Inspection Processes Study

ICAMS

Interdisciplinary Center for Advanced Manufacturing Systems

1 Technical Report 23-02 Introduction

Product inspection helps to ensure that all parts are produced within the allowable tolerances according to specific dimensions and quality standards. While there are many inspection opportunities during production, in-process inspection is the most effective. It is desirable to perform automated parts inspection as this is the most proactive way to control processes. This approach to inspection helps to control the quality of products by identifying the origin of potential defects during production. This allows for improved productivity, reduced (total) defect rates, and reduced rework/waste. There are many tools to use in the inspection process such as Coordinate Measurement Machines (CMMs) and Light Scanning systems. However, it can be challenging to understand the capabilities and applicability of the different inspection systems.

In today's Industry 4.0 technology environment, the move towards digital manufacturing requires seamless data flow throughout the production process. The integration of manufacturing capability models into operational control and decision-making allows for this transition to happen. This is often referred to as the Model-Based "X" (where "X" stands for Enterprise, Manufacturing, Design, Definition, etc.) Model-Based Design results in a 3-D annotated model and its associated data elements that fully define the product in a manner that can be used effectively by all downstream customers in place of a traditional drawing.

Metrology is the science of measurement and its application. Thus, Model-Based Metrology (MBM) can be described as the process of using the model-based design to develop and execute the most efficient and effective inspection plan for the product or system. Currently, in industry, the two most used MBM systems are Coordinate Measuring Machines and Blue Light Scanning systems.

Before improvements to a system can be implemented, it is essential to understand fully the tools and capabilities within the process. CMMs use a probing system to detect discreet points on the surfaces of objects. Blue Light Scanners are a type of structured-light device which measures the three-dimensional shape of an object using projected light patterns and a camera system. Of interest is how to effectively compare the CMM and Blue Light inspection systems and produce a comprehensive analysis for different part geometrical characteristics.

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2 Literature Review

Through the analysis of 40 journal articles and papers, it has become apparent there is no significant emphasis on implementing metrology systems in industry. This is often due to the fact that quality control (QC) is considered a nonvalue added, but necessary, area of production. However, QC/inspection is necessary to meet customer requirements and discover problem areas in production that are often value-added. Value added refers to a procedure or step within a process which transforms raw materials or work in progress (WIP) into much more valuable goods and/or services to customers down the line. In general, value-added can be thought of as something the customer would directly pay for. Nonvalue added, but necessary, is the opposite concept, it is a process or step that the customer would not see directly reflected in the product but allows for the product to meet the customer's demands, such as quality and inspection. Model-Based Enterprise is the approach designating the way to utilize model data the entire life cycle from design to disposal of the produced system. Model-Based Design (MBD) / Model-Based Metrology (MBM) is the technology of attaching GD&T to a CAD model, ideally with an automatic program to create a semantic model. A semantic model in theory allows for smart software to automatically create a measurement program from the semantic CAD model. In order to begin to implement MBM, it is essential to understand the existing systems, software, and capabilities.

2.1 CMM Analysis

CMMs are excellent for measuring GD&T feature control frames such as true position, flatness, parallelism, and perpendicularity because they allow for great precision and accuracy. This includes measurements of angles, radii, and circles. Any rounded objects, such as holes, slots, cones, radii, and spherical radii, as well as roundness and concentricity, are easily measured with a CMM. However, a CMM is not ideal for measuring features smaller than its probe tip. Several of the most popular CMM probes contain ruby tips which are .020-inch-diameter spheres of ruby that have been precision machined. In addition to the size of the ball, the CMM also needs a specific amount of space for the probe tip to approach the feature being measured. Hence, a hole smaller than .040 or .045" may not be able to be probed with a .020" probe tip. The same is true for radii. A radius smaller than the ball itself cannot be measured by it. Rough surfaces also cause problems for CMMs. The roughness may hinder the CMM from making precise, accurate contact with the part. In general, threaded holes cannot be measured with a CMM, primarily because they seldom begin in the same location each time. Threads are frequently difficult to measure since automated CMM software requires consistency.

2.2 Structured Light Scanning Analysis

A structured-light 3D scanners uses white or blue light technology to capture the entire area of an object using multiple patterns and images. A structured light scanner is composed of two cameras and a projector. To create a scan, various light patterns are projected onto an item, and the scanner captures how and where the light patterns are warped by the object. The distance and position of thousands of data points where the light pattern contacts the item are computed resulting in a point cloud representation of the part geometry. Light scanning systems are often used because structured light scanning is non-contact, thus, fragile parts can be scanned without the risk of damaging delicate features. Scanning metrology systems are often chosen for their rapid speed of data collection and the performing reverse engineering. The 3D light scanner allows millions of data points to be recorded in seconds. However, shiny, reflective, transparent, or black surfaces can cause issues with data collection/quality. To minimize this issue, a powder or water-soluble paint is applied to the object to create a matte surface. This adds a layer of thickness to the part dimensions which can be as small as 0.0001" to as large as 0.0080" depending upon the material applied and the expertise of the user.

2.3 Blue Light vs. White Light

The color of the light scanning system also plays an important factor. The two predominant light systems in industry right now are the white light and blue light scanning systems. In general, white light incandescent bulbs have a relatively limited lifespan and can experience performance loss halfway through their lifecycle as they become less bright with use. LED lighting became a viable alternative. The creation of white LEDs for white light scanning resulted in a more difficult and expensive technology. Thus, the introduction of blue LED lighting was introduced. Blue light scanning produces higher resolution and more accurate scans than white light due to a few different factors. White light scanning uses the entire visible spectrum and thus is made of all the different wavelengths of visible light. This results in a less accurate scan as the light is easier to distort and scatter. A blue light scanner works with only one color of light and has a short wavelength that is not as prone to reflection, which results in a more accurate scan. The wavelength of blue light also helps facilitate better filtering of interference from ambient light. White light systems do not operate well in bright light environments due to the system's inability to distinguish between light sources.

Because ambient light is also typically white light, a white light system will often blend the light sources together resulting in a less precise and accurate scan. If it is not feasible to change the lighting in the area to accommodate the system, using a white light scanner becomes problematic. Because the blue light scanner only recognizes blue light, it is easier for it to block out the external light source and thus less easily impacted by the same ambient light. Blue light scans are less sensitive to heat than white light scans which results in a more consistent system because it can run for larger durations.

2.4 Training

Zeiss is a prominent provider of metrology products. To utilize the Zeiss metrology systems, the user must be trained on the Calypso software. Calypso is Zeiss' universal software for dimensional metrology applications. The minimum training offered for users is the Calypso Basic training. Calypso Basic is a four-day class that provides the necessary information to begin creating and executing measurement plans. This course is a prerequisite for all other Calypso training courses. Further classes can be taken in addition to the basic training for more detail.

The Keyence blue light scanning system does not have the official or necessary training requirement.

3 Project Statement

Currently, there is no guide to assist Small and Medium Manufacturers in determining the most efficient way to analyze and inspect their specific part type. This sort of uncertainty often leads to several wastes including time, money, and unnecessary data gathering. Truly understanding the diverse capabilities of different inspection systems will decrease these wastes and increase the collection of relevant data and efficiency. Most current inspection plans in industry are based on a trial-and-error basis which can be very costly and wasteful of time and resources. Inspection could be made more efficient by providing industry with a guide. The guide will serve as a foundation for industry to base their inspection plans on without conducting their own exploration.

4 METHODOLOGY

This research will utilize a Zeiss DuraMax CMM, and Keyence VL Series 3D Scanner CMM Systems on several parts with different geometries made of different materials resulting in a deliverable intended to help guide industry to choose the most appropriate inspection plan for their product with certain characteristics. First, precision gauges that possess some of the below defined key characteristics. These will be used because their exact measurements have been certified along with an acceptable tolerance range. In addition to the precision gauges, another part will be constructed with CAD software consisting of a combination of many key geometries crucial to the part's functionality. This will be produced in aluminum and have different surface finishes. Key characteristics of each part will be identified to ensure the inspection plans and execution is consistent through each inspection system. The parts will then be inspected using the metrology systems applying the same process for each part. Performance metrics will be developed that represent the issues with surface finish difficulty, geometry issues, the accuracy of measurement, the best inspection systems to use with regard to material types, geometry, and the time required to perform the measurements.

4.1 MEASURING SYSTEMS

The Zeiss DuraMax Coordinate Measuring Machine is categorized as a shop floor production CMM specifically intended to eliminate the need for fixed gauges. It is equipped with scanning and single point measuring of a range of 500 x 500 x 500 mm respectively on the (X, Y, Z) planes [*Appendix A Figure 1*]. It is also equipped with a white light optical sensor specifically designed for scanning strongly reflective surfaces without any need for a contrast medium. The styli that will be used is the standard, star, and t stylus which all possess a ruby probe tip. Ruby is the most used sphere material in metrology and is suitable for the most common measurement tasks. The Keyence 3D Scanner CMM [*Appendix A Figure 2*] uses blue LED lights along with a motorized turntable that moves in the X, Y, and θ directions. The measuring range for this machine is ø300 × H 200 mm. However, stitching functions of the data points allow for an even larger combined measuring range. These types of systems have been chosen for analysis due to their popularity in industry and accessibility.

Standard Probe

T-probe

Star Probe

4.2 KEY MEASUREMENT COMPONENTS

When assessing each metrology system's capabilities, it is important to identify key part components that will be measured. Each of the above listed parts will be measured on the each of the metrology systems (CMM and blue light scanner). They will be first be measured on their capability to capture the desired part geometry/key characteristics as well as recording the system's limitations on performing the desired task.

In addition to documenting each system's ability to capture physical constraints/limitations with part geometries and surface finishes, this research will also be capturing further ways of measurement such as time to prepare the system/program being run, time for the user to get the appropriate training on the system for usage, and the actual time the system takes to run the inspection.

It is important to note that there are many different methods when writing a program for a CMM. Depending on the information needed and purpose of the part, the CMM can be instructed to measure the maximum inscribed diameter, minimum circumscribed diameter, or the average volume (using diameter) for other needed calculations such as mass. There are also many techniques for getting certain measurements. For example, if measuring an internal cylinder diameter, the probe can either touch several programmed points, have many vertical passes dragging up the side of the cylinder at several programmed starting points, or vertically drag up the side of the cylinder while spiraling around the internal circumference with only one pass. This also presents another factor of how many points or the location of the starting point are sufficient enough to measure the desired metric.

4.3 Part Characteristics

To fully exercise the systems, it is first necessary to understand the key part geometries/characteristics common in industry. Research resulted in four categories of popular geometry characteristics and two categories of cosmetic/material characteristics:

4.3.1 Parts:

- 2" SPI Master Setting Ring Gage [*Appendix B, Figure 3*]
- HFS Steel Pin Gage Set (0.061-0.250") [*Appendix B, Figure 4*]
- Accusize Steel Gage Block Set Grade B [*Appendix B, Figure 5]*
- DMG MORI Calibration Ball [*Appendix B, Figure 6]*
- Aluminum "Guide Block" with multiple geometries [*Appendix B, Figure 7]*

4.3.2 Geometry characteristics:

- Edge: sharp, angled, fillet, chamfer
- Surfaces: flat, curved, complex surface
- Pockets (depth and diameter): hole, evacuated pockets, tapped holes (threads)
- External Extrusion features: caused by the overall shape of the part
    - Cause shadows (relationship between height and/or depth)

4.3.3 Cosmetic/Material Characteristics:

- Material: steel/stainless steel, polymer
- Color: black, white, blue, yellow, orange, red

4.4 Procedure

4.4.1 General System Procedure

Each metrology system has a standard/general set up procedure that should be followed each time of use. These initial steps are important to ensure the machines are calibrated and have spatial awareness within the measurement plane. This ensures consistent and accurate measurements.

CMM:

1. Turn on computer and CMM, turn on drives

2. Set up reference sphere on surface plate
3. Open new/load inspection plan
4. Run geometry requalification on the master probe
5. Run qualify passive on every additional probe needed for inspection plan
6. Position and secure part for measurement
7. Identify & capture base alignment
8. Identify and capture features
9. Identify characteristics desired to measure from features
10. Define clearance plane
11. Follow Zeiss cookbook[1] in accordance to evaluation and strategy for features and characteristics

CMM Duramax Reference Sphere

Blue Light Scanner:

1. Turn on computer and blue light scanner
2. Reset turntable to original position
3. Set part on turntable & ensure light curtain is lowered
4. Take new measurement scan & adjust settings as needed
    a. Settings that can be adjusted: manual vs automatic capture, light refraction level, number of captures & angle of rotational change
5. Take additional scans as needed and mesh with previous scan

Key metrics of each part, as defined by the literature review, will be measured by each system. Each system will attempt to measure the same key characteristics to ensure standardization throughout the experiment and results. Specifics on key characteristics measured and method for collection can be found in the following:

1. 2” SPI Master Setting Ring Gage
    a. Flatness of surface will be measured
    b. Internal diameter will be measured
    c. Cylindricity will be measured
    d. Height of part will be measured (through internal cylinder)
2. HFS Steel Pin Gage 0.250”
    a. External diameter will be measured – minimum circumscribed (CMM)
    b. Height of part will be measured
    c. Cylindricity will be measured
3. Accusize Steel Gage Block Set Grade B 4”
    a. Flatness of sides will be measured
    b. Perpendicularity will be measured
    c. Length, height, and width will be measured
4. DMG MORI Calibration Ball
    a. Diameter will be measured
    b. Roundness will be measured
5. Aluminum “Guide Block”
    a. location of holes will be measured
    b. depth of hole will be measured
    c. cylindricity of hole will be measured

[1] The Zeiss Academy Metrology Cookbook: Measuring strategies for tactile Coordinate Metrology tries to cover some of the most common measuring tasks (as evaluated in a study by Carl Zeiss Global Application Knowledge Group). These "default recipes" are a place to start when there is no additional information provided for measurement. These are only default suggestions, however when you know more about process and function/assembly of a part, these suggestions should be modified for your application. Remember all changes and modifications should always be documented for each measurement.

d. diameter of hole will be measured – maximum inscribed (CMM)
e. flatness of surfaces will be measured
f. perpendicularity will be measured
g. angle of chamfer will be measured
h. radius of fillet will be measured

6. Polymer Colors (Only for Blue Light Scanner)
    a. Black [*Appendix C Figure 8]*
    b. White [*Appendix C Figure 9]*
    c. Blue [*Appendix C Figure 10]*
    d. Red [*Appendix C Figure 11]*
    e. Yellow [*Appendix C Figure 12]*
    f. Orange [*Appendix C Figure 13]*

5 RESULTS

The results for this experiment will be measured both by qualitative and quantitative metrics as described in the methodology. The qualitative metrics will be described as ease of use of the systems, skills necessary to be able to operate systems / execute functions, trainability of system in order to become proficient, ability of system to capture desired geometries, and issues and/or adaptations to process for measurement. The quantitative metrics will include time to create inspection program, time to run inspection measurements, and associated costs of systems.

5.1 2” SPI MASTER SETTING RING GAGE

5.1.1 CMM *[Appendix D, Figures 14,15]*

Measurements Collected by CMM

a. Flatness of surface
b. Internal diameter
c. Cylindricity
d. Perpendicularity of cylinder to surface

Time Results

Turn on machine, set up part, open new inspection plan, geometry requalification, qualify passive – 15 minutes
Define base alignment, collect features and characteristics, define inspection by cookbook parameters - 1 hour 30 minutes
Trouble shoot program – 4 hours
Run Program at tolerance +- 0.005 inches – 3 minutes
Run Program at tolerance +-0.005 inches – 3 minutes

Ring Gage positioned on CMM with putty

Process Notes

Inspection was run at two tolerance ranges (0.005 and 0.0005) to test time parameters related to tolerance.

Had trouble with spacing. Machine was overestimating distances, such as machine said 9 inches but actual distance was 4 inches, had to repeat CMM initialization process.

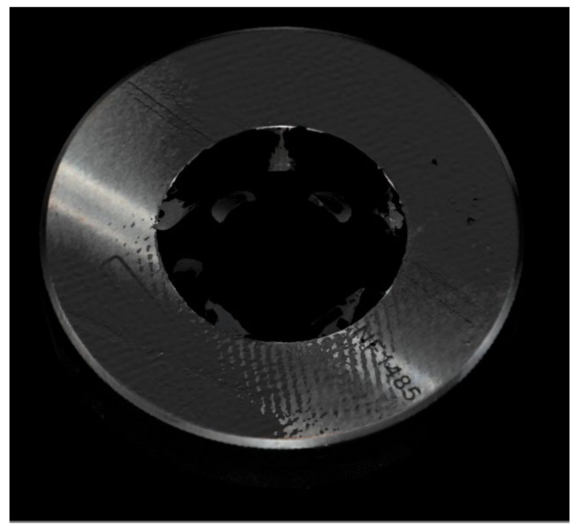
Had trouble with using cylinder for base alignment, reason unknown. The fix was to use a separate plane and circle for base alignment, and then collect plane and cylinder for features. Had to use a reference not on part for rotational reference: used separate vice.

Vice

5.1.2 Blue Light Scanner *[Appendix D, Figures 16,17,18]*

<u>Measurements Collected by Blue Light Scanner</u>

a. Flatness of surface plane
b. Internal diameter of cylinder
c. Internal radius of cylinder
d. Internal diameter of inner circle
e. Internal radius of inner circle
f. Cylindricity
g. Perpendicularity of cylinder to surface
h. Angularity of cylinder axis to plane



Ring Gage without matte spray

<u>Time Results</u>

Auto on high magnification
- 6 positions, 2 minutes 45 sec scan
- Completing data acquisition 2 minutes

Manual on high magnification manual adjusted brightness to 2315
- 8 positions, 4 minutes 25 sec scan
- Completing data acquisition 3 minutes

Mesh the point clouds – 2 minutes

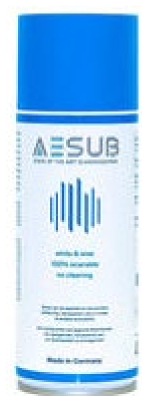
<u>Process Notes</u>

Both scans would not capture inside cylinder, and material type was an issue. Showed material on the internal cylinder to be above the actual plane.

Matte spray was necessary to remove the shine of the part. Removing the shine reduced eliminated the reflection of the light refraction. When using matte spray to maintain the integrity of the material, after inspection the part must be rinsed well to remove spray completely and rubbed with way oil.

After spraying, and propping on an angle, internal cylinder was able to be captured

- Minimum 2 scans
    - One flat, one angled



Matte Spray

5.2 HFS Steel Pin Gage 0.250”

5.2.1 CMM *[Appendix D, Figures 19,20]*

<u>Measurements Collected by CMM</u>

a. External diameter

b. Cylindricity
c. Roundness

Time Results

- Turn on machine, set up part, open new inspection plan, geometry requalification, qualify passive – 15 minutes
- Collect features and characteristics, clearance plane, define inspection by cookbook parameters - 30 minutes
- Run inspection plan – 3 minutes

Process Notes

Because the same time of use, geometry requalification and qualify passive are not necessary. As noted above, the difference in tolerance is irrelevant to speed, thus only one tolerance will be measured from here on. The vice was also used for base alignment as the cylinder geometry does not allow for satisfactory rotational restrictions due to its symmetry.

5.2.2 Blue Light Scanner *[Appendix D, Figures 21,22]*

Measurements Collected by Blue Light Scanner

a. External diameter of cylinder
b. Radius of cylinder
c. Height (distance of planes)
d. Parallelism of planes
e. Perpendicularity of plane to cylinder axis
f. Cylindricity

Time Results

- 2 scans on each side of the cylinder– 3 minutes each
- Completing data acquisition – 2 minutes for each scan
- Mesh the point clouds – 2 minutes

Pin Gage without matte spray

Process Notes

Given the material/surfaced finish of the pin gage, it was necessary to use matte spray.

5.3 Accusize Steel Gage Block Set Grade B 4”

5.3.1 CMM *[Appendix D, Figures 23,24,25,26]*

Measurements Collected by CMM

a. Flatness of sides
b. Perpendicularity of planes
c. Length and width

Time Results

- Turn on machine, set up part, open new inspection plan, geometry requalification, qualify passive – 15 minutes

- Create base alignment, clearance plane, collect features and characteristics, define inspection by cookbook parameters - 30 minutes
- Run inspection plan – 6 minutes

Process Notes
It was notes on the gage block set that the tolerance for distance measurement is affected by the thermal expansion based on the temperature of the building.

5.3.2 Blue Light Scanner *[Appendix D, Figures 27, 28]*

Measurements Collected by Blue Light Scanner

a. Flatness of sides
b. Perpendicularity of planes
c. Length and width (distance of planes)
d. Parallelism of planes
e. Angle of intersection of two planes

Time Results

- 2 scans on each side of the block – 3 minutes each
- Completing data acquisition – 2 minutes for each scan
- Mesh the point clouds – 2 minutes

Process Notes

Matte spray was not necessary given the surface finish of the part. However, if there were concave geometries, matte spray would be necessary to capture them (similar to the cylinder geometry on the ring gage).

5.4 DMG MORI Calibration Ball

5.4.1 CMM *[Appendix D, Figure 29]*

Measurements Collected by CMM

a. Diameter
b. Roundness

Time Results

- Turn on machine, set up part, open new inspection plan, geometry requalification, qualify passive – 20 minutes
- Create base alignment and clearance plane - 20 minutes
- Collect features and characteristics, define inspection by cookbook parameters - 30 minutes
- Run inspection plan – 14 minutes

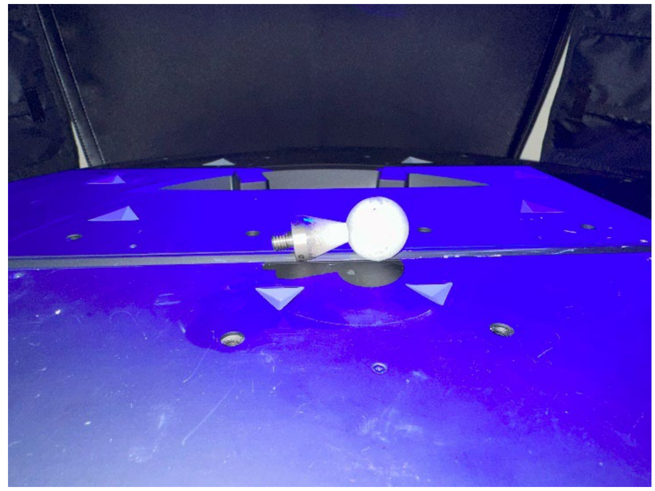
Process Notes

The initial set up of the CMM was longer than the previous because the star stylus was necessary. Thus, each probe tip used must go through passive qualification. The vice was also necessary for creating the base alignment with this part due to the symmetry of the sphere. It was necessary to recapture features for base alignment. This is essential if the calibration ball and/or the vice (used for planar reference) have been moved. It was necessary to completely redo the base alignment to only be the vice, then add sphere as feature in relation to the base alignment.

5.4.2 Blue Light Scanner *[Appendix D, Figure 30]*

Measurements Collected by Blue Light Scanner

a. Diameter
b. Radius
c. Roundness
d. Center coordinates (X,Y,Z)


Callibration Ball positioned in Blue Light Scanner System with matte spray

Time Results

- 2 scans on each side of the sphere – 3 minutes each
- Completing data acquisition – 2 minutes for each scan
- Mesh the point clouds – 30 minutes

Process Notes

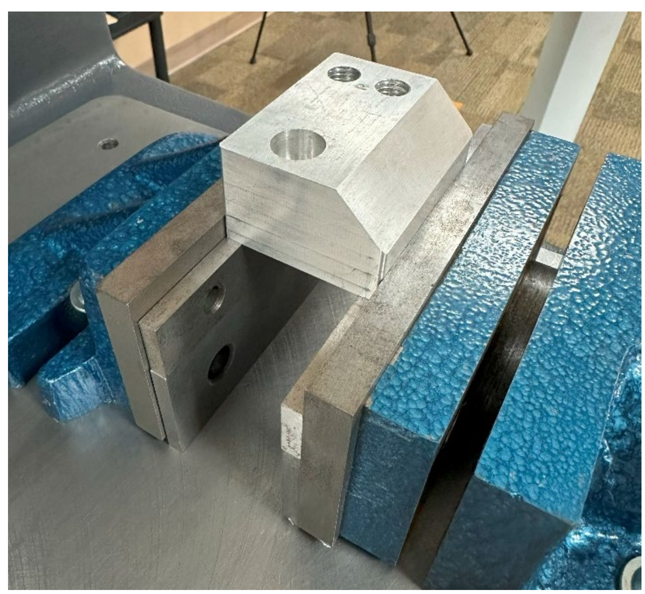
Data composition took 30 minutes due to the part did not want to stich to the correct side. Clocking issue due to symmetry, but mostly due to the lack of any planes. Putty was added to thread to distinguish feature side.

5.5 Aluminum "Guide Block"

5.5.1 CMM *[Appendix D, Figure 31]*

Measurements Collected by CMM

a. location of holes
b. depth of holes
c. cylindricity of hole
d. diameter of holes
e. flatness of surfaces
f. perpendicularity
g. angularity of slanted plane (joint of two planes)
h. parallelism between planes


Guide block positioned on vice

Time Results

- Turn on machine, set up part, open new inspection plan, geometry requalification, qualify passive – 20 minutes
- Import CAD drawing, create base alignment and clearance plane, collect features and characteristics, define inspection by cookbook parameters - 20 minutes
- Run inspection plan – 3 minutes

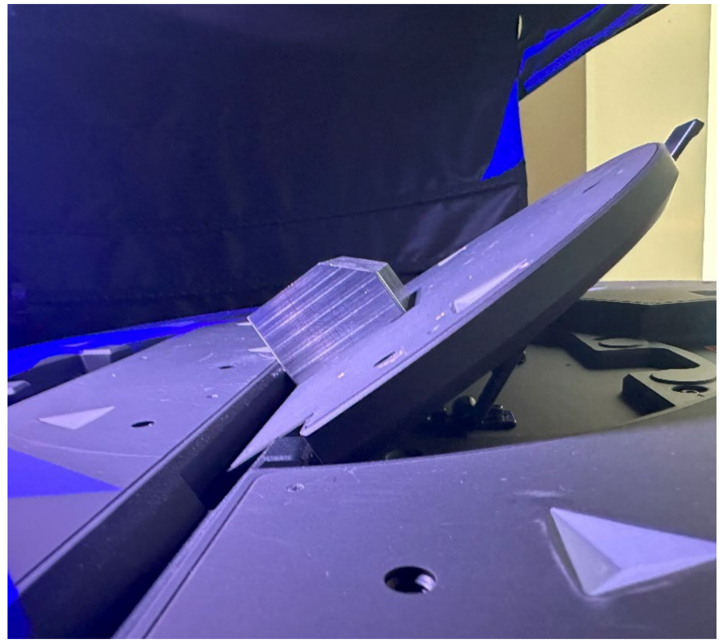
Process Notes

It was necessary to use the vice previously used for base alignment to secure the guide block in place for inspection. The aluminum guide block has a CAD drawing that can be imported to the CMM versus the standard procedure used previously. By importing the CAD drawing of the guide block, lots of time was saved.

5.5.2 Blue Light Scanner *[Appendix D, Figures 32,33]*

Measurements Collected by Blue Light Scanner

a. location of holes
b. depth of holes
c. cylindricity of hole
d. diameter of holes
e. flatness of surfaces
f. perpendicularity
g. angularity of slanted plane
h. parallelism between planes



Guide Block positioned for second scan

Time Results

- 3 scans - 1 minute 45 seconds each
    - One flat upright, one upright propped up on angled stand, one downright
- Data acquisition and merge for all three – 15 minutes

Process Notes

It was necessary to manually turn down the brightness of the lighting to reduce the refraction. Even with spraying matte spray, bore hole (internal cylinder) could not be captured with this system.

5.6 POLYMER COLORS

Colors Collected by Blue Light Scanner

a. Black
b. White
c. Blue
d. Red
e. Yellow
f. Orange

Process Notes

The purpose of this section is to capture results related to the color of the material finish and analyze this factor in relation to blue light. This is due to the blue light scanning system visually collecting data while the CMM gathers the data tactilely. The above colors did not have an effect on the data collection [*Appendix E, Figures 34-39].*

6 Analysis

6.1 CMM

Overall, it can be noted that the CMM does require more training and knowledge base to be sufficiently able to successfully create an inspection plan. The CMM also resulted in more technical and process errors which requires active troubleshooting and monitoring. With that being said, this issue presented itself more in this research due to the low volume of parts and high variety of geometries. This would be far less of a concern with a large volume of minimal variety parts. The operator of this machine would not necessarily need to be able to program and create the inspection plan but would simply need to place the part and run the program. There was also a large disadvantage to using this system with highly symmetrical parts that lacked planes such as cylinders, spheres, etc.

The cookbook was formulated with statistical analysis and significance for the part/feature size, thus in a standard inspection, the cookbook specifications should take the longest inspection time running at the max speed specified. So hypothetically, most environments will not need to be as detailed data collection as the cookbook and thus inspection time will decrease.

However, if there is a circumstance where there needs to be more data collection for a certain characteristic, it should be noted that the number of points/steps should be increased and thus the max speed may decrease due to the concentration of data points needing to be collected over whatever distance. Increasing the number of data points collected does not affect the tolerance, it simply gives more opportunity for the part to be out of tolerance. For example, collecting three points of a plane for flatness compared to collecting 1300. Overall, more points collected will provide greater accuracy of the plane but does not necessarily increase inspection time.

6.2 Blue Light Scanner

Contrary to the CMM, the blue light scanning system requires much less training and experience in order to efficiently complete an inspection. Opposite of the CMM, there is not an inspection plan created, the data collection is the entire process. With that being said there is not a benefit to having a large volume of the same part as each one would be processed the same. Thus, this system is more valuable for a low volume, high variability situation. It should be noted that while color was not a hindrance to the visual data collection, material finish such as shininess must be compensated with a matte spray for effective collection.

7 Conclusion

The development of the Model-Based Metrology Inspection Guide uncovered key lessons applicable beyond this project. One lesson emphasizes the pivotal role of precision and accuracy in robust quality control. A comparison between CMMs and Blue Light Scanning systems highlighted their respective strengths and limitations. CMMs excel in precision for geometries like angles and radii, but struggle with small features and rough surfaces. Conversely, Blue Light Scanners adeptly capture unique features but may need a surface treatment for reflective materials. Manufacturers must comprehend these system-specific advantages and disadvantages to choose the most suitable one for their applications.

Another vital lesson underscores the importance of selecting the right system for optimal efficiency and waste reduction. Making the correct choice initially enables manufacturers to minimize trial-and-error, advancing directly to part inspection. This aligns with Industry 4.0 goals, fostering an interconnected, data-driven manufacturing floor and establishing a lean environment with streamlined processes and reduced waste.

7.1 Future Work

There are a number of steps that can be taken to further improve the functionality of MBM systems. The first, which is directly tied to emerging technologies today, is the advancement of software that can automate various aspects of

MBM. An example of this would be the automatic generation of inspection plans based on the data found in CAD models. This generation would be powered by artificial intelligence and continuously refined by machine learning algorithms. In the age of Lean and time reduction, this method would drastically reduce the time and experience required to operate these systems thus making them more accessible to a wider range of users. Another possible area for advancement is the development of more advanced and less intrusive surface treatment techniques for Blue Light Scanners. For reflective surfaces, this would improve their accuracy and extend the use of these scanners across a wider range of situations. Lastly, an excellent area for advancement is directly tied to key Industry 4.0 technologies: the integration of real-time data analytics and predictive modeling into MBM systems. This active tracking information would allow manufacturers to address quality issues potentially before they ever even occur, enhancing the efficiency and accuracy of manufacturing processes far beyond any level we have ever seen. Integrating MBM systems with Industry 4.0 technologies like the Internet of Things (IoT) devices would lead to a more connected manufacturing ecosystem. Ultimately, integration would not only streamline quality control processes but also provide important data insights for continuous improvement in manufacturing.

From this project, contributions to the Model-Based Metrology process were made not just for small and medium manufacturers, but for all environments by developing a MBM Inspection Guide that provides insights and strategies for operations.

8 APPENDICES

8.1 APPENDIX A

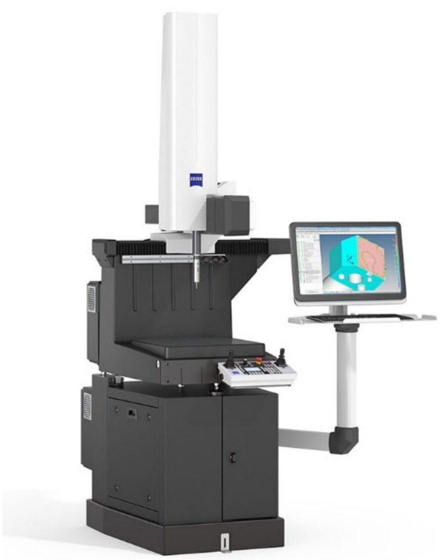


Figure 1

Figure 2

8.2 Appendix B

Figure 3

Figure 4

Figure 5

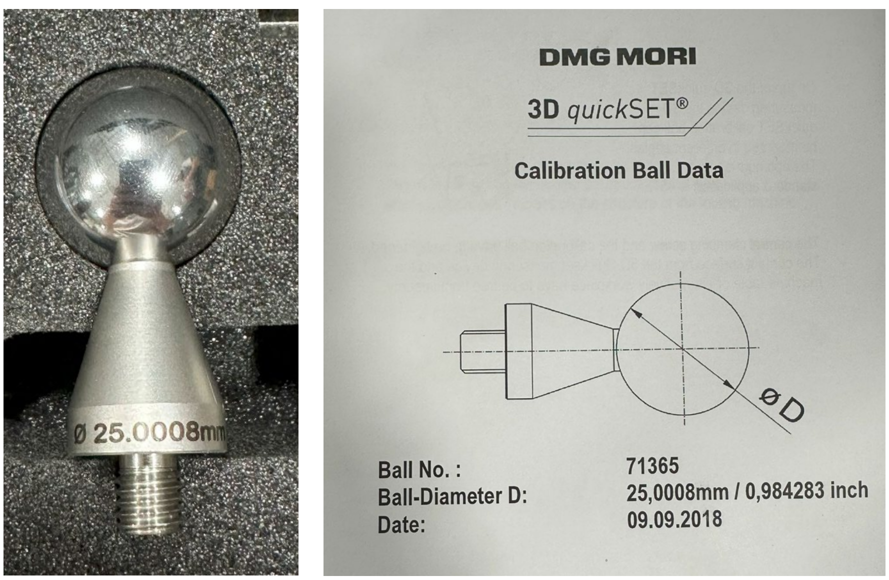


Figure 6

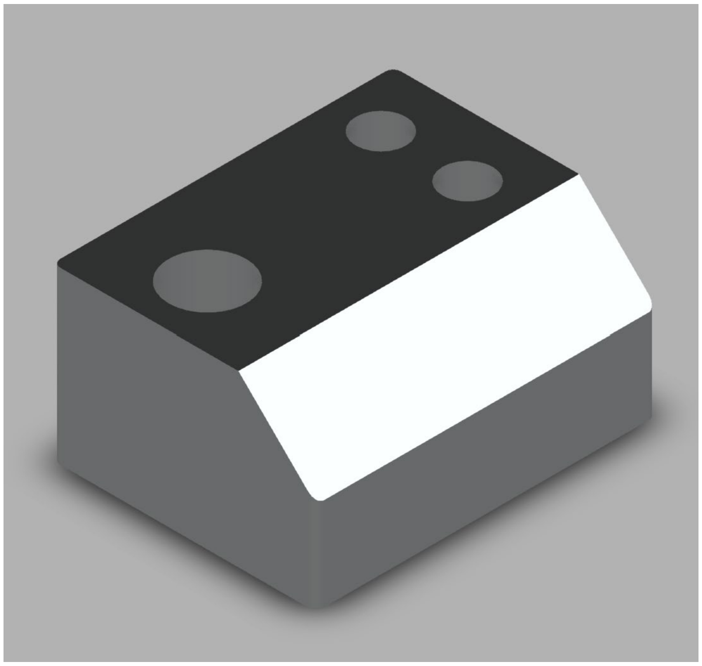


Figure 7

8.3 Appendix C

Figure 8

Figure 9

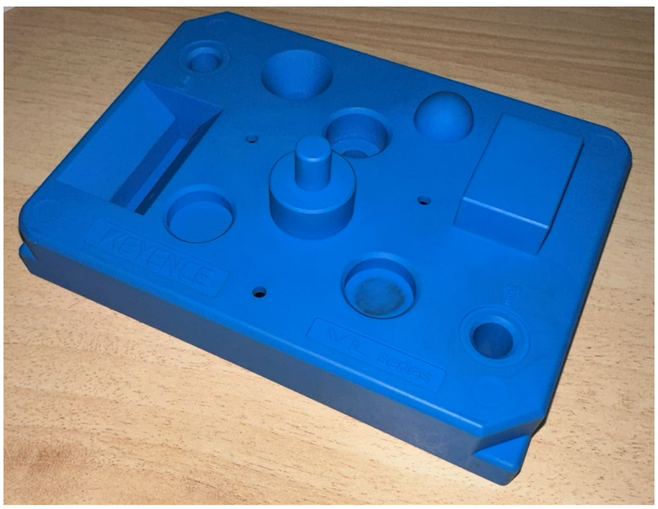


Figure 10

Figure 11

Figure 12

Figure 13

8.4 Appendix D

ZEISS CALYPSO
7.0.08

Part name	**RingGageCw2**		
Drawing number			
Order number		Last 1 measurements	
Variant		► Approval ≠ Blocked	
Company		Part ident	3
Department		Time/Date	5/30/2023 1:23 PM
CMM Type	DURAMAX	Run	All Characteristics
CMM No.	120122	No. measured values	4
Operator	Master	No. values: red	0
Text		Measurement Duration	00:03:03.0

Name	Measured value	Nominal value	[illegible]	-Tol	Deviation	+/-
Diameter_Cylinder1	2.0001	2.0000	0.0050	-0.0050	0.0001	
Cylindricity1	0.0002	0.0000	0.0050	0.0000	0.0002	
Perpendicularity1	0.0007	0.0000	0.0050	0.0000	0.0007	
Flatness1	0.0002	0.0000	0.0050	0.0000	0.0002	

Figure 14

ZEISS CALYPSO
7.0.08

Part name	**RingGageCw2**		
Drawing number			
Order number		Last 1 measurements	
Variant		► Approval ≠ Blocked	
Company		Part ident	4
Department		Time/Date	5/30/2023 1:36 PM
CMM Type	DURAMAX	Run	All Characteristics
CMM No.	120122	No. measured values	4
Operator	Master	No. values: red	1
Text		Measurement Duration	00:03:03.0

Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Diameter_Cylinder1	2.0001	2.0000	0.0005	-0.0005	0.0001		
Cylindricity1	0.0002	0.0000	0.0005	0.0000	0.0002		
Perpendicularity1	0.0008	0.0000	0.0005	0.0000	0.0008		0.0003
Flatness1	0.0002	0.0000	0.0005	0.0000	0.0002		

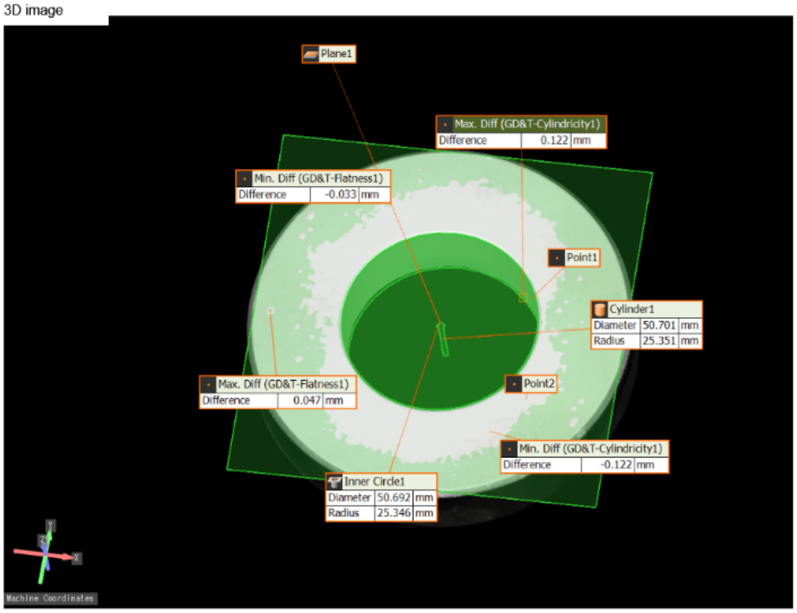
Figure 15

RingGageStitched

3D Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Value	
Cylinder1	Diameter	50.701	mm
Cylinder1	Radius	25.351	mm
Inner Circle1	Diameter	50.692	mm
Inner Circle1	Radius	25.346	mm
Max. Diff (GD&T-Flatness1)	Difference	0.047	mm
Min. Diff (GD&T-Flatness1)	Difference	-0.033	mm
Max. Diff (GD&T-Cylindricity1)	Difference	0.122	mm
Min. Diff (GD&T-Cylindricity1)	Difference	-0.122	mm

Color palette

- 0.200mm
- 0.100mm
- 0.000mm
- -0.100mm
- -0.200mm

Measurement date and time : 7/6/2023 1:47:55 PM

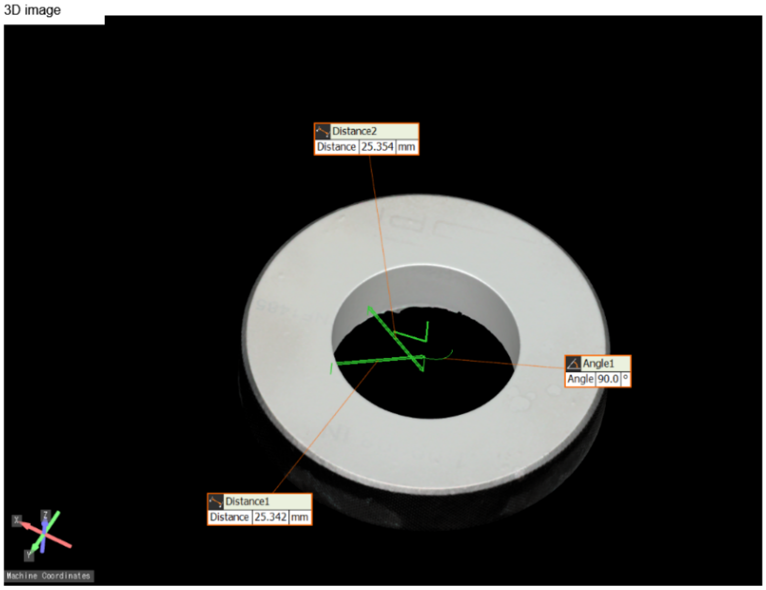
Figure 16

RingGageStitched

3D Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Value	
Angle1	Angle	90.0	°
Distance1	Distance	25.342	mm
Distance2	Distance	25.354	mm

Color palette

- 0.200mm
- 0.100mm
- 0.000mm
- -0.100mm
- -0.200mm

Measurement date and time : 7/6/2023 1:47:55 PM

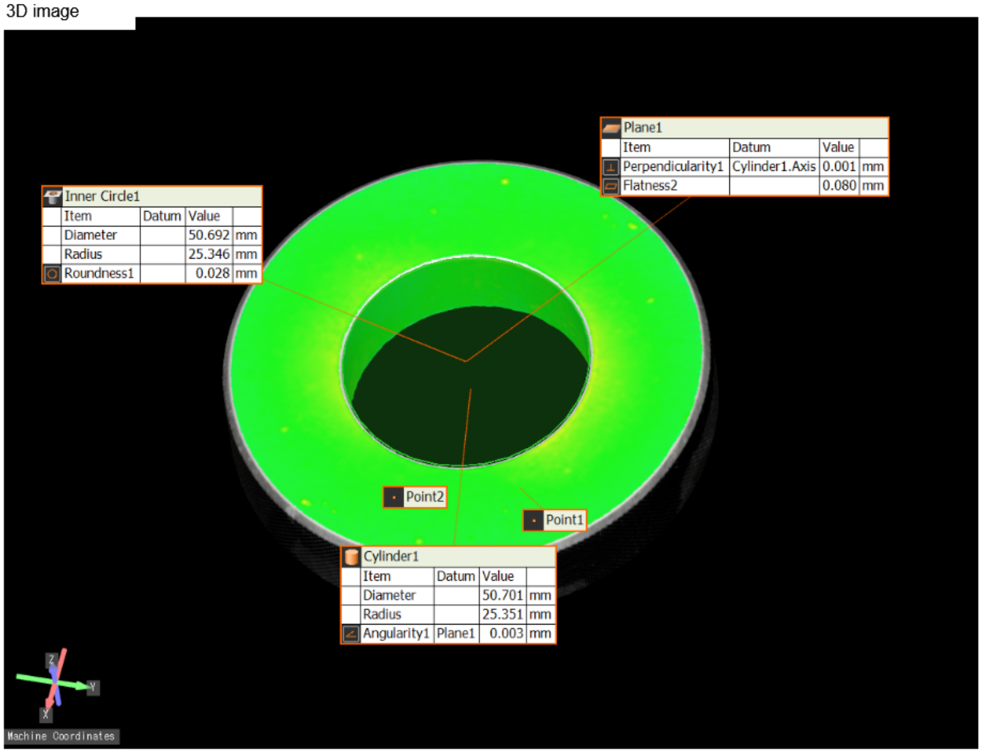
Figure 17

RingGageStitched

GD&T Measurement

Measurement equipment : KEYENCE VL Series

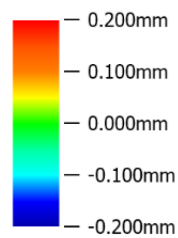
3D image



Measured value list

Element Name	Item Name	Target Element	Datum	Value	
Cylinder1	Diameter			50.701	mm
Cylinder1	Radius			25.351	mm
Inner Circle1	Diameter			50.692	mm
Inner Circle1	Radius			25.346	mm
Perpendicularity1	Perpendicularity	Plane1	Cylinder1.Axis	0.001	mm
Roundness1	Roundness	Inner Circle1		0.028	mm
Angularity1	Angularity	Cylinder1.Axis	Plane1	0.003	mm
Flatness2	Flatness	Plane1		0.080	mm

Color palette



Measurement date and time : 7/6/2023 1:47:55 PM

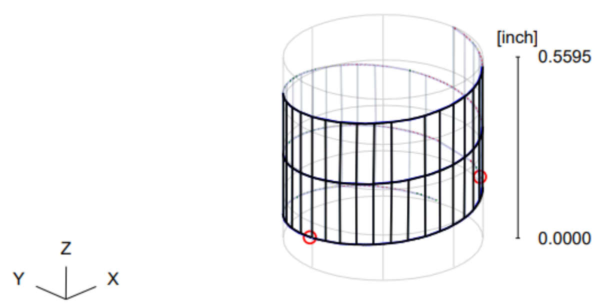
Figure 18

ZEISS CALYPSO
7.0.08

Part name	**PinGageCw1**		
Drawing number			
Order number		Last 1 measurements	
Variant		► Approval ≠ Blocked	
Company		Part ident	7
Department		Time/Date	8/15/2023 3:03 PM
CMM Type	DURAMAX	Run	All Characteristics
CMM No.	120122	No. measured values	6
Operator	Master	No. values: red	4
Text		Measurement Duration	00:03:23.0

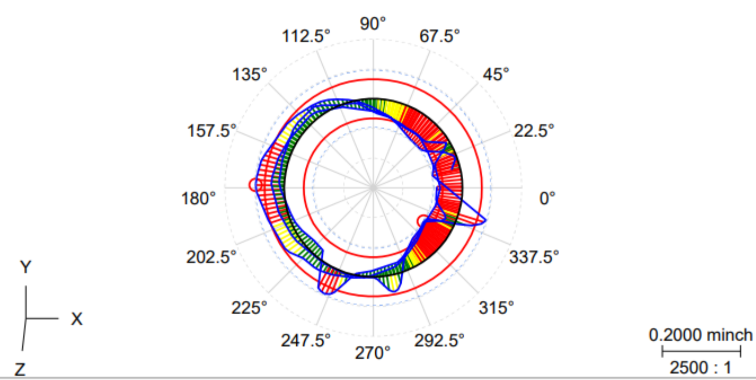
Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Cylindricity1	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000

Points	1583
Filter type	Low-pass Gauss
Lc	
upr	15
Vmess[mm/sec]	2.00
Probe radius	1.4996
Evaluation method	Minimum Feature



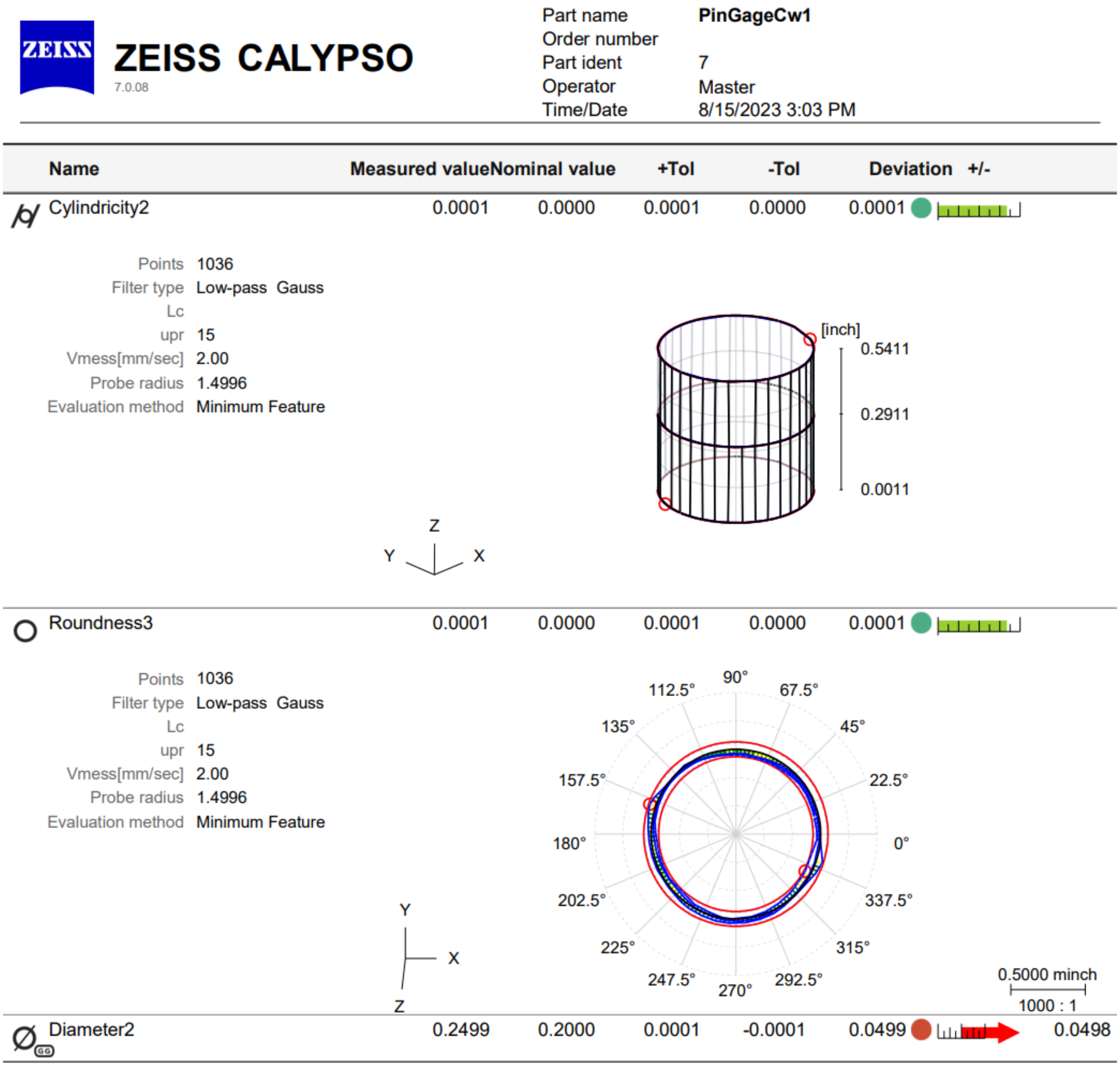
Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Roundness2	0.0001	0.0000	0.0001	0.0000	0.0001	0.0000

Points	1583
Filter type	Low-pass Gauss
Lc	
upr	15
Vmess[mm/sec]	2.00
Probe radius	1.4996
Evaluation method	Minimum Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Diameter1	0.2499	0.2000	0.0001	-0.0001	0.0499	0.0498

Figure 19



Part name	**PinGageCw1**
Order number	
Part ident	7
Operator	Master
Time/Date	8/15/2023 3:03 PM

ZEISS CALYPSO
7.0.08

Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Cylindricity2	0.0001	0.0000	0.0001	0.0000	0.0001	
Roundness3	0.0001	0.0000	0.0001	0.0000	0.0001	
Diameter2	0.2499	0.2000	0.0001	-0.0001	0.0499	0.0498

Cylindricity2:

Points	1036
Filter type	Low-pass Gauss
Lc	
upr	15
Vmess[mm/sec]	2.00
Probe radius	1.4996
Evaluation method	Minimum Feature

Roundness3:

Points	1036
Filter type	Low-pass Gauss
Lc	
upr	15
Vmess[mm/sec]	2.00
Probe radius	1.4996
Evaluation method	Minimum Feature

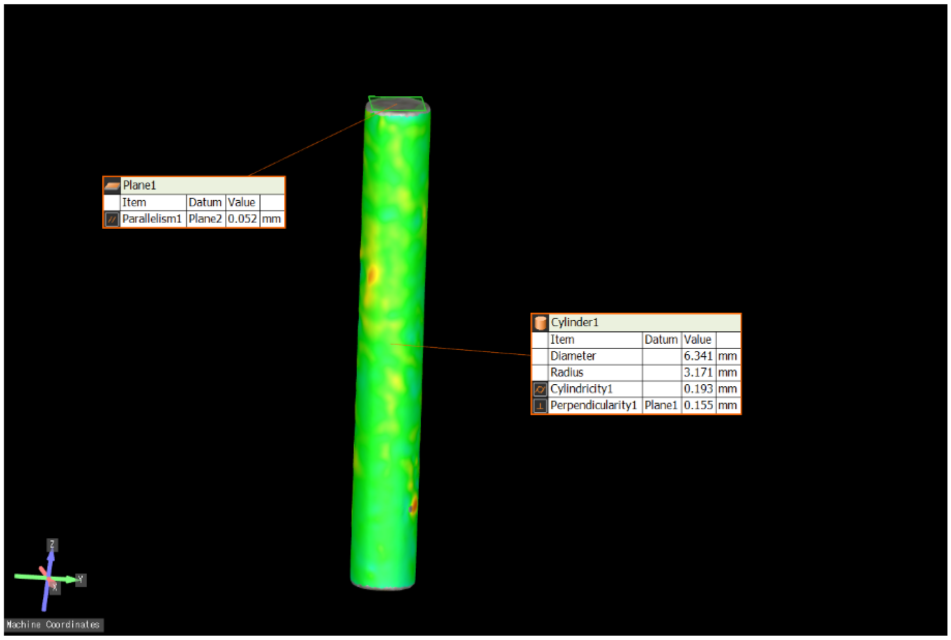
Figure 20

PinGageStitched

GD&T Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Target Element	Datum	Value	
Cylinder1	Diameter			6.341	mm
Cylinder1	Radius			3.171	mm
Cylindricity1	Cylindricity	Cylinder1		0.193	mm
Parallelism1	Parallelism	Plane1	Plane2	0.052	mm
Perpendicularity1	Perpendicularity	Cylinder1.Axis	Plane1	0.155	mm

Color palette

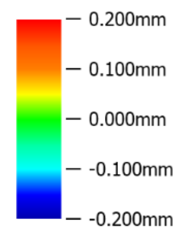


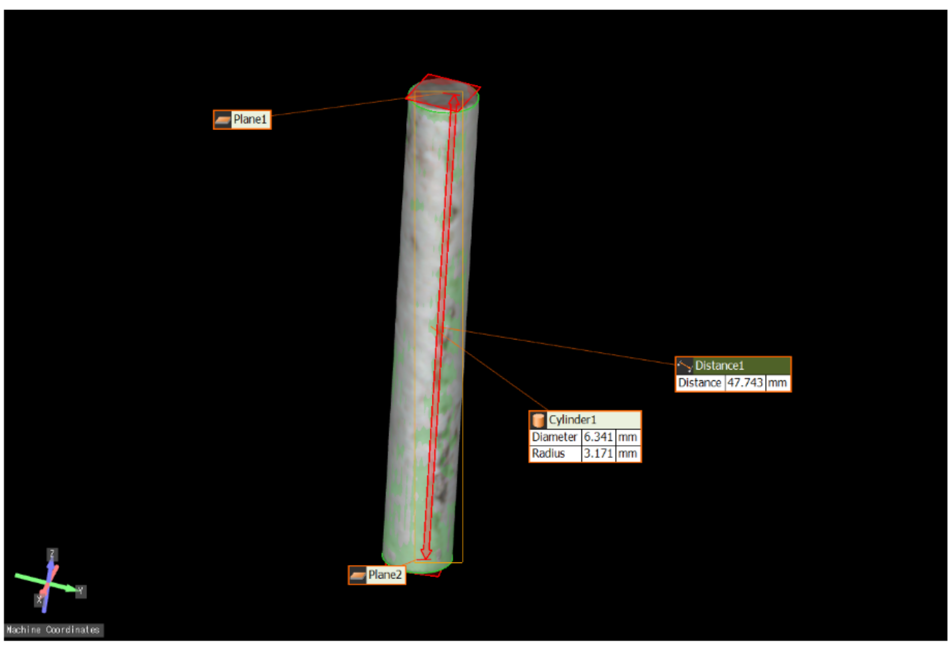
Figure 21

PinGageStitched

3D Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Value	
Cylinder1	Diameter	6.341	mm
Cylinder1	Radius	3.171	mm
Distance1	Distance	47.743	mm

Color palette

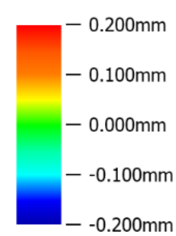


Figure 22

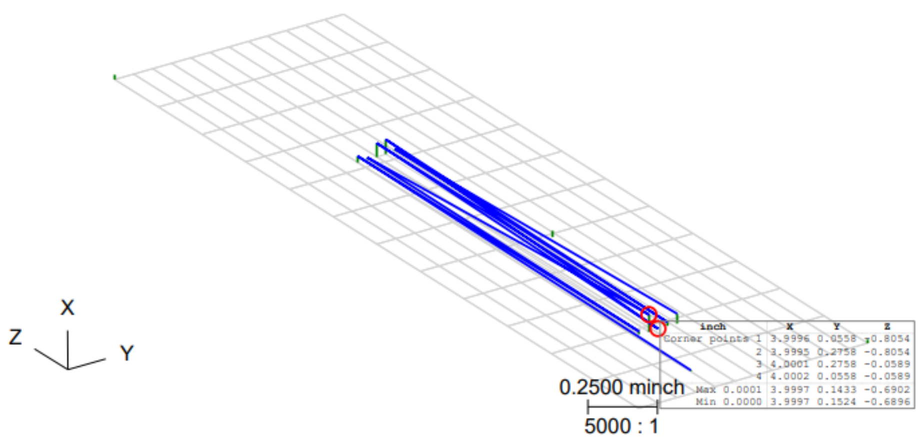
ZEISS CALYPSO

7.0.08

Part name	**4inGageBlock**			
Drawing number				
Order number			Last 1 measurements	
Variant			► Approval ≠ Blocked	
Company			Part ident	1
Department			Time/Date	8/15/2023 12:13 PM
CMM Type	DURAMAX		Run	All Characteristics
CMM No.	120122		No. measured values	11
Operator	Master		No. values: red	2
Text			Measurement Duration	00:06:17.0

Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
// Primary Parallelism	0.0001	0.0000	0.0005	0.0000	0.0001	

Points	14
Filter type	No Filter
Lc	
upr	
Vmess[mm/sec]	15.00
Probe radius	1.4996
Evaluation method	LSQ Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Gage Distance	4.0002	4.0000	0.0002	-0.0002	0.0002	
Flatness_Plane1	0.0003	0.0000	0.0005	0.0000	0.0003	

Points	2839
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	Minimum Feature

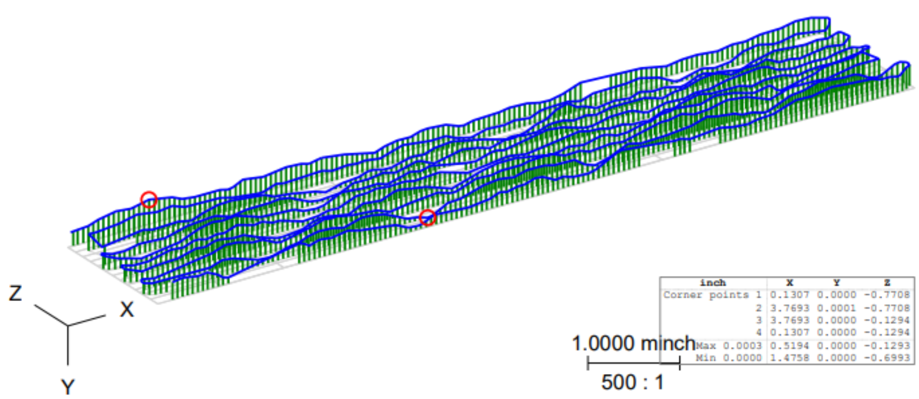


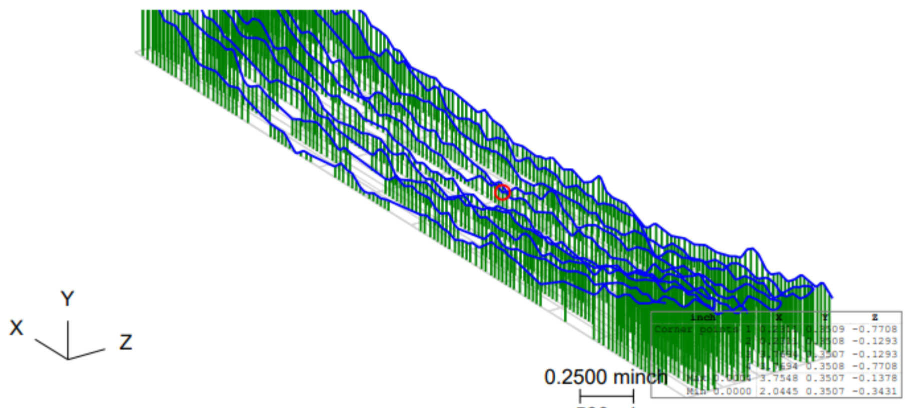
Figure 23

ZEISS CALYPSO
7.0.08

Part name	**4inGageBlock**
Order number	
Part ident	1
Operator	Master
Time/Date	8/15/2023 12:13 PM

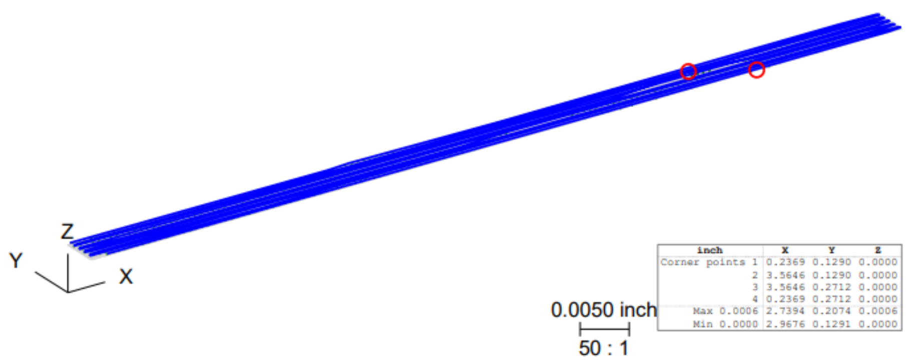
Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Flatness_Plane2	0.0004	0.0000	0.0005	0.0000	0.0004		

Points	2655
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	Minimum Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Flatness_Plane3	0.0006	0.0000	0.0005	0.0000	0.0006		0.0001

Points	2491
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	Minimum Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Flatness_Plane4	0.0000	0.0000	0.0005	0.0000	0.0000		

Points	561
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	Minimum Feature

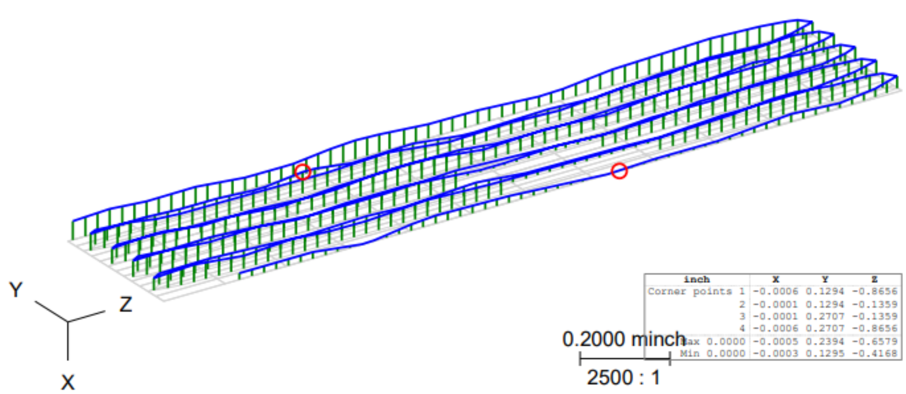


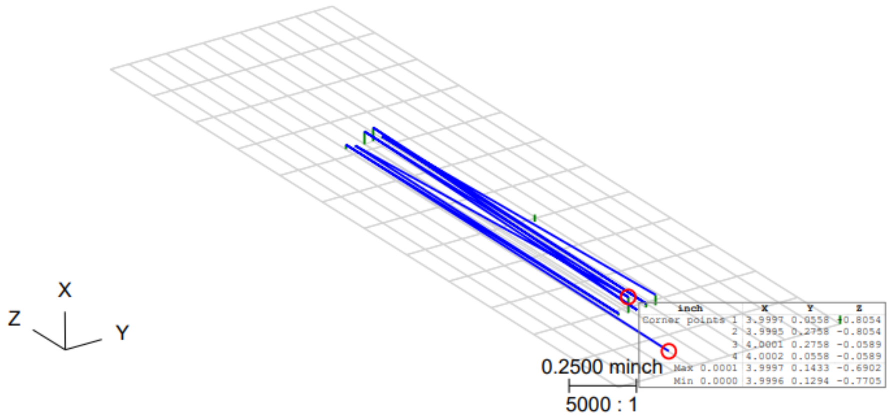
Figure 24

ZEISS **ZEISS CALYPSO**
7.0.08

Part name	**4inGageBlock**
Order number	
Part ident	1
Operator	Master
Time/Date	8/15/2023 12:13 PM

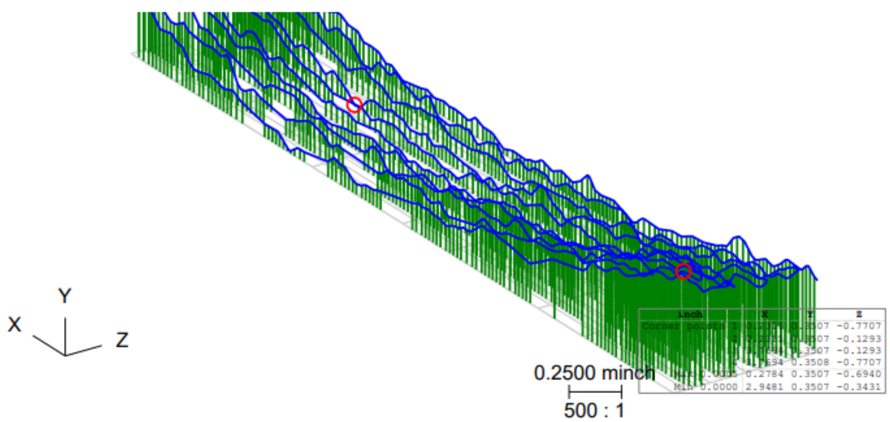
Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Flatness_Plane5	0.0001	0.0000	0.0005	0.0000	0.0001		

Points	14
Filter type	No Filter
Lc	
upr	
Vmess[mm/sec]	15.00
Probe radius	1.4996
Evaluation method	Minimum Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Secondary Parallelism	0.0005	0.0000	0.0005	0.0000	0.0005		0.0000

Points	2655
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	LSQ Feature



Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-	
Perpendicularity1	0.0019	0.0000	0.0050	0.0000	0.0019		

Points	2655
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	LSQ Feature

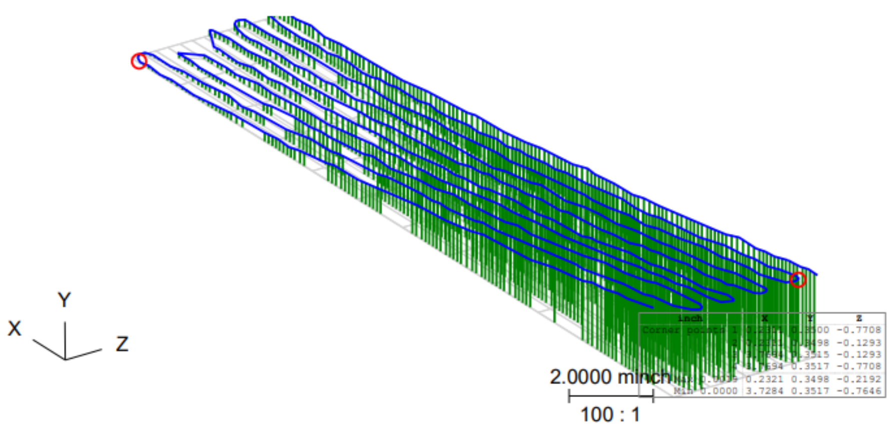


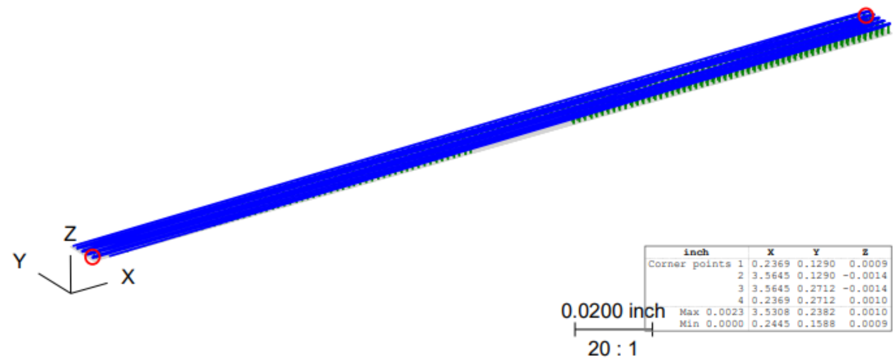
Figure 25

ZEISS CALYPSO
7.0.08

Part name	**4inGageBlock**
Order number	
Part ident	1
Operator	Master
Time/Date	8/15/2023 12:13 PM

	Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
⊥	Perpendicularity2	0.0023	0.0000	0.0050	0.0000	0.0023	

Points	2491
Filter type	Low-pass Gauss
Lc	2.5
upr	
Vmess[mm/sec]	10.01
Probe radius	1.4996
Evaluation method	LSQ Feature



	Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
⊥	Perpendicularity3	0.0008	0.0000	0.0050	0.0000	0.0008	

Points	14
Filter type	No Filter
Lc	
upr	
Vmess[mm/sec]	15.00
Probe radius	1.4996
Evaluation method	LSQ Feature

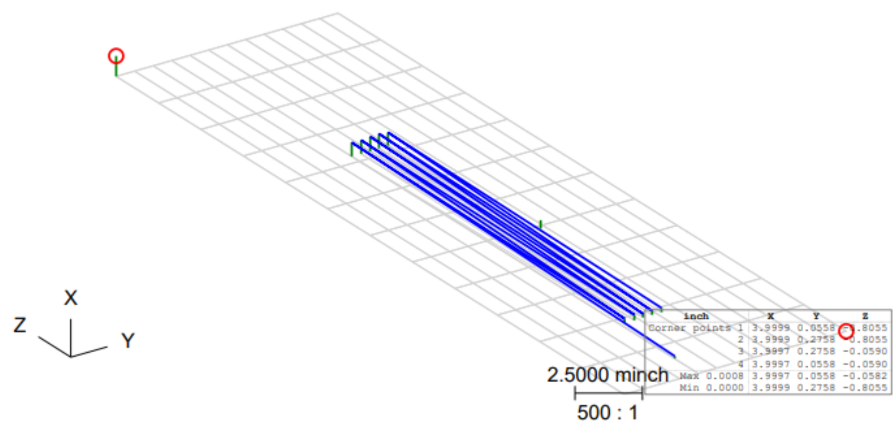


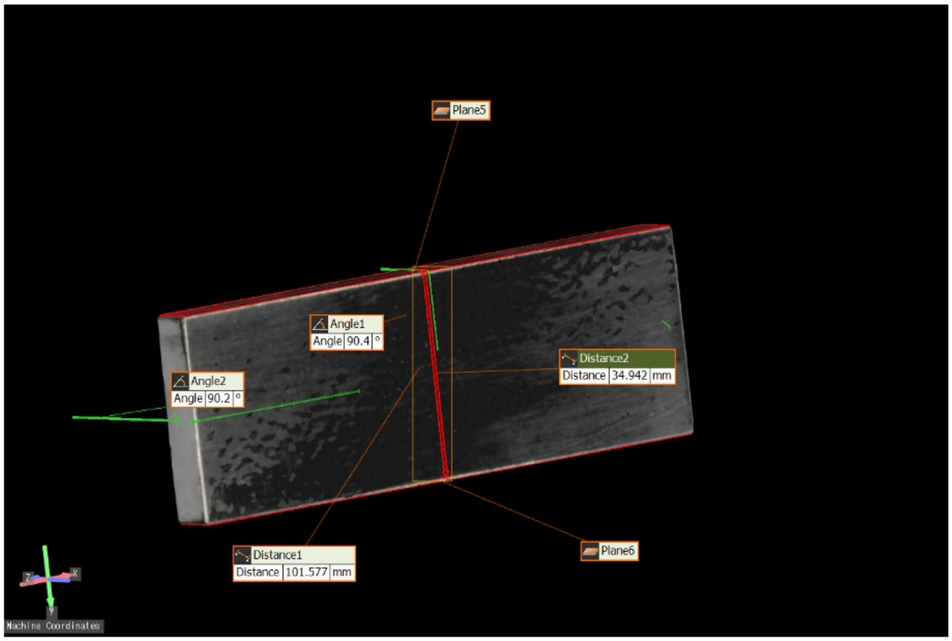
Figure 26

GageBlockStitched

3D Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Value	
Distance1	Distance	101.577	mm
Distance2	Distance	34.942	mm
Angle1	Angle	90.4	°
Angle2	Angle	90.2	°

Color palette

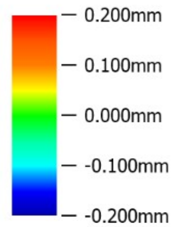


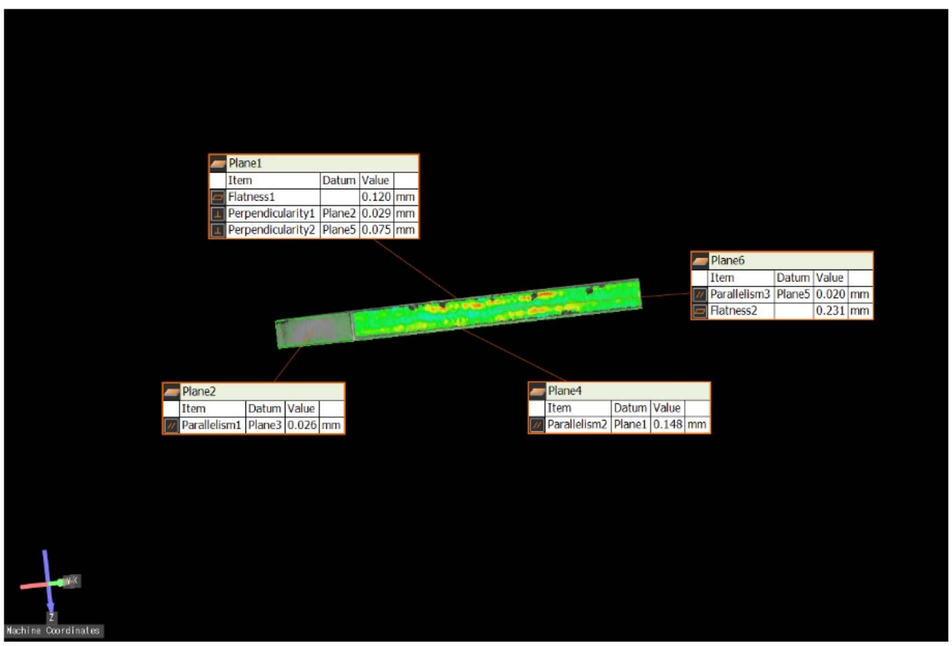
Figure 27

GageBlockStitched

GD&T Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Target Element	Datum	Value	
Parallelism1	Parallelism	Plane2	Plane3	0.026	mm
Parallelism2	Parallelism	Plane4	Plane1	0.148	mm
Parallelism3	Parallelism	Plane6	Plane5	0.020	mm
Flatness1	Flatness	Plane1		0.120	mm
Flatness2	Flatness	Plane6		0.231	mm
Perpendicularity1	Perpendicularity	Plane1	Plane2	0.029	mm
Perpendicularity2	Perpendicularity	Plane1	Plane5	0.075	mm

Color palette

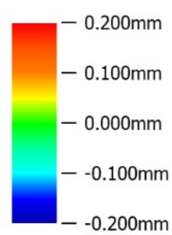


Figure 28

ZEISS CALYPSO
7.0.08

Part name	**SphereGageCw**		
Drawing number			
Order number		Last 1 measurements	
Variant		► Approval ≠ Blocked	
Company		Part ident	6
Department		Time/Date	8/15/2023 11:13 AM
CMM Type	DURAMAX	Run	Current Selection
CMM No.	120122	No. measured values	2
Operator	Master	No. values: red	0
Text		Measurement Duration	00:13:47.0

Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Roundness1	0.0004	0.0000	0.0005	0.0000	0.0004	
Diameter_Sphere2	0.9843	0.9843	0.0001	-0.0001	0.0001	

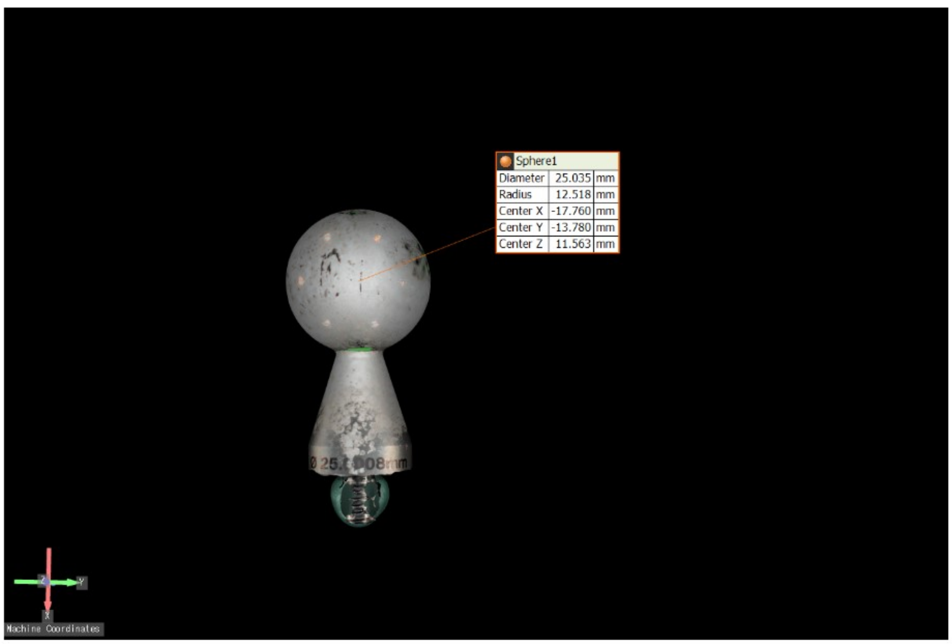
Figure 29

SphereGageStitched

GD&T Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Target Element	Datum	Value	
Sphere1	Diameter			25.035	mm
Sphere1	Radius			12.518	mm
Sphere1	Center X			-17.760	mm
Sphere1	Center Y			-13.780	mm
Sphere1	Center Z			11.563	mm
Roundness1	Roundness	Multi-Pt Cl1		Disabled	mm

Color palette

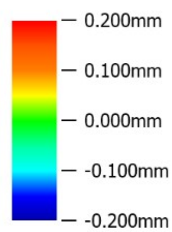


Figure 30

ZEISS CALYPSO
7.0.08

Part name	**guideblockcw**		
Drawing number			
Order number		Last 1 measurements	
Variant		► Approval ≠ Blocked	
Company		Part ident	1
Department		Time/Date	9/7/2023 11:54 AM
CMM Type	DURAMAX	Run	All Characteristics
CMM No.	120122	No. measured values	13
Operator	Master	No. values: red	2
Text		Measurement Duration	00:02:31.0

Name	Measured value	Nominal value	+Tol	-Tol	Deviation	+/-
Hole Depth	0.4994	0.5000	0.0050	-0.0050	-0.0006	
width	2.7531	2.7500	0.0059	-0.0059	0.0031	
length	2.1282	2.1250	0.0059	-0.0059	0.0032	
Angularity1	0.0002	0.0000	0.0050	0.	0.0002	
left	0.0008	0.0000	0.0050	0.0000	0.0008	
right	0.0013	0.0000	0.0050	0.0000	0.0013	
front_back	0.0007	0.0000	0.0050	0.0000	0.0007	
largeHole	0.6263	0.6250	0.0050	-0.0050	0.0013	
minordiameterback	0.3621	0.4045	0.0050	-0.0050	-0.0423	-0.0373
minordiameterfront	0.4111	0.4045	0.0050	-0.0050	0.0066	0.0016
CylindricityLargeHole	0.0000	0.0000	0.0050	0.0000	0.0000	
FlatnessTop	0.0004	0.0000	0.0050	0.0000	0.0004	
FlatnessAngle	0.0002	0.0000	0.0050	0.0000	0.0002	

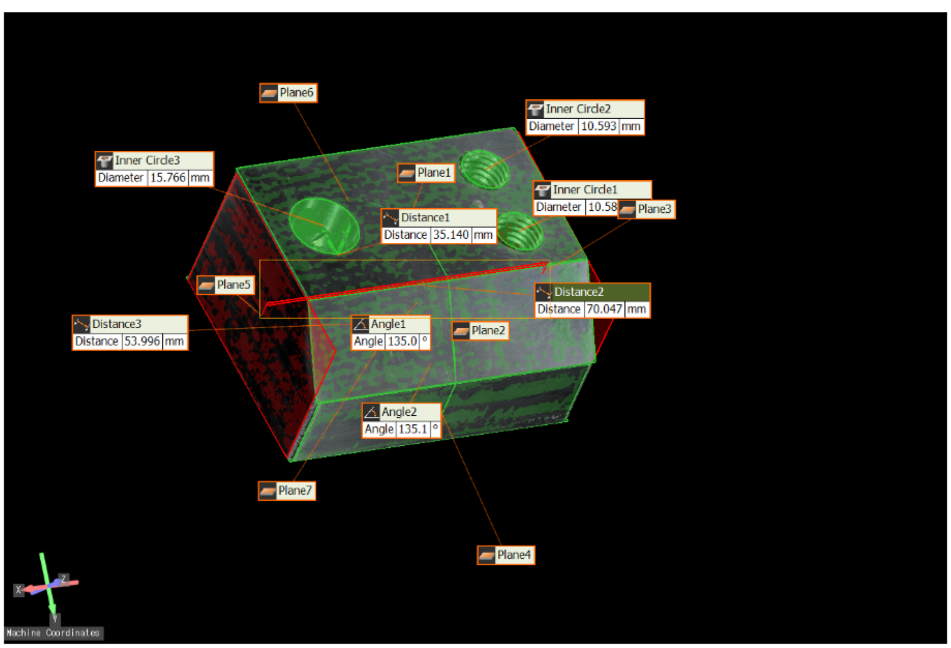
Figure 31

guideblockstitched

3D Measurement

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Value	
Inner Circle1	Diameter	10.585	mm
Inner Circle2	Diameter	10.593	mm
Inner Circle3	Diameter	15.766	mm
Distance1	Distance	35.140	mm
Distance2	Distance	70.047	mm
Distance3	Distance	53.996	mm
Angle1	Angle	135.0	°
Angle2	Angle	135.1	°

Color palette

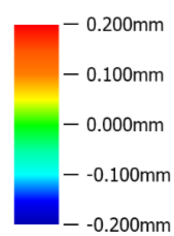
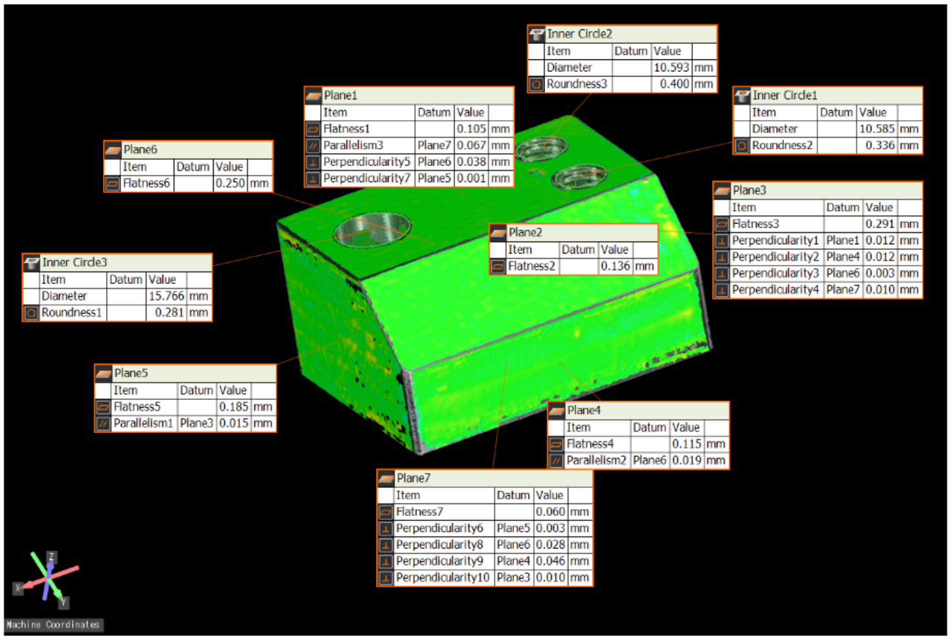


Figure 32

Measurement equipment : KEYENCE VL Series

3D image



Measured value list

Element Name	Item Name	Target Element	Datum	Value	
Inner Circle1	Diameter			10.585	mm
Inner Circle2	Diameter			10.593	mm
Inner Circle3	Diameter			15.766	mm
Flatness1	Flatness	Plane1		0.105	mm
Flatness2	Flatness	Plane2		0.136	mm
Flatness3	Flatness	Plane3		0.291	mm
Flatness4	Flatness	Plane4		0.115	mm
Flatness5	Flatness	Plane5		0.185	mm
Flatness6	Flatness	Plane6		0.250	mm
Flatness7	Flatness	Plane7		0.060	mm
Roundness1	Roundness	Inner Circle3		0.281	mm
Roundness2	Roundness	Inner Circle1		0.336	mm
Roundness3	Roundness	Inner Circle2		0.400	mm
Parallelism1	Parallelism	Plane5	Plane3	0.015	mm
Parallelism2	Parallelism	Plane4	Plane6	0.019	mm
Parallelism3	Parallelism	Plane1	Plane7	0.067	mm
Perpendicularity1	Perpendicularity	Plane3	Plane1	0.012	mm
Perpendicularity2	Perpendicularity	Plane3	Plane4	0.012	mm
Perpendicularity3	Perpendicularity	Plane3	Plane6	0.003	mm
Perpendicularity4	Perpendicularity	Plane3	Plane7	0.010	mm
Perpendicularity5	Perpendicularity	Plane1	Plane6	0.038	mm
Perpendicularity7	Perpendicularity	Plane1	Plane5	0.001	mm
Perpendicularity6	Perpendicularity	Plane7	Plane5	0.003	mm
Perpendicularity8	Perpendicularity	Plane7	Plane6	0.028	mm
Perpendicularity9	Perpendicularity	Plane7	Plane4	0.046	mm
Perpendicularity10	Perpendicularity	Plane7	Plane3	0.010	mm

Color palette

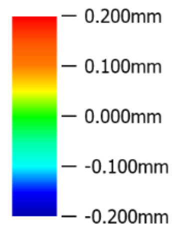


Figure 33

8.5 Appendix E

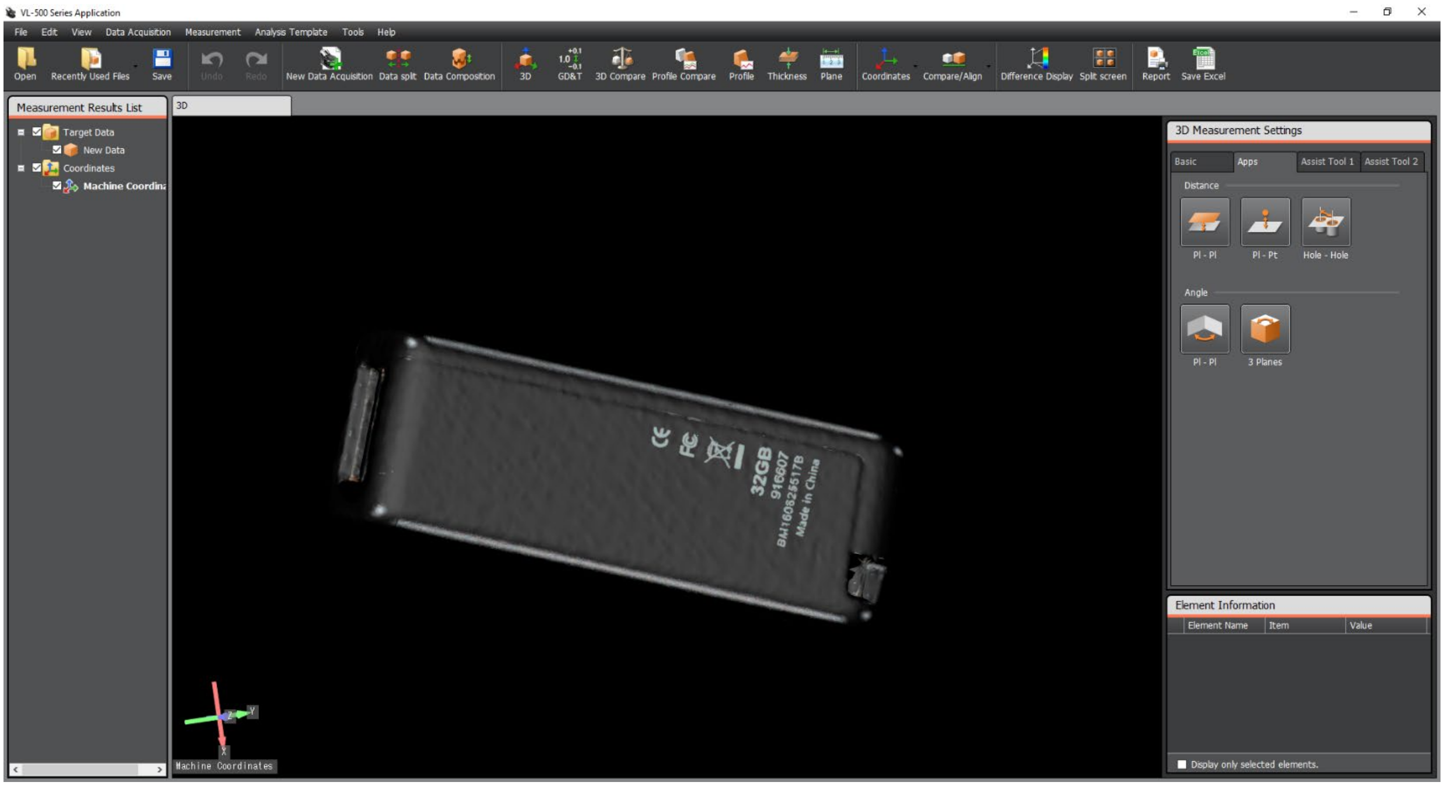


Figure 34

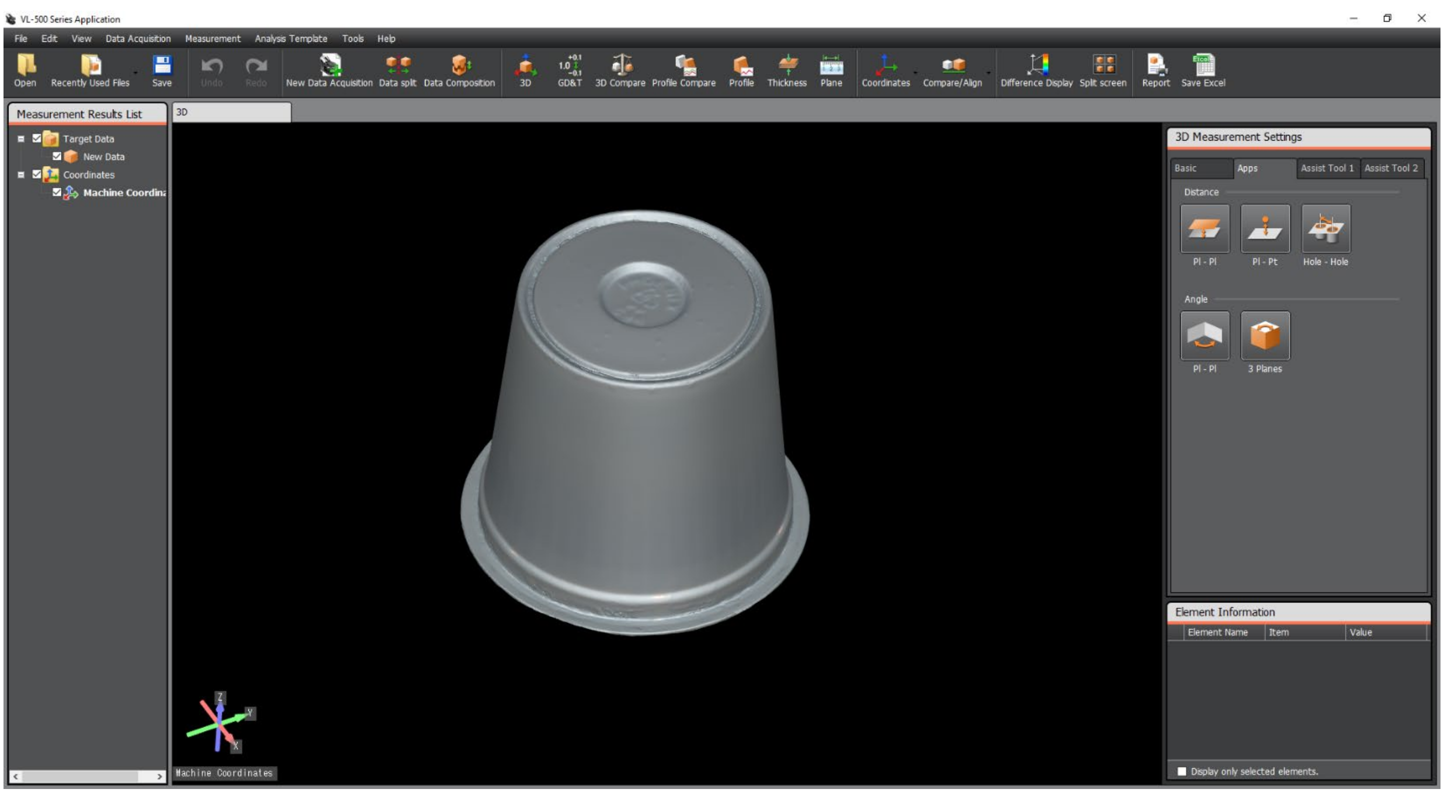


Figure 35

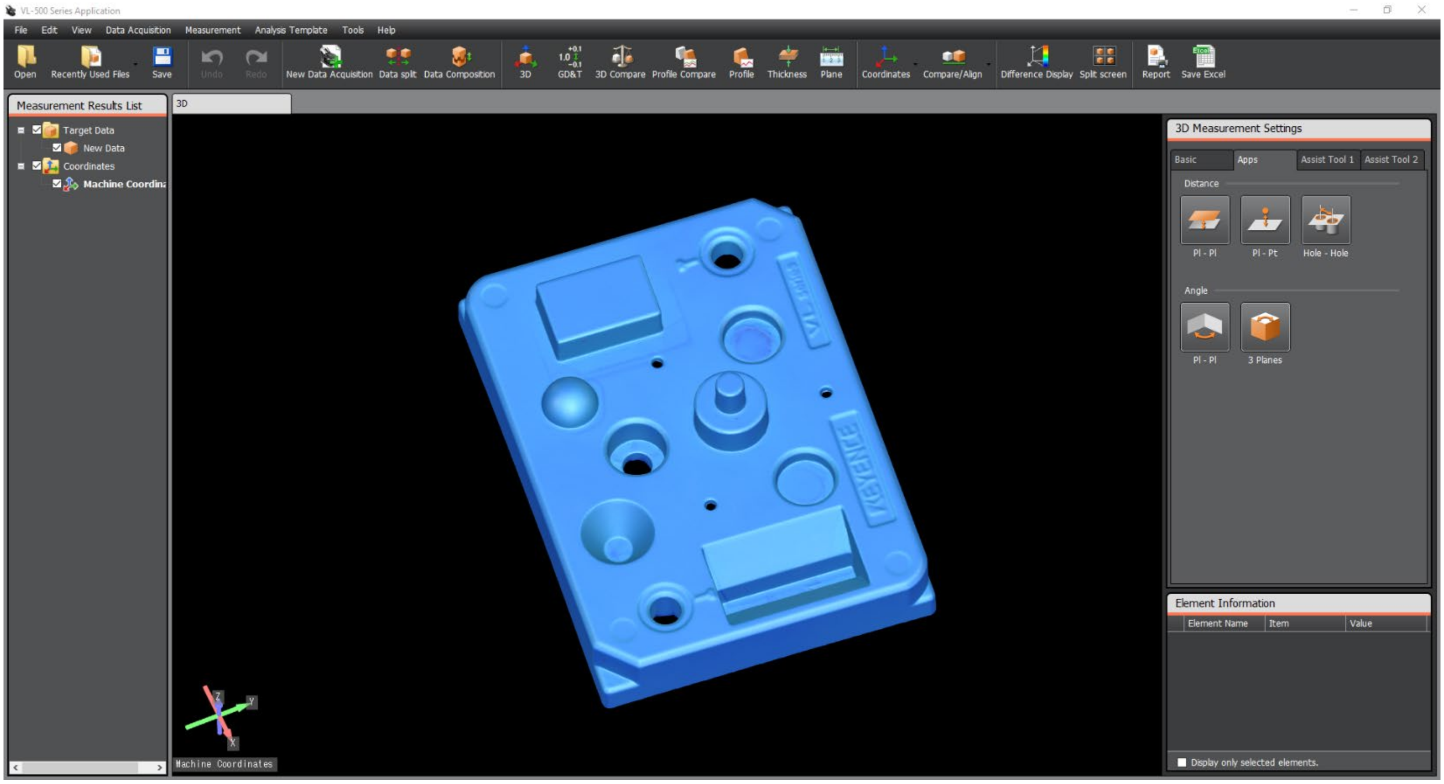


Figure 36

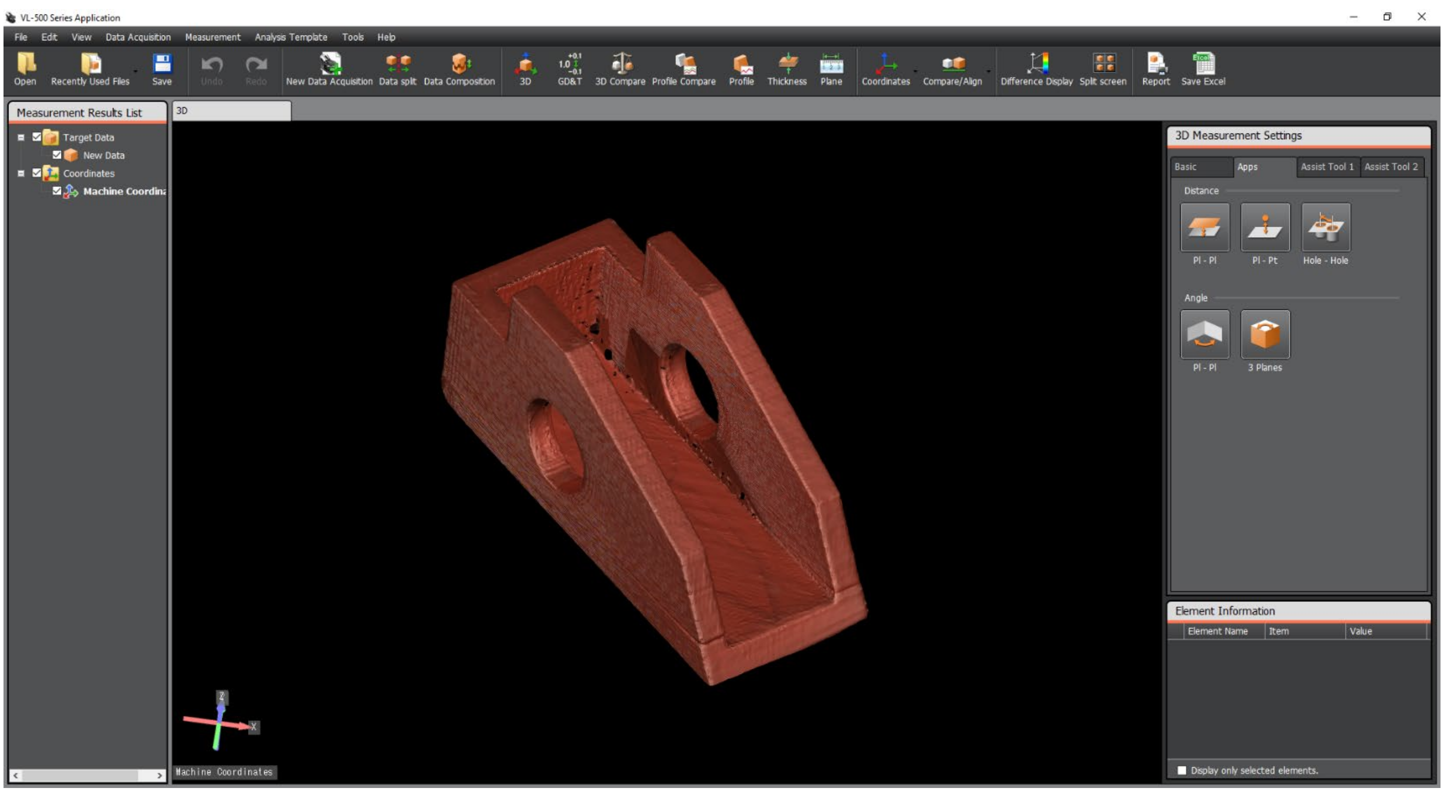


Figure 37

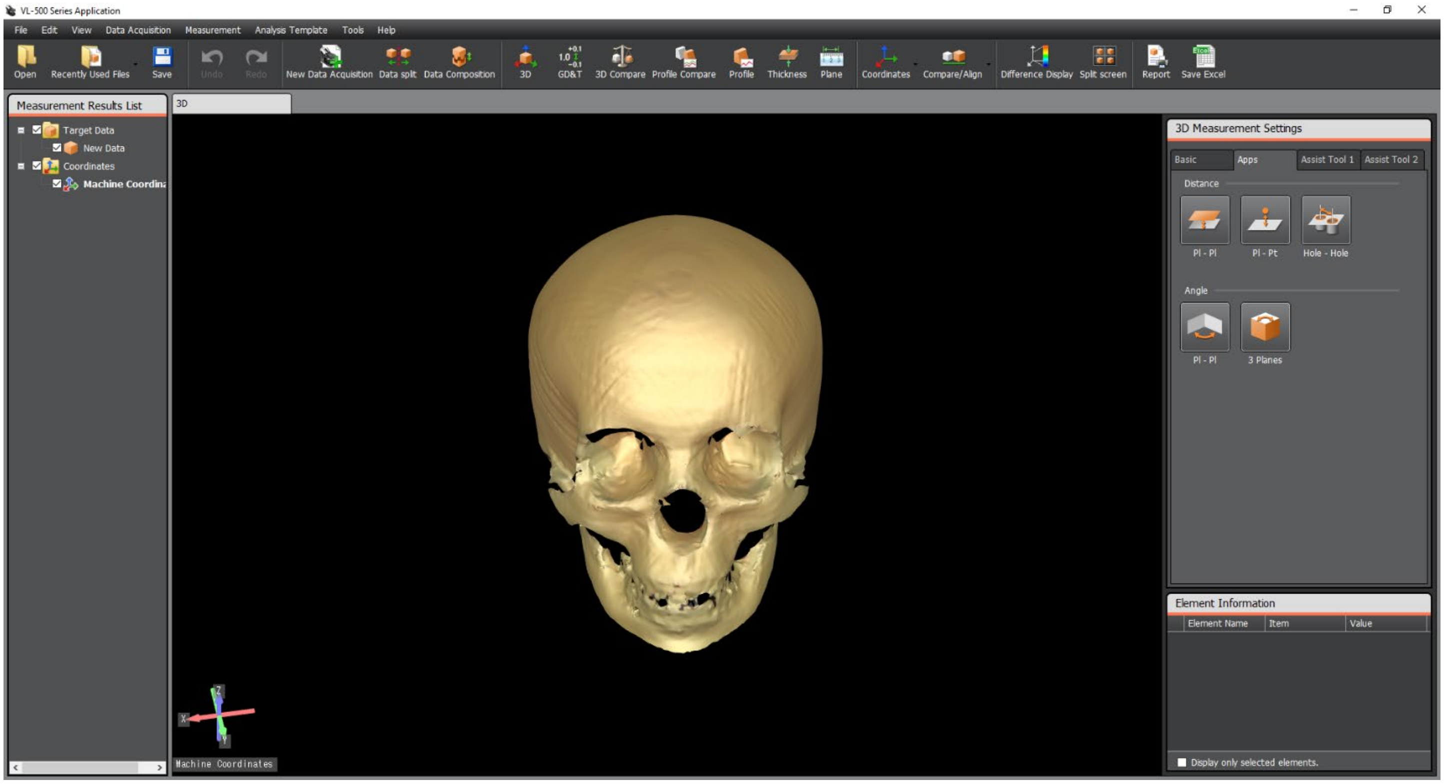


Figure 38

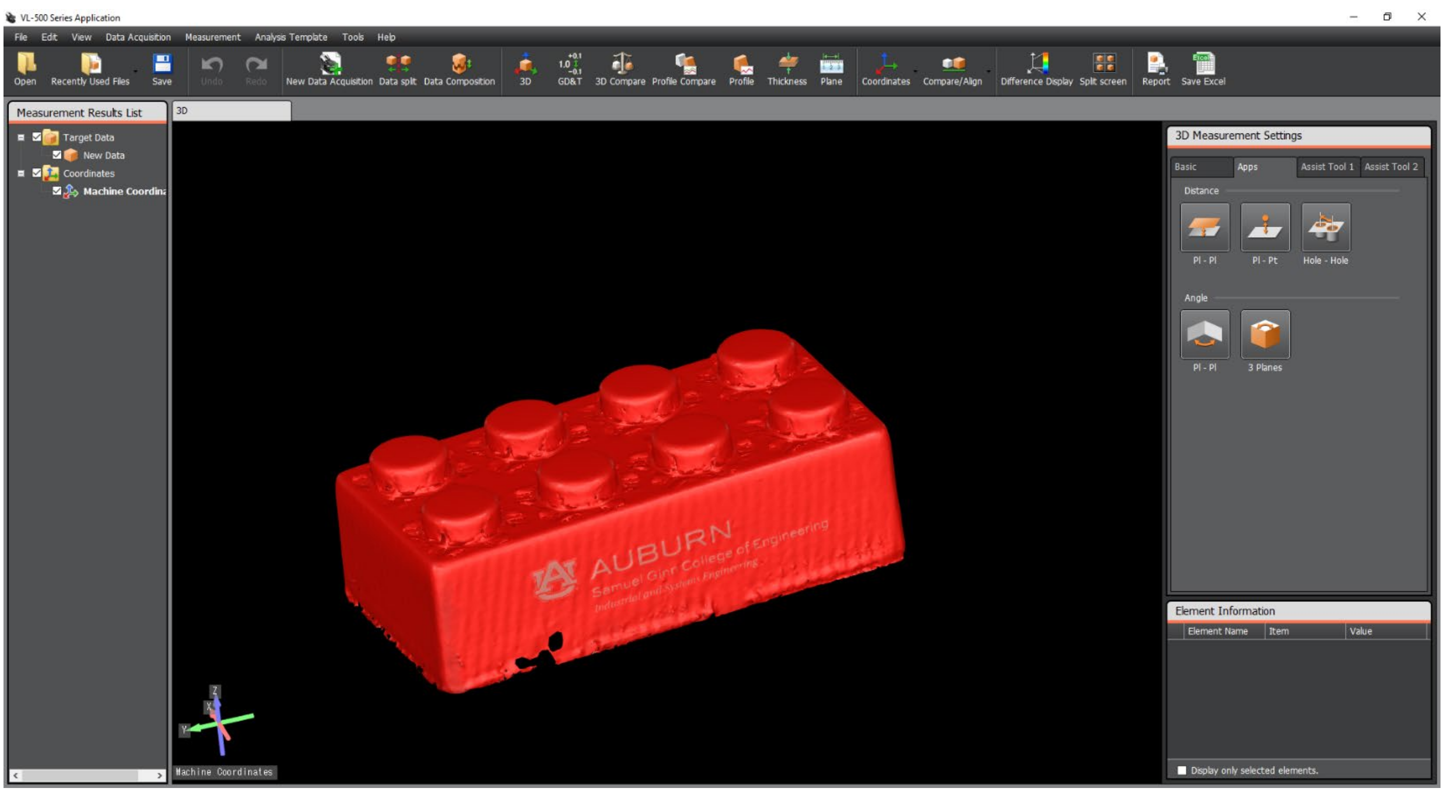


Figure 39

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