Measuring the accuracy of digitization of contactless scanners

Master Thesis

Master Thesis Assignment Form

Measuring the accuracy of digitization of contactless scanners

Name and surname: **Lakshman Kumar Ramesh**
Identification number: S19000364
Study programme: N2301 Mechanical Engineering
Study branch: Machines and Equipment Design
Assigning department: Department of Manufacturing Systems and Automation
Academic year: **2020/2021**

Rules for Elaboration:

The aim of the thesis will be practical verification and determination of the accuracy of digitization of several contactless 3D scanners available at the department in accordance with the procedures used for calibration (acceptance tests) of these devices.
Recommended methods for elaboration:
1. Get acquainted with the laboratory equipment needed to implement the practical part of the work (3D contactless scanner Atos II 400, ATOS Triple Scan, MetraScan, SW GOM Inspect, etc.), with the principles of optical digitization and the so-called Acceptance tests.
2. Research of works on a similar topic – an overview of the current state of knowledge (will be part of the theoretical part of the thesis). Search for procedures and standards used to assess the measurement accuracy of optical 3D systems.
3. Formulation of the solved problem and its analysis, proposal of a methodical approach to the solution.
4. If necessary – design and manufacture a calibration standard that will enable the recommended procedures for testing the accuracy of optical 3D scanners to be implemented. Determine the nominal dimensions of the standard (eg by CMM). Using the standard, determine the accuracy of digitization of individual scanners, process the results and, if necessary, compare them with the data provided by the device manufacturer.
5. Evaluation and analysis of results, discussion, conclusion.
6. Prepare paper on this topic for publication in a technical journal or conference.

Scope of Graphic Work:	according to need
Scope of Report:	about 60 pages
Thesis Form:	printed/electronic
Thesis Language:	English

List of Specialised Literature:

[1] ZHANG, S. Handbook of 3D Machine Vision: Optical Metrology and Imaging. Boca Raton: CRC Press, 2013. ISBN: 978-1-4398-7219-2.

[2] GOM MbH.GOM Software 2018: Inspection Basic. Braunschweig (Germany): GOM MbH, 2018.

[3] GOM MbH. ATOS: Process Description, GOM Acceptance Test according to the Guideline VDI/VDE 2634 Page 3. Braunschweig (Germany): GOM MbH, 2010.

[4] VDI/VDE 2634, Blatt 3. Bildgebende Systeme mit fŭächenhafter Antastung in mehrenen Einzelansichten. Düsseldorf: Verein Deutscher Ingenieure – Verband der Elektrotechnik Elektronik Informationstechnik, 2008

[5] BARBERO, Basilio Ramos a Elena Santos URETA. Comparative study of different digitization techniques and their accuracy. Computer-Aided Design [online]. 2011, 43(2), 188 – 206. ISSN 0010-4485. DOI:10.1016/j.cad.2010.11.005

[6] KERSTEN, ThomasP., Heinz-Jurgen PRZYBILLA a Maren LINDSTAEDT. Investigations of the Geometrical Accuracy of Handheld 3D Scanning Systems. Photogrammetrie – Fernerkundung – Geoinformation [online]. 2016, 2016(5), 271 – 283. ISSN 1432-8364. DOI:10.1127/pfg/2016/0305

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Dean   Head of Department

Liberec   March 5, 2020

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THEME: Measuring the Accuracy of Digitization of Contactless scanners

ABSTRACT: The aim of the thesis is practical verification and determination of the accuracy of digitization of contactless 3D scanners which were available at the TUL/KSA department in accordance with the procedures used for calibration (acceptance tests) of these devices. The steps involved in this thesis are, to gain knowledge of laboratory equipment needed to implement the practical part of the work (3D contactless scanner such as Atos III Triple scan, Metra-Scan, Ein-scan, REV scan, Leica AT901-MR, SW GOM Inspect), with the principles of optical digitization and the so-called Acceptance tests. This thesis requires a Calibration standard, which is also termed Etalon that will enable the recommended procedures for testing the accuracy of optical 3D scanners to be implemented and determination of the nominal dimensions of the standard i.e., by CMM. By using this standard, the accuracy of digitization of individual scanners is determined and the results are processed and the accuracy results are compared with the data provided by the device manufacturer.

KEYWORDS: 3D Optical Scanner, 3D digitization, Accuracy, CMM, GOM, Calibration standard, Nominal dimension, Acceptance test, ATOS III, Metra scan, Leica, Ein scan Pro 2X plus, REV scan

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TÉMA: **Měření přesnosti digitalizace bezkontaktních skenerů**

ABSTRAKT: Cílem práce je praktické ověření a stanovení přesnosti digitalizace bezkontaktních 3D skenerů, které jsou dostupné na oddělení TUL / KSA, v souladu s postupy používanými pro kalibraci (přejímací zkoušky) těchto zařízení. Součástí práce jsou informace o laboratorním vybavení potřebném k implementaci praktické části práce (3D bezkontaktní skener Atos III Triple Scan, Metra-Scan, Ein-scan, REV scan, Leica AT901-MR, SW GOM Inspect), o principech optické digitalizace a tak zvaných akceptačních testech. Implementace doporučených postupů pro testování přesnosti optických 3D skenerů je realizována na kalibračním standardu (etalonu), jehož nominální rozměry jsou určeny měřením na souřadnicovém měřicím stroji (CMM). S využitím standardu je stanovena přesnost digitalizace jednotlivých skenerů, výsledky jsou zpracovány, analyzovány a konfrontovány s údaji poskytnutými výrobci zařízení.

KLÍČOVÁ SLOVA: 3D optický skener, 3D digitalizace, přesnost, souřadnicový měřicí stroj, GOM, kalibrační standard, acceptance test, ATOS III TripleScan, Metra Scan, Leica, Ein scan Pro 2X plus, REV scan

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LIST OF ABBREVIATIONS AND SYMBOLS

2D – Two Dimensional

3D – Three Dimensional

CAD – Computer Aided Design

CMM – Co-ordinate Measuring Machine

Dev – Deviation

$\emptyset$ – Diameter

HD – High Definition

Kg - Kilogram

LED – Light Emitting Diode

mm - Millimetre

MR – Medium Range

MV – Measuring Volume

res – Resolution

$\boldsymbol{\sigma}$ – Standard Deviation

1. Introduction

At present, there has been persistent use of optical three-dimensional scanners also called as contactless scanners in industries and this is mainly due to the reason that Optical 3D scanners offers measurement of very complex shapes and quick measurement time. The demand for speed of digitization of various objects like machine parts, human body, historical monuments, buildings etc is of high expectations. 3D digitizers are significantly faster and of more efficient. The resulting model is almost a perfect copy of a real object and with the help of available software, the model can be created. From this obtained model it is easy to extract data of its shape and appearance. Standard measuring methods are replaced with new methods and the reason behind this optical scanner provide measurement of more complex shapes and one of the important factors for the industries is measuring time which is reduced.
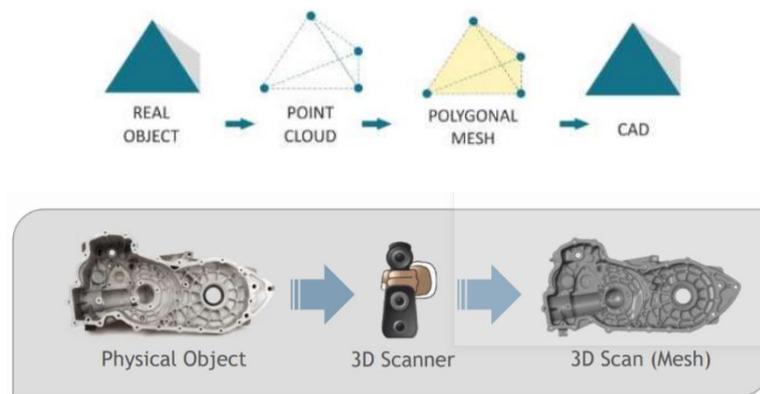
Figure 1: 3D scanning process[1]

Many types of 3D scanners are available in the market and each of the devices has its own restrictions and they differ in their performance. Although traditional measurement methods which is contact measurement like Coordinate Measuring Machine provides results of inspection with good accuracy and measurement guide for CMM is available in[2], there are some limitations like it is difficult to measure surface with complex shapes and secondly, parts with elastic properties cannot be easily measured as the part to be measured will undergo deformation when touch probe gets in contact with the object.

The approach of scanning is very simple, firstly 3D digitization of physical model is performed and then the inspection is done on the obtained virtual model from digitization.

From the obtained model inspection, evaluation of dimension and shape accuracy is done[3][4]. There are many advantages in using 3D scanners for inspection such as quick measurement of parts and it is easy to measure parts with complex shapes, high clouds of points are obtained as a result of digitization from which minute and detailed surface results is provided for the user the inspect and mainly material conditions and stiffness of the part will have no impact on the results of measurement. More information about the part is obtained as a result of digitization which makes the user to perform more detailed analysis of the part. Another significant use of 3D scanner is to detect deviations.

There are many different 3D scanners from the manufacturers available these days but the problem is that their accuracies are unknown. Although manufacturers of 3D scanners have their own standard of measurement in finding the accuracy of individual scanner but manufacturer provided accuracy is not met when used in industries or other laboratories i.e., for regular operations. The reason for this accuracy difference is that manufacturer perform digitization in special metrological lab where environment condition (atmospheric temperature, light, dust and humidity, etc.) for measurement is satisfied and good precision of measurement is obtained. For finding accuracy of the devices, they use standard component which is so called etalon which consists of conventional shape such as spheres. The so-called acceptance test, in fig1 the standard etalon for calibration manufactured and used by the company GOM (GOM mbH.2014)

Figure 2:Standard part of GOM for Calibration[5]

There are several fields in which three-dimensional scanners are used for data acquisition. In mechanical engineering, they are often used for object inspection, deformation analysis, reverse engineering, re-engineering of moulds, dies etc. and also for general quality control procedures. There are diverse range of optical scanners based on different principles, some devices with one or two cameras and with different range and resolutions from 2 mega-pixels

to 12 mega-pixels, with or without turntables etc. These factors make it difficult to standardize the measurement accuracy and result is uncertain without calibration for each scanner.

2. Research work

2.1. Hand-held 3D scanners vs Structured light projection systems[6]

Hand-held 3D scanners are designed as optimal substitute for structured light projection systems. Although, hand-held scanners cost very low and also these devices are simple to handle than expensive stable light system, their accuracies, stability and performance cannot match the rigid systems. In the study research of comparison between some hand-held 3D scanners which is of medium priced one and stable or structured light projection systems. The research gives us detailed information about geometrical accuracies of different scanners. Stable reference bodies of complex shapes were used and it concluded that accuracy for handheld scanners is very low when compared to stable light systems. Hence, it concludes that to meet the desired accuracy, experienced operator is needed.

Figure 3: Scanning output of some handheld 3D scanners used in the research work[6], with green colour being the most accurate.

Nowadays, 3D scanners are widely used by many industries for digitisation and is considered as standard inspection device in many fields which includes Automotive, Aerospace etc. 3D scanners can be used only to a close range of measurement i.e., between one metre up to few metres. The users should be aware of defined criteria for use of devices provided by the manufacturers to meet the requirements because some scanners provide good accuracy in a particular range of environment conditions.

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2.2.   Calibration of 3D scanners[7]

Calibration is another factor that should be done by the user before starting the 3D digitization. The manufacturer advices to perform calibration one time in a year or more frequently for specific measurement which depends upon the part to be measured or industries to obtain results in good range.

Generally, it is necessary to do calibration

➢ when device is moved from one place to another and

➢ when the optics of the scanner is changed and

➢ when the environment conditions are changed.

The device is independent that it can able to tell the user that the need to be calibrated if it is not done. But when the device is used in a scanner stable condition, the device will not indicate about the calibration which makes the user not to perform calibration.

In the study from the experiment was performed five times after the calibration and the obtained result for five different time measurement after calibration is same. The results obtained with calibration and without calibration is different. This difference is not a slight deviation of value from nominal dimension.

2.3.   Effect of Anti-reflective coating[7]

The 3D scanners cannot scan the shiny surfaces or transparent surfaces. The effect of anti-reflective coating is one of the important factors for 3D digitisation. In order to achieve the optimal condition, it is necessary to apply the anti-reflective coating material on to the surface of the object. It is a difficult task to achieve the perfect coating all over the surface because uneven or imperfection in coating will result in inaccuracy in measurement and will result in improper scanned data. From the research papers, measurement uncertainty was addressed. In the study from[8], the research was done by using chalk powder and titanium powder coating. ATOS Triple scan was used for 3D digitisation and data evaluation. In the experiment, the coating of chalk increased the surface thickness by 44 microns and usage of titanium powder provided good results as only 5 microns of layer thickness was increased.

In the study, the experiment was done by applying two layers of coating and result is that coating does not affect the deviation of value from nominal dimension, there is only slight difference. However, coating has little or no impact on the resulting accuracy, there is irregularity in shape of the object from the scanned data. Thus, insufficient coating will cause local reflections which will affect the shape of the scanned surface. Therefore, for uniform coating well experienced operator is needed to perform because non-uniform coating results in irregularities.

Following interferences occur when scanning the object without coating,

Dark objects	Light projected is absorbed by the object
Shiny objects	Light projected will be scattered and moves in different direction.
Transparent	Light projected will pass through the surface

Table 1: Light projection interferences for different Part conditions

2.4.   Optimum conditions for scanning[9]

As explained in the introduction, there are many external factors like light, temperature, humidity, dust etc. affect the accuracy of the optical 3D scanners. These factors influence the quality of scanning data, thereby the output of 3D digitization is irregular model. The accuracy data from the manufacturers are not achieved in common practise as they do the measurement in special laboratory where conditions are favourable for digitization. In the study research, an experiment was conducted that how much impact does these parameters and atmospheric conditions have on the resulting shape and accuracy. The parameters considered in the experiment are,

- ➢ quality of used reference points,
- ➢ scanning angle,
- ➢ number of images,
- ➢ camera shutter,
- ➢ scanner heat up process,
- ➢ calibration and exposure time.

The research concluded that reference points, calibration of the device and scanner warm up had huge impact on the resulting shape and accuracy of diameter of sphere and spacing of spheres. When the number of scans is more it result is good for diameter of sphere and cylinder and also for sphericity. and vice-versa for spacing of spheres and cylindricity. Other factors such as used reference paper does not affect the accuracy. In case of cylindricity, with high scanner angle, the deviation is more. The experiment concluded that, although the external factors does not significantly affect the shape and accuracy of the object as much as only by 30 microns, it is important to consider all the factors when doing measurement.

The quality of scanning mainly depends upon accuracy of digitization, acquisition of points and smooth mesh of the object. Furthermore, digitization techniques should also be considered when scanning because it has huge impact on the resulting accuracy. The resulting shape of the object mainly defined by acquisition of point clouds from which surface of the object is created. The acquisition of point clouds mainly depends upon the calibration and distance between the scanner and the surface and the movement of the scanner. They are different digitization techniques like laser scanner, fringe projection method etc.

2.5. Laser system vs white light projection system[10]

The research was focused on smoother creation of point clouds in order to obtain good meshed surface by eliminating noise, reduction of points obtained and creating smooth triangular mesh. Also, it is necessary to know the number of scans, number of points and number of polygons. The research concluded that using laser systems, it is difficult to collect data for small objects, complex shapes, and with sudden change of the shape. And, system with white light projection provides good accuracy and computerized tomography technique also resulted in greater accuracy with filtration of points to obtain smoother mesh.
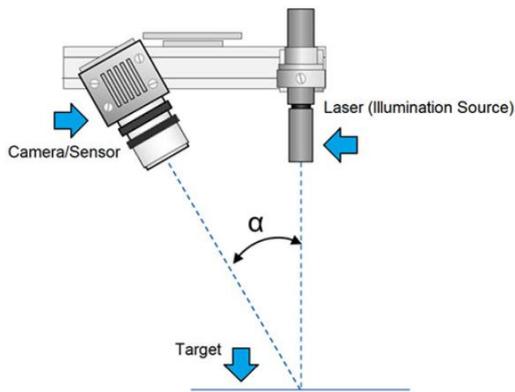
Figure 4: Laser Scanner[11]   **Figure 5: Structured Light Scanner[11]**
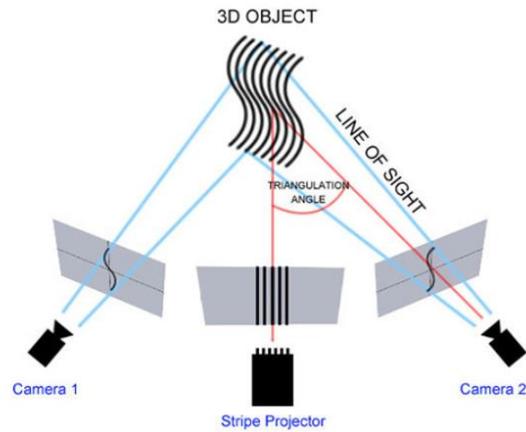
2.6. Geometric accuracy of complex shapes[12]

From the research which was mainly focused on geometric accuracy of complex shapes for scanners and in addition to that, the achievable accuracy of optical scanners is tested using several gauge blocks to confirm its accuracy. Mainly this research was done for GOM Atos II three-dimensional scanner which will be used in this project. As already stated, that the reference points which will be attached to the object or on the outside of the object for scanning the object from different angles which will be recorded by two cameras. The cameras capture the image which is visible in both the cameras.

2.6.1. Experimental Uncertainty

This research also dealt with experimental uncertainty. There are several artefacts which includes gauge blocks, step gauges, ball plates, rings and balls to perform calibration and acceptance test for CMM. On the other hand, there are no such procedures for optical scanners. The manufacturers of optical devices have developed their own standards and they will perform periodical inspection which is so called acceptance test for their customers. Firstly, gauge blocks were scanned and cloud points were acquired. And for further inspection, cloud points were converted to three-dimensional polygonal mesh. Three different length of gauge blocks of 20mm, 30mm and 70mm were used for inspection and the measurement deviation from nominal value does not depend on the different sizes. Standard uncertainty which was determined using propagation law, which is within the limits of 12 microns for the gauge blocks.

Complex shape like metal Sphere was used to determine the accuracy. Also, there is advantage of using sphere for experiment which requires only one scan neglecting the error for scan assembly which occurs when there are two or three scans. This research concludes that for gauge blocks where scan assembly is required as there are two scans the deviation from nominal value is more when compared to sphere.

2.7. Internal vs External post-processing[13]

The research was based on the working limits and performance of three-dimensional optical scanners for fringe projection using blue light technology. In this research, special gauge was used as calibration standard with specific optical properties and also the gauge is made of matt white ceramic material with several geometric features. Two different post processing tests were followed after scanning the part and the results were obtained. In the first test (internal post-processing), after scanning point clous were merged and mesh cleaning is done and then the file is exported as (.STL) format in scanning software and analysis is performed in inspection software. In the second test (external post-processing), after scanning the file is exported as (.ASC) format and then during analysis the mesh cleaning and merging point clouds was done. The first test provided good result of measurement when compared to second test in case of evaluating sphere and cylinder dimensions. But it is vice-versa in case of form errors.

Post-Processing	Scanning Activities Steps ⟶			Analysis Activities Steps ⟶		
Internal	Scanning	Point clouds merging and cleaning mesh	Total mesh export as (.STL) file	Import as (.STL) file and further inspection		
External	Scanning	Single scan exported as (.ASC) file		Import as (.ASC) file	Point clouds merging and cleaning	Inspection

Table 2: Internal vs External post-processing Steps

Thus, this research also focused on measurement volume i.e., range of measurement and it is obvious that as the measurement volume is low, number of scans increases which results in more deviation from nominal value.

2.8. Effective way of use of optical scanners[14]

The research was focused on various ways of use of optical scanners and the optimum condition where the optical scanners is more effective. There are two methods of scanning the object,

➢ destructive and

➢ non-destructive scanning.

In destructive scanning, the object to be scanned is destroyed in to small parts and scanning is performed. This method is mainly performed on historical objects like monuments and archaeological findings. On the other hand, non-destructive testing is done without destroying the object and the scanning is done. To eliminate the shadow created, it is necessary to inverse the patterns which is projected on to the object from bright area to dark area and from dark to bright. Thus, the image range will be from negative to positive. The two patterns are subtracted to obtain the correct image. And lastly, for scanning it is better to have object with non-reflective surfaces. It is good to have light or white object because if we have dark object, it is difficult to distinguish between light and dark stripes.
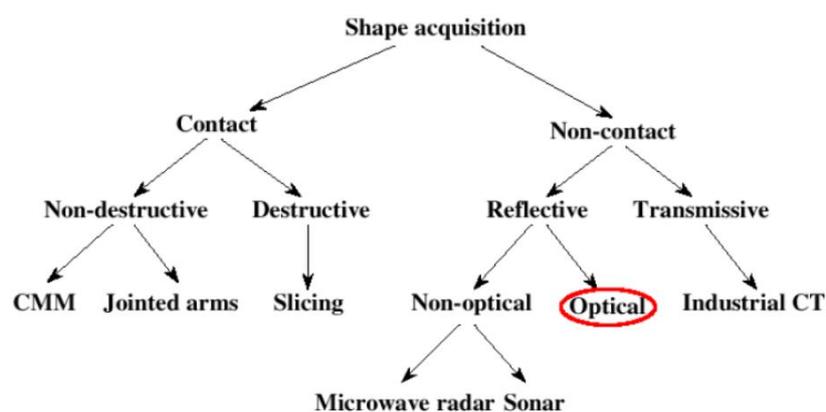
Figure 6: Scanning Methods[15]

2.9. Measuring capability of Optical scanner[16]

The research deals with the measuring capability of optical three-dimensional scanner. In this research, scanner used is ATOS triple scan II and the object is hard metal rod. The parameter to be inspected is rod diameter when using different measuring volumes. Measurement with optical systems requires specific steps to be followed by the operator for preparation and optimum scanning conditions. Rod diameter is 12 mm and two measuring volumes are MV100 and MV170. Diameter of the rod was evaluated from three reference sections i.e., focus of 10mm, 25mm and 40mm. In this first evaluation, average value of diameter from three sections is taken for finding capability. In the second evaluation, average value from each section is taken separately and capability of the device is determined. From this analysis, it is observed that ATOS is not capable of measuring such small and precise objects with small tolerances. Therefore, with wider tolerances ATOS is well suitable for digitization and provides better results with medium and large sized objects.

2.10. Repeatability and error in simple vs complex shape[17]

From the research deals with the repeatability and error in accuracy of low-cost and high-cost laser scanners when scanning a bone femur and gage block. The main aim is to determine whether the manufacturer value of accuracy can be applicable to all the objects from simple to more complex shapes. Five laser scanners were used for the research and objective was to compare one low-cost scanner with high-cost scanners. It is known from the previous research papers that laser scanner cannot get more detailed for complex shapes. Laser scanner usually consists of laser sensor which is used to calculate the position of the object from the laser source and it consist of motion tracking device which determines the position and orientation of the object in three-dimensional space. Usually for motion tracking, manual either a measuring arm or photogrammetric system is used. With this motion tracking device, it is possible to view the data generated about the three-dimensional object instantaneously. The gage block and distal femur were sent to the manufacturer to determine the accuracy. The manufacturer after scanning both the models 10 times, they sent the scanned file in stereolithography format to the researcher. It is found that the arm-based laser scanner has more accuracy when compared to photogrammetric system because of lower bias. And the root mean square of gage block measurement values was lower than the overall error stated

by the manufacturer. The mean root mean square value for bone femur is higher than the gage block. The precision of low-cost scanner is same as the high-cost scanner but the it may change when using large sized objects. Thus, repeatability mainly depends upon the shape of the object i.e., it is good for simple shapes. Therefore, the manufacturer data can be taken into account when scanning simple shapes. To conclude the main difference between the low-cost and high-cost scanner is the bias between them while the precision is comparable.

2.11. Accuracy and precision dependency on shapes[18]

The research gives us information about the precision and accuracy parameters for structured light systems. This research was mainly focused on the calibration parameters, angular range of scanner for calibration and how many observations are required for calibration. In this research, the user developed own structured light system with two cameras and a projector and the user compared it with the GOM ATOS Triple scanner. The parameters considered for experiment are probing error form, probing error shape, sphere distance error and flatness. For accuracy, it is better to use larger camera angle for calibration. To conclude, the user system produced good result for probing error form when compared to ATOS. But with flatness and sphere diameters, Atos produced good result. Therefore, as in previous research standard guidelines for scanners are with respect with some common shapes and not for complex shapes i.e., accuracy and precision vary based on the complexity of the object used.

2.12. Different measurement strategies[19]

The research deals with the measurement strategy for optical scanners to determine the accuracy of measurement. For this research, the user used large objects which is greater than the scanner measurement volume. The strategy for measurement does not depends on the scanner i.e., it is not possible to follow the same condition for all the geometry. This research focuses on particular geometry i.e., conditions change with respect to the object geometry. Four strategies were taken in to account for experiment,

➢ first one is that the object size is smaller than the measurement volume and the object does not change position with respect to reference points during scanning.

➢ Second one is using object larger than the measuring volume and reference points for each scan is determined first based on the principle of photogrammetry.

➢ Third one is without using the principle of photogrammetry i.e., by assembling the individual scans based on common reference points (three common points).

➢ And the last one is without reference points i.e., based on best-fit assembly of scans in to three-dimensional object.

Thus, from this research, for large objects, second strategy base on photogrammetry produced better results close to the nominal value.

3. Principles of 3D scanning

Optical 3D scanners work relatively fast when compared to contact method of measurement. They have fast acquisition rate. This method uses several principles such as stereovision. Optical triangulation technique, photogrammetry, light-strips projection method, Laser triangulation 3D scanning technology, structured light 3D scanning technology, laser pulse also called as time of flight.

3.1. Stereovision[20]

Stereovision process uses two or three cameras to capture the images of the same object. Baseline separates the two cameras. Two cameras simultaneously capture two images. Then, two images captured are compared to find the difference. Like a human-eye, this principle captures two-dimensional images of object using two cameras. Using triangulation method which is based on the similarity of triangles it is then possible to create three-dimensional image from the captured 2D images.

The problem occurs when we try to find identical points on images captured from individual cameras automatically. When we have the identical points on specific areas from two cameras, it limits the scanned part. The result of a measured part is such that only few points on the surface are taken into account to create a part. These points can be used as reference when we complete the individual measurement into a single unit.

The stereovision principle can also be applied with the help of one camera. Subsequently, all captured images are processed from which the spatial coordinates of significant points on the object are calculated. However, the condition is to know the position of camera in advance. The second way is to individually calculate the position of camera in space with the help of suitably selected reference points found in each image.

For the first method i.e., use of single camera, an additional precision device is required to measure the position of the object in relative to the camera. Subsequently, the image is processed on a similar principle as in classical stereovision which uses two por three cameras.

The second method which uses two or three cameras is based on the principle of digital photogrammetry. Images can be captured from any positions and it is not necessary to know the exact position of sensor. The condition for this is that each frame should contain at least three reference points and it is necessary to know the position of at least four of all these points. Mainly coded points are used so that they can be easily identified without any difficulties and also, we can calculate the camera position analytically. From the calculated image position and again it is possible to determine the position of particular points in the component.

The advantage of this light strip projection principle over the surface of subject is in less demands as it is not possible to scan without appropriate surface treatment as mentioned in the previous chapter i.e., chalk powder coating or titanium powder coating. The back side of part is scanned with less accuracy of results.

$$\frac{x_l}{f} = \frac{x_P}{z_P}$$

$$\frac{x_r}{f} = \frac{x_P - b}{z_P}$$
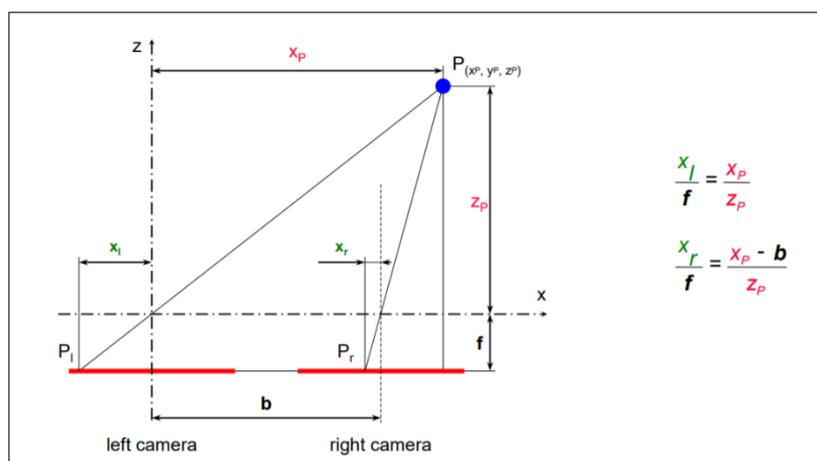
Figure 7: Stereovision Principle[21]

3.2.   Light Strip projection principle[20]

The camera which is positioned relative to the light source captures the image illuminated by a light strip projected by a projector. The shape and orientation of the part can be determined from the obtained image where any change in shape of object i.e., in curvature shape of light patterns is captured.

The most important tools for obtaining a spatial description of the scanned surface of the components are sensors, for example camera and a light strip source (projector). The low power laser is the simplest source of light strips in practice. From the original point beam, it is then possible to form a strip of light in two ways. The first way is to sweep the beam and scatter it to others by using lenses. This method has their advantages and disadvantages. The sweeping technique requires a relatively complex one for the movement of the mirror which sweeps the beam of light. By using laser power control, it is possible to regulate the light intensity in different section of the strips. Therefore, we can obtain same visibility of the strip for the camera even on surfaces with different reflectivity. Relatively cheap and simple optics that scatter the entire beam of light at once and it is obvious that complex areas should be scanned several times to obtain sufficient visibility of the whole strip for the camera.

The projection of the light strip is based on the triangulation method. Unlike from laser triangulation or stereo vision, it requires the projection of a strip of static light objects for 3D image processing. Measurements are extremely fast - the time required is up moves in the order of seconds or even fractions of a second.

This technology works with structured light, the object can be illuminated with the help of DLP projector. The light is projected on the object in stripes at a suitable distance with respect to the size of the object. The result is a light strip on the object which is then recorded by a set of cameras at a known angle. a 3D image can be calculated from a 2D sequence slides.

Light projector with bulb, or special lamp are mostly used in case it is necessary to project more strips at once or to use different combinations. The strips are created with the help of suitably designed screens, which often allow automatic exchange. In combination with the projector's optics, they subsequently create required light strips.

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Using triangulation, it is possible to calculate the coordinates of individual points on the surface components in place of illumination by a strip of light. It is necessary to know the angle of view of the camera and distance between camera and projector lighting. For a complete description object, it is necessary to gradually scan the whole component with a light beam.

Compared to a laser scanner, where the maximum light intensity is evaluated into several pixels of the camera, allows a projected light strip evaluation of light intensity for each individual pixel of the camera. This leads to an increase the maximum achievable scan resolution that is greater than 1: 10,000. Thanks to the high speed when digitizing large volumes, it is a strip projection method lights very suitable for industrial inspections such as shape, deviations, completeness, position of components, volume measurement, etc.
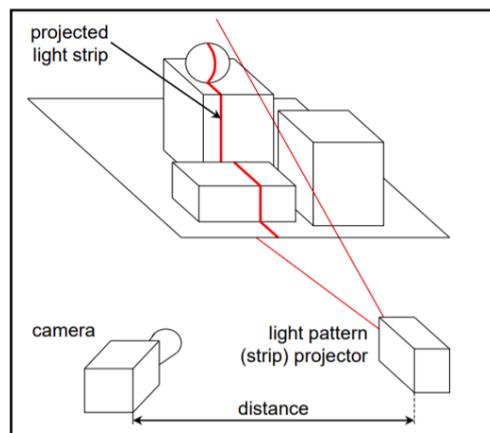
Figure 8: Light strip projection principle[20]

4. Scanning Devices

4.1.   ATOS Triple Scan[22]

Atos triple scan as in Figure 9. is an optical scanning device developed by GOM. This system gives the user flexible measurement condition and the system is more stable. It is used in many industries for scanning and inspection of complex objects such as turbine blades, injection moulding etc. because of its high accuracy and also it provides the user with quick measurement time and most importantly this device can be used to measure very small to large objects. Atos triple scan can scan glossy surfaces and complex shape components.

Because of its advanced measurement and projection approach, high density data up to 8millions dots per one shot and thousands of dots per one square-millimetres area is produced because of its high resolution which makes the user to measure deep pockets, ribs, sharp edges etc.

Figure 9: ATOS triple scan[22]

Atos Triple scan consists of two cameras to capture the images and one projector which projects fringes of light pattern as in Figure 10. onto the surface of the object to be scanned. Atos triple scan follows the principle of triple scan principle and stereo camera technology and fringe projection technique. This device uses band of blue LED for projection which can able to filter the light that appears on its projection path. This is a big advantage as it be used in any lighting condition regardless of the environment. This measuring principle provides the user to scan and measure reflective surfaces and complex cavity and dent areas. The sensors used in the system continuously monitors the environment conditions and able to adjust to suitable scanning conditions. In order to achieve this, the software of the sensor continuously monitors the calibration status and movement of parts and change in environment conditions.

Scanner collects information about the surfaces where the intersection of cameras and projector occurs i.e., at the intersection of light beams as in Figure 11. The combination of light beams are as follows, 1. Left camera and projector, 2. Projector and right camera, 3. Right camera and left camera. Therefore, it collects more information in a single scan which largely minimizes the scanning and data collection time.
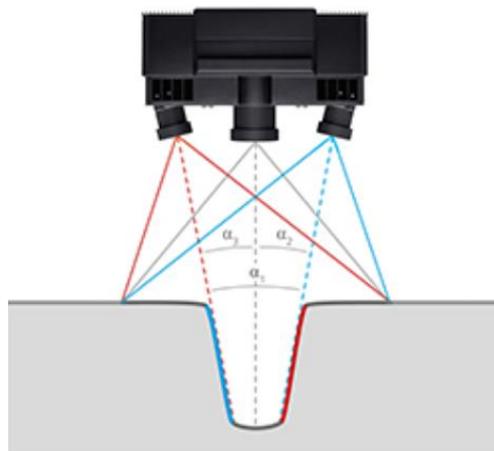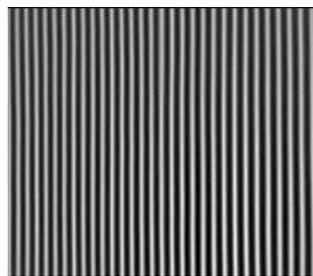
Figure 10: Fringe projection patterns[23]

Figure 11: Ray of Intersection of beams[22]

- Length of camera support (center of cameras)
- Fringe projector
- Camera support
- Camera lens right **R**
- Projector lens **P**
- Camera lens left **L**
- Measuring distance
- Camera angle
- Width **W** (measuring volume)
- Height **H** (measuring volume)
- Center of the measuring volume
- Length **L** (measuring volume)
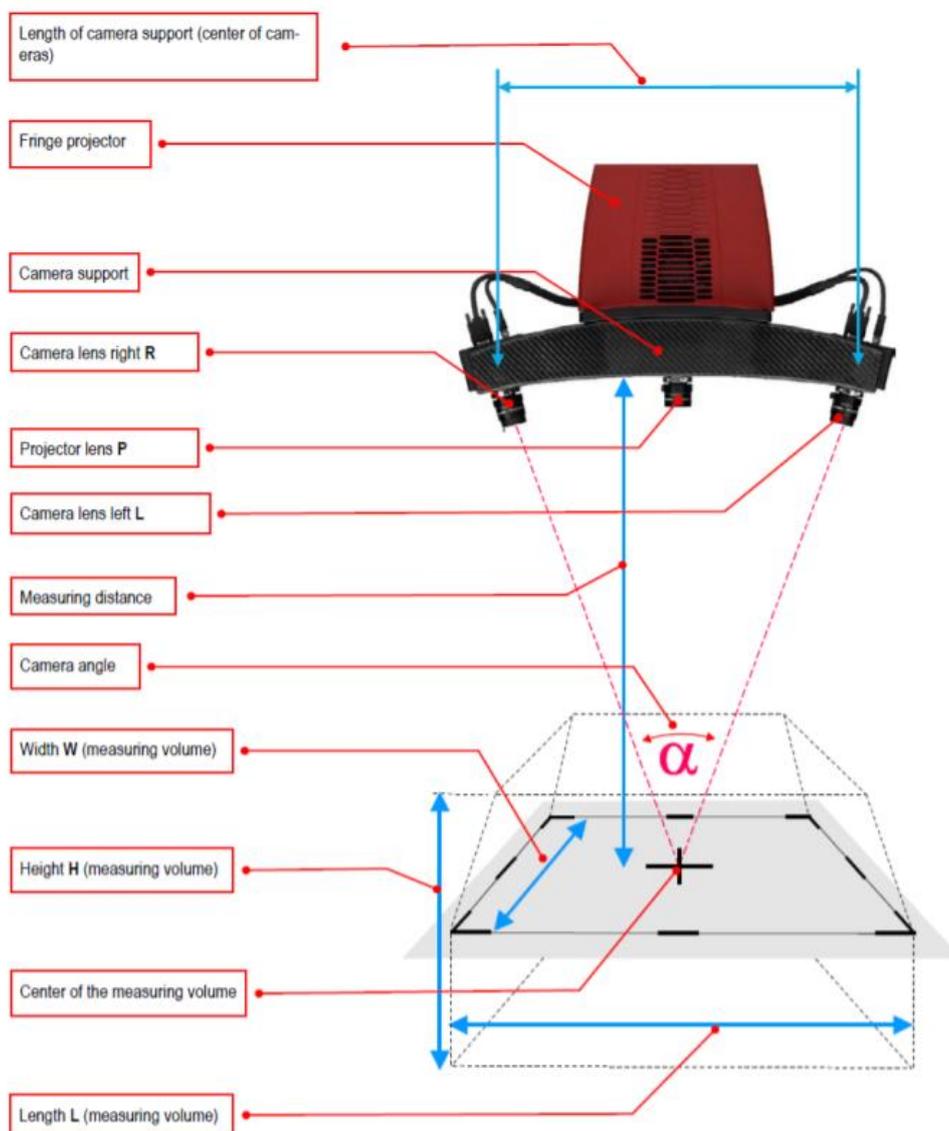
Figure 12: Measurement volume[21]

4.2.   REVSCAN[25]

REV scan as in Figure 13, is an optical 3D scanner which is a portable device developed by CREA-form. This system works on the principle of light strip projection where the laser cross is projected in to the measured object. This method is similar to ATOS II 400 scanner but the difference is the source of light and laser cross in a red-light spectrum. System precision is of 0.05mm from the manufacturer.

Figure 13: REV scan Scanner[25]

REV scan is first handheld and self-positioning device as it does not need any external device to find its position relative to the component to be scanned. The position of the scanner is determined by special reflex points which is marked on and around the object to be scanned. This system requires this kind of unique-points to define its position but in ATOS points marked in white paper is enough to identify the reference points of the scanning. The main reason for that is camera light are fitted with special filters that emits only a narrow beam of red-light. Therefore, the reference marks on and around the component is scanned by the red light from the LED beam which is placed around each camera.

The main advantage of REV-scan is its mobility that gives the user to easily move around the object and can be carried in a small bag with ease. In comparison with ATOS scanner, its accuracy is not good and also it is not possible to scan the small gaps and it is not easy to reach some areas i.e., minute detailed surface is not scanned and the result of the scanned object with less density points which gives the user less information about the surface features. Measuring volume is adjusted in the software and the scanner is not adjusted to achieve the desired measuring volume.

Technical parameters are as follows, weight 980gms, laser class is II which has no impact to the eyes, system accuracy is approximate to 0.05mm from the manufacturer data, measurement rate is 18000 measurement per second density of points obtained mainly depends upon the measuring volume usually in the range between 0.2mm to 2mm, measuring volume as stated in the previous paragraph is adjusted in the software which is in the range of 100 to 1000 cubic millimetres.

4.3.   METRA-scan 350[26]

METRA-scan as in Figure 14: 3D METRA-scan 350**[26]** is a hand-held three-dimensional scanner developed by Creaform3D and it is also a portable device like Rev-scanner. This system is one among the accurate 3D scanning device available in the market. METRA-scan works on the principle of three laser cross wherein Rev-scan uses one laser cross as a source for projection. Regardless of the working conditions, METRA-scan can be used in any atmospheric condition like lighting, different laboratories and it can also be used outside the working environment. This is one of the major advantages of this system as these factors mentioned above are not met with some scanners. Furthermore, METRA-scan can produce the image without any irregularities and blurs.

As mentioned in the introduction about 3D scanning, when scanning the object with METRA-scan, the object does not need to be coated with special powders like chalk or titanium powders as this system can scan any shiny or glossy surfaces and also this device can scan light or dark coloured objects without any special requirements.

As mentioned in the introduction about 3D scanning, when scanning the object with METRA-scan, the object does not need to be coated with special powders like chalk or titanium powders as this system can scan any shiny or glossy surfaces and also this device can scan light or dark coloured objects without any special requirements.

Figure 14: 3D METRA-scan 350[26]

METRA-scan uses C track reference system for finding the position of scanner and object to be scanned in spatial configuration. This tracker system provides the user with accurate capturing image which are in spotlights. METRA-scan continuously keeps track of the position of the laser scanning head and the touch probe. Also, this system allows the object to move during scanning as METRA-scan recalculates the position of the scanner placed relative to the object. The controller of the system provides the user with information about the change of ambient condition and the resulting measurement accuracy.

Therefore, METRA-scan 3D scanning system meets all the expectation of the user, such as fast measurement device, does not depend upon the environment conditions as it can operate with full stability in any atmospheric conditions and also, it can be used to scan very large objects because of its expandable measuring volume and METRA-scan can scan all sort of surfaces regardless of the colour and object to be scanned does not need any coating.

Technical parameters from manufacturer are as follows, accuracy up to 0.04mm and measurement rate of 205000 measurements per second and part size of up to six metres and light source is 3M which is eye safe and weighs 1.38kg.

4.4.   LEICA 3D Scanner[27]

LEICA AT901-MR(Mid-range) is a portable scanning device developed by Leica Geosystems. This system uses laser beam as a source of projection and can be used to

measure accurately and inspect objects with measuring volume up to 18 metres. It can also be used with a cube of a corner; in which case the volume of measurement goes up to 50 m. The sensor is designed for large objects and comes with the technology of our Leica Absolute Interferometer and Power-lock. There are three methods to collect surface coordinates information using Leica absolute tracker. As stated by the developer, it mainly depends upon the application of use. First one is by using hand-held wireless contact probe which one can carry and move around to track the Leica T-probe around the object. Second one is by using a small mirrored sphere which is known as reflector. And the last one is by tracking the Leica T-probe which is of high-speed scanner and it is contactless method.

Figure 15: LEICA AT901-MR[27]

Results from Leica 3D scanner is used in many applications such as, for reverse engineering, Rapid prototyping, inspection in automotive and aerospace industries. And the advantage of using is that the user doesn't need keep the laser beam in particular position for projection, as this system comprises of power-lock which locks the laser beam in place. This avoids laser beam from losing or breaking. The camera system used in this system is operating with visible light and near Infrared radiation with zoom parameter and motor for vertical and angular movement. It is mounted on the device and keeps capturing the images.

The main advantage is that regardless of the working environment such as ambient light parameter which is one of the major problems for other scanning devices, this device works

well. And it is robust structure, good thermal stability, smooth internal design and sensor head which doesn't warm up, quick scanning of objects, easy to handle and very compact. The technical descriptions include weight of around 22 kilograms and length of 62 centimetres.

4.5.   Ein-Scan Pro 2X[28]

Ein-Scan Pro 2X is a handheld device which is mainly used for scanning small to medium sized components and this device is developed by the company Shining 3D. Unlike many handheld scanners, this device delivers high quality results. Ein-Scan Pro 2X can be used in many options depending upon how the user desires to scan the object, it is a portable device which is available in many scanning modes such as manual scanning with HD option, fast manual scanning process and fixed scanning with or without turn table.

Figure 16: Ein-Scan Pro 2X Plus [28]

When used in fast scanning mode, this scanner can obtain 1.5 million points per second and in this mode, the user can obtain the output at much quicker rate. In fixed mode and without turntable, it gives output with accuracy of 0.04 millimetres. The density of points obtained is with distance of 0.02 millimetres and with this accurate capturing, even information for fine details can be noted.

This scanner is also available with optional extension modules such as colour pack which can be added when buying and with this option, it can scan original texture of the object and can reproduce the same in the output. And the second option is in automatic ode with tripod and turntable and this can produce results with high accuracy.

Technical description of this scanner includes, accuracy as specified by the manufacturer in three different modes are 0.05 mm for manual scan, 0.1 mm for fast scan and 0.04 mm for fixed scan, the working distance is 400 mm, it weighs around 1.13 kilograms, and operates with light source of LED (Ice light) and to operate this scanner and to get good results, it has to be used in anti-reflective coating which is one of the main disadvantages for optical scanners.

5. Acceptance Test Parameters[29]

➢ Probing error form

➢ Probing error size

➢ Sphere spacing error

➢ Length measurement error

These parameters are used to determine the measuring accuracy of scanning devices. The acceptance test is performed with reference to guideline given by GOM VDI/VDE 2634.

Generally, to perform an acceptance test, a calibration standard is created which mostly consists of standard common shapes like sphere, cylinder, gauge block, holes, ribs etc., and the nominal dimensions for these shapes are measured using Co-ordinate measuring machine (CMM) as this device gives the most accurate values of dimensions.

5.1. Probing error form

The software calculates from the measurement data the best-fit spheres for a sphere pair to determine the corresponding current parameter values. For the Calculation, the software uses the least squares method. A parameter of the type (sigma) of the test error leads to the standard deviation.

The standard deviation is determined with respect to the corresponding suitable sphere with a freely estimated diameter, from the radial distance of all the measured points of a sphere. This parameter usually gives the information about shape deviation i.e., from maximum deviation to minimum deviation of sphericity.

PF(Sigma) = σ PF(Range) = | max-min |

5.2. Probing error size

The probing error size is defined as the difference between nominal diameter and the measured diameter. This parameter gives us information about deviation of sphere dimension from nominal sphere value.

PF(Size) = D_a – D_n   (D_a – Measured diameter, D_n – Nominal diameter)
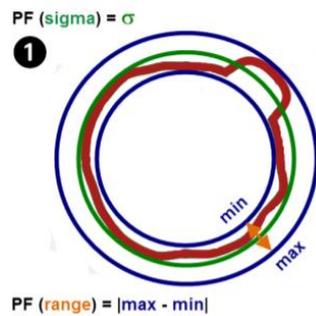
Figure 17: Probing error form[29]   *Figure 18: Probing error size[29]*
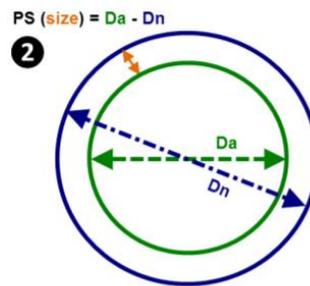
5.3. Sphere spacing error

Sphere spacing error shows the deviation of sphere centres i.e., spacing deviation. Generally, this parameter is used to determines the error of pitch distance between two spheres by fitting sphere method.
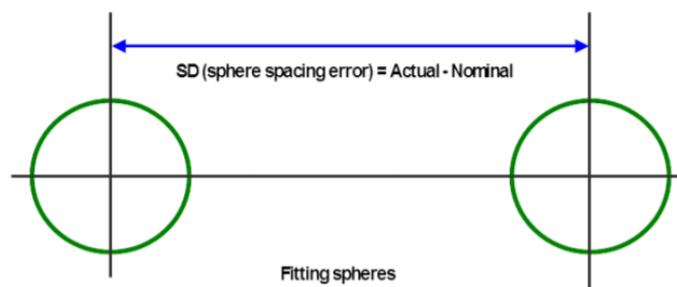
Figure 19: Sphere spacing error[29]

5.4. Length measurement error

The Length measurement error is the difference between the calculated error and two opposite points in length and the corresponding calibrated spacing of them. This

measurement is done using bi-directional probe by taking the nominal parallel surfaces in opposite direction which is perpendicular to one of the surfaces.
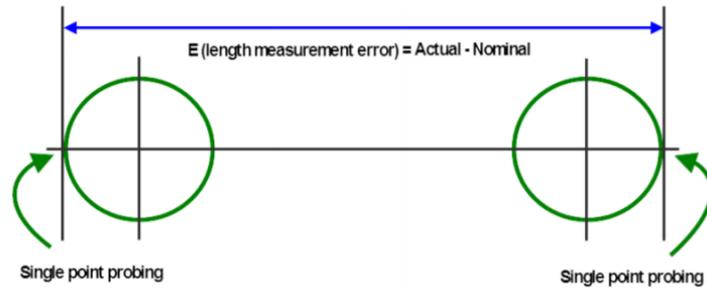
Figure 20: Length measurement error[29]

6. Calibration Standard

Calibration standard which is so called as Etalon is made in previous research at the department by FRKAL [30] and MENDRICKY [7] was used for acceptance test. The etalon is designed usually with basic shapes such as sphere, cylinder, blocks, holes, ribs and some general surfaces. These are the common shapes which are mostly found in many industrial components. In this research, calibration etalon from previous research as stated above was used which consists of spheres of three different dimensions. The etalon consists of 6 spheres in total, two spheres with diameter of 40 mm and two spheres of diameter 20 mm and two spheres of diameter 8 mm.
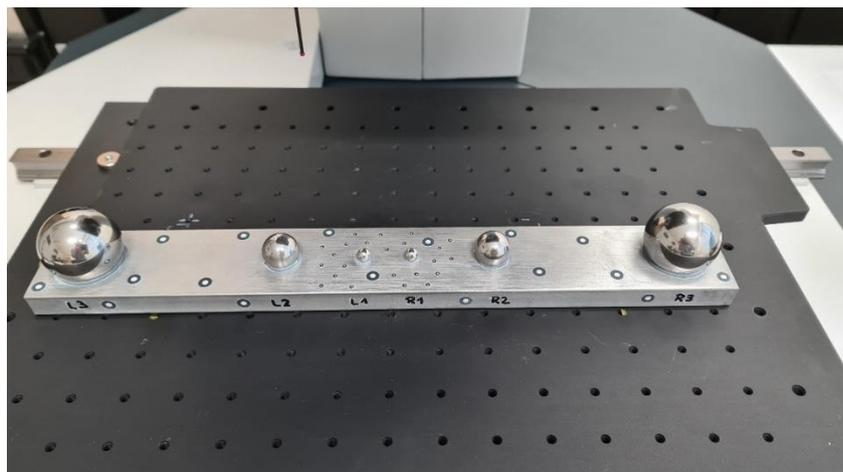
Figure 21: Calibration Standard (Etalon)

Calibration standard which is used to verify the accuracy of three-dimensional scanners is initially measured on Coordinate measuring machine (CMM). As already stated, CMM produces most accurate results. For this reason, the values from the CMM are taken as nominal or reference dimension for the comparison with the scanner results.

The etalon is measured on Zeiss O-INSPECT 322 Coordinate measuring machine. The accuracy of this device is usually given by the relation (2.4 + L / 150) microns. This device is multi-sensor measuring machine where measurement is performed either by contact using touch probe or optically (white light is used for projection). In this experiment, contact measurement is done.

Figure 22: Zeiss O-INSPECT 322 CMM

6.1.   Measurement of Calibration Standard on CMM

The Calibration Etalon consists of six spheres and the elements considered are,

➢ Six spheres which is termed as left spheres L1, L2, L3 and right spheres R1, R2, R3.

➢ Spacing between the spheres is termed as S1 between L1 and R1, S2 between L2 and R2, S3 between L3 and R3.

➢ Sphere external distance as in length measurement error, C1 between L1 and R1, C2 between L2 and R2, C3 between L3 and R3.

➢ Sphere space error as in sphere form for L1, L2, L3, R1, R2, R3.

Totally 10 times measurement is carried out in order to determine the most optimal value for reference dimension. In that measurement series, measurement is done 5 times without considering the right sphere R3 i.e., only spheres L1, L2, L3, R1, R2 are taken into account. The reason is because of smaller workspace, the calibration standard does not fully fit to the workspace. The results from the measurement are with temperature correction of 20°C which is set in ZEISS Calypso software.
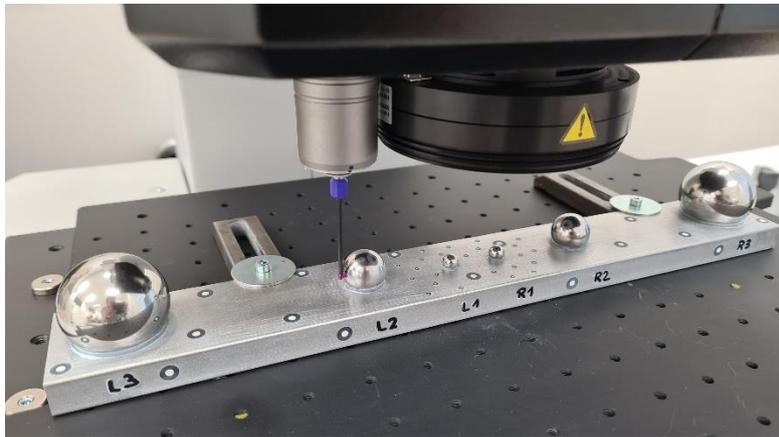
Figure 23: Etalon position for measurement series (1-5)

In the second measurement series, calibration standard is rotated and sphere L3 is not considered and spheres L1, L2, R1, R2, R3 are taken into account. The spacing between the sphere is determined by, first measurement series gives the result of Sax which is distance between L2 and L3, and Sbx which is distance between L3 and R2. From the Second measurement series, we obtain Scx which is distance between R2 and R3, and Sdx which is distance between L2 and R3. Therefore, spacing S3 is determined either by (Sax + Sdx) or by (Sbx + Scx).
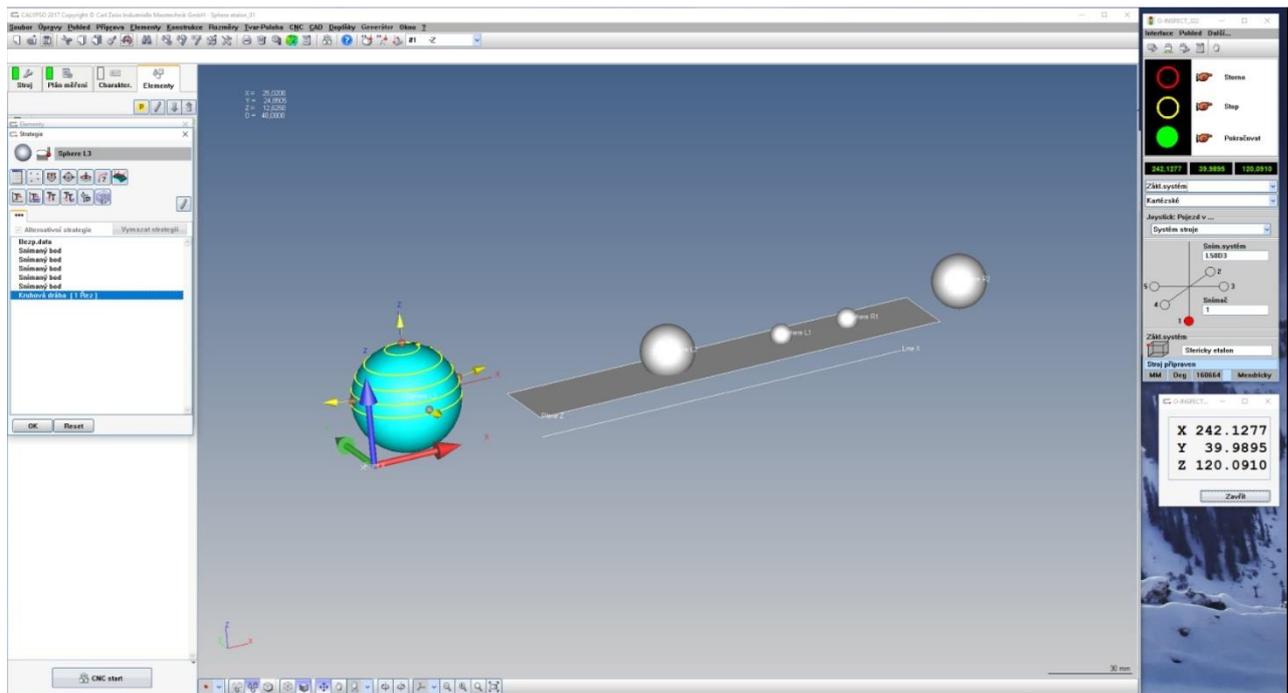
Figure 24: Etalon from SW CALYPSO software

The Figure 24*: Etalon from SW CALYPSO software* shows the measurement of etalon from SW Calypso software. This software gives the optimal values of the measuring parameters which is in compliance with ISO-10360. The advantages of this software include large field of view with high image output, optical solutions for measuring fragile or sensitive surfaces of the part, very quick measurement and increased reliability[31].

The spheres were measured by touch (ball) in a scanning manner. 8 mm sphere in 4 cuts, 20 mm sphere in 5 cuts and 40 mm sphere in 6 cuts. The first cut was in the area of the equator and the next evenly upwards - the last cut was 1 mm from the top of the sphere. The pitch of the point on each circle of the section was 0.1 mm. Thus, a total of about 1180 points (8 mm sphere), 2887 points (20 mm sphere) and 6297 points (40 mm sphere) were taken.

6.2. Summary of results on CMM

Summary of Reference dimension results		
Elements	**CAD dimensions**	**CMM (Nominal dimensions)**
Sphere diameters		
L1	8.0000	8.0004
L2	20.0000	20.0016
L3	40.0000	40.003
R1	8.0000	7.9997
R2	20.0000	20.0017
R3	40.0000	40.0032
Spacing between spheres		
S1	26.0000	26.0169
S2	115.0000	115.0054
S3	320.0000	319.933
External distances		
C1	34.0000	34.018
C2	135.0000	135.008
C3	360.0000	359.9371
Sphere space error		
L1	0.0000	0.0053
L2	0.0000	0.0065
L3	0.0000	0.0086
R1	0.0000	0.0042
R2	0.0000	0.0067
R3	0.0000	0.0079

Table 3: Reference dimensions
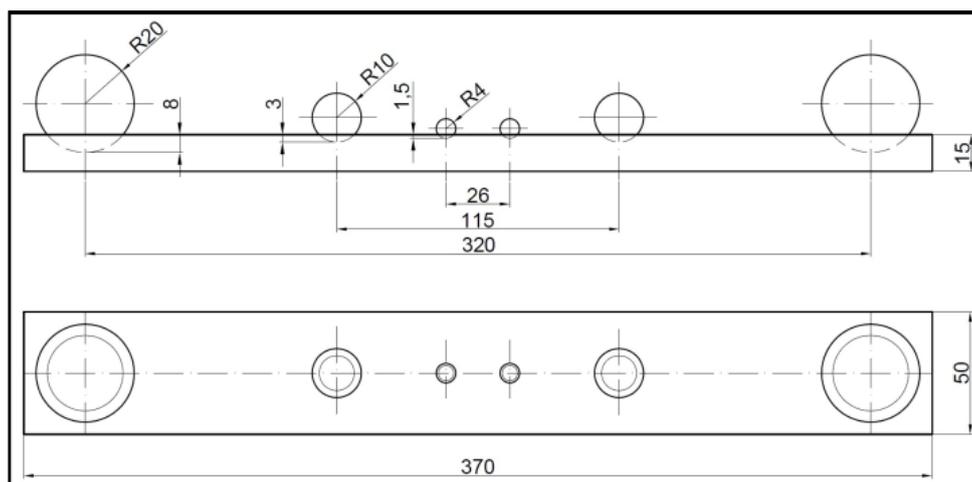
Figure 25: CAD dimension - Calibration standard design[7]

The Figure 25*: CAD dimension - Calibration standard design[7]* is the actual CAD dimension of the etalon. But in real, it is impossible to produce the part with exact CAD dimension considering the manufacturing dimensional and process inaccuracies. Taking the aforementioned factor into account, CAD model is created using 3D design software, PTC Creo Parametric 2.0 from the dimension values measured in Zeiss O-Inspect 322 CMM and results from CMM are considered as nominal dimension for each parameter as shown below in *Figure 26: CAD Part – CMM dimension - Calibration standard design*
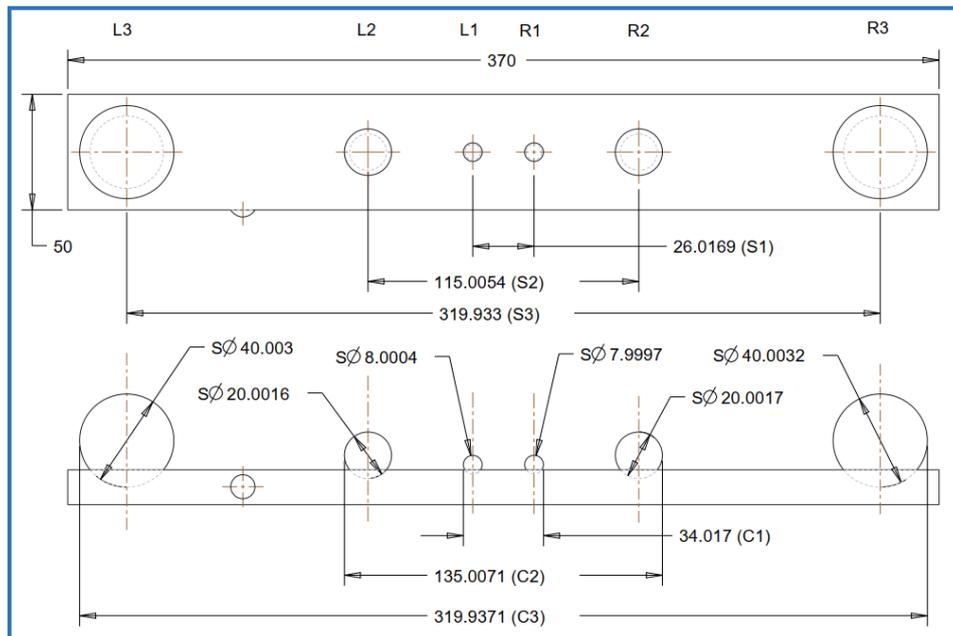
Figure 26: CAD Part – CMM dimension - Calibration standard design

7. Measurement of Calibration standard using 3D Optical scanners

The practical measurement of calibration standard which is so called Etalon was done using different three-dimensional optical scanners in the TUL laboratory. During this process, all necessary steps before measurement such as Calibration of the device, environmental conditions, anti-reflective coating, scanner warm-up time, placement of reference points, camera angle, number of scans, stable placement of part on the table, measuring volume of each scanners and reference point diameter as stated by the manufacturer were followed.

The measurement procedure is as follows,

1. Installation of suitable optics (measuring volume) to the scanner.

2. Calibration of the device as instructed by the manufacturer.

3. Preparation of part for measurement (placement of reference points, application of anti-reflective coating).

4. Setting the parameters like resolution, measurement in static mode, Light intensity

5. Scanning part from all sides until we get the whole geometry.

7.1. Calibration Standard (Etalon) for Scanning

With anti-reflective coating
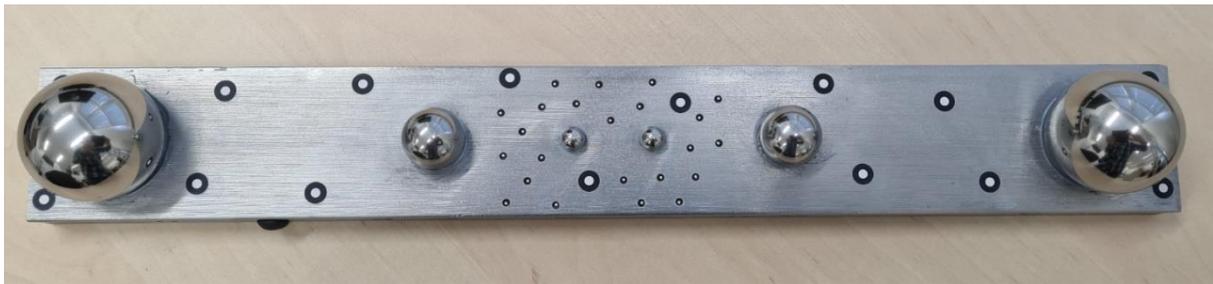
Figure 27: Etalon without anti-reflective coating

As already stated, one of the main factors determining the accuracy of the scanners is anti-reflective coating. The parameter light intensity is set according to the brightness of the part which was done in the software of the scanner. Before coating the standard, the etalon is degreased. As the part is symmetric, the scanner cannot distinguish between the left and right sphere. For that reason, the button shaped marker is attached to the side of the part between the left sphere L3 and L2. Also with this mark, it makes easier to align the CAD model and mesh in SW GOM Inspect. The reference is placed in a way that points are distributed throughout the whole length, width and height of the measured part.

Without anti-reflective coating
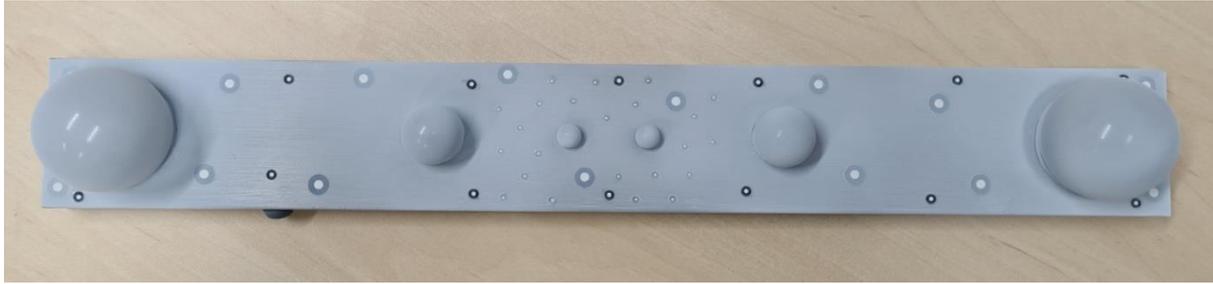
Figure 28: *Etalon with anti-reflective coating*

Figure 29: Titanium and Ethanol

For coating the part to avoid the limitations of optical scanning i.e., to prevent reflection, the part is sprayed with thin layer of titanium dioxide (TiO_2). The reason for using titanium dioxide is that, it adds only around 5 microns to the surface of the part which is less when compared to chalk powder coating of 44 microns. Titanium and ethanol are mixed to give Titanium dioxide (TiO_2).

7.2. ATOS III Triple Scan

7.2.1. Adjustment and Calibration of the device

It is necessary to adjust and calibrate the device before each measurement, some steps are performed prior to each measurement and some are done only after the optics are changed. All settings for calibration and control of the scanning process are performed directly in GOM ATOS Professional SW. Before the start of calibration, the sensor is warmed up for 20 minutes as suggested by the manufacturer.

Figure 30: Calibration Panel CP40 for MV320[22]

As stated by the manufacturer, calibration objects are very sensitive. The surface of the calibration should not be touched. The surface is cleaned gently with the enclosed microfiber cloth which is there in the standard tool box.
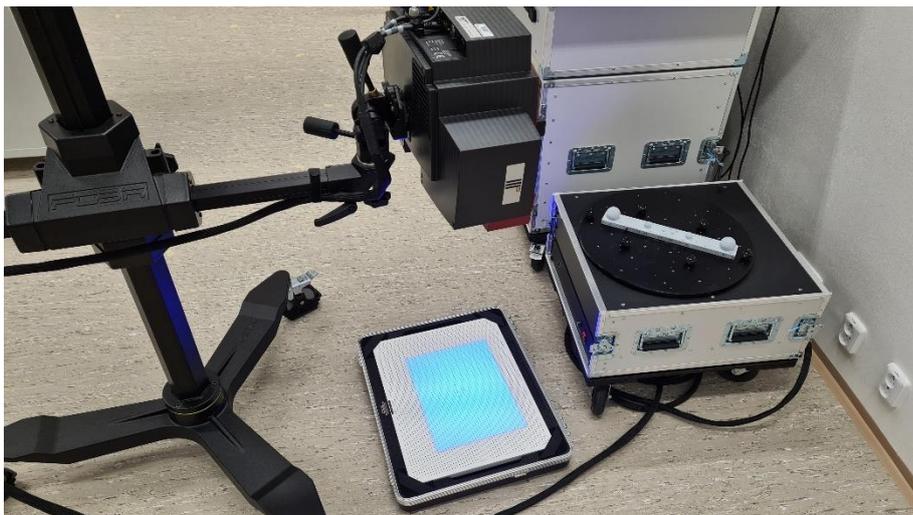
Figure 31: Scanner Placed perpendicular to the calibration panel

The scanner is placed perpendicular to the sensor. The first step is to make sure that calibration object is in the centre of measuring volume. Next step is to focus on exposure time setup for the scanner. 18 positions have been taken for calibration three different angles 25, 30 and 45 degrees and the measuring point distance which is resolution at 0.1 millimetre. The result of successful calibration is indicated in the software with the green light. When the red area which is indication of overexposed area as in is no longer visible, an exposure time is given.
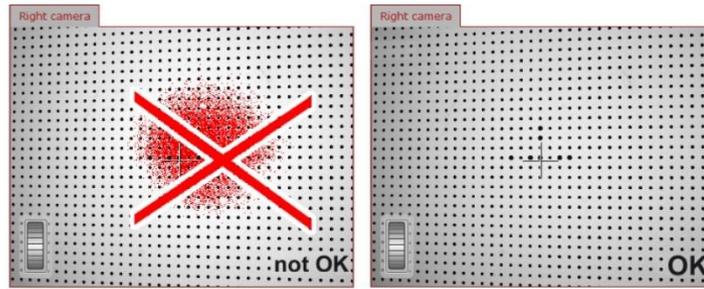
Figure 32: Exposure time adjustment for calibration[22]
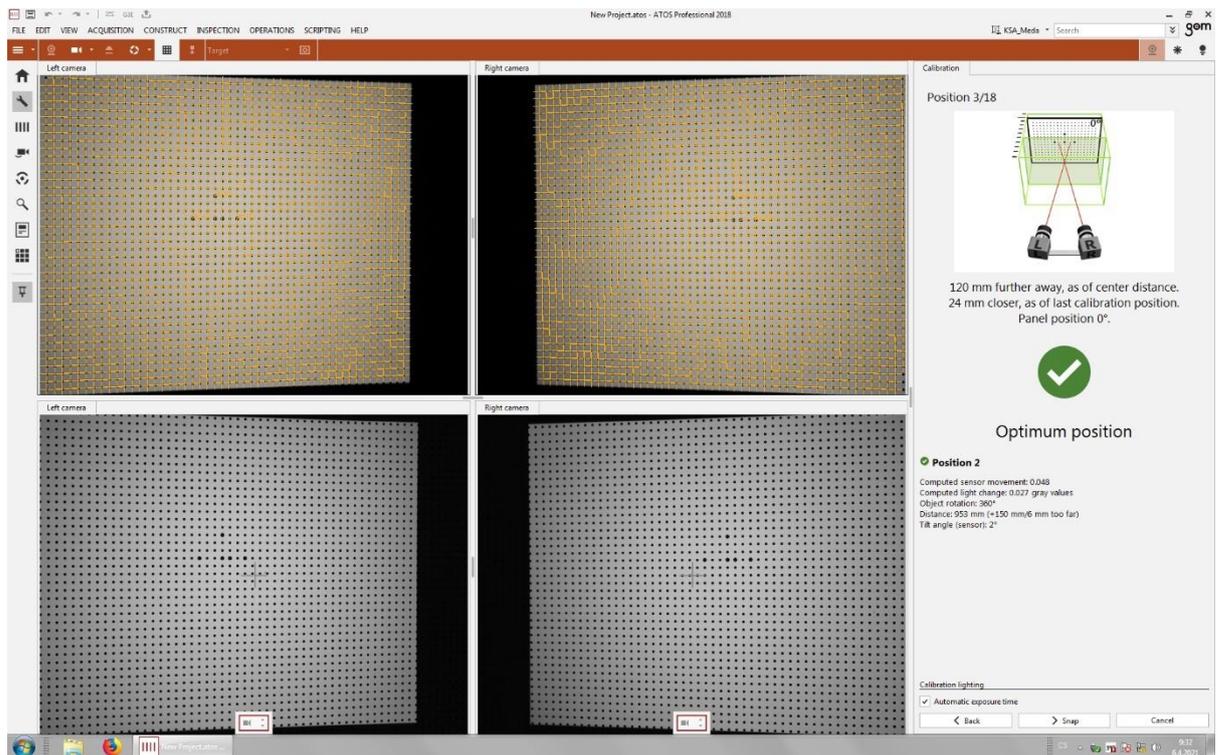
Figure 33: Calibration panel at position 3 of 18

7.2.2. Calibration procedure:

1. Calibration object is placed on the floor.

2. Next step is positioning the sensor perpendicular to the scanner which was done with the help of adjustable stand.

3. The stand height is adjusted until the laser points meets at one common point.

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The scanner is placed perpendicular to the sensor. The first step is to make sure that calibration object is in the centre of measuring volume. Next step is to focus on exposure time setup for the scanner. The result of successful calibration is indicated in the software with the green light. When the red area which is indication of overexposed area as in **Error! Reference source not found.** is no longer visible, an exposure time is given.

7.2.3. Calibration Results
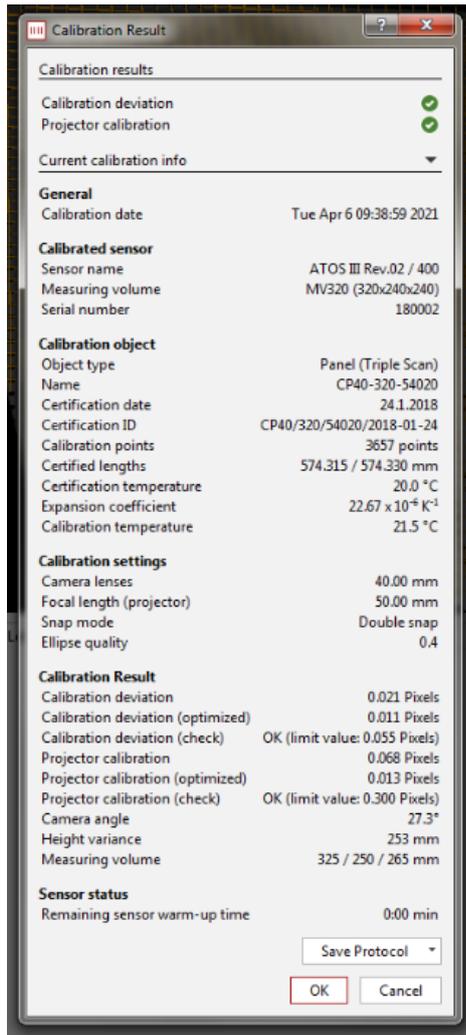
Figure 34: Calibration Information and Results

7.2.4. Measurement of the Calibration standard (Etalon)

ATOS III Triple scan is based on the principle of fringle light projection as shown in the image below, scanner projects blue light in the pattern of fringes. Thus, by this way scannere collects the information of the part surface.

Scanning Procedure

1. Placement of reference points, as specified by the GOM for measuring volume MV320, diameter of reference point should be 1.5 mm and there are some rules followed while placing reference points (they are not placed close to edges, all points are not in the same line, they are distibuted throuhout the whole body, they are placed on flat surface).

2. Calibration standard is mounted on the turn table. Temperature maintained is around 21.7 degree celsius.

3. Scanner is positioned at angle 45˚ in horizontal plane to the part. Part distance from the scannere for MV320 is 830 mm.
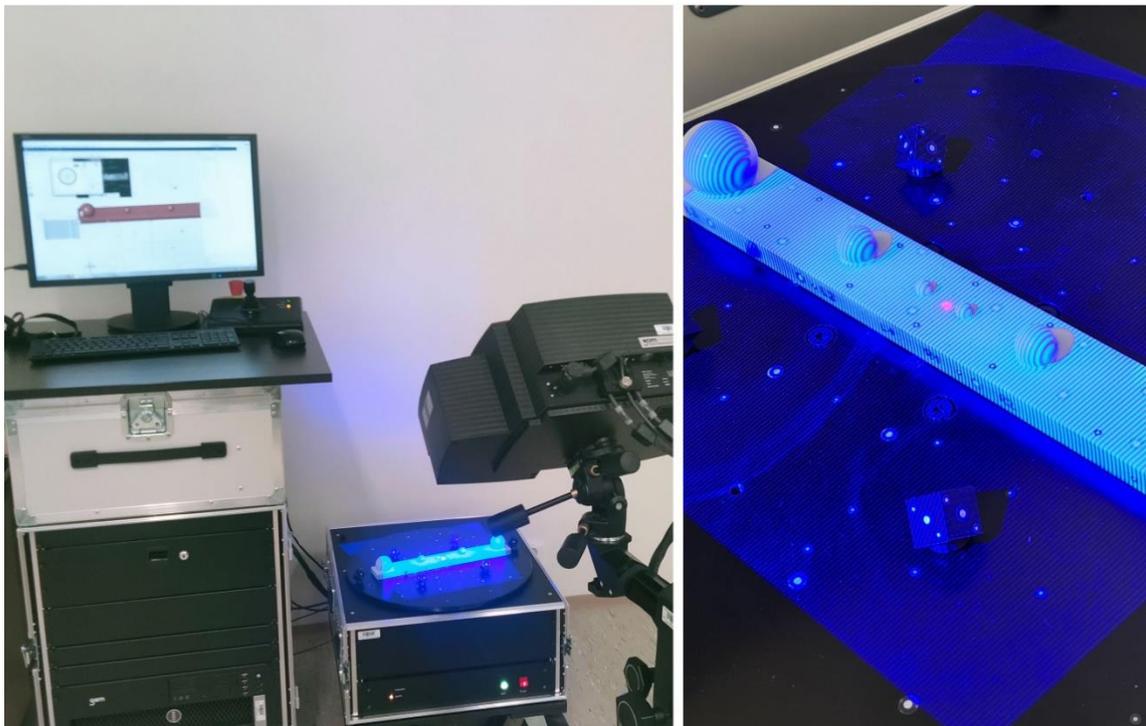
Figure 35: Measurement of Etalon in ATOS III Triple scan

4. Setting of optimal shutter speed for measurement which is otherwise known as exposure time, in this case it is set as 40 milliseconds.

5. Part is scanned from all the the sides, total of 10 images were captured by rotating the turn table 360˚ as shown in the image below.
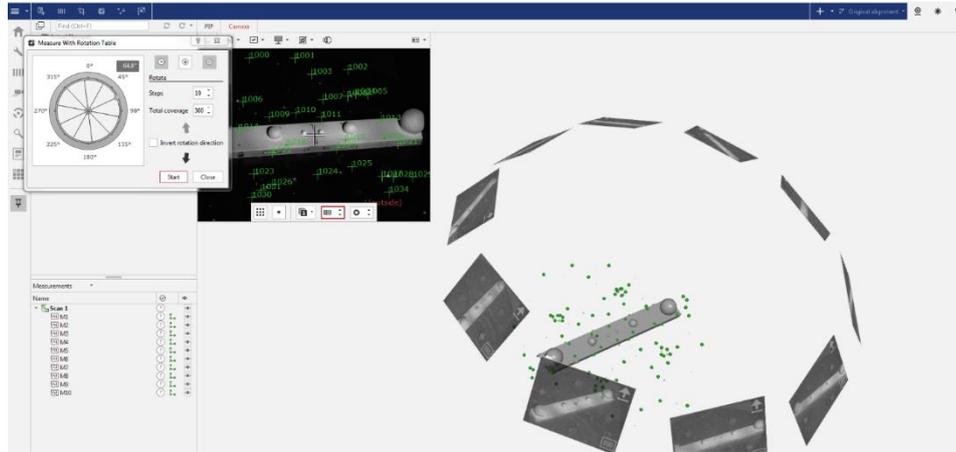
Figure 36: Position of 10 images in the software GOM

6. As the part length is 370 mm, the entire feature of the calibration standard cannot be captured in single position of the scanner. This is because of measuring volume MV320, as seen in the image above, part is not scanned completely on the sides.

7. To get the complete part, the scanner is moved to left and right to capture the remaining area in the part as seen in the image below, more images are there in the software window.
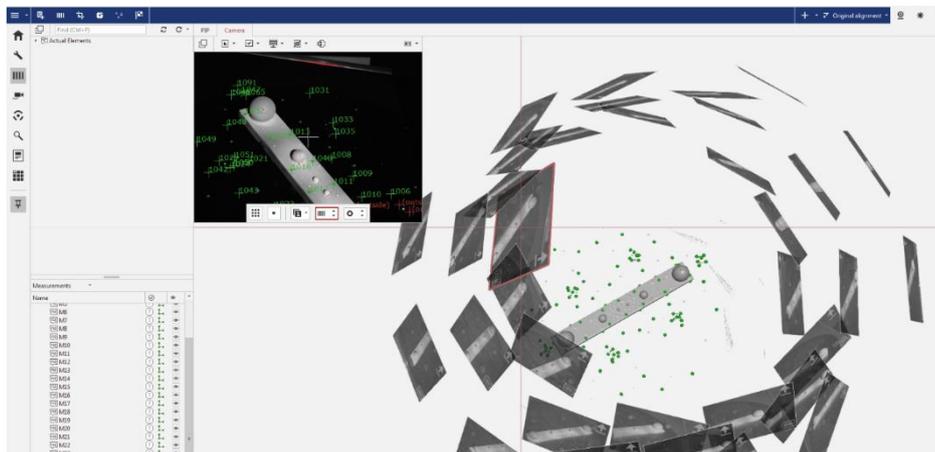
Figure 37: Position of more images for complete part in GOM

8. After the part is scanned, the resulting part obtained will contain noise around the object which is removed in the software GOM.

9. For conformity, the measurement procedure is repaeted two times, and two output mesh file is exported for inspection in GOM. The setting parameter is same for both the measurement with scanner resolution at 0.1 mm.
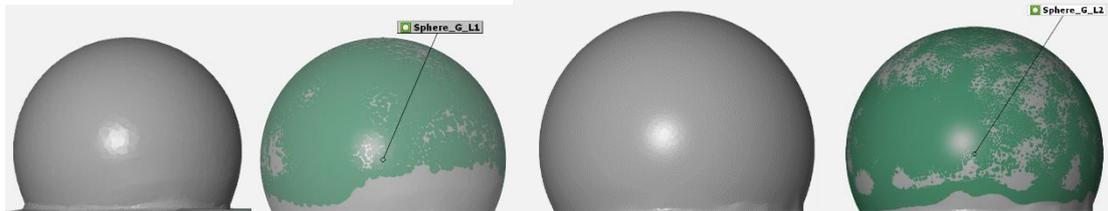
Figure 38: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2

7.3.   METRA-Scan

7.3.1. Calibration of C-Track and Scanning head

Calibration Accuracy of C-Track = 0.02 mm

Before starting the measurement, the system is calibrated in order to achieve the required accuracy and to avoid the inactivity during the measurement process.
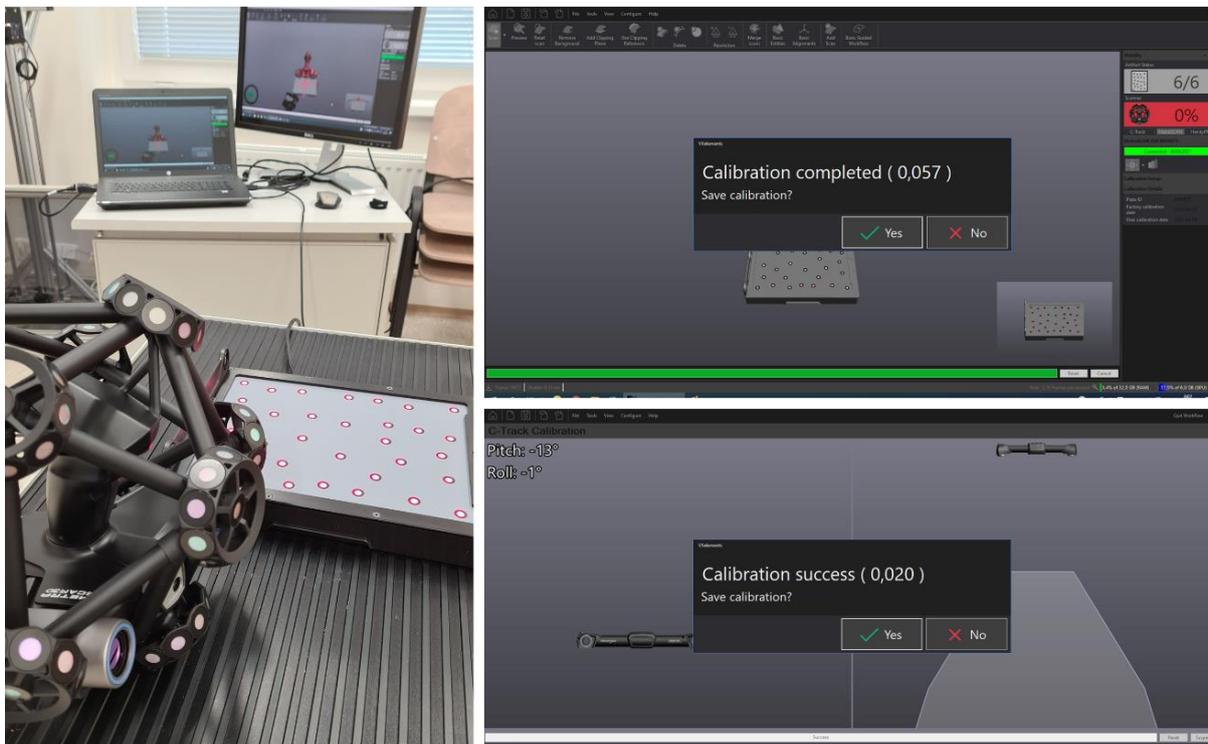
Figure 39: Calibration of C-Track and Scanning head

7.3.1.1. Calibration of METRA-Scanning head[32]

Calibration Accuracy of laser head = 0.057 mm

We ensure a high-quality surface is scanned with the specified accuracy by calibrating the 3D scanner. For the purpose of calibration, a reference plate is used by the scanning head and is held in a portable case next to the METRA-scan head. This calibration board must be connected to the control unit or a device through a USB cable.

Place a calibration plate in front of the C-Track before beginning the calibration phase. To begin the operation, place the board in space so that it is in the green field, and calibrate it as precisely as possible.

The calibration process starts after the start button is used to ensure that the board is in the correct position. When calibrating the scanner again, we must achieve the true scanner shape and complete all measures.

7.3.1.2. Calibration of C-Track[32]
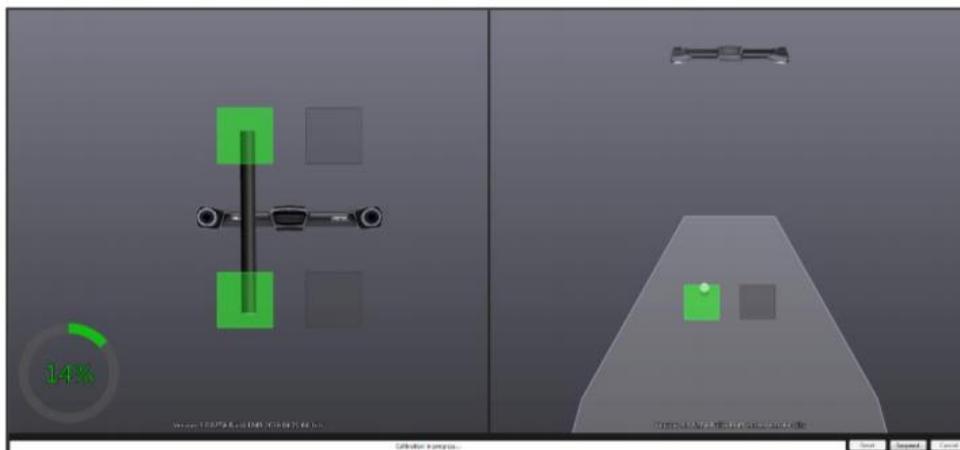
Figure 40: C-Track calibration[32]

The optical reference is calibrated using a calibration rod. This rod is an artifact from which you obtain optical information, such as verifying the reference's vision or adjusting its settings. Only this artifact is sent while calibrating the C-Track.

The machine forces you to rotate the calibration bar in different positions and distances during calibration. The accuracy of the information will be verified by the device.

The system will involve three forms of rod rotation during calibration: vertical grip, horizontal grip, and oblique grip points up and down.

The entire procedure is accompanied by a user-friendly environment that clearly displays where the rod should be positioned.

If the rod is in the proper position, the machine automatically conducts the calculation and moves on to the next position. The circular indicator at the bottom left can be used to display the overall condition calibration.

7.3.2. Measurement of Etalon In METRA-scan

METRA-scan is based on the principle of light strip projection where the laser beam is projected on to the part. The laser projection used here is of 3 laser cross and it is one of the most accurate 3D scanning devices.

Scanning Procedure:

1. Reference points is not needed for this type of scanner as C-track makes note of part details. C-track keeps complete track of laser head. As mentioned before, for symmetric object, button-like mark is used to identify the difference.

2. As this device is hand-held, with measuring volume up to 16 m, this scanner can digitise the part in one go around the object.

Figure 41: Scanning using METRA-scan (C – Track and Laser Head)

3. Temperature during measurement is set at 21.7 degree Celsius and is maintained as suggested by the manufacturer in the range between 5 to 40 degree Celsius.

4. Setting of optimal shutter time also called as Laser intensity is 0.15 milliseconds. This parameter mainly depends upon the colour of the measuring object, for white background, laser intensity can be set as 0.15 milliseconds and will be displayed in the screen. If red spots appear on the part while setting laser intensity, the result will not be good and it is over exposed. Therefore, this parameter is carefully set before scanning.
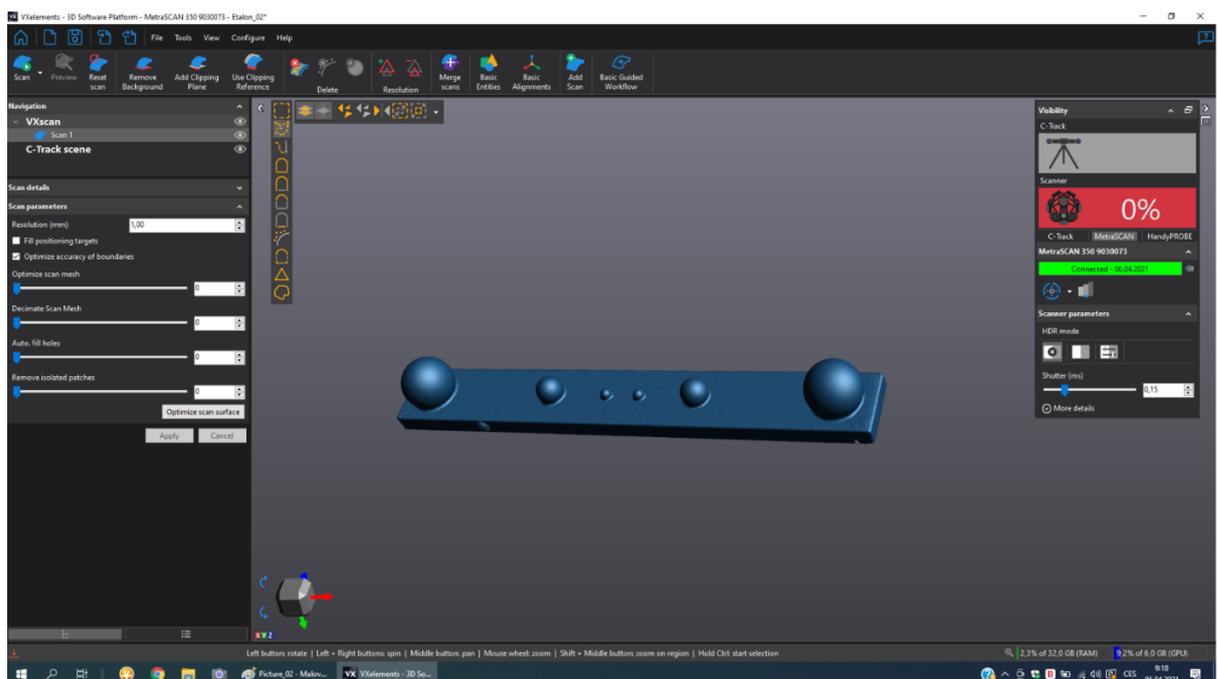
Figure 42: Digitised part in VX Elements (METRA-scan)

5. The above image shows the complete scan of part using METRA-scan in VX Elements, and the red area with 0% indicates the visibility of Laser head for C-track.

6. After the part is scanned, the resulting part obtained will contain noise around the object which is removed in the software VX Elements.

7. For conformity, the Etalon is scanned 2 times with resolution 0.2 mm which is minimum value for resolution for scanner and 2 times with resolution 1 mm which is maximum resolution for the scanner.
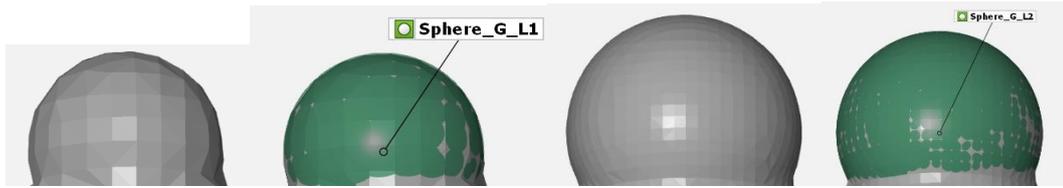
Figure 43: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (res = 0.2 mm)
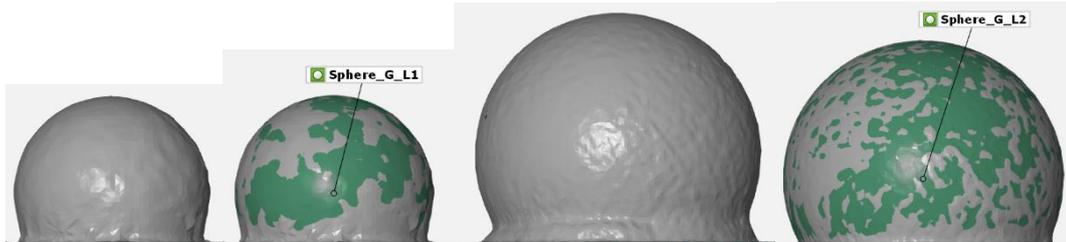
Figure 44: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (res = 1 mm)

7.4. REV scan

7.4.1. Calibration of the device

Prior to each digitisation, the scanner must be calibrated. Changes in the environment, such as pressure or temperature fluctuations, may affect the scanner calibration. You will get back to the original measuring characteristics by optimizing the calibration. The scanner must be connected to the machine through a FireWire (IEEE 1394) port, and the scanner power adapter must be connected to the scanner. VX elements includes a scanner calibration optimization program, which can be accessed via Configure | Scanner | Calibration or by selecting Scanner calibration from the main toolbar. This is something CREA-form recommends you do every time you use the scanner. To maintain the scanner's highest accuracy, an annual factory calibration is also recommended.

Figure 45: REV-scan Calibration with Calibration plate in VX scan software

Then, on the screen, run the VX scan program, or the newer VX elements, and select the "Sensor Calibration" command from the "Configure" menu. For the calibration, a special calibration board must be used, which is included with the scanner. Unless, the software captures 10 images of the board from different distances, calibration in the VXscan program is done by gradually changing the scanner distance from the calibration board with a pressed "scan" button ("trigger" on the scanner handle). The scanner can then be placed on a stand20 and the calibration completed according to the instructions in the software window. VX elements device calibration is more complicated and similar to Atos scanner calibration. Follow the graphical instructions in the application window. The calibration should be approved with the OK button once it's done. The REV-scan is now able to scan if you approve the terms.

7.4.2. Scanning with REV-scan

REV-scan follows the same principle as METRA-scan, projection light strips in the form of single laser cross, whereas METRA-scan with three laser crosses. This device is relatively low-cost scanner and also the accuracy is comparatively less.

Figure 46: Scanning with REV-scan

Scanning Procedure

1. Placement of reference points, special reflex points are used as specified by the manufacturer and there are some rules followed while placing reference points (they are not placed close to edges, all points are not in the same line, they are distibuted throuhout the whole body, they are placed on flat surface).

2. Calibration standard is mounted on the reference plate. Temperature maintained is around 21.7 degree celsius.

3. As this device is hand-held, with measuring volume between 100 – 1000 mm^3, this scanner can digitise the part in one go around the object.

4. Setting of optimal shutter time also called as Laser intensity is 1.5 milliseconds for first set and 2 milliseconds for second set. This parameter mainly depends upon the colour of the measuring object, for white background, laser intensity can be set as according to the resolution and will be displayed in the screen. If red spots appear on the part while setting laser intensity, the result will not be good and it is over exposed. Therefore, this parameter is carefully set before scanning.
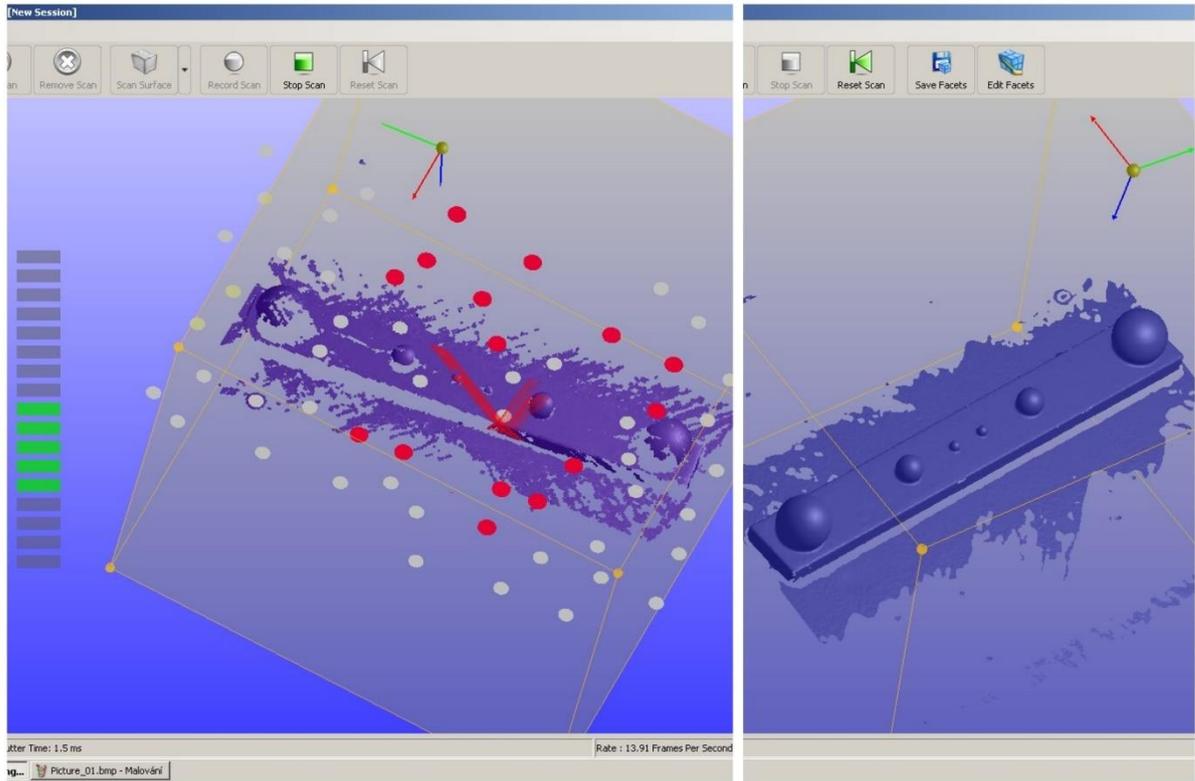
Figure 47: Left – mesh file during scanning, Right – mesh file after scanning

5. After the part is scanned, the resulting part obtained will contain noise around the object which is removed in the software VX Scan.

6. For conformity, the Etalon is scanned 2 times with resolution 1.5 mm which is minimum value for resolution for scanner and 2 times with resolution 0.76 mm which is maximum resolution for the scanner.
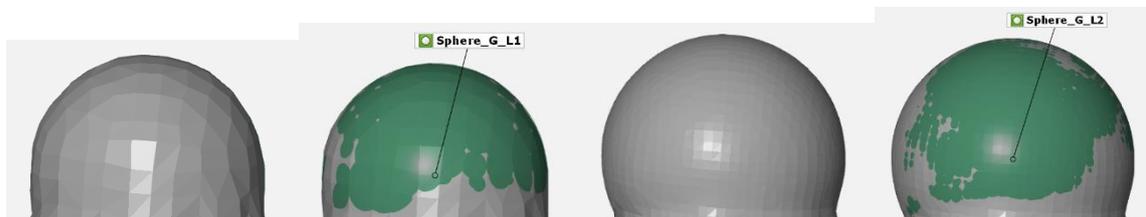
Figure 48: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (res = 1.5 mm)
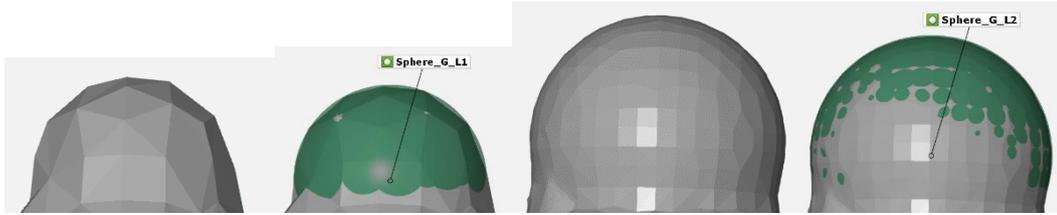
Figure 49: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (res = 0.76 mm)

7.5.   Ein-scan Pro 2X Plus

7.5.1.   Calibration of Ein-scan Pro 2X Plus[33]

Like other scanner calibration, Ein-scan Pro 2X Plus is also calibrated with the instructions provided by the manufacturer SHINING 3D. The software EX Scan Pro is suitable for controlling the scanner device and for calibrating the device. There are totally 2 steps in calibration, one is for camera calibration and another is for high detail scan calibrate.
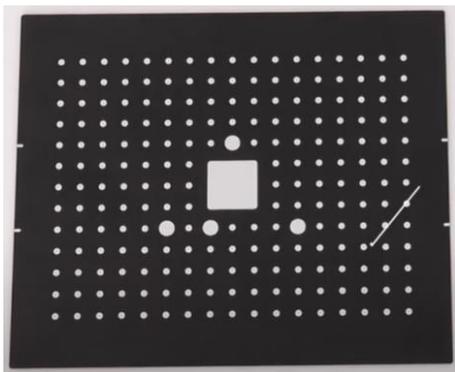
Figure 50: Calibration Board   *Figure 51: Calibration in 1ˢᵗ position*
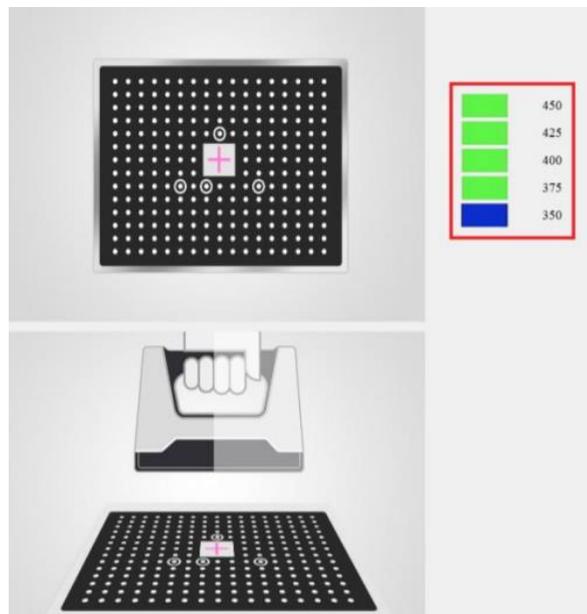
Calibration board was scanned in 5 different positions by holding the scanner vertically and by covering the screen range. The software indicates the user to calibrate before starting the

digitisation. From the software, it can be seen that, there are 5 different positions distance ranging between 350 mm to 450 mm.

In each position, the scanner is moved from top to bottom or bottom to top until the distances specified in the software bar appears green. This concludes that the photos are all captured for different distances specified. Blue light indicates the current position of the scanner. And when capturing the images, the cross from the scanner is placed in the centre of the white square area.
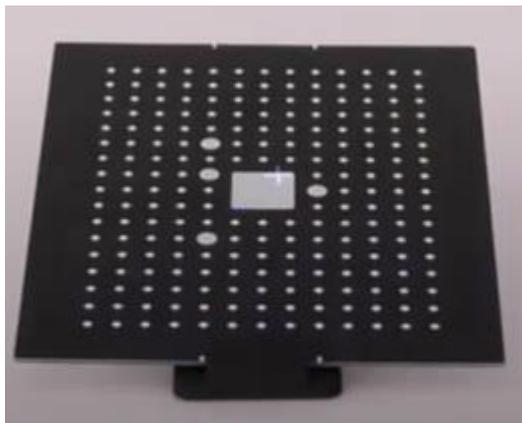
Figure 52: Calibration board with support   Figure 53: Calibration in 2nd position
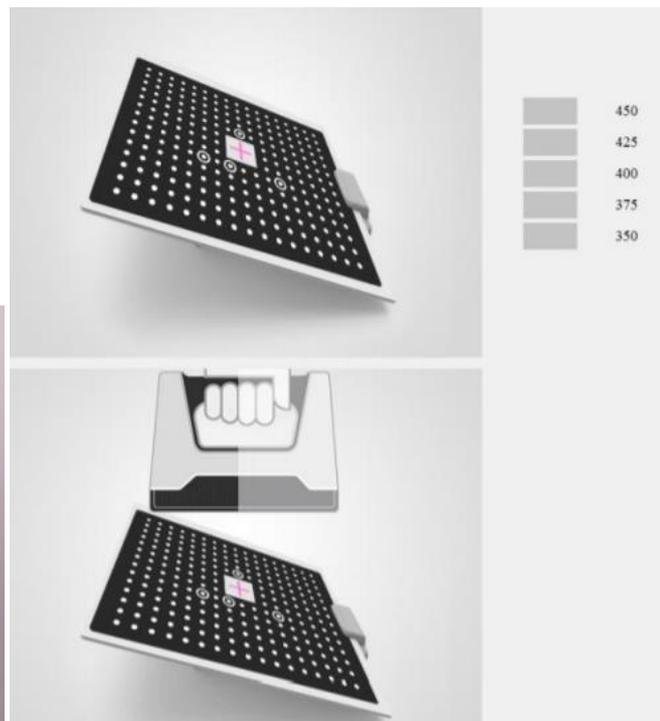
In the next position, calibration board is tilted and placed in the support provided by the manufacturer and same procedure is followed as in first position. When the calibration is finished, the software indicates the calibration is success. Camera calibration is completed, next the system enters to the HD scan calibration.

Calibration procedure: **Camera calibration** (Calibration board and support)

1. Calibration board is placed flat on the surface as shown in the software.

2. Projecting cross is kept within the white square of the calibration board.

3. With scan button and scanner held 90 degree to the calibration board, data is collected for the first position by moving the scanner from top to bottom or bottom to top until all distances turns green.

4. After the first position data is collected, the software automatically changes to second position.

5. **In the second position, the calibration board is placed in the support and the steps 2 and 3 are repeated.**

HD calibration
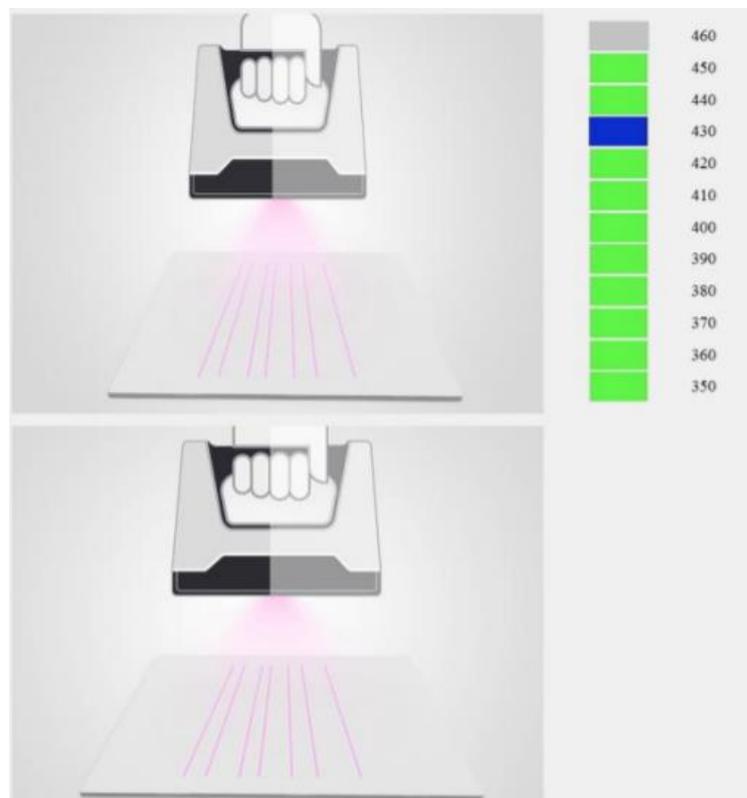
Figure 54: HD calibration

6. **In the next step, the backside of calibration board which appears white is scanned for HD calibration.**

7. For HD calibration, the above steps as in 1st and 2nd position are repeated.

7.5.2. Scanning the Calibration Standard (Etalon) using Ein-scan

Ein-Scan follows the principle of projection of LED light source and it is hand-held device used for scanning small to medium sized components. Ein-Scan Pro 2X can be used in many options depending upon how the user desires to scan the object, it is a portable device which is available in many scanning modes such as manual scanning with HD option, fast manual scanning process and fixed scanning with or without turn table.

Scanning Procedure

1. First step in the software is to set the operating mode like alignment, texture and resolution. For fixed scan with turn-table, alignment mode is set to "turn-table coded target" and texture mode to "non-texture".

   For hand-held HD1 and HD2, scan mode is set to "hand-held" scanning, alignment mode is set to "markers alignment", texture mode to "non-texture" and resolution to 0.2 mm.

   For hand-held rapid, scan mode is set to "hand-held" rapid scanning, alignment mode is set to "hybrid alignment", texture mode to "non-texture" and resolution to 0.25 mm.

2. Alignment with markers will operate in a way that scanner in first frame will identify the marker. If no marker is there, scanner will operate in feature mode.

   Hybrid alignment for objects only lacking features in certain areas where markers are needed. Resolution less than 1 mm is taken as high detail mode.

3. Scanner is placed straight to the object during scanning and start button is pressed to preview the scanning, in the preview if it is in green range, then the scanner is at correct distance from the object.

4. Next step is start button is double-clicked to check the intensity like in laser scanner, if it is in slight red area then it is good.
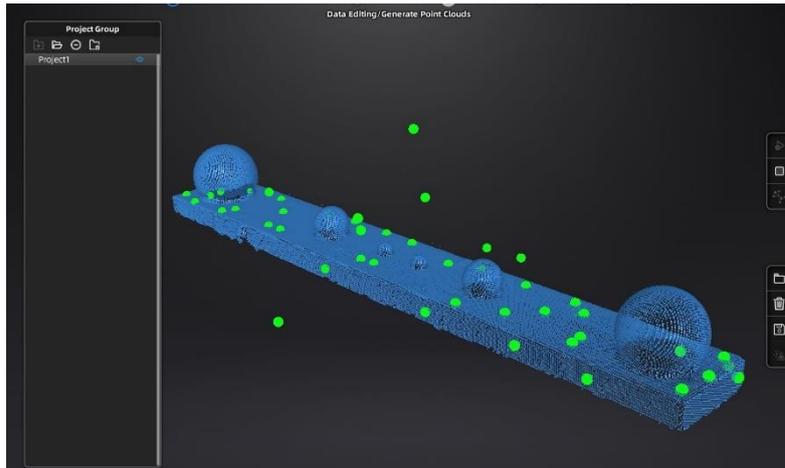
Figure 55: Scanning in progress (Generation of pint clouds)

5. With optimum brightness adjustment during scanning the object will give the correct feature of the object and finally the scanning is complete.

6. In post-processing, the redundant data is checked and if there is any, it is removed instantly. And point cloud is generated in the software option by selecting it. The result is generated by optimising the alignment which software does this automatically.
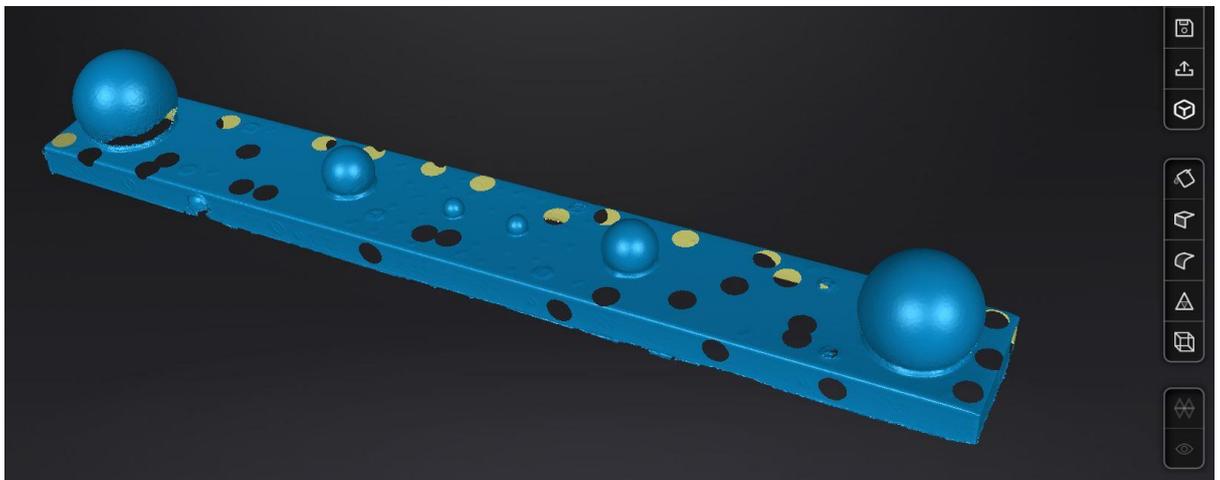
Figure 56: Scanned mesh model (Ein-scan Pro 2X plus)

7. Next for HD scan mode, the scanning is done with reference points and the remaining procedure is same as rapid mode scanning.

8. During scanning, if the scanner misses the alignment, the software indicates as "track lost" and then the scanner is moved to the scanned area.

9. For fix scan with turn-table, alignment is dine based on white coded markers on turn-table and same procedure for above scans are repeated. Therefore, the scanning is complete and mesh model is generated.
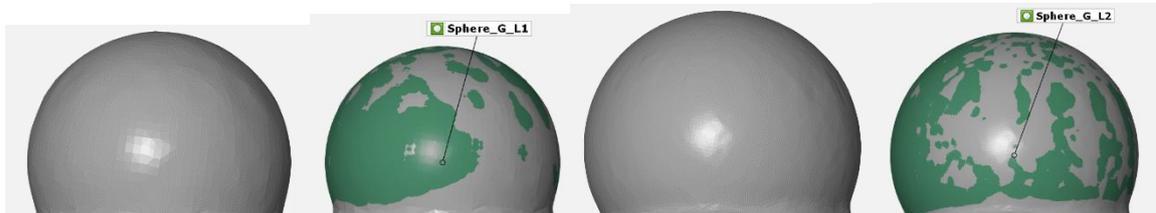
Figure 57: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (fixed)
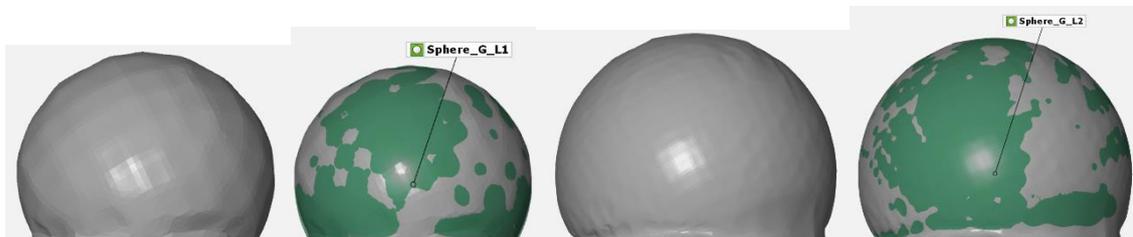
Figure 58: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (HD)
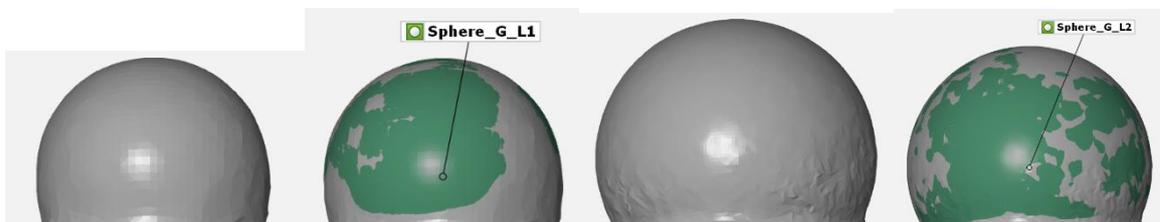
Figure 59: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2 (Rapid)

7.6. Leica AT901-MR Scanner

LEICA AT901-MR(Mid-range) is a portable scanning device developed by Leica Geosystems. This system uses laser beam as a source of projection and can be used to measure accurately and inspect objects with measuring volume up to 18 metres.

7.6.1. Calibration and Scanning parameter

Výsledky měření na etalonu délky [mm]

Laser Tracker

Poloha	Nominální	Měřené	Odchylka	± Tolerance	Výsledek
2000	800.017	800.023	0.006	0.041	Vyhovuje
4500	800.017	800.032	0.015	0.061	Vyhovuje
7000	800.017	800.012	-0.005	0.082	Vyhovuje

T-Probe

Poloha	Nominální	Měřené	Měřené	± Tolerance	Výsledek
2000	800.019	800.029	0.010	0.060	Vyhovuje
4500	800.019	800.029	0.010	0.060	Vyhovuje
7000	800.019	800.032	0.013	0.060	Vyhovuje

T-Scan

Poloha	Nominální	Měřené	Odchylka	± Tolerance	Výsledek
2000	1154.995	1155.029	0.034	0.060	Vyhovuje
4500	1154.995	1155.037	0.042	0.060	Vyhovuje
7000	1154.995	1155.041	0.045	0.060	Vyhovuje

Závěr: Kalibrace byla vykonána na základě interních předpisů NMS_IP_201001_001. Byly použity etalony s platným certifikátem. Naměřené hodnoty vyhovují technické specifikaci přístroje.

Figure 60: Calibration Parameters (Leica)

Figure 61: Measurement in company "Modelárna Liaz"

Scanning parameters,

Measuring volume (working space) **= 18 m**

Distance between measured points **(Resolution) = 0.1 mm**

Exposure time **= 1000 milliseconds**
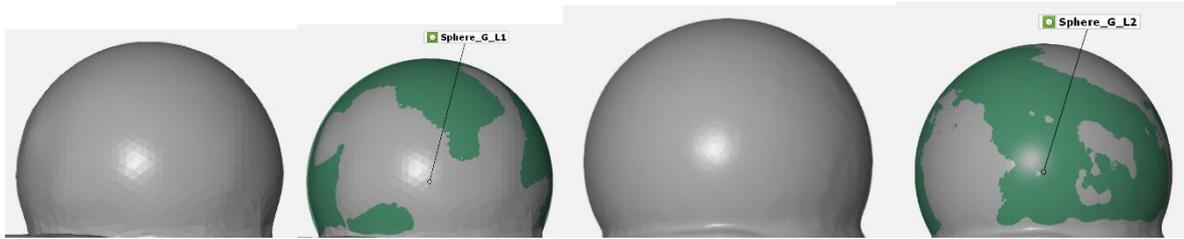
Figure 62: details of mesh from left, sphere L1 – Fitting element L1 - sphere L2 – Fitting element L2

8. Inspection in GOM

GOM is a 3D Inspection software for general dimensional analysis and geometrical analysis of the 3D point clouds. GOM Inspect is used for evaluation of 3D data from light and laser projection scanners, co-ordinate measuring machine (CMM), and other measurement devices. Product development, quality control, and production all use the GOM program.

8.1. Inspection steps for Calibration Standard (Etalon) in GOM

First step is to mesh two models, Nominal element which is CAD model created in PTC Creo 2.0 software, exported as (.STP) file with dimensions from CMM values and the actual element which is created mesh output from the scanner exported as (.STL) file.
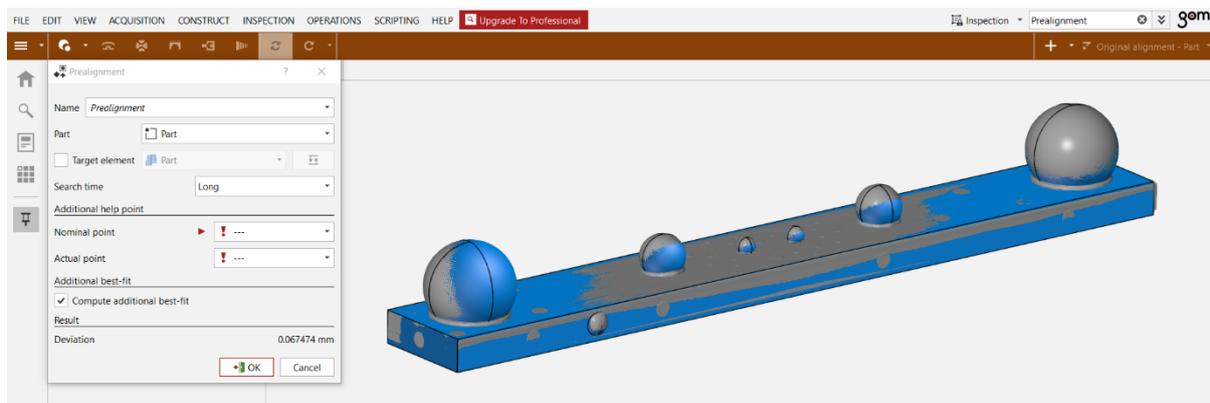
Figure 63: Pre-alignment of CAD model and Mesh model

Second step is alignment of nominal element and actual element according to best fit as provided by the software. Pre-alignment is done as the software automatically aligns the parts in required orientation. As the calibration standard used in the inspection is symmetric, in-

between the left spheres L3 and L2, a button shaped mark is created on the sides for differentiation.

8.2. Probing error size

Step 1: Construction of spheres:

It is important to "fit" the evaluation bodies (balls) when evaluating all parameters. First, we choose the region where we want the structural feature to intersect.

Construct – Sphere – Fitting sphere
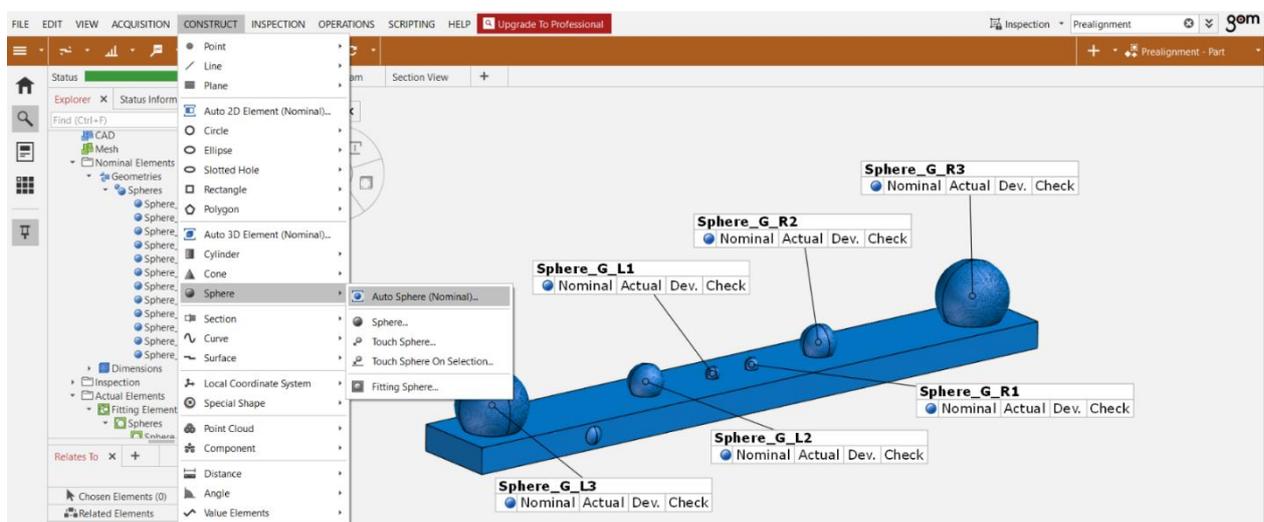
Figure 64: Construction of spheres

Step 2: Measuring Principle

The software provides the user with different interpolation methods, Gaussian, Chebyshev, maximum and minimum inscribed element as shown in the image below.

The Gaussian method follows the principle of 3 sigma points (as suggested by GOM VDI/VDE 2634) where the software squares the deviation of selected points to best possible fitting element. (where 1 σ = 68.27% points; 2 σ = 95.45% points, 3 σ = 99.73% points)

Chebyshev method, the software calculates the maximum and minimum deviation of the sphere diameter taking into account of all points. And also mean value (middle) between the maximum and minimum deviation.

And the last method, for minimum and maximum inscribed elements, the software computes maximum and minimum deviation but the resulting element is not created from the centre of the nominal model. Therefore, the last method is not suitable for this inspection.

Select Nominal sphere – Inspection – Measuring principle – Fitting element
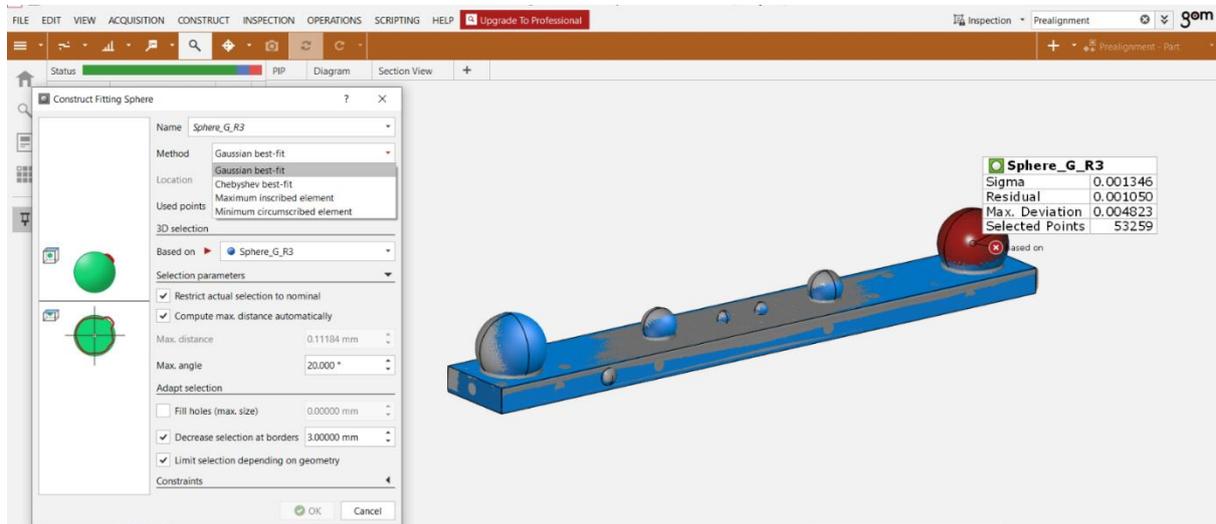
Figure 65: Measuring principle

Step 3: Dimension check

Select Nominal sphere – Inspection – Check – Diameter
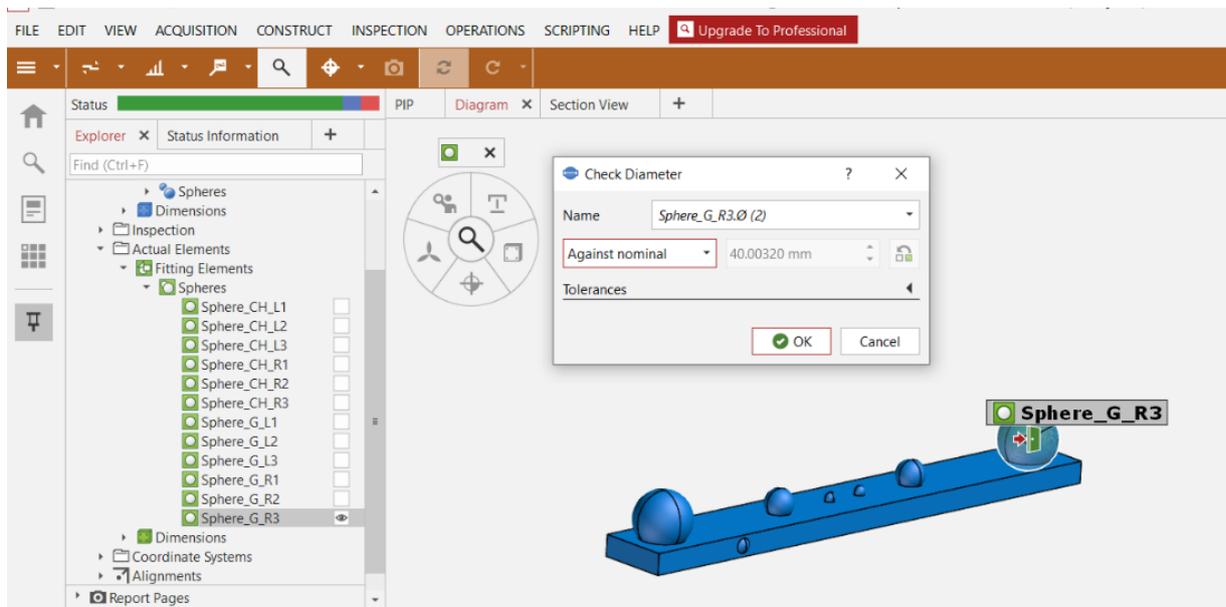
Figure 66: Dimension check

Thus the software gives the result of deviation between the nominal value and actual value.
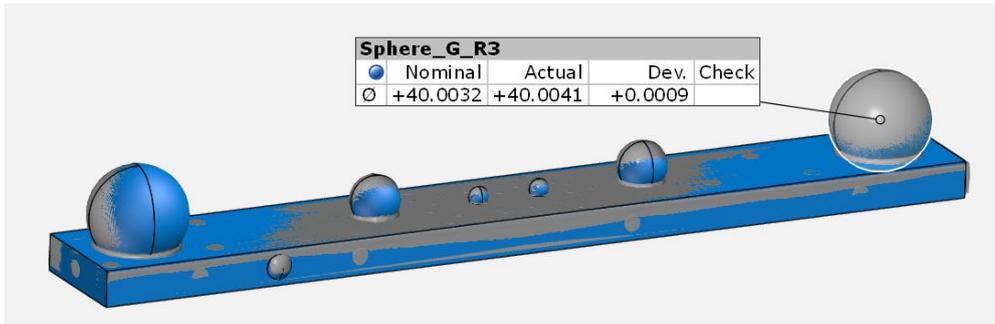
Figure 67: Deviation between nominal and actual value

8.3. Sphere Spacing Error

The fit sphere balls are used to determine the pitch once more. Their distance is computed in the same way that the elements of the spheres were created. When deciding between which bodies we want to decide the distance between, it's sufficient for example, the spacing of the left sphere L3 and right sphere R3.

Step 1: Construction of sphere distances

Construct –Distance– 2-point distance
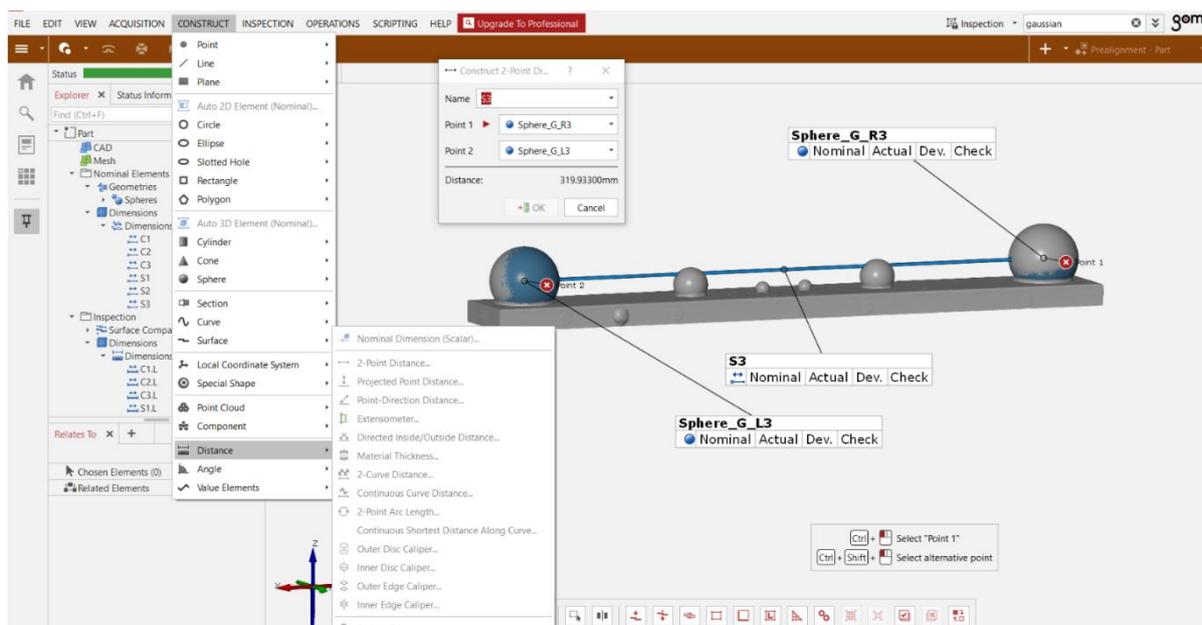
Figure 68: Construction of sphere distances

Step 2: Measuring principle

Select distance – Inspection – Measuring principle – Reference construction

The next step is assigning the measuring principle for the selected parameter which is 2-point distance and reference construction is given from the option Inspection.
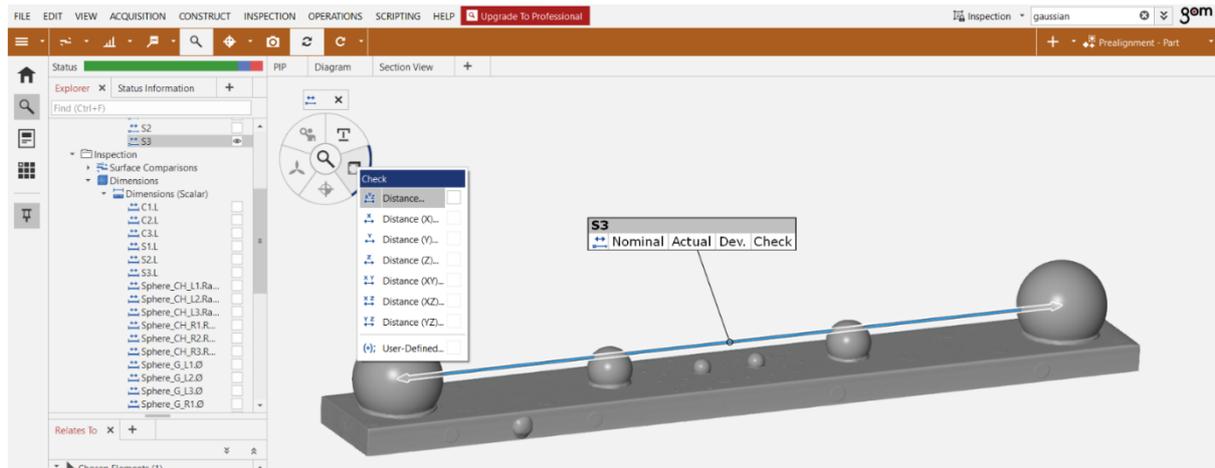
Figure 69: Dimension check

Step 3: Dimension check

Select distance – Inspection – Check – Distance
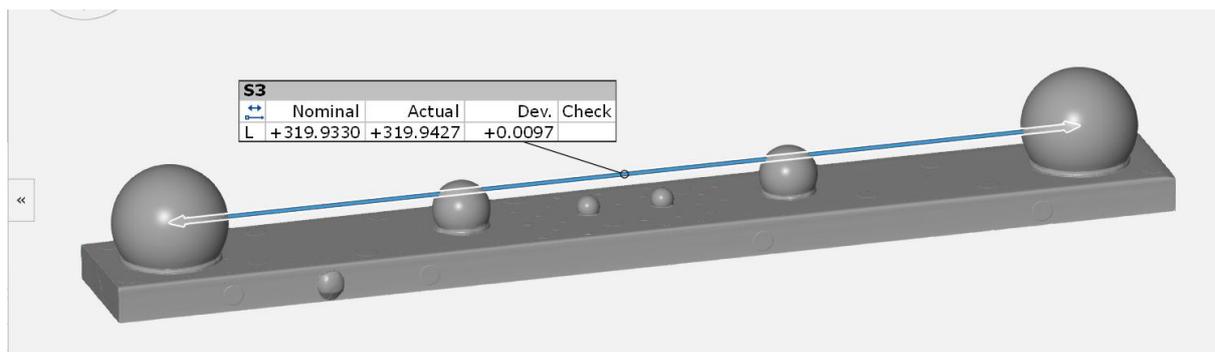
Figure 70: Deviation between nominal and actual values

Therefore, the sphere centre distance is computed using the fitting sphere balls and from the measuring principle, reference construction and in the dimension check, distance option is

used to determine the length and in the dialog box, the nominal value which is CMM value is set as standard and deviation for sphere distance is evaluated.

8.4.   Length Measurement Error

Step 1: Construction of sphere external distances

Construct – Distance – Outer disc caliper

For length measurement error, the first step is to construct distance between spheres using outer disc caliper. Nominal spheres are selected when constructing the spheres distances. The disc size depends upon the size of the sphere as it can be seen from the image below Nominal spheres L3 AND R3 is chosen and clearance is given for the disc from the sphere which is 10% and radius is 5 mm.
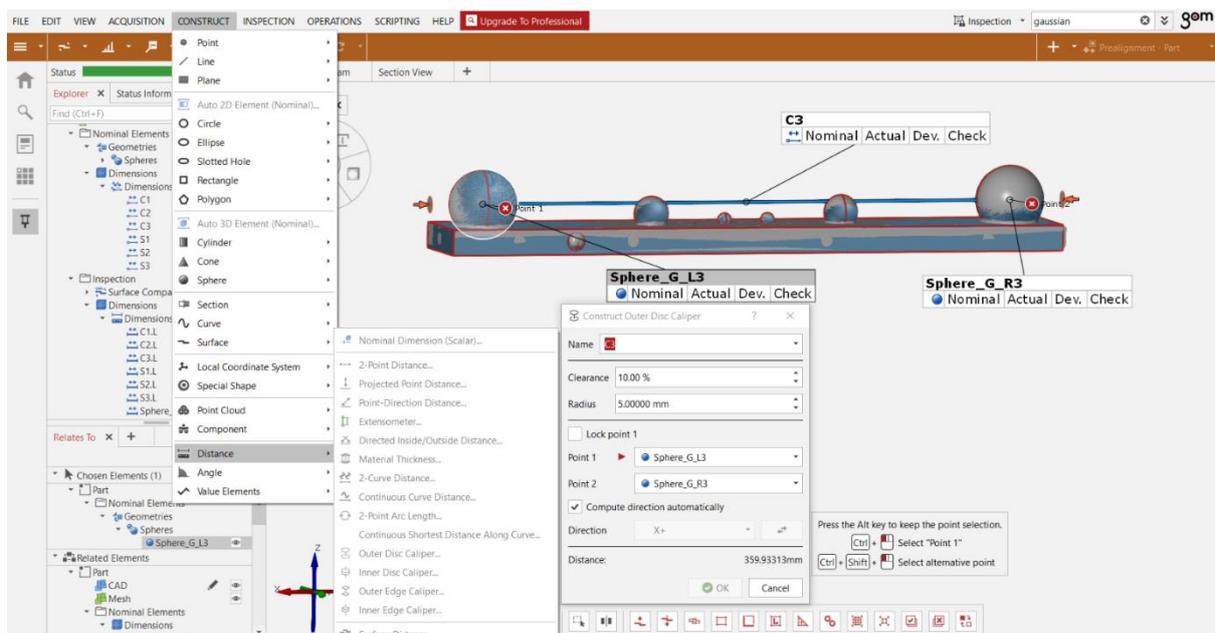
Figure 71: Construction of sphere external distance

Step 2: Measuring principle

Select distance – Inspection – Measuring principle – Reference construction

The next step is assigning the measuring principle for the selected parameter which is outer disc caliper and reference construction is given from the option Inspection.
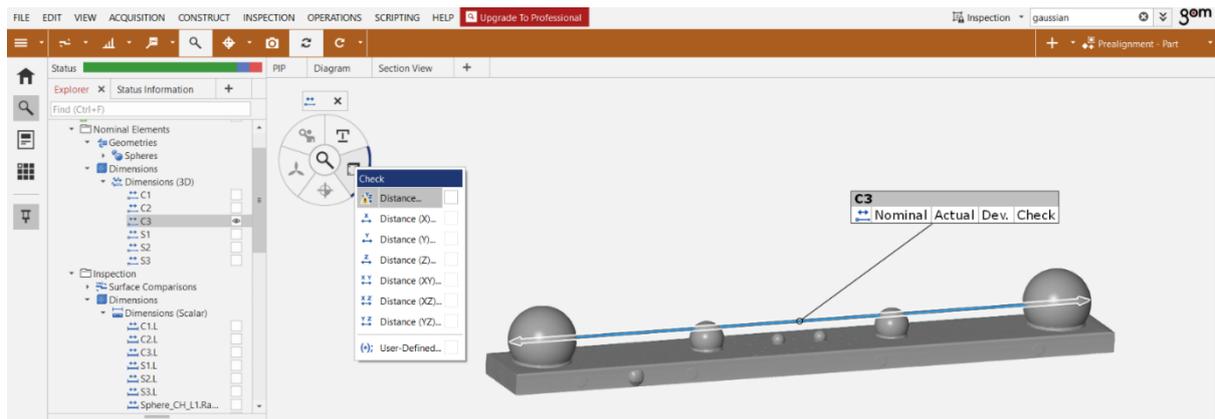
Figure 72: Measuring Principle and dimension check

Step 3: Dimension check

Select distance – Inspection – Check – Distance

This procedure is same as in sphere spacing error, in the option Inspection, check parameter is chosen and the distance icon is selected to compute the result. During this distance selection, the software in default assigns the nominal value which is CAD model dimension. It is important to check this value and incase it is not same as CMM dimension, there is option where software allows the user to enter the value manually i.e., against fixed values. In my case, this option is not used as nominal dimension is same as CMM value.
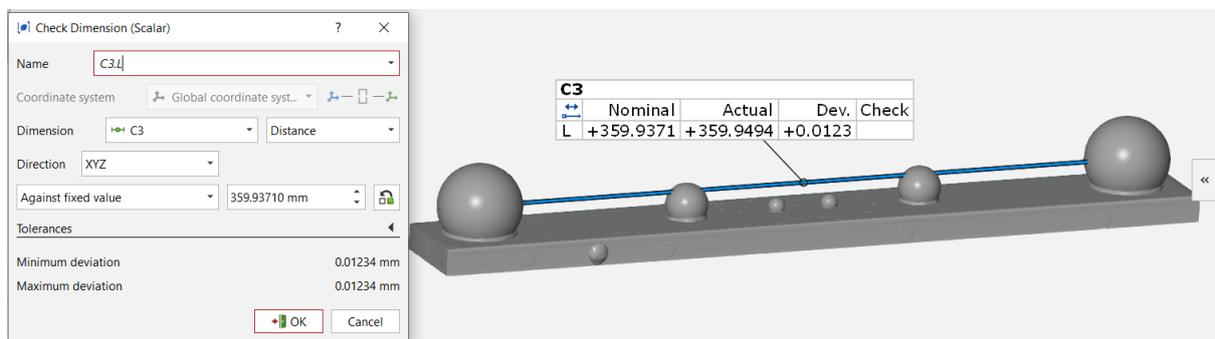
Figure 73: Deviation between the nominal and actual value

8.5.　　Probing Error Form

Step 1: Construction of spheres:

It is important to "fit" the evaluation bodies (balls) when evaluating all parameters. First, we choose the region where we want the structural feature to intersect.

Construct – Sphere – Fitting sphere

The fitting sphere is again created because the measuring principle for sphere probing form changes which is based on the principle of Chebyshev fit. The reason is that the maximum and minimum deviation is computed from this method.
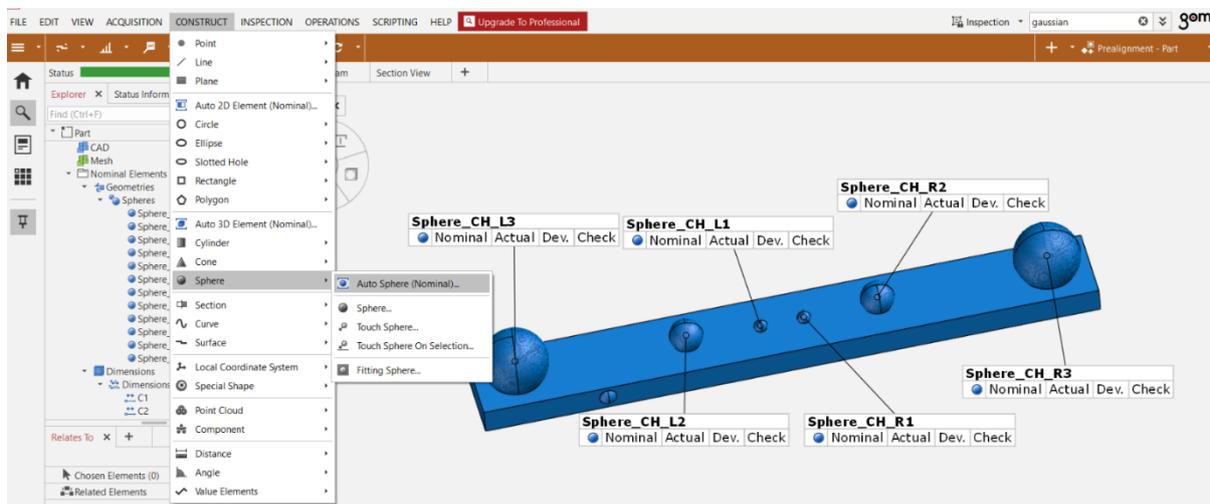
Figure 74: Sphere construction for probing error form

Step 2: Measuring principle

Select sphere – Inspection – Measuring principle – Fitting element

The next step is assigning the measuring principle for the selected parameter which is for sphere and fitting element is given from the option Inspection. As it can be seen from the below image, the boundary adjustment is done inorder to compute the best possible output because the boundary of sphere and rectangular block is glued, and in the area of assembly, there is some extra prjection because of glue which is neglected when computing this parameter.
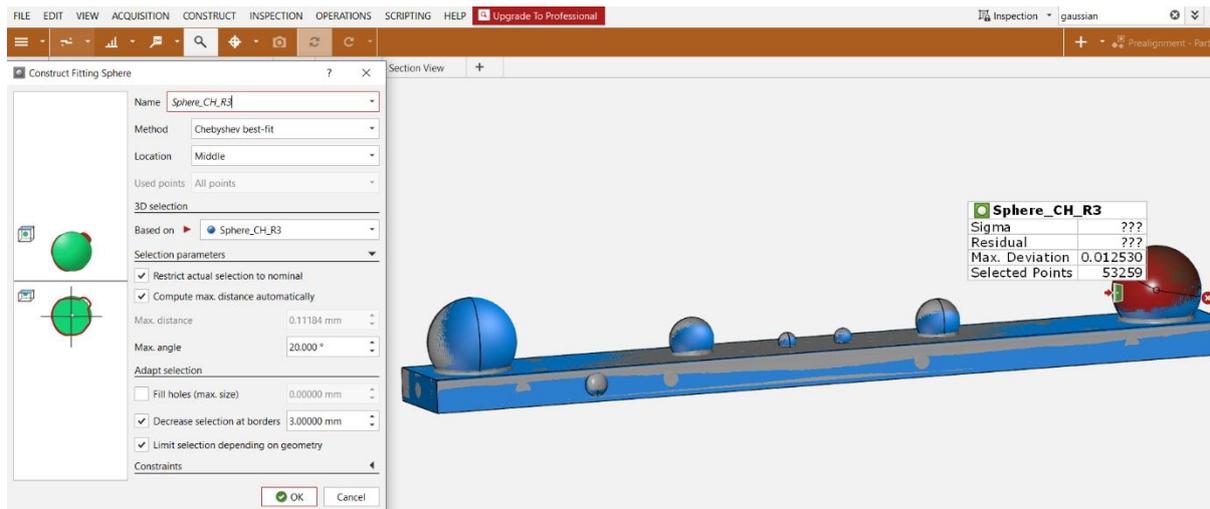
Figure 75: Measuring principle for probing error form

Step 3: Sphere form check to determine the range

Inspection – Check dimensions – Quality – Adjustment residual range
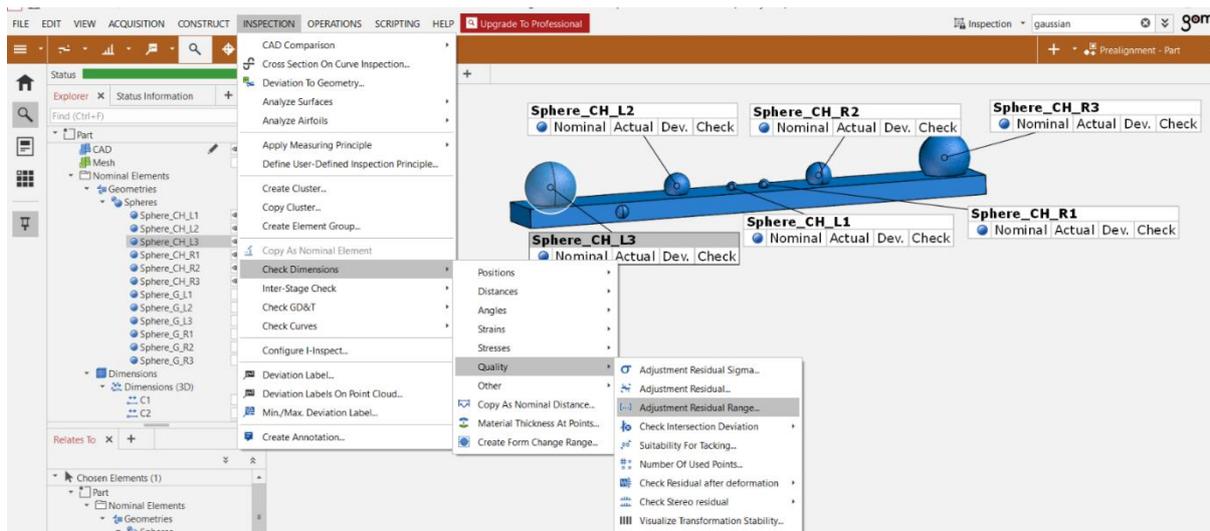
Figure 76: Inspection for Sphere deviation

Next step is to determine the range. For this, as can be seen from the image above, the adjustment resisual range option is given from the Innspection menu and range is determined in the below iage which difference between maximum and minimum value of the deviation. For this parametr determination, CMM values is not used and nominal value is considered as zero because scanner calculates the sphere form with different number of cloud points and the software computes the sphere form with different number of cloud points. Because of this difference, CMM value is not used.
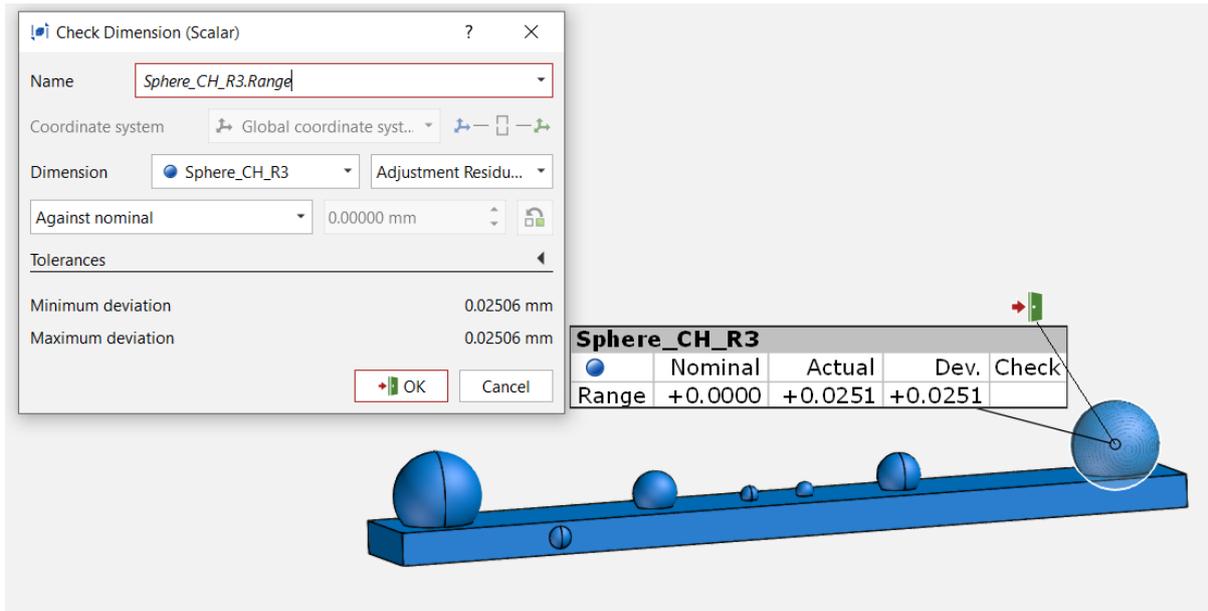
Figure 77: Sphere form error – Range determination

All the parameters inspected in GOM Inspect is generated in the form of report for all the scanners as shown in appendix and the sample report for ATOS is attached in the Appendix.

9. Analysis of Results of Acceptance test from SW GOM Inspect

The deviation values between the actual value and nominal value are depicted in the graph with "Elements" such as spacing, caliper, diameter and sphericity in X-axis and "amount of deviation" in Y-axis.

In total, there are multiple measurement series for each scanner where the calibration standard is scanned with different scanning parameters, for example "resolution".

It is important to scan the part multiple number of times because there can be errors during the scanning process and also the accuracy of the scanners cannot be concluded from one measurement. Therefore, for conformity the part is scanned many times with different scanning parameters.

9.1. ATOS III Triple Scan – Deviation Graph

Scanning **parameters**,

Measuring volume **MV320 = (320x240x240) mm**

Distance between measured points **(Resolution) = 0.10 mm**

Angle between cameras = **27°**

Angle for scanning = **45° horizontal plane**

Reference point diameter = $\phi 1.5\ \text{mm}$

Exposure time = **40 milliseconds**

Element	Dev_Scan01	Dev_Scan02	Average deviation = $\frac{\|Dev_{Scan01}\|+\|Dev_{Scan02}\|}{2}$
Spacing			
S3	0.0097	0.0043	**0.007**
S2	0.0029	0.0016	**0.0023**
S1	0.001	0.0006	**0.0008**
Caliper			
C3	0.0123	0.0021	**0.0072**
C2	-0.0007	-0.0026	**0.0017**
C1	-0.0035	-0.0058	**0.0047**
Diameter			
R3	0.0009	-0.0007	**0.0008**
R2	-0.002	-0.0039	**0.003**
R1	-0.0047	-0.0061	**0.0054**
L3	0.001	0.0006	**0.0008**
L2	-0.0031	-0.0038	**0.0035**
L1	-0.0054	-0.0067	**0.0061**
Sphericity			
R3	0.0251	0.03	**0.0276**
R2	0.0148	0.0194	**0.0171**
R1	0.0196	0.0233	**0.0215**
L3	0.023	0.0338	**0.0284**
L2	0.0183	0.0171	**0.0177**
L1	0.0166	0.0163	**0.0165**

Table 4: ATOS III Scan Deviation Values – Scan 01 and Scan 02 - (Resolution = 0.1 mm)

The table contains deviation values for two scanning results which was generated in SW GOM Inspect. The average was taken for two deviation values from scan 1 and scan 2 and the graph is generated for average deviation values.

The graph depicts the deviation of actual value from nominal value for all the parameters as shown below. As this accuracy from the manufacturer is obtained in special metrological laboratory, it is uncertain that the same accuracy can be achieved in normal working

environment. For this reason, the practical test has been carried out and results are evaluated in SW GOM Inspect. This table and graph information are same for all the scanners.

The manufacturer's (GOM) accuracy for ATOS III Triple scan is 0.01 mm.
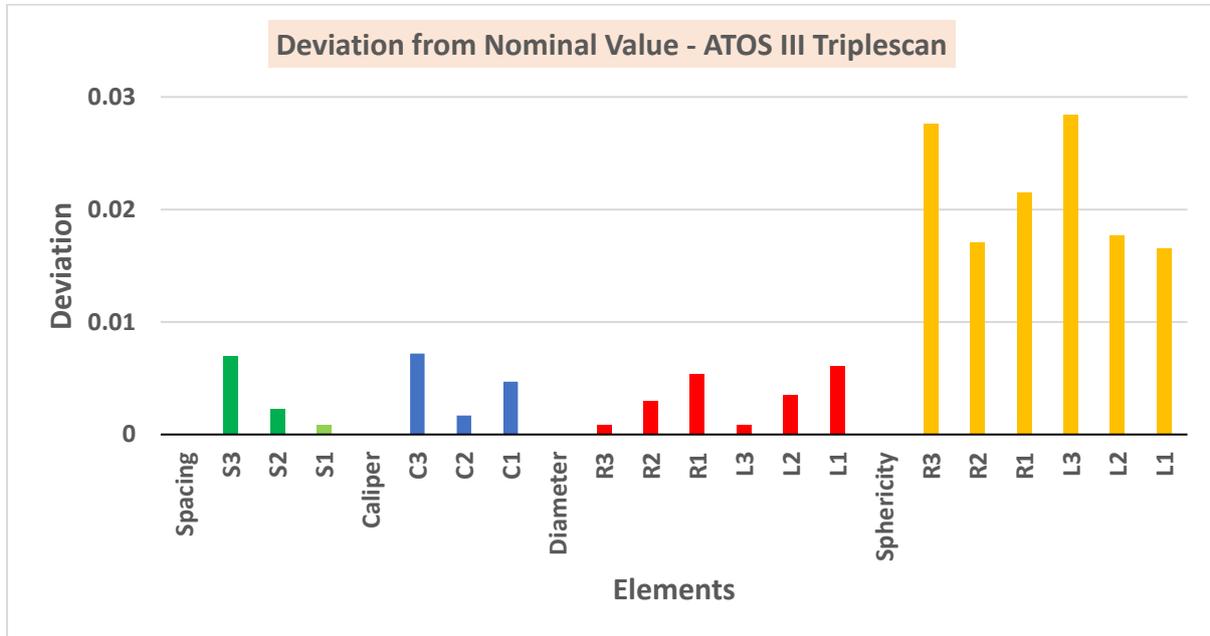
Graph 1: ATOS III - Deviation Graph for Average value (Scan01 and Scan02)

X-axis – Acceptance test parameters – "Elements"

Y-axis – "Deviation"

From the graph, it can be seen that the parameters Sphere spacing, Sphere external distance (Caliper) and Sphere diameter indicated with the colour green, blue and red respectively, show only a slight deviation from the nominal value and they are within the manufacturer's accuracy range of 0.01 mm.

(Sphere spacing, Caliper distance, Sphere diameter) < 0.01 mm (manufacturer's accuracy)

(Sphere form error) > 0.01 mm (manufacturer' accuracy)

But the parameter Sphere form error which is indicated with the colour orange deviates from the nominal value and it is not within the limit of manufacturer's accuracy of 0.01 mm. Also these values are not affected by the diameter, as in some cases for larger diameter, error will be more and vice-versa. The deviation value goes up to maximum of 0.03 mm.

9.2.   Metra Scan – Deviation Graph

Scanning parameters,

Measuring volume (working space) **= 16.6 m³**

Distance between measured points **(Resolution) = 1 mm**

Shutter time **(Laser Intensity) = 0.15 milliseconds**

Element	Dev_Scan01	Dev_Scan02	Average deviation = $\frac{|Dev_{Scan01}| + |Dev_{Scan02}|}{2}$
Spacing			
S3	0.032	0.0251	0.0286
S2	0.0136	0.0172	0.0154
S1	0.0148	0.0027	0.0086
Caliper			
C3	0.0483	0.01	0.0292
C2	0.0043	0.0084	0.0064
C1	-0.0704	-0.1395	0.105
Diameter			
R3	0.022	0.009	0.0155
R2	-0.0056	-0.01	0.0078
R1	-0.1063	-0.0928	0.0996
L3	0.0095	-0.0055	0.0075
L2	-0.0116	-0.0177	0.0147
L1	-0.0968	-0.0898	0.0933
Sphericity			
R3	0.1643	0.1272	0.1456
R2	0.0881	0.0758	0.0816
R1	0.0708	0.0734	0.0721
L3	0.1119	0.1234	0.1177
L2	0.0662	0.0863	0.0763
L1	0.0758	0.087	0.0814

Table 5: Metra-Scan Deviation Values – Scan 01 and Scan 02 - (Resolution = 1 mm)

The manufacturer's (Crea-Form) accuracy for Metra-scan is 0.04 mm.

Deviation from Nominal Value - Metra Scan_Res = 1mm
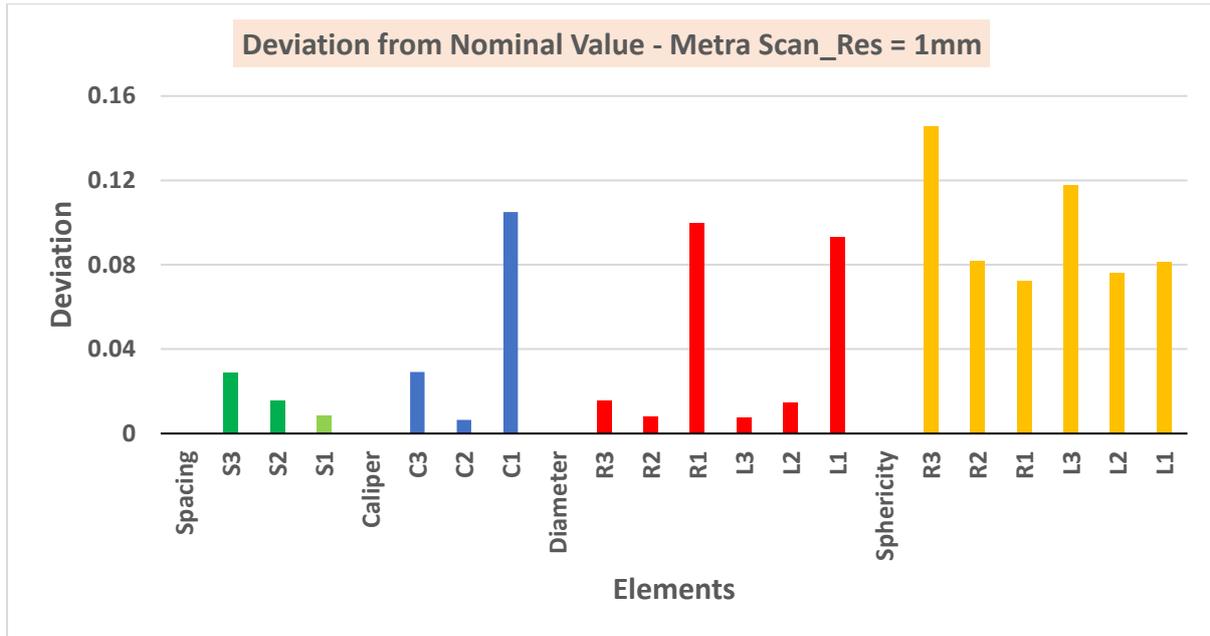
Graph 2: Metra-Scan Deviation Graph for Average value - (Resolution = 1 mm)

From the above graphs, Sphere spacing shows less deviation from the nominal value for all sphere diameters and it is within the manufacturer's specified accuracy value of 0.04 mm.

The parameter Caliper values C2 and C3 shows less deviation but Caliper C1 goes up to 0.1 mm which is above the desired accuracy. Like Caliper values, Sphere diameter also shows good results for larger spheres i.e., for R2, R3, L2 and L3 but for smaller sphere L1 and R1, the deviation is up to 0.1 mm which is not close to the manufacturer's accuracy.

But the parameter Sphere form error which is indicated with the colour orange deviates from the nominal value and it is not within the limit of manufacturer's accuracy of 0.04 mm.

(Sphere spacing, Caliper distance, Sphere diameter) < 0.04 mm (manufacturer's accuracy)

Except for parameter caliper and diameter for smaller sphers C1, R1 and L1.

(Sphere form error) > 0.04 mm (manufacturer' accuracy)

This parameter, sphere form error is similar to the ATOS III triple scan values and in general it is evident that this parameter deviates more for both scanners.

**Scanning parameters,** Measuring volume (working space) = **16.6 m³**

Distance between measured points **(Resolution) = 0.2 mm**

Shutter time **(Laser Intensity) = 0.15 milliseconds**

Element	Dev_Scan01	Dev_Scan02	Average deviation $= \frac{|Dev_{Scan01}| + |Dev_{Scan02}|}{2}$
Spacing			
S3	0.0276	0.0262	**0.0269**
S2	0.0082	-0.0005	**0.0044**
S1	0.0096	0.0046	**0.0071**
Caliper			
C3	0.1193	0.1274	**0.1233**
C2	0.0548	0.2413	**0.1481**
C1	0.0331	0.0678	**0.0505**
Diameter			
R3	0.0329	0.0272	**0.0301**
R2	0.0017	-0.0096	**0.0057**
R1	-0.0377	-0.0363	**0.037**
L3	0.0136	0.0141	**0.0139**
L2	0.0012	0.0042	**0.0027**
L1	-0.0318	-0.0435	**0.0377**
Sphericity			
R3	0.4502	0.2684	**0.3593**
R2	0.1816	0.2003	**0.191**
R1	0.1337	0.1741	**0.154**
L3	0.4129	0.3777	**0.3953**
L2	0.1594	0.3228	**0.2411**
L1	0.1523	0.2651	**0.2087**

Table 6: Metra-Scan Deviation Values – Scan 01 and Scan 02 - (Resolution = 0.2 mm)
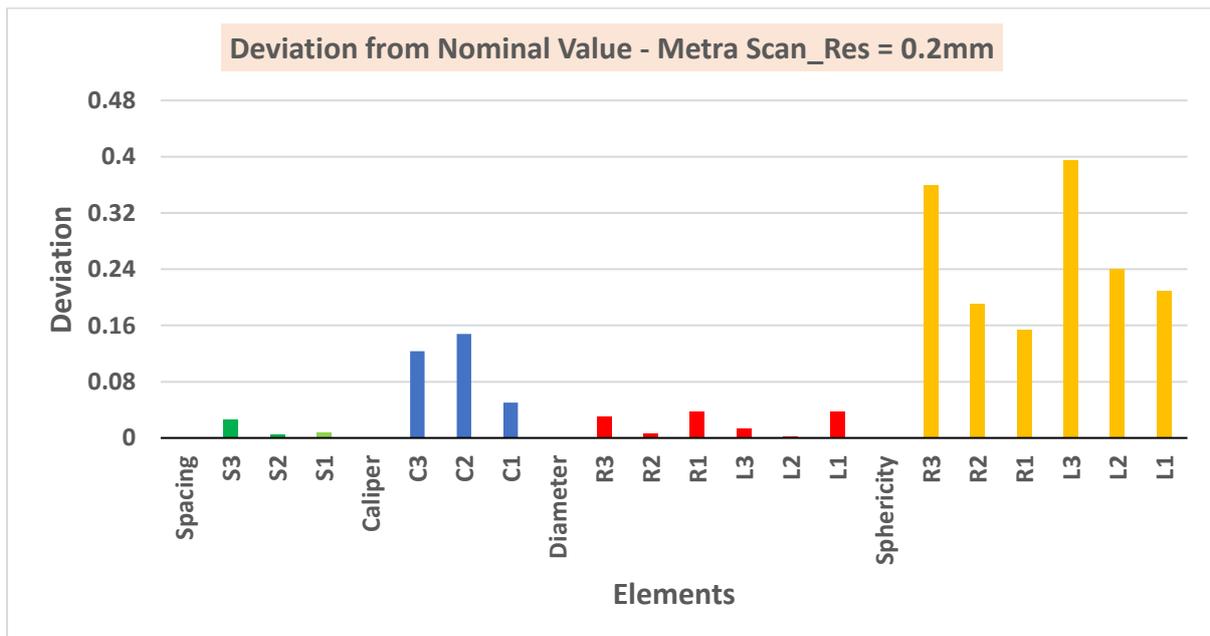
Graph 3: Metra-Scan Deviation Graph for Average value - (Res = 0.2 mm)

From the above graph, Sphere spacing and sphere diameters shows less deviation from the nominal value and it is almost equal to the nominal value for all sphere diameters and it is within the manufacturer's specified accuracy value of 0.04 mm.

(Sphere spacing, Sphere diameter) < 0.04 mm (manufacturer's accuracy)

(Sphere form error, Caliper values) > 0.04 mm (manufacturer' accuracy), Except for C1

The parameter Caliper values C2 and C3, and sphericity shows deviation of actual value from the nominal value and it is not within the manufacturer's accuracy. Only the caliper value C1 is within the limit.

9.3.   REV Scan – Deviation Graph

Scanning parameters, Measuring volume (working space) **= 100 - 1000 mm³**

Distance between measured points **(Resolution) = 1.5 mm**

Shutter time **(Laser Intensity) = 1.52 (medium) milliseconds**

Element	Dev_Scan01	Dev_Scan02	Average deviation $= \frac{|Dev_{Scan01}|+|Dev_{Scan02}|}{2}$
Spacing			
S3	0.3761	0.3105	**0.3433**
S2	0.0737	0.0747	**0.0742**
S1	0.0266	0.0689	**0.0476**
Caliper			
C3	0.2997	0.3199	**0.3098**
C2	-0.1016	-0.0574	**0.0795**
C1	-0.1193	-0.2437	**0.1815**
Diameter			
R3	-0.1861	-0.0461	**0.1161**
R2	-0.1071	-0.0551	**0.0811**
R1	-0.591	-0.7485	**0.6696**
L3	-0.2092	-0.0199	**0.1146**
L2	-0.1575	-0.0839	**0.1207**
L1	-0.4089	-0.5178	**0.4634**
Sphericity			
R3	0.659	0.2027	**0.4309**
R2	0.3951	0.2485	**0.3218**
R1	0.1275	0.104	**0.1156**
L3	0.7394	0.4246	**0.582**
L2	0.3018	0.3563	**0.329**
L1	0.116	0.0572	**0.0866**

Table 7: REV Scan Deviation Values – Scan 01 and Scan 02 - (Resolution = 1.5 mm)

The manufacturer's accuracy for REV-scan which is 0.1 mm from CREA-form.

Deviation from Nominal Value - REV Scan_Res = 1.5mm
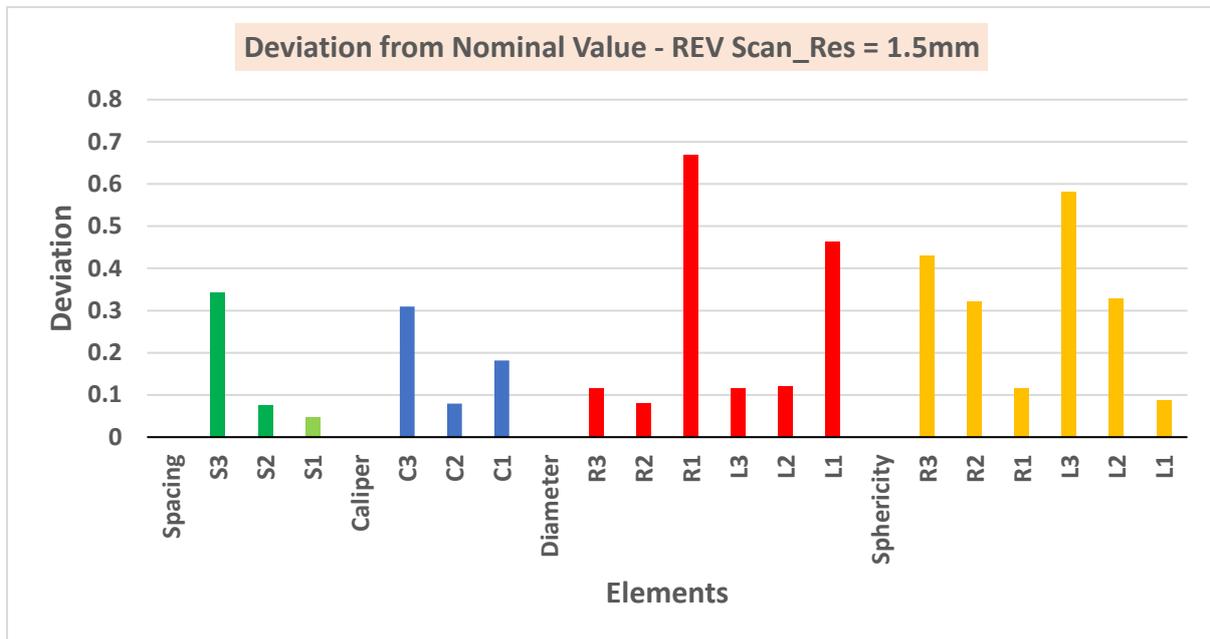
Graph 4 : REV-Scan Deviation Graph for Average value – (Resolution = 1.5 mm)

The above graph depicts that sphere spacing error for parameter S2 and S3 with resolution 1.5 mm is within the limit of manufacturer's accuracy of 0.1 mm but for S1, it deviates more, it goes up to 0.3 mm which is above the manufactuter's accuracy.

From the graph, only C2 for sphere calipers is within the limit and the values C1 and C3 is above the limit of 0.1 mm. For the parameter diameter, smaaler diameter sphere R1 and L1 are out of range from nominal value, rest of the values are well within the range of 0.1 mm.

(Sphere spacing, Sphere diameter) < 0.1 mm (manufacturer's accuracy)

Except for spacing for larger sphere S3 and diameter for smaller spheres L1 and R1

(Sphere form error, Caliper values) > 0.1 mm (manufacturer' accuracy)

Except for parameter caliper for spheres C3 and C1 and form error for spheres L1 and R1

The parameter sphere form error for smaller spheres L1 nad R1 are within the limit whereas other parameters deviates above 0.3 mm.

Scanning parameters,

Measuring volume (working space) **= 100 - 1000 mm³**

Distance between measured points **(Resolution) = 0.76 mm**

Shutter time **(Laser Intensity) = 1.52 (medium) milliseconds**

Element	Dev_Scan01	Dev_Scan02	Average deviation = $\frac{|Dev_{Scan01}|+|Dev_{Scan02}|}{2}$
Spacing			
S3	0.2462	0.2108	**0.2285**
S2	0.0474	0.1191	**0.0833**
S1	0.0023	0.028	**0.0152**
Caliper			
C3	0.1437	0.0742	**0.109**
C2	-0.135	-0.082	**0.1085**
C1	-0.3018	-0.2679	**0.2849**
Diameter			
R3	-0.2138	-0.1893	**0.2016**
R2	-0.2806	-0.1882	**0.2344**
R1	-0.3548	-0.3287	**0.3418**
L3	-0.1421	-0.1546	**0.1484**
L2	-0.2179	-0.2434	**0.2307**
L1	-0.3597	-0.3427	**0.3512**
Sphericity			
R3	0.2467	0.1915	**0.2191**
R2	0.1799	0.1908	**0.1854**
R1	0.0923	0.0974	**0.0949**
L3	0.4008	0.2348	**0.3178**
L2	0.1886	0.1589	**0.1738**
L1	0.1048	0.1234	**0.1141**

Table 8: REV Scan Deviation Values – Scan 01 and Scan 02 - (Resolution = 0.76 mm)
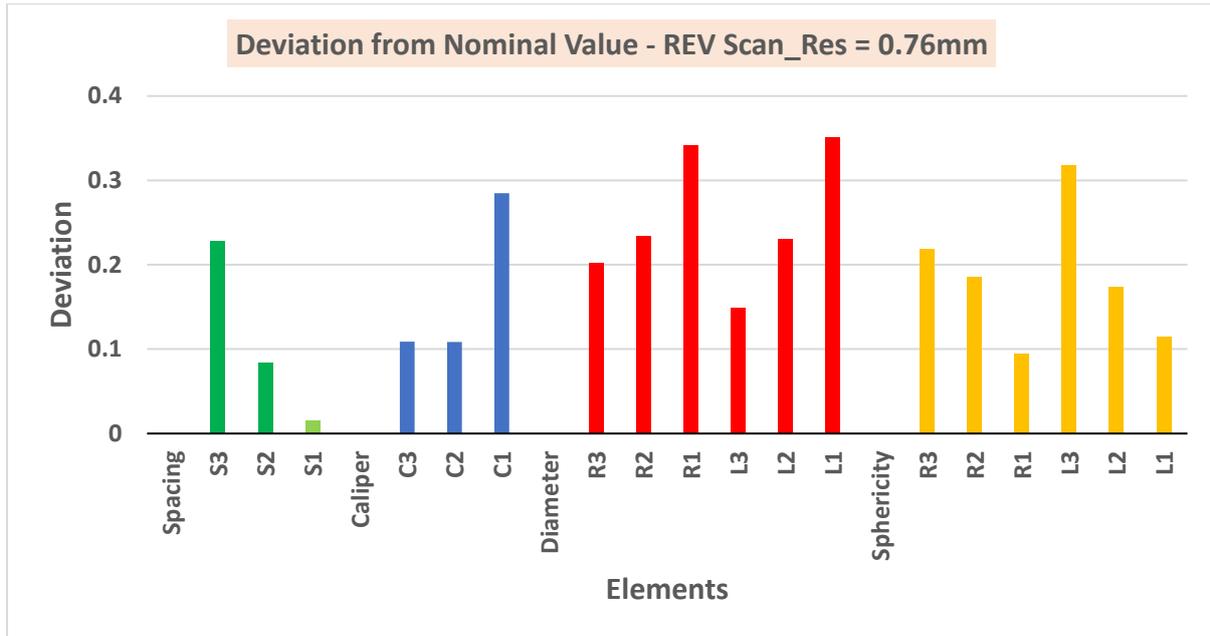
Graph 5: REV-Scan Deviation Graph for Average value – (Resolution = 0.76 mm)

The above two graph depicts that sphere spacing error for this scanner with resolution 0.76 mm is within the limit of manufacturer's accuracy of 0.05 mm for S2 and S1, but for S3, it deviates more.

Almost all the values for sphere diameters are out of range from nominal value.Therefore, this deviation is caused because of scanning inaccuracy.

(Sphere spacing, Caliper values) < 0.1 mm (manufacturer's accuracy)

Except for parameter spacing for larger sphere S3 and caliper for smaller spheres C1

(Sphere form error, Sphere diameters) > 0.1 mm (manufacturer' accuracy)

Except for parameter form error for smaller spheres L1 and R1

But for caliper values, only form smaller sphere value C1 is out of range and other values C2 and C3 are well within the range.

The parameter sphere form error for smaller spheres L1 nad R1 are within the limit whereas other parameters deviates above 0.2 mm.

9.4. Leica AT901-MR

Scanning parameters,

Measuring volume (working space) **= 18 m**

Distance between measured points **(Resolution) = 0.1 mm**

Exposure time **= 1000 milliseconds**

Element	Dev_Scan01	Dev_Scan02	Average deviation = $\frac{\lvert Dev_{Scan01}\rvert + \lvert Dev_{Scan02}\rvert}{2}$
Spacing			
S3	0.0177	0.0274	**0.0226**
S2	0.0193	0.0378	**0.0286**
S1	-0.0235	-0.0169	**0.0202**
Caliper			
C3	0.0459	0.0724	**0.0591**
C2	0.0247	0.021	**0.0229**
C1	-0.0712	-0.0845	**0.0779**
Diameter			
R3	0.0303	0.0266	**0.0285**
R2	0.0108	-0.0008	**0.0058**
R1	-0.021	-0.0171	**0.019**
L3	0.019	0.0545	**0.0368**
L2	0.0212	0.0587	**0.04**
L1	-0.0012	-0.0227	**0.012**
Sphericity			
R3	0.1227	0.1138	**0.1183**
R2	0.0884	0.0954	**0.0919**
R1	0.1042	0.1318	**0.118**
L3	0.102	0.1157	**0.1089**
L2	0.1194	0.1724	**0.1459**
L1	0.1071	0.0877	**0.0974**

Table 9: Leica Deviation Values – Scan 01 and Scan 02 - (Resolution = 0.1 mm)

The manufacturer's accuracy for Leica AT901 MR which is 0.03 mm from Hexagon (Leica Geosystems).
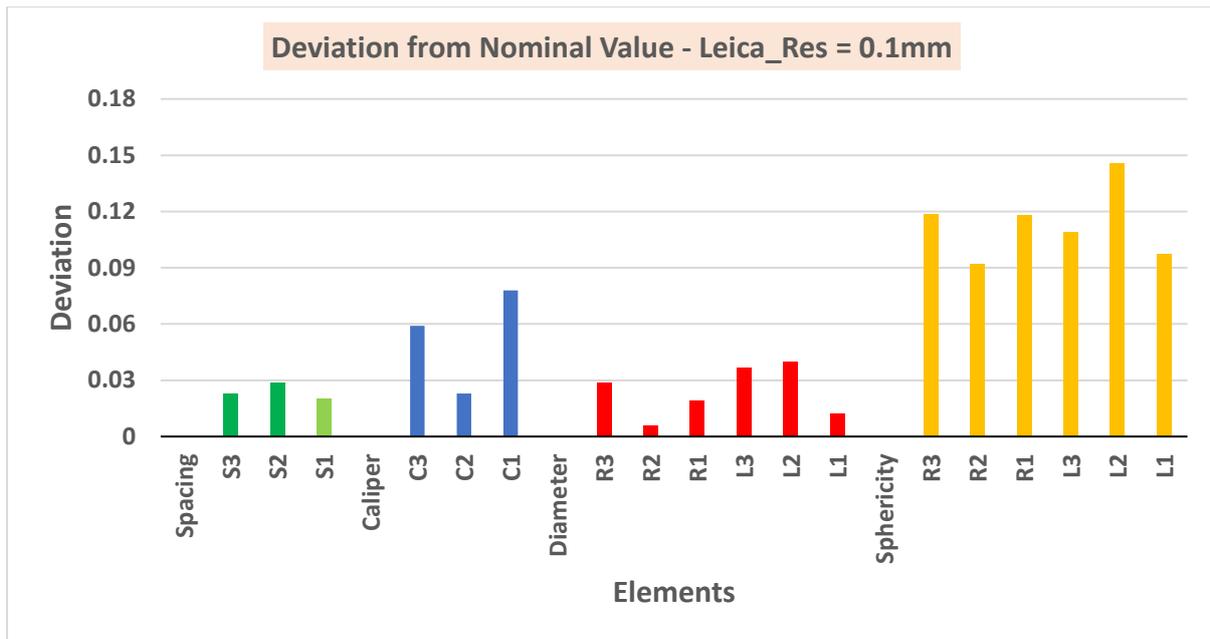
Graph 6: Leica Deviation Graph for Average value – (Resolution = 0.1 mm)

From the graph, Sphere spacing shows less deviation from the nominal value for all sphere diameters and it is within the manufacturer's specified accuracy value.

Caliper parameter C1 and C3 shows slightly more deviation when compared to C2. Sphere diameter are within the range of manufacturer's accuracy of 0.03 mm.

(Sphere spacing, Sphere diameters) < 0.03 mm (manufacturer's accuracy)

(Sphere form error, Caliper Values) > 0.03 mm (manufacturer' accuracy)

Except for parameter caliper value C2

But the parameter Sphere form error which is indicated with the colour orange deviates much from the nominal value and it is not within the limit of manufacturer's accuracy of 0.03 mm. Also these values are not affected by the diameter, as in some cases for larger diameter, error will be more and vice-versa.

9.5. Ein-Scan Pro 2X plus

Scanning parameters

Shining Fix Center 1 and Shining Fix Center 2

Scan Mode - **Fixed Scan with Turntable**

Align Mode - **Turntable Coded Targets**

Distance between point clouds (Resolution) - **0.24 mm**

Element	Dev_Scan01	Dev_Scan02	Average deviation = $\frac{|Dev_{Scan01}|+|Dev_{Scan02}|}{2}$
Spacing			
S3	-0.0053	-0.0005	**0.0029**
S2	0.0029	0.0163	**0.0096**
S1	0.0045	0.0116	**0.0081**
Caliper			
C3	-0.0488	-0.0199	**0.0344**
C2	0.0075	0.0534	**0.0305**
C1	0.0312	0.0828	**0.057**
Diameter			
R3	-0.0235	-0.0033	**0.0134**
R2	0.0475	0.0561	**0.0518**
R1	0.0355	0.0463	**0.0409**
L3	-0.0143	0.0047	**0.0095**
L2	0.0435	0.0548	**0.0492**
L1	0.0348	0.0486	**0.0417**
Sphericity			
R3	0.2399	0.1299	**0.1849**
R2	0.0769	0.0739	**0.0754**
R1	0.1788	0.2636	**0.2212**
L3	0.2493	0.1497	**0.1995**
L2	0.1123	0.1341	**0.1232**
L1	0.1356	0.1543	**0.145**

Table 10: Ein Scan Deviation Values – Fixed - Scan 01 and Scan 02 - (Resolution = 0.24 mm)

The manufacturer's accuracy for EIN-scan Pro 2X Plus which is 0.05 mm from (Shining 3D).

Deviation from Nominal Value - Ein Scan_Fixed
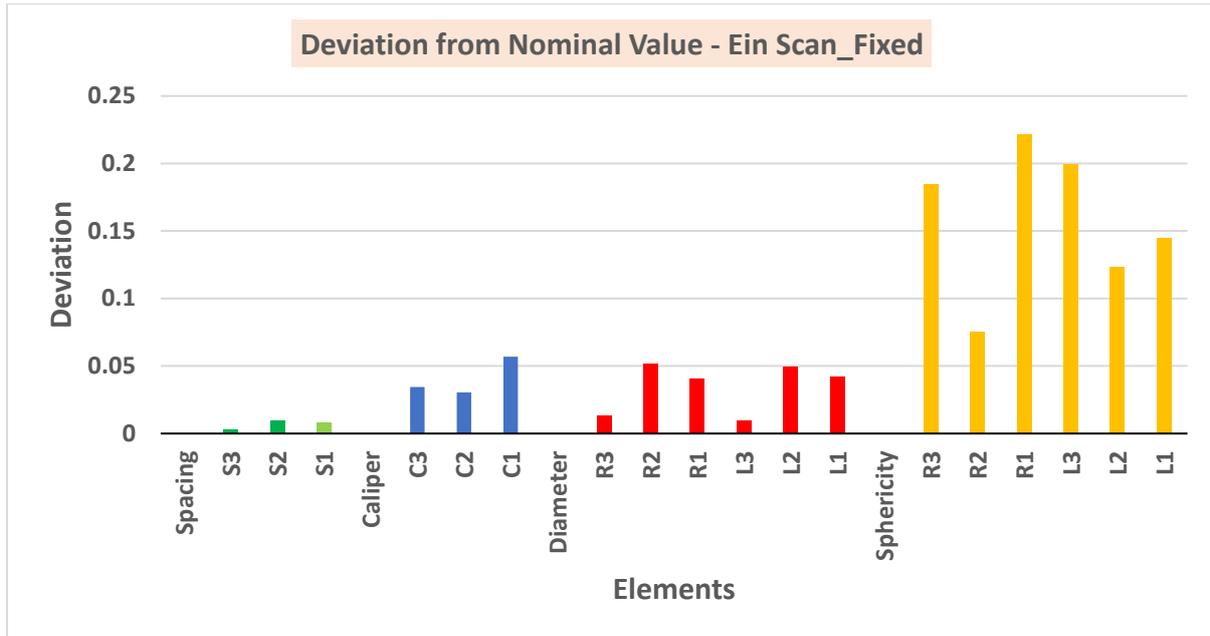
Graph 7: Ein Scan Deviation Graph for Average value- Fixed Scan – (Res = 0.24 mm)

From the above graph, it can be understood that the scanner results show good value of result for sphere spacing, caliper (external distances) and sphere diameters i.e., shows less deviation from nominal value and it is within the manufacturer's accuracy of 0.05 mm for fixed scan.

(Sphere spacing, Caliper distance, Sphere diameter) < 0.05 mm (manufacturer's accuracy)

(Sphere form error) > 0.05 mm (manufacturer' accuracy)

For parameter sphere form error, the deviation ranges from 3 to 5 times the manufacturer's data of accuracy. This problem was like in most of the scanners and it has to be taken in to account while scanning.

Scanning Parameter

Shining Hand HD1 and Shining Hand HD2

Scan Mode - **Handheld HD Scan**

Align Mode - **Markers Alignment**

Point Distance (Resoltion) - **0.2 mm**

Element	Dev_Scan01	Dev_Scan02	Average deviation = $\dfrac{|Dev_{Scan01}|+|Dev_{Scan02}|}{2}$
Spacing			
S3	0.036	0.0415	0.0386
S2	0.0366	0.0319	0.0343
S1	0.0205	0.0209	0.0207
Caliper			
C3	-0.0005	-0.0171	0.0088
C2	0.1143	0.0779	0.0961
C1	0.0583	0.0376	0.048
Diameter			
R3	-0.0479	-0.011	0.0295
R2	0.0192	0.0388	0.029
R1	0.0379	0.0609	0.0494
L3	0.0083	-0.0412	0.0248
L2	0.0207	0.0206	0.0207
L1	0.0348	0.0393	0.0371
Sphericity			
R3	0.6652	0.3912	0.5282
R2	0.1622	0.2316	0.1969
R1	0.165	0.148	0.1565
L3	0.3009	0.5235	0.4122
L2	0.2353	0.1987	0.217
L1	0.1326	0.1303	0.1315

Table 11: *Ein Scan Deviation Values – HD - Scan 01 and Scan 02 - (Resolution = 0.2 mm)*
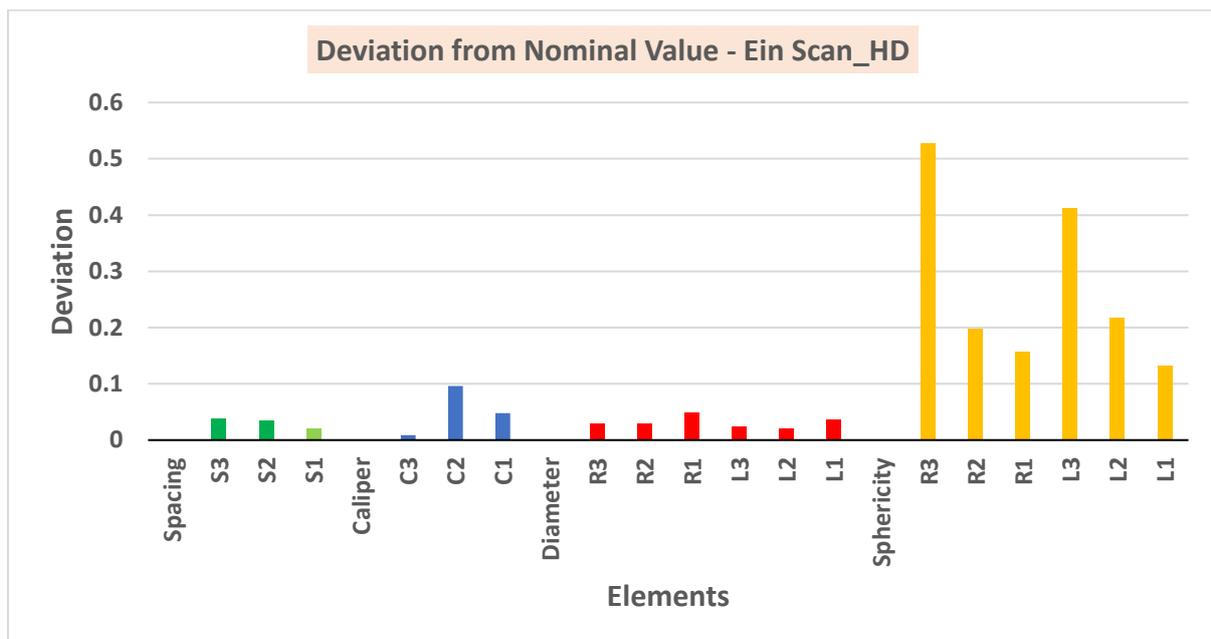
Graph 8: Ein Scan Deviation Graph for Average value- HD Scan – (Res = 0.2 mm)

From the above two graph, it can be understood that the scanner results show good value of result for sphere spacing, caliper (external distances) and sphere diameters i.e., shows less deviation from nominal value and it is within the manufacturer's accuracy of 0.05 mm for hand-held HD scan.

(Sphere spacing, Caliper distance, Sphere diameter) < 0.05 mm (manufacturer's accuracy)

(Sphere form error) > 0.05 mm (manufacturer' accuracy)

For parameter sphere form error, the deviation ranges from 3 to 5 times the manufacturer's data of accuracy. This problem was like in most of the scanners and it has to be taken in to account while scanning.

Scanning Parameters - Shining Hand Rapid

Scan Mode - **Handheld Rapid Scan**

Align Mode - **Hybrid Alignment**

Point Distance (Resolution) - **0.25 mm**

Element	Deviation from Nominal Value - Ein Scan_Handheld_Rapid01	Absolute Value
Spacing		
S3	0.0657	0.0657
S2	0.0347	0.0347
S1	-0.0048	0.0048
Caliper		
C3	0.0542	0.0542
C2	0.0379	0.0379
C1	-0.0751	0.0751
Diameter		
R3	-0.0378	0.0378
R2	-0.028	0.028
R1	-0.0945	0.0945
L3	-0.0817	0.0817
L2	-0.0499	0.0499
L1	-0.0839	0.0839
Sphericity		
R3	0.3147	0.3147
R2	0.2486	0.2486
R1	0.0848	0.0848
L3	0.2474	0.2474
L2	0.232	0.232
L1	0.0817	0.0817

Table 12: Ein Scan Deviation Values – Rapid Scan - (Resolution = 0.25 mm)
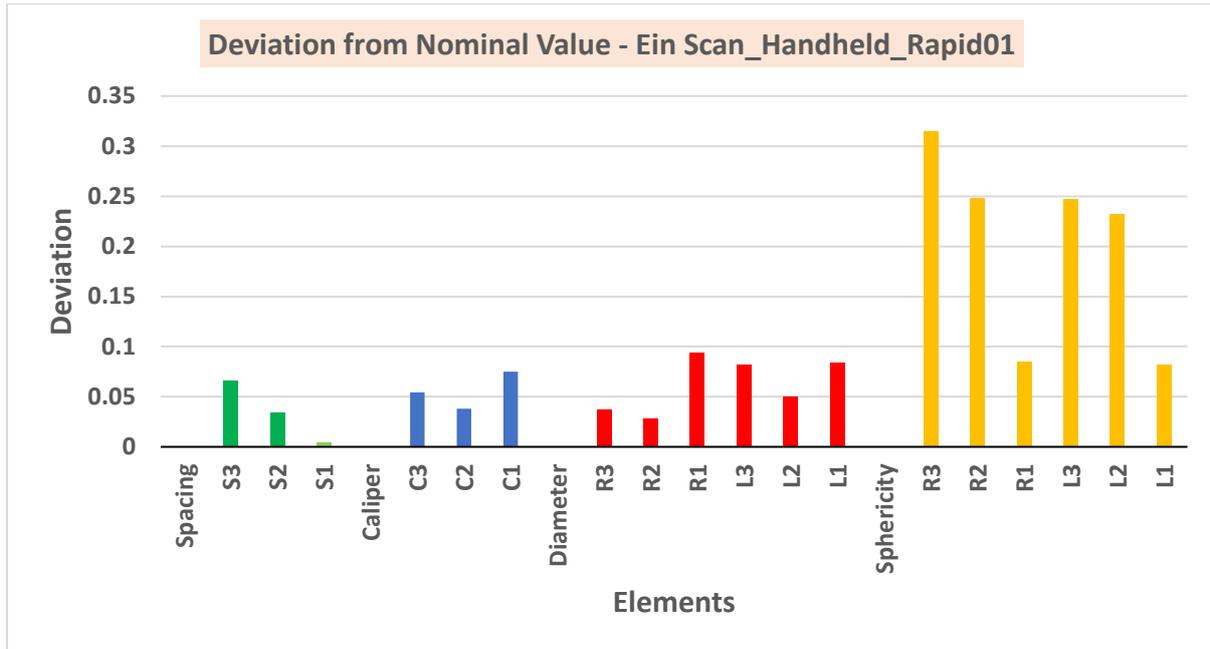
Graph 9: Ein-Scan Deviation Graph – Scan Rapid 01 - (Resolution = 0.25 mm)

From the above graph, it can be understood that the scanner results show good value of result for sphere spacing, caliper (external distances) and sphere diameters i.e., shows less deviation from nominal value and it is within the manufacturer's accuracy of 0.05 mm for Rapid scan, except for caliper C1 and sphere diameters R1, L1 and L3.

(Sphere spacing, Caliper distance, Sphere diameter) < 0.05 mm (manufacturer's accuracy)

Except for parameters caliper C1 and sphere diameters R1, L1 and L3.

(Sphere form error) > 0.05 mm (manufacturer' accuracy)

For parameter sphere form error, the deviation ranges from 3 to 5 times the manufacturer's data of accuracy. This problem was like in most of the scanners and it has to be taken in to account while scanning.

10. Summary of Results of comparison between each Scanner

The result of comparative geometrical accuracy evaluation for different 3D Optical scanners were given in this part of thesis work. The graphs in the chapter 9 gives the information about deviation of actual value from the nominal value for each parameter (Sphere spacing, Caliper distance, Sphere diameter and sphere form error).

10.1. Spacing between the spheres
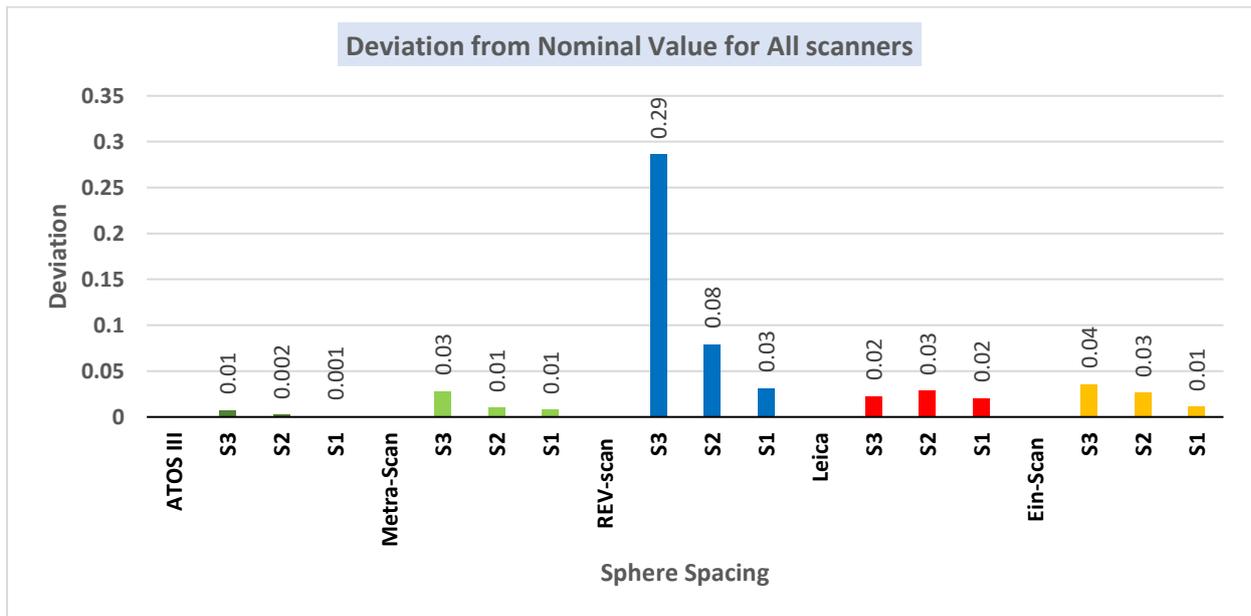
Graph 10: Deviation Graph – Sphere spacing error

The graph is generated for average values of scanner results i.e., deviation value for each parameter from all measurement for individual scanner is averaged. This information for graph is same for all the scanners.

It is clear from all the graphs that this parameter, sphere spacing for all the scanners is within the limit of manufacturer's accuracy and also it is not deviating much from the nominal value, shows only a slight deviation.

From the graph, ATOS III produces considerably good result when compared to other scanners and deviation value is almost equal to nominal values (less than 10 microns). Metra-scan deviation is comparatively good than Leica and Ein-scan (results of these two scanners is almost same). REV-scan results as clear from the graph, shows a larger deviation than other four scanners.

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Therefore, all the scanners quite good result in terms of sphere spacing parameter for all sphere diameters. Scanners with good accuracy are as follows,

ATOS III > Metra scan > Leica > Ein scan > REV scan

10.2.   Length measurement error
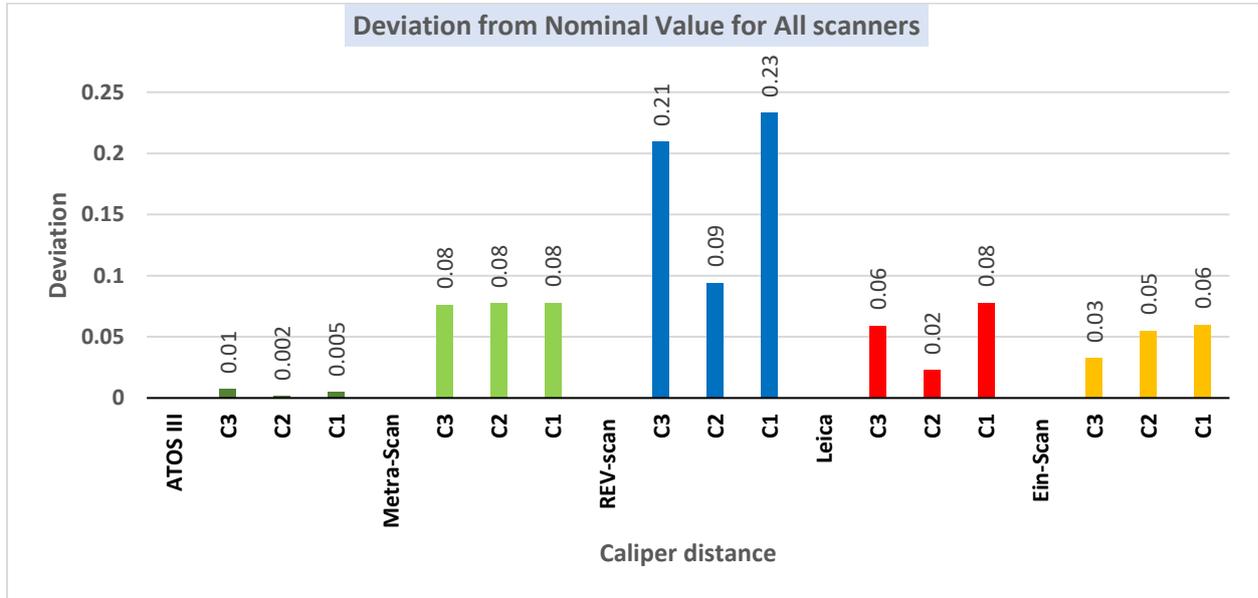
Graph 11: Deviation Graph – Length measurement error

For this parameter, it Is clear from the graph, ATOS III Triple scan shows good result i.e., deviation from the nominal value for all sphere diameters (caliper distance C1, C2 and C3) is less than 10 microns.

Ein-scan deviation is comparatively good than Leica and Metra-scan (Leica produces better result than Metra-scan). REV-scan results as clear from the graph, shows a larger deviation than other four scanners.

Therefore, ATOS III is best among all scanners, Ein scan and Leica shows relatively less deviation results when compared to Metra scan. The order for scanners for the parameter length measurement error are as follows,

ATOS III > Ein scan > Leica > Metra scan > REV scan

10.3. Probing error size
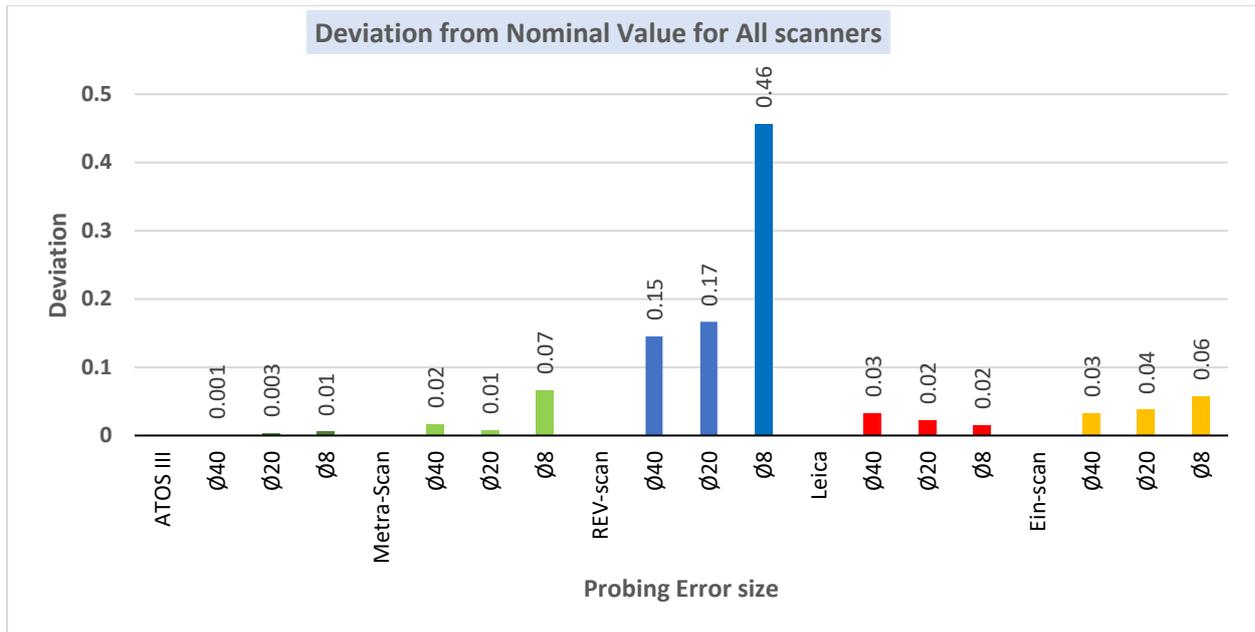
Graph 12: Deviation Graph – Probing error size

The deviation value for this graph is evaluated by considering only the diameters of spheres (Ø40, Ø20 and Ø8), not for individual spheres separately. The deviation results is generated for average values of scanner results i.e., deviation value for each parameter from all measurement for individual scanner is averaged.

For all sphere diameters, ATOS III Tripe scan shows relatively good result in terms of deviation i.e., less than 5 microns and it is almost equal to the nominal value.

These three scanners result for deviation is considerably in the same range i.e., they do not differ much when compared between each other. But in specific for this parameter, Leica produced better result than Metra-scan and Ein-scan (Metra-scan shows only a slight deviation when compared to Ein-scan).

Scanner with highest accuracy for this parameter are as,

ATOS III > Leica > Metra-scan > Ein scan > REV scan

10.4.   Probing error form
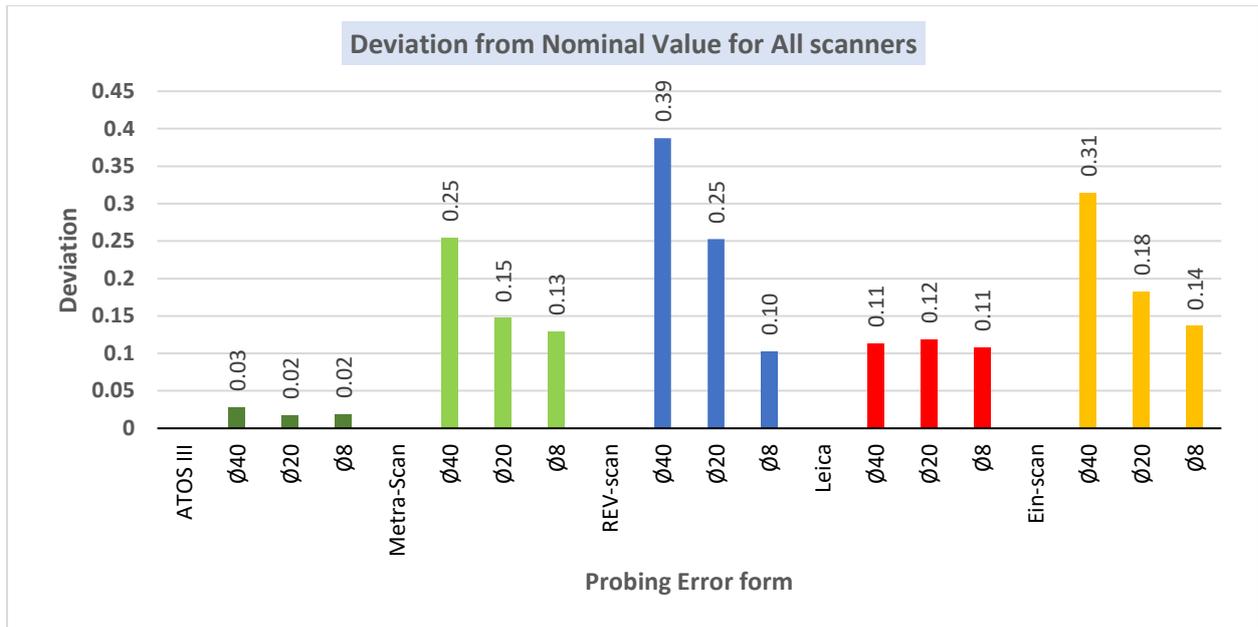
Graph 13: Deviation Graph – Probing error form

From the results evaluated in SW GOM, this parameter sphere form error, for all scanners and for all sphere diameters lies out of the manufacturer's limit. And one of the closest results is produced from the scanner, ATOS III triple scan.

Also, the results from the scanner Metra scan and Leica are comparatively good than Ein scan but REV scan deviates more as in other parameters.

Although, this parameter shows more deviation for all the scanners, ATOS produces better result as it is not deviating much from the nominal value and it is also within the other scanners manufacturer's accuracy value. Scanner with highest accuracy for this parameter are as follows,

ATOS III Triple scan > Leica > Metra scan > Ein scan > REV scan

11. Discussion of Results

The thesis focused on evaluation of measuring accuracy of various 3D optical scanners which are used in the application of reverse engineering, object inspection and deformation analysis. As already stated, the accuracy of scanner is affected by many parameters like atmospheric temperature, light, dust and humidity, etc. Generally, accuracy verification is done in the special metrology laboratory by the manufacturer and accuracy of each scanner is given. It is unknown that the specified accuracy can be achieved. For this reason, test was performed in the KSA/TUL laboratory.

The scanning was carried out two times for each scanner for conformity. The scanning of the calibration standard (Etalon) was carried out only after the calibration of each scanner according to the procedure recommended by the manufacturer. As Calibration is one of the important factors which affects the measuring accuracy of scanner, this procedure is followed before each digitization.

The obtained mesh model is then exported as .STL file and mesh model was compared with the CAD model in SW GOM Inspect for deviation of actual values from nominal values. In the previous chapter, the results of each scanner are compared with one another and scanners are ordered in terms of highest accuracy for each acceptance parameters. The reason for using the calibration standard with spheres and acceptance test parameters is mainly because of standard procedure followed by GOM for accuracy evaluation.

The obtained results of deviation from GOM Inspect is shown in graph in chapter 9. From the graph, the deviation for each scanner and each acceptance test parameter is summarized. It was observed that the results of accuracy from graph clearly depicted how much the actual deviation for each parameter.

Firstly, the manufacturer's accuracy for each scanner is compared for each acceptance test parameters. From this, ATOS III Triple scan produced comparatively good result and also deviation is almost equal to the nominal value except for sphere form error, which actually showed larger deviation for all the scanners. Other 4 scanners, Metra scan, Leica, Ein Scan and REV scan also produced results within the limit of manufacturer's accuracy except for few parameters. But sphere form error largely deviates from nominal value for all the scanners

and this parameter should be taken in to consideration when accuracy is evaluated in future. Therefore, in comparison with manufacturer's accuracy, the parameters sphere spacing, diameter and caliper distance produced comparatively better results and sphere form error is an exception.

Secondly, in chapter 10, the scanner accuracy was compared with each other and from the evaluation of results, ATOS III triple scan showed good results for all acceptance test parameters when compared to other scanners. And REV scan showed least accuracy for all parameters among all the scanners. The reason is that REV-scan is the oldest one among all the scanners and the REV-scan has not been checked in the calibration laboratory as required, and so the errors are larger than the other scanner. In terms of comparison for other 3 scanners, Metra scan, Leica and Ein Scan, for sphere spacing, the order is as follows, Leica produced good results than Metra scan and Ein-scan. For length measurement error, the order is as follows, Ein scan produced good results than Leica and Metra scan. For probing error size, the order is as follows, Leica produced good results than Metra-scan and Ein scan. For probing error form, the order is as follows, Leica produced good results than Metra scan and Ein-scan.

Therefore, these parameters results are determined for accuracy evaluation of each scanner and can be considered for further evaluation of accuracy and digitization of parts in future.

12. Conclusion

The aim of this thesis was to determine the measurement accuracy of optical 3D scanners which are available at the KSA/TUL laboratory. The scanners from TUL laboratory are ATOS III Triple scan, Metra-scan 350, REV scan and Ein Scan Pro 2X Plus. In addition to these scanners, Leica AT901 MR from the company "Modelárna Liaz" was used. Although, the manufacturer has provided the scanning accuracy for each scanner, it is uncertain that the specified accuracy by the manufacturer can be achieved in normal environmental conditions. Because the manufacturer determines the accuracy in special metrology lab where all conditions for scanning is met.

For practical verification, Calibration standard which is so called as Etalon is made in previous research at the department by FRKAL [30] and MENDRICKY [7] was used for acceptance test. As stated in the research part, this etalon generally is created with common shapes which we can see in many industrial parts. In the so-called Acceptance test, the measurement process through which the scanner's accuracy can be checked is defined. This test is defined according to VDI / VDE directive 2634.

The nominal dimension for the calibration standard was determined using Zeiss O-INSPECT 322 CMM. Although, the CAD dimension is already known, it cannot be used as nominal value. It is because of manufacturing tolerances.

The practical measurement of calibration standard was done using different three-dimensional optical scanners in the TUL laboratory and for Leica, measurement is carried out in the industry. During this process, all necessary steps before measurement such as Calibration of the device, environmental conditions, anti-reflective coating, scanner warm-up time, placement of reference points, camera angle, number of scans, stable placement of part on the table, measuring volume of each scanners and reference point diameter as stated by the manufacturer were followed.

For conformity, the scanning for each scanner is done two times with different resolution and the results were evaluated in SW GOM Inspect.

After the evaluation of mesh in SW GOM, the accuracies for each scanner were determined for each acceptance test parameters. The scanner ATOS III Triple scan produces good results

for all parameters of acceptance test and deviation from the nominal value is very less when compared to other scanners. Other mentioned scanners Metra scan, Leica and Ein scan also less deviation from the nominal value but ATOS III produces comparatively good results of accuracy. REV scan shows more deviation from the nominal value for all parameters and it is not best when compared to other four scanners. The reason for larger error is that REV-scan is the oldest one among all the scanners and the REV-scan has not been checked in the calibration laboratory as required, and so the errors are larger than the other scanner. However, the parameter, sphere form error for all the scanners is out of the limit of manufacturer's accuracy and it has to considered during measurement and evaluation.

Acceptance tests can be performed as needed to determine the ability of the scanner, and it can be evaluated on a frequent basis. It should be stated, however, that the analysis results are primarily for our knowledge and are not a certified calibration. Therefore, verification of accuracy for each scanner is a great advantage for the department as in general, accuracy verification takes place at the manufacturer's place.

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APPENDIX - GOM Inspection Report - ATOS

gom

CAD Model - Nominal dimension

Length unit: mm
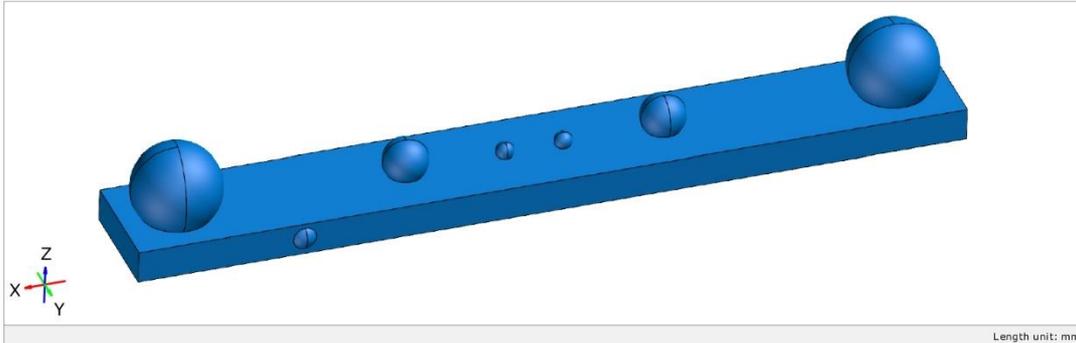
Inspector:	Lakshman Kumar Ramesh	**Part:**	
Company:	Technicka Univerzita v Liberci	**Part no.:**	Etalon_03
Department:	KSA	**Version:**	ATOS III Triple Scan
Location:	Liberec	**Charge no.:**	03_FullMV
Date:	18-04-2021	**System:**	GOM Inspect Professional 2019
Project:	Acceptance Test		

Acceptance Test   Etalon_03   ATOS III Triple Scan   03_FullMV   1/7

gom

CAD (blue) and Mesh (gray) - ATOS III Triple Scan

Prealignment   Length unit: mm
Acceptance Test   Etalon_03   ATOS III Triple Scan   03_FullMV   2/7

gom

Probing Error Size - ATOS III Triple Scan

Sphere_G_R2

●	Nominal	Actual	Dev.	Check
Ø	+20.0017	+19.9997	-0.0020	

Sphere_G_R3

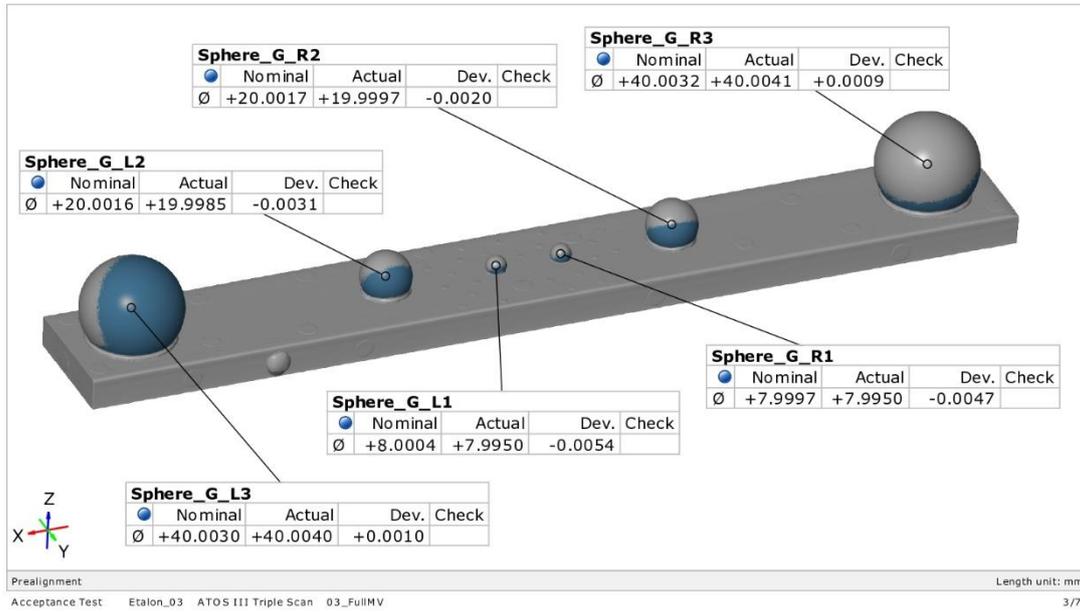| ●	Nominal	Actual	Dev.	Check
Ø	+40.0032	+40.0041	+0.0009	

Sphere_G_L2

●	Nominal	Actual	Dev.	Check
Ø	+20.0016	+19.9985	-0.0031	

Sphere_G_R1

●	Nominal	Actual	Dev.	Check
Ø	+7.9997	+7.9950	-0.0047	

Sphere_G_L1

●	Nominal	Actual	Dev.	Check
Ø	+8.0004	+7.9950	-0.0054	

Sphere_G_L3

●	Nominal	Actual	Dev.	Check
Ø	+40.0030	+40.0040	+0.0010	

Z
X
Y

Prealignment Length unit: mm

gom

Spacing between Spheres - ATOS III Triple Scan

100

S3

↔	Nominal	Actual	Dev.	Check
L	+319.9330	+319.9427	+0.0097	

50

S2

↔	Nominal	Actual	Dev.	Check
L	+115.0054	+115.0083	+0.0029	

0

↔ S1

S1.L

↔	Nominal	Actual	Dev.	Check
L	+26.0169	+26.0179	+0.0010	

-50

Z
X
-100

400   350   300   250   200   150   100   50   0

Prealignment Length unit: mm

gom

Length Measurement Error - ATOS III Triple Scan

C3				
↔	Nominal	Actual	Dev.	Check
L	+359.9371	+359.9494	+0.0123	

C1				
↔	Nominal	Actual	Dev.	Check
L	+34.0180	+34.0145	-0.0035	

C2				
↔	Nominal	Actual	Dev.	Check
L	+135.0080	+135.0073	-0.0007	

Prealignment | Length unit: mm

Acceptance Test   Etalon_03   ATOS III Triple Scan   03_FullMV   5/7

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gom

Probing Error Form - ATOS III Triple Scan

Sphere_CH_L1				
●	Nominal	Actual	Dev.	Check
Range	+0.0000	+0.0166	+0.0166	

Sphere_CH_R3				
●	Nominal	Actual	Dev.	Check
Range	+0.0000	+0.0251	+0.0251	

Sphere_CH_R1				
●	Nominal	Actual	Dev.	Check
Range	+0.0000	+0.0196	+0.0196	

Sphere_CH_R2				
●	Nominal	Actual	Dev.	Check
Range	+0.0000	+0.0148	+0.0148	

Sphere_CH_L3				
●	Nominal	Actual	Dev.	Check
Range	+0.0000	+0.0230	+0.0230	

Sphere_CH_L2				
●	Nominal	Actual	Dev.	Check
Range	+0.0000	+0.0183	+0.0183	

Prealignment | Length unit: mm

Acceptance Test   Etalon_03   ATOS III Triple Scan   03_FullMV   6/7

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gom

Acceptance Test Parameters- ATOS III Triple Scan

Element	Datum	Property	Nominal	Actual	Tol -	Tol +	Dev	Check	Out
⇄ S3		L	+319.9330	+319.9427			+0.0097		
⇄ S2		L	+115.0054	+115.0083			+0.0029		
⇄ S1		L	+26.0169	+26.0179			+0.0010		
⇄ C3		L	+359.9371	+359.9494			+0.0123		
⇄ C2		L	+135.0080	+135.0073			-0.0007		
⇄ C1		L	+34.0180	+34.0145			-0.0035		
● Sphere_G_R3		Ø	+40.0032	+40.0041			+0.0009		
● Sphere_G_R2		Ø	+20.0017	+19.9997			-0.0020		
● Sphere_G_R1		Ø	+7.9997	+7.9950			-0.0047		
● Sphere_G_L3		Ø	+40.0030	+40.0040			+0.0010		
● Sphere_G_L2		Ø	+20.0016	+19.9985			-0.0031		
● Sphere_G_L1		Ø	+8.0004	+7.9950			-0.0054		
● Sphere_CH_R3		Range	+0.0000	+0.0251			+0.0251		
● Sphere_CH_R2		Range	+0.0000	+0.0148			+0.0148		
● Sphere_CH_R1		Range	+0.0000	+0.0196			+0.0196		
● Sphere_CH_L3		Range	+0.0000	+0.0230			+0.0230		
● Sphere_CH_L2		Range	+0.0000	+0.0183			+0.0183		
● Sphere_CH_L1		Range	+0.0000	+0.0166			+0.0166		

Prealignment

Length unit: mm