAD model used is saved with sufficiently high resolution for the level of accuracy required. Similarly, when importing a CAD model into the analysis software, it is important to ensure that, where the option to adjust it is offered, the resolution of the mesh created from the CAD model is sufficiently high for the level of accuracy required.

Once the CAD model has been imported into the analysis software, it is important to ensure that the CAD model is the correct size for comparison. Errors can occur with incorrect dimensions being selected during the import phase. Similarly, CAD drawings are not without error, and the user should ensure the CAD model is checked before making comparisons to it.

6.2 Importing scanned data

Methods for importing scanned data will vary slightly depending on the software used but will largely follow the same process as importing CAD data. If the analysis software accepts raw point clouds as an input then it is usually possible to create a mesh within the analysis software. If this isn’t possible then it will be necessary to import a mesh previously created from the scanned data. Again, care needs to be taken to ensure there are no errors made in the importing process and the user should check to ensure the mesh created from the scanned data is of approximately the right size before continuing.

6.3 Aligning scanned data for comparison

The scanned data can be aligned to the CAD model in various ways and the method used for alignment will vary on the desired outcome. Methods available for alignment in different software packages will vary but will generally be the same as described here. The method of alignment chosen will need to reflect the requirements of the user. An auto-alignment may be most suitable for a general inspection task, where as a feature based alignment of 3, 2, 1 alignment may be more useful for GD&T inspection tasks.

6.3.1 Auto-alignment

Most software packages will offer an auto alignment feature. Some software packages will require a point cloud to be converted into a mesh before alignment can be carried out while others will allow the raw point cloud to be aligned without creating a mesh. Using this method, the software will use a “best fit” alignment, comparing every point in the scanned data with every point in the CAD data, trying to minimise the deviation between each and every point. Some software packages will require a certain amount of pre-alignment to be manually entered by the user while others will align the data automatically without this user input. Artefacts with low levels of rotational or translational symmetry will have the greatest level of success under this method. Parameters controlling target alignment levels, statistical weightings and confidence levels, amongst others, can often be adjusted, as directed in the software guidelines.

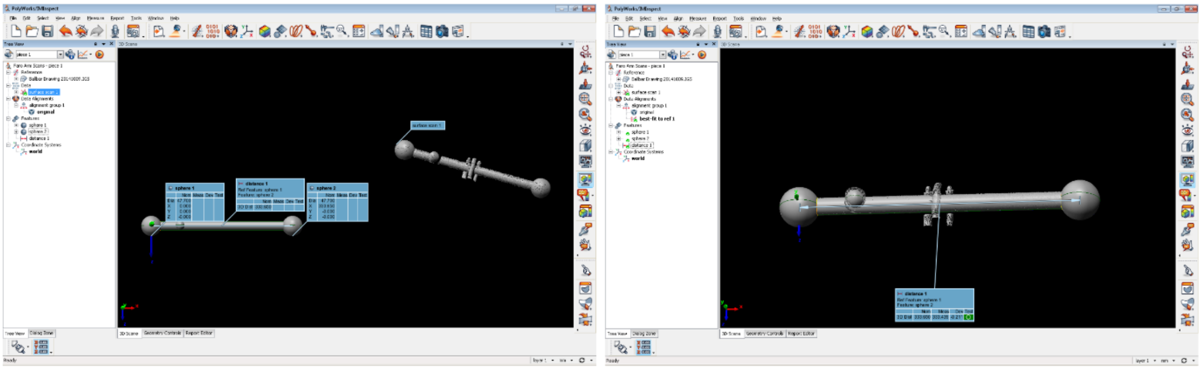

Figure 7. Polyworks software used to perform an auto alignment on data captured using a Faro Laser Line Scanner

6.3.2 Feature based alignments

Certain artefacts may contain particular geometric features that lend themselves particularly well for alignment. Position critical holes in a sheet metal part for example may be used as features for the scanned data to be aligned with the CAD model. This method is particularly useful for aligning datum surfaces and points, specified in the GD&T of the drawing of the CAD piece.[3]

Methods for aligning in this way will vary between software packages but generally revolve around the selection features on the CAD model and the scanned data, using a best fit function to fit geometric shapes to the features, and then aligning the CAD and scanned data around those features. For example, a sheet metal part with 5 position critical holes in it could have 5 circles defined around the holes on both the CAD model and the scanned data. Then, the central positions of these holes could then be used to align the two data sets together. The software will then perform a best fit alignment based solely on the positions of the centres of the circles, ignoring the surrounding geometry.

6.3.3 Degrees of freedom alignment

A “degrees of freedom alignment”, also known as a “3, 2, 1 alignment”, works by gradually removing degrees of freedom of movement between the scan and CAD data. Initially, three points are picked to define a plane, which removes 3 degrees of freedom of movement (2 axis of rotation and 1 axis of translation). Two additional points are then picked to define a line, which remove another 2 degrees of freedom (1 axis of rotation and 1 axis of translation). Finally, a point is chosen and this removes the last degree of freedom of the data (1 axis of translation). By picking the same points on the CAD and the scan data it is possible to align the two pieces of data together and allow comparisons between the two to be made.

6.4 Comparing the data

There are several approaches to comparing scanned data to CAD data but they can all be thought of as comparing surfaces, lines and points. Whether they are flat surfaces; as found on the edge of a square, curved surfaces; as found on a sphere, lines formed when two surfaces intersect or points at the coming together of three planes, all of these features can be compared between the CAD data and the scanned data in a similar way.

Points, found either at the centre of a sphere, middle of a circle or at the intersection of three planes, can be defined on the CAD and scanned data. After the scanned data has been aligned to the CAD the

[3] NPL Good Practice Guide No. 79. “Fundamental Good Practice in the Design and Interpretation of Engineering Drawings for Measurement Processes”. David Flack and Keith Bevan. October 2012.

positions of these points can be calculated and the deviation of the measured points from the CAD points can be evaluated.

Lines can be defined along edges, through axis of cylinders and normal to surfaces. These lines, defined on both the CAD and scanned data, can be compared to give deviation from expected angles and position.

Surfaces, either flat planar surfaces or curved cylindrical and spherical surfaces, can be compared and give linear displacements between the CAD model and the scanned data.

Using a combination of surfaces, lines and points, it is possible to determine the uncertainty of the machine manufactured piece and the CAD model. The deviation of the measured geometry from the CAD model can give an indication of the uncertainty in the manufacturing process.

An axis defined through a cylinder offset from the CAD model could indicate either a blunt cutting head or an offset axis of rotation. By combining this information with the size of the measured cylinder surface it is possible to see which is the most likely cause; with a blunt cutting head leaving a rough, oversized surface or an offset axis of rotation giving rise to a deformed cylinder. Through careful selection of features on the artefact being measured, which will vary according to the form of the artefact in question, it is possible to assess the accuracy of the machine used to produce the artefact.

It is important to remember that these optical systems are not traceable to a defined standard, meaning that it is not possible to follow an unbroken chain of calibration back to the meter. This is because it is impossible to calibrate and test a 3D scanning system against all the different circumstances it will be used in, such as: variations in surface colour or texture, the angle between scanner and surface, differing meshing and fitting algorithms and many other factors all have an effect on the uncertainty of the system. However, that does not mean that it is impossible to achieve useful measurements using a 3D scanning system. By taking into account the various sources of uncertainty during the inspection process it is possible to still quote meaningful values. A 3D scanner used in a workshop environment is very unlikely to be able to achieve measurements with single micron precision. However, a system calibrated in the workshop, in the position it is used to carry out the inspection, at a stable temperature, isolated from vibration as much as possible could still achieve measurements to within tens of microns. What is critically important is remembering the limitations of the system are, in the environment it will be used in, and taking those factors into account.

6.5 Displaying the deviation data

6.5.1 Inspection of geometric features

The most common features measured in inspection are geometric features. Geometric features are regular shapes that can be easily measured and include spheres, cylinders and holes amongst others. These features can be measured using traditional inspection tools and as such are often specified as inspection points. For this reason, the majority of 3D scanning systems will be used to measure these features. Once the captured data has been compared to the CAD model it is easiest to review, or pass onto a customer, in the form of a report containing GD&T inspection summary tables, graphical representations of feature sizes or tables of scan point to CAD model deviations. GD&T feature comparisons displayed in tables, often accompanied by pass/fail results, allow an inspector to quickly decide whether a part is fit for purpose or not.

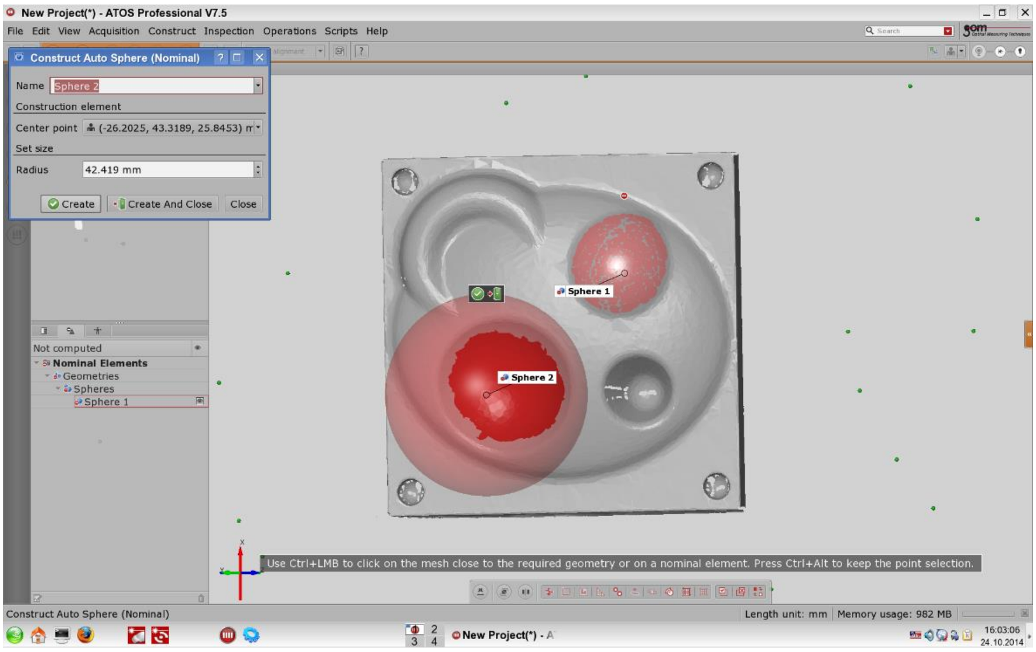

Figure 8. Fitting spheres to a scanned data for comparison in surface using GOM ATOS Professional

Where multiple parts are being produced and inspected, it is also useful to plot the results of inspection on a graph. This may give an indication of conformity of the part to the CAD model with respect to time. A graph will quickly indicate if/when the inspected parts start to be produced outside of tolerance. Using this information it can more easily be determined if there is some cause of the deviation of the machine. Maybe it is indicative of tool wear over the course of a job, in which case it helps the operator improve the accuracy of their machine by being reminded of the need to maintain their equipment. Perhaps there is a batch of parts produced outside of tolerance around a particular time of day that happens to correspond with a delivery arriving and the door to the workshop being left open. Graphs and tables help to quickly display the data in a form that helps the user identify issues and may help lead to solving the causes of these issues.

6.5.2 Inspection of non-geometric features

Geometric features, as mentioned before, are the most commonly measured features in inspection. It is no coincidence that this is because they are the easiest shapes to define and easiest to measure using traditional inspection techniques. Spheres, holes and flat surfaces can all easily be measured using traditional metrology instruments such as callipers and micrometers, where as a swept curved surface can be very difficult, if not impossible, to measure using the same traditional inspection equipment. Similarly, some large features may be very time consuming to inspect traditionally or may require a large number of measured points to define a feature. 3D scanning systems have the advantage over traditional inspection techniques in that they can capture a large number of points across all sorts of surfaces. Using 3D scanners it is now possible to quickly measure large freeform surfaces like those found on car door panels or complex moulded surfaces that may be found on the inside of a plastic cover. Using this information it is possible to get an indication of the form of a whole surface rather than just in specific measured places and can be easily displayed for entering into a report.

Most 3D scanning analysis software packages allow the user to align their scanned data to the CAD data and the comparisons between the two are used to carry out the inspection, using points, lines and surfaces as discussed previously. An additional feature that is often included is the ability to compare a whole “surface” of the scanned data to that of the CAD data. This comparison works by comparing all the captured data points with their nearest neighbouring point in the CAD data and calculating a displacement distance. This distance is then displayed in the form of a “colour map”, regions of varying colour corresponding to differing displacements, projected on the surface of the object. This means the user can very quickly identify areas of the part that may need improvement. A blunt press may be overly distorting a surface when punching a hole in it or a bend angle may be too great; both are quickly identifiable by looking at the changing colour on the surface of the inspected part and the associated key.

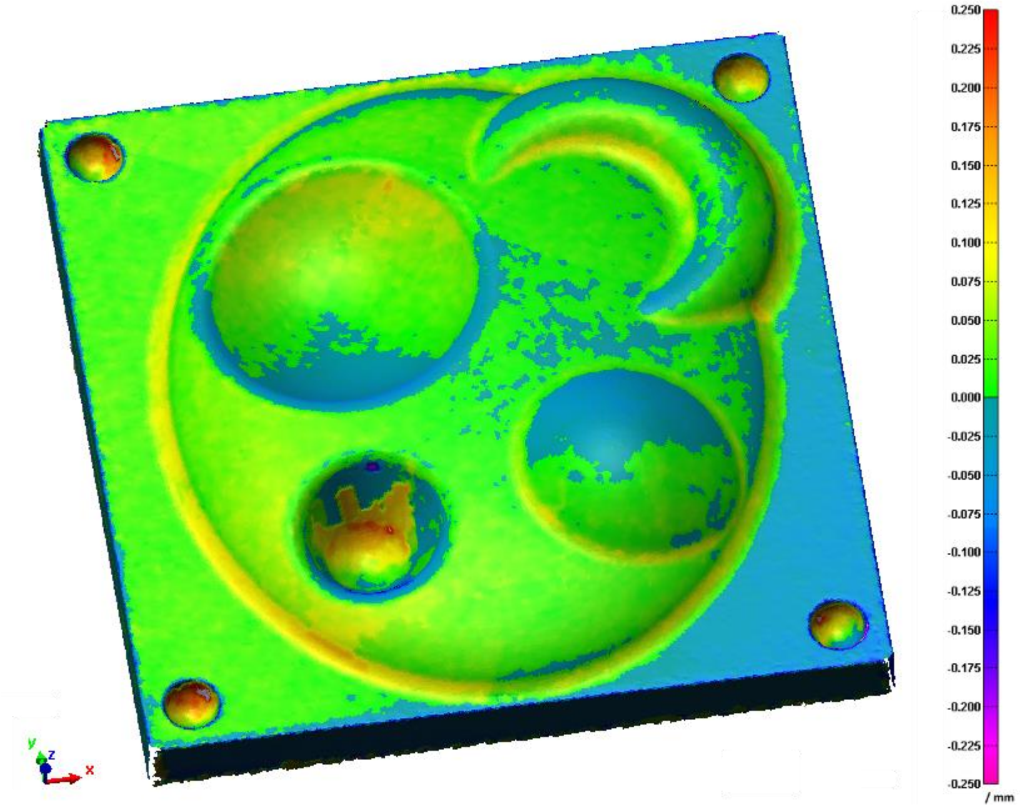

Figure 9. Colourmap showing deviations of scanned in surface from CAD model, produced using PolyWorks 2014

Using a colourmap, as seen in Figure 9, it is easy to identify where deviations between the machined part and the CAD model occur. In Figure 9 it can be seen that majority of the surface aligns well with the CAD. There does appear to be some deviation from the CAD model in the recesses in the corners and the feature in the bottom left of the artefact. This could be caused by incorrect machining techniques or the difficulty in scanning this type of internal feature.

Typically, the best way for reporting inspection data is a combination of both techniques given above, selecting the most suitable method depending on the data to be displayed.