COORDINATE MEASUREMENT TECHNOLOGY: A COMPARISON OF SCANNING VERSUS TOUCH TRIGGER PROBE DATA CAPTURE

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Abstract

Manufacturers in the United States utilize coordinate measurement machines to ensure part compliance with specifications. While component material may affect actual results, this study attempted to determine if there was a difference between 3D-printed rapid-prototyped parts using different probes and part contact methodologies. Through the use of a coordinate measurement machine and ZCast® parts for measurement, it was determined statistically that there is a difference in cylindricity accuracy between scanning and touch trigger probe technology.

Introduction

Coordinate measuring machines (CMMs) are widely used in industry to precisely measure parts for inspection or quality control. This study utilized a CMM to measure cylindricity and assess accuracy results between scanning and touch trigger probe technologies on rapid-prototyped (RP) parts that were 3D printed using ZCast® build material and a ZCorp 310 printer. Since no prior studies were found that compared scanning and touch trigger probes, this study sought to evaluate these measurement devices and their potential measurement variances to aid both academic and industrial metrology practitioners.

Review of Coordinate Measuring Machines (CMM)

A coordinate measuring machine (CMM) is used to accurately record part geometry data through the use of a contact probe and a mechanism which can position the probe relative to surfaces and features of a work part [1]. A direct computer-controlled coordinate measuring machine (DCC/CMM) is a programmable, computer-controlled coordinate measuring machine. They are different from manual CMMs because DCC units are computer numerically controlled (CNC) machines with precise motors that can accurately control the movements of the CMM [2]. CMMs are widely used in industry today. They are versatile enough to be used for inspection and statistical process control for virtually any geometric shape [3], [4]. Due to the CMM's versatility, speed, and high accuracy, it is considered a suitable measurement device for RP parts [5]. The DCC/CMM can carry out a variety of automatic measurements to determine dimensional and shape errors. This automatic feature minimizes inconsistencies that would be incurred with manual measurements using a non-DCC CMM [5], [6].

Coordinate Measuring Machine Errors and Probe Types

Coordinate measurement machine errors generally occur through two sources: machine structure errors and probe errors. The machine structure errors include geometric errors, dynamic errors, and thermal errors. Probe errors include mechanical lobbing error and delays in the touch detection circuitry [7], [8]. All CMM probes, including optical probes, induce a certain amount of systematic error [9], [10]. Probe pre-travel or lobbing error is the distance between the point at which the probe touches the workpiece and the point at which the trigger is registered [8]. Cosine error occurs when there is a lack of squareness between the part being measured and the contact surface of the CMM probe [11]. Other factors such as temperature and vibration can have a large effect on measurement accuracy. Thermal errors can originate from a wide variety of sources which include: room temperature, lights, and pneumatics [9]. Most manufacturers of CMMs suggest 68ºF as the best precision measuring temperature. Also, temperature variation should be kept to less than 0.2ºF per hour and no more than 1ºF per eight hours [12]. The temperature of the part is just as important as CMM environment temperature. Controlling part temperature can be accomplished through acclimating the part for 15-30 minutes in the CMM's environment [13].

One of the disadvantages of using many CMMs is that they acquire point-by-point data (discrete measurements) which then need to be analyzed so that a substitute geometry can be developed for the part [9], [14]. There are some inherent problems with evaluating geometric errors with discrete measurement points. These problems include: proper definition of geometric errors, proper sample size to evaluate the error, method used to evaluate geometric error, and method used to interpret a given geometric error specification [14]. Most CMMs utilize the least-squares method to calculate these substitute features. The least-squares algorithm is used to fit an ideal form to coordinate data by minimizing the sum of the squared deviations. [3], [4]. However, the point-by-point sampling procedure performed by most CMMs will not determine all of the form deviations of the part, but rather they simply sample the fixed data points. Therefore, the sampling strategy using a CMM (the selection of the number and position of points) can influence the test results [4], [15].

Common probe types include kinematic touch probe (incorporates an internal strain gauge to indicate measurement), optical digitizer probe (utilizes high-quality optics and light to discriminate measurements), analog probe (varying signal style), and force probe (small springs with contact switches). The most popular is the kinematic touch probe which is designed to sense the mechanical contact of the part by closing electrical switches—in tandem with internal strain gages—when force is applied to the probe [7], [8], [10], [16].

Active scanning probes are a relatively new style of probe which is becoming increasingly popular. Active scanning probes have many advantages over conventional touch trigger probes such as increased data acquisition, decreased measurement time, and the elimination of many errors common in conventional probes. There are some major differences in how active scanning probes work compared to touch trigger probes. The main difference with active scanning probes is the use of electrical springs, small linear drives, which generate their probing force electronically instead of mechanically like touch trigger probes. This allows for constant and consistent contact pressure as well as a larger measurement range. This also allows contact pressure to be adjusted, depending on the measurement application. Active scanning probes obtain measurement samples by measuring the deflection of the probe electronically, which virtually eliminates many conventional probe errors. In addition to better accuracy, active scanning probes can collect thousands of sample points in a matter of seconds, which might take conventional touch trigger probes hours [17], [18].

Measuring Cylindricity with a Coordinate Measuring Machine

Cylindricity is defined as a condition of a surface of revolution in which all points of the surface are equidistant from a common axis [19]. When measuring cylindricity, the entire surface is one tolerance zone where the surface must not only be round but also be straight [20]. The three most common ways to measure cylindricity is through the use of air, mechanical, or optical gaging [21].

Throughout the literature, sampling issues are heavily represented. Sampling issues that can affect validity of results deal mainly with the location and number of the sampling points. Careful planning is essential when writing an inspection program for a computer-controlled CMM. Considerations such as number of sample points, location of sample points, path planning, and probe qualification are very important. The higher the number of sampling points taken, the more accurate the results. However, this increase in sampling is directly related to measurement time and data processing costs [6], [14], [22]. CMM inspection techniques may affect the geometric shape of the sample and ultimately part measurements. This is especially true in the presence of unknown part forms and unknown measuring machine errors. Therefore, a much higher number of data points must be taken, especially in the presence of unknown form error [9]. The optimum number of sampling points for cylindricity measurement is still somewhat of a question. However, according to statistical rules, if too few points are taken, the measurement uncertainty will increase. By the same token, if too many points are measured, the cost of measurement will increase [23].

The conventional practice of measuring cylindricity with a CMM is to measure a dense set of points evenly spaced around the circumference at two or three axial locations [24]. The review of literature conveyed a wide range of ideas pertaining to the number of sample points and axial locations that should be measured for determining cylindricity. In industry, it is common to keep the sample size as small as possible such as 4-8 points for cylinder features, whereas most CMMs use six measurement points to determine diameter and cylindricity [3]. However, when using this number, there is a risk of accepting an out-of-specification part [23]. According to the Weckenmann et al. [15], for thorough analysis of the maximum inscribed circle and least-squares circle, 10-20 points are required for accurate measurement data. This correlates with the Jiang & Chiu study [23] which suggests that when the number of measurement points on a cylinder is greater than eight, the confidence interval of 95% is achieved. Also, surface roughness has a great effect on the number of points required for an accurate measurement of form error [9].

The number of axial planes that should be measured on a cylinder is another issue which is very important for the measurement of cylindricity. Again, the literature conveyed a wide range of ideas in this area. For the most part, studies pertaining to the measurement of cylindricity use between 2 -4 axial planes. Jiang & Chiu [23] used three axial measurement planes while Summerhays [24] used four axial measurement planes.

Rapid Prototyping Fundamentals

In the late 1980s, new and faster ways of producing a prototype were developed. These new technologies are considered rapid prototyping (RP). RP is a term used to denote a class of additive processes by which complex, three-dimensional (3-D) objects are created from a computer-generated database [25]. RP techniques use a layer-by-layer process of building a part. The parts that can be produced range from artificial limbs, hearing aids, and filtering devices to cell phone covers and almost anything which can be created in a three-dimensional digitized format. The three-dimensional printing (3DP) process implemented by ZCorp uses ink-jet technology to produce parts for direct manufacturing as well as for rapid prototyping. The process begins by spreading a layer of powder build material at the top of the fabrication chamber to a precise thickness. The jetting head then deposits a liquid adhesive in a two-dimensional pattern, specified by the program, onto the layer of powder. This process is repeated layer after layer until a three-dimensional part is developed.

One of the more recent developments of ZCorp is the material called ZCast® which is engineered for the purpose of producing mold cavities and cores to be used in the casting of many non-ferrous metals. By using ZCast®, companies have the ability to make low-production runs or functional prototypes of castings and cores in a very short period of time. Traditionally, developing a mold or core could take weeks, depending on its complexity. Also, many geometric shapes and attributes, which are not possible with traditional molding techniques, can be accomplished easily with 3DP. However, the accuracy of printed molds and cores can be a limitation. There is a need to develop functional prototypes that are cost effective for the designer and are representative of production castings [26].

Problem Statement

Using a coordinate measurement machine and ZCast® parts for measurement, is there a difference in cylindricity accuracy between scanning and touch trigger probe technology for measurement of rapid-prototyped components?

Hypothesis Statements

Null Hypothesis: There will be no statistically significant difference in the cylindricity accuracy between scanning and touch trigger probe measurements of 3D-printed parts about the X axis at the 0.05 level of significance.

Alternative Hypothesis: There will be a statistically significant difference in the cylindricity accuracy between scanning and touch trigger probe measurements of 3D-printed parts about the X axis at the 0.05 level of significance.

Assumptions of the Study

To obtain sufficient measurement variation, calibration standards were not used in this study. Manufactured rapid-prototyped parts appeared to be the best option to achieve the variance needed. For the purpose of this study the following assumptions were applied in an attempt to improve the feasibility of this study.

1. The build and measurement process did not affect the specimen cylindricity.
2. Cylindricity was not related to the mix consistency of virgin and recycled powder.
3. Build location within the build chamber did not have an effect on measurements.
4. Powder consistency was not affected by age or chemical separation.
5. Variations in material shrinkage did not exist.
6. Variations in layer thickness did not exist or have an effect on the specimens.
7. After a one-hour cure time, variations in natural cure time did not exist between batches.
8. Variations in oven cure time and temperature did not exist between batches.
9. CMM geographical locations far from any major highways or industrial facilities did not produce vibrations that might affect the accuracy.
10. Preparation of the 310 Printer and the ZD4i depowdering station was sufficient.
11. The "purge" command did not adversely wear the printhead.
12. Each specimen was located in the same position in the measurement envelope of the CMM during measurement by a fixture to reduce volumetric error.
13. The CMM used to measure cylindricity was in good working order, certified, and calibrated before measurement began.
14. Two individual measurement programs—one at a diameter of 1" and another at a diameter of 0.75"—were used for all measurement cycles.
15. Observations were paired and dependent.
16. Pairs were normally distributed with approximately the same variance.

Limitations of the Study

For the purpose of this study, the following limitations apply.

1. The 310 Printer had been maintained and had not been used excessively over the past four years.
2. The CMM used was capable of measuring to an accuracy of at least 0.00002” but other minute errors may have been present below this measurement threshold.
3. Each specimen in each batch was a copy of one original STL file created by SolidWorks version 2006. However, minute tessellation errors existed in all STL files.
4. The CMM utilized Zeiss Calypso® software and implemented a best-fit calculation in order to determine the attributes of a circle. This calculated geometry may not have been the “true” geometry measurement.
5. All measurements were obtained in a semi-controlled temperature and humidity environment.
6. A calibration of the ZCorp 310 printer used in this study was not performed.
7. The surface finish of the 3DP parts may have had variations of surface finish depending upon the part’s build orientation.
8. The temperature and humidity were not precisely controlled during the build of the specimens.
9. The 8mm ball could come into contact with larger crevasses and create erroneous data.
10. Fifteen measurement points at three axial levels were used.
11. Both virgin and recycled build powder was sifted through a screen with openings of approximately 1mm to separate any large granules and prevent them from entering the build chamber of the 310 Printer. However, grains small enough to pass through the screen, yet large enough to affect eventual measurement, could have been introduced into the specimen build chamber.
12. Due to the cost of the ZCast® build material and zb56 binder, only a limited number of samples were made. Only eleven batches of twelve specimens (132 parts) were produced with existing materials.

Experimental Design and Data Collection

Specimens were designed in Solid Works, built in a ZCorp 310 printer, cured in a convection oven at approximately 375ºF for four hours, and placed in sealed containers prior to measurement. Laboratory measurement temperature varied from 71.44ºF to 80.78ºF. Sealed-container specimen humidity varied from 44 to 75% relative humidity.

All specimens were allowed to stabilize at the DCC/CMM room temperature and humidity for at least 1 hour before measurement occurred. Prior to measurement, all specimens were cleaned by low-pressure compressed air to remove any loose particles that might affect measurement accuracy. Eleven total batches, with each batch consisting of 12 total specimens (132 total specimens) at 3 different build orientations and 2 different diameters, were measured. A certified Zeiss Contura® G2 DCC/CMM with a VAST XXT passive scanning head, 125mm carbon-fiber shaft probe, and 8mm synthetic ruby was used to collect measurement data. A steel fixture held the specimens vertically as well as indexed the specimens in the same location relative to X-axis rotation while the measurement occurred. Figure 1 provides the specimen prints for the 1"- and 0.75"-diameter specimens used in the study. Figure 2 depicts the measurement planes. Figure 3 illustrates how specimens were secured for measurement.

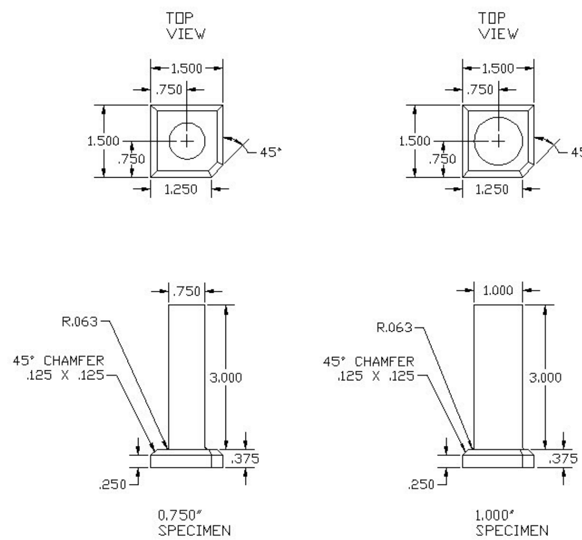

Figure 1. Specimen Prints

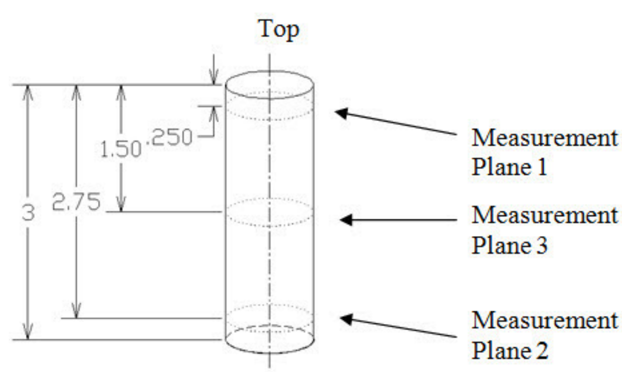

Figure 2. Axial Measurement Planes

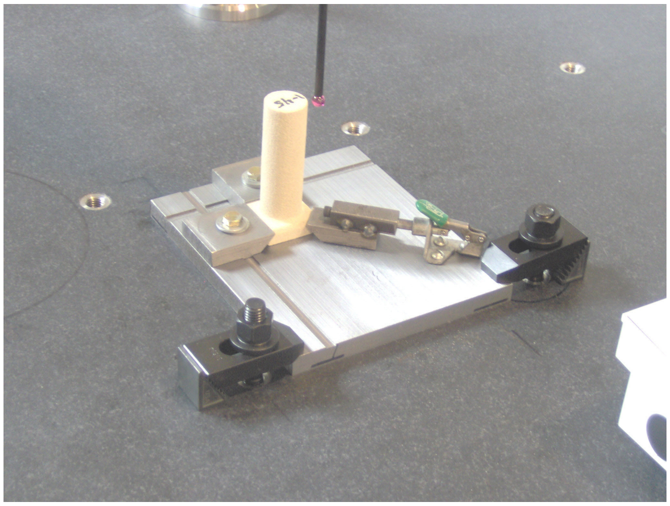

Figure 3. Specimen Measurement Fixture

One DCC/CMM program was written for each specimen diameter measured (one at a diameter of 1" and another at a diameter of 0.75"). Temperature and humidity readings were recorded during the testing of each specimen. After each specimen was measured, the fixture was cleaned using compressed air to remove any particles that might affect measurement results. Each specimen in each batch was tested. Three vertical axial measurement planes acquired measurements with 15 points (Touch Trigger), and continuous scanning, around the cylinder specimen. Figure 4 is provided as a reference for the measurement equipment.

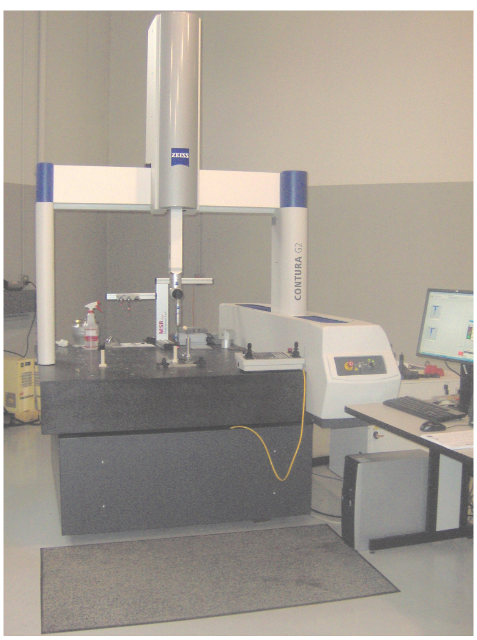

Figure 4. Zeiss Contura® G2 DCC/CMM

Variables and Data Recording Information

The dependent variable in this study was the cylindricity of the 3D-printed part as measured by a probe using either Scanning or Touch Trigger. Units for the measurements were in inches, carried out to six places (0.000000).

Specimen Creation and Handling Details

The cylinder models, which were used in this experiment, were initially generated with SolidWorks version 2006. The design of the specimens incorporated a base design which allowed all specimens to be fixtured consistently and in reference with each specimen's X axis of rotation when measurement occurred. From this 3D model, an STL file was generated using default values. The STL files of the 1" and 0.750" specimens were then imported into the ZPrint® 6.2 software. Once the cylinder files were loaded into the ZPrint® software, they were copied and rotated. The cylinders being printed were located in different locations in the build chamber in order to account for any variation in build accuracy due to a cylinder's location in the build chamber. The specimens were only rotated at 0º, 45º and 90º about the X axis of the 310 Printer. The single axis and limited rotations were chosen largely because of the extremely high cost of the ZCast® build material and the extended period of time it would take to build and test all axes at an increased number of rotation angles. A 3" (overall length) specimen was utilized with dimensions of 0.25", 1.50", and 2.75" from the top of the specimen while it was held in the measurement fixturing.

Statistical Analysis and Results

In this study, a Dependent Paired T-Test using SPSS 19 was chosen because of the continuous variable output values of cylindricity. One hundred and thirty two values were obtained for cylindricity through both the scanning and touch trigger probe acquisition modes. The variable for scanning was termed "CYLSCAN" and the variable for touch trigger probe was termed "CYLTTP." To meet the normality assumption of a Paired T-Test, a Normal Q-Q Plot was created for both CYLSCAN and CYLTTP (see Figure 5). While the Anderson-Darling statistics did not support normality (CYLSCAN: $p = <0.005$, $AD = 2.986$; CYLTTP: $p = <0.005$, $AD = 1.893$), approximate normality for both variables was obtained, as illustrated in Figure 5. Equal variance was present between CYLSCAN and CYLTTP.

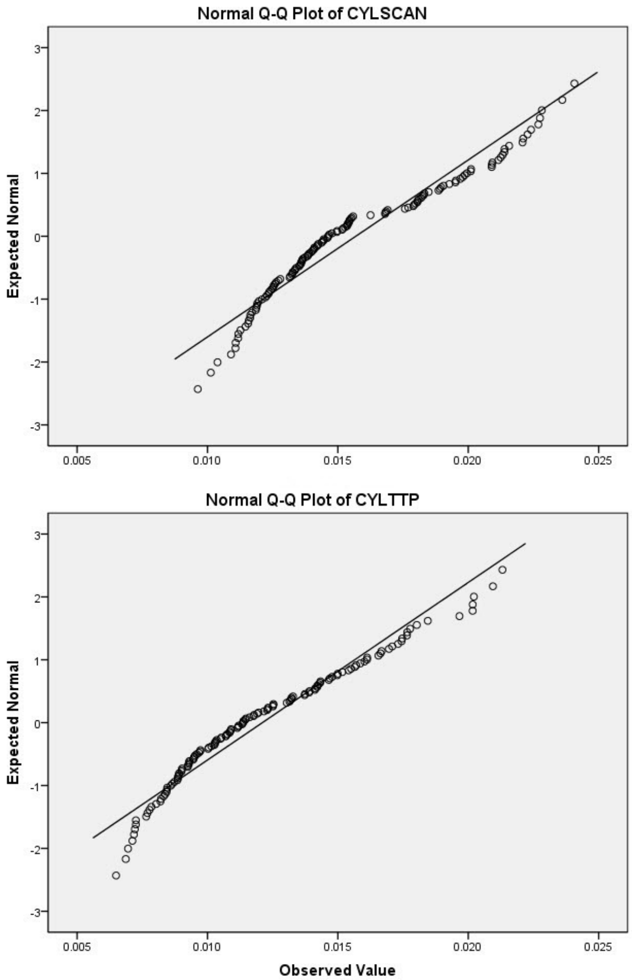

Figure 5. Q-Q Plots of CYLSCAN and CYLTTP

Hypothesis Results and Conclusion

On average, Cylindricity Scanning (CYLSCAN: M = 0.01568, SD = 0.00355) has experienced a significant difference compared with Cylindricity Touch Trigger Probe (CYLTTP: M = 0.01210, SD = 0.00354) with Dependent Paired T-Test results of M = 0.00358, SD = 0.00138, R^2 = .924, $t(131)$ = 29.694, p = .000 (two-tailed). Therefore, the null hypothesis was rejected indicating there was a statistically significant difference in the cylindricity accuracy between scanning and touch trigger probe measurements of 3D-printed parts about the X axis at the 0.05 level of significance. A Boxplot between CYLSCAN and CYLTTP is provided in Figure 6.

Using a coordinate measurement machine and ZCast® parts for measurement, it was determined statistically that there was a difference in cylindricity accuracy between scanning and touch trigger probe technology. Both measurement technologies have found a place in industry and academia. It is significant that parts measured in one manner, using one technology, can be significantly different from that of a similar measurement technology using the same machine.

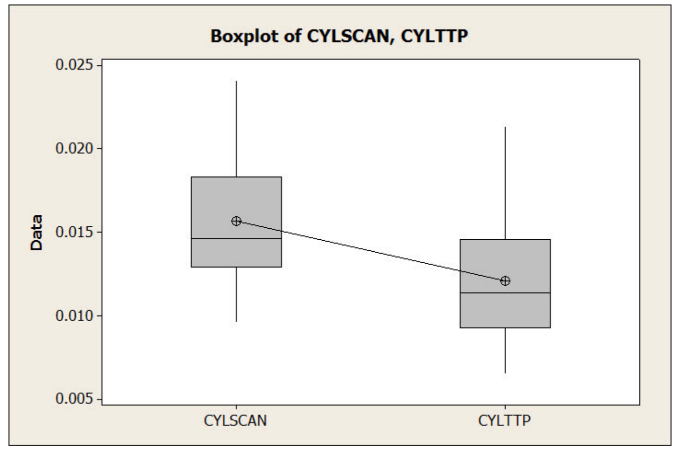

Figure 6. Boxplots of CYLSCAN and CYLTTP

The statistical significance of this study could be attributed to the inherent errors associated with touch trigger probes through mechanical action and/or deformation of the rapid-prototyped parts, whereas the scanning probe possesses miniaturized linear actuators which provide increased data acquisition (a higher number of data points), decreased measurement time, and the elimination of many errors common in conventional probes. One potential limitation affecting study results, and possible application to other such studies, could be variations in temperature and humidity. While extensive measures were taken to control these variables, ambient temperature and humidity may still have had an effect on the measurement results.

Rapid-prototyped parts using the ZCast® material may potentially change the results of this test if components were fabricated using machined steel, forged metal, or possibly another type of powdered rapid-prototyping material. While this may not be a substantial limitation, other materials could have changed the results of the study. The interesting part of this study was that identical components were measured using the same method, using two types of measurement technologies, and yet yielded a statistically significant difference.

Recommendations for Further Research

The study should be replicated using a different material with parts that have intentional variance in cylindricity to build a body of knowledge of how different materials are affected by these measurement techniques. The measurements taken by both the scanning and touch trigger probe could also be expanded to include other geometric aspects such as roundness, flatness, and straightness. Results of research such as this will greatly expand the knowledge base pertaining to this branch of metrology. Additional studies could be conducted on the optimal level of automation comparing scanning and touch trigger probe component measurement. Basically, to determine which method is best optimized for minimal waste in time and effort.

Lean Automation requires the efficient use of all available resources [27]. The Six Sigma methodology could also be investigated in terms of DMAIC (Define, Measure, Analyze, Improve, Control) in an applied metrology environment using both scanning and touch trigger probe DCC/CMM technology. The basic application of the Six Sigma methodology is well illustrated in an article by Farahmand et al. [28]. In tandem with this study, analysis of DCC/CMM reliability should be investigated to validate DCC/CMM measurement results [29].

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