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Coordinate Measuring Machine Variations for Selected Probe Head Configurations

By Dr. Kevin Berisso & Dr. Troy Ollison

Dr. Kevin Berisso is the Director of the AIDC Lab at Ohio University as well as an Assistant Professor in the Department of Industrial Technology. He received his BS in Industrial Technology from Ohio University and a MS in Industrial Technology from Indiana State University before taking a position with Applied Tactical Systems, a warehouse management software company. While at ATS, Dr. Berisso worked as a project engineer with companies such as Colgate-Palmolive and TRW. He then went to work for Delphi Automotive as a manufacturing engineer in the automotive battery division. In 2003 Dr. Berisso received his PhD in Technology Management from Indiana State University. He then proceeded to teach at Central Missouri State University before returning to OU in the summer of 2005. Included in Dr. Berisso's research interests are RFID, direct part marking and the integration of AIDC with manufacturing processes and automation."

Dr. Troy Ollison is an Assistant Professor of Technology and Engineering Technology at the University of Central Missouri in Warrensburg, Missouri. Ollison has been teaching both graduate and undergraduate courses for eight years. He is also an active member of the Society of Manufacturing Engineers as well as the Association of Technology Management and Applied Engineering (ATMAE). His primary interest and research areas are in metrology, rapid prototyping and materials processing and testing.

Abstract

In coordinate measuring machine (CMM) research, there is often a need to measure the same feature repeatedly using multiple settings. However, the effects of changing the probe head configuration were previously unknown. The goal of this research was the determination of what effects the selection of the measurement plane, adaptor style, stylus length, and stylus size would have on the CMM's ability to repeatedly measure a single diameter.

An analysis of variance (ANOVA) study was conducted using a Brown & Sharpe MicroVal CMM. Three measurement planes (XY, XZ, and YZ), two adaptor styles (a star probe and an indexable head), two stylus lengths, and two stylus sizes were selected for the study. Ten measurements were taken on a single gage ring for each variable combination and the data were processed in SPSS.

The results of this study indicate that if the measurement plane, stylus length, or stylus size were changed, the CMM would not repeatedly result in the same measurement reading. However, the user would be able to alter the adaptor style without affecting the resulting measurement. Additionally, the interactions of (a) measurement plane and adaptor style; (b) measurement plane and stylus length; (c) measurement plane, adaptor style and stylus length; (d) measurement plane, adaptor style and stylus size; and (e) measurement plane, adaptor style, stylus length, and stylus size all show significant measurement variations for the same feature. As future research is done on CMMs, care will be needed with the assumptions that are made when researching a specific effect. Based on this study, future researchers will have to determine whether observed changes are due to the probe head configuration or the changes they are studying.

Introduction

Reductions in product life-cycle durations are driving companies to develop and produce products at an ever-increasing rate. Industry experts are predicting the arrival of rapid manufacturing through the use of flexible manufacturing systems. Even a brief examination of industry periodicals such as *Manufacturing Engineering, Technometrics, Production, Quality* or *Supply Chain Systems*, would reveal discussions about highly integrated systems that are flexible, agile and lean. One result of these trends is the incorporation of coordinate measuring machines (CMMs), which allow companies to perform data collection and process verification within the manufacturing cell.

Research on various coordinate metrology issues have paralleled the increased usage of CMMs in industry as inadequacies are uncovered and new needs develop. Research topics have covered such areas as the development of new probe compensation algorithms, sampling strategies, part orientation optimization, and computer generated inspection paths. As is often the case in research, assumptions have to be made in the interest of ensuring study feasibility. One such assumption is that the part orientation will not affect the measurements made by the CMM. This is one of the assumptions that this study challenged.

Another assumption(s) challenged is that various probe and stylus configurations will not affect the measurements made on a CMM. There are many probes available for CMMs. One of the more prevalent CMM probes currently in use is the touch trigger probe (TTP). TTPs work by sensing the impact of the stylus tip with the work piece. Studies have shown that touch trigger probes, similar to the one used for this research, have inherent errors (Wozniak & Dobosz, 2003; Hocken, Raja, & Babu, 1993; Shen & Zhang, 1999; Shen & Springer, 1998). However, due to the proliferation of touch trigger probes in both industry and academia, a common assumption made in CMM usage is that probe head configuration errors are negligible.

Currently, much of the research being done makes assumptions about the CMM's ability to probe parts from multiple directions (Corrigall & Bell, 1991; Ziemian, 1996; Osawa, Busch, Franke & Schwenke, 2005; Piratelli-Filho & Di Giacomo, 2003). Because a feature's measurement plane will have a significant impact on the probe configuration, an understanding of probe head configuration induced errors is necessary. For the purposes of this study, the probe head configuration is comprised of the required probe head rotational orientation (the selected measurement plane), whether or not a star adaptor or an indexable head is used (the selected adaptor style), the stylus tip size and the stylus length.

Review of Literature

Extensive writing and research has occurred in the area of coordinate metrology and its associated issues. Research has been done on many of the sources of errors including sampling errors, probe induced errors and algorithm induced errors. As CMMs see continued use in flexible manufacturing system environments, the need for a better understanding of how to best use them will continue to grow.

Coordinate metrologists have two basic options when choosing a probing solution, contact or non-contact. Often the application will dictate the choice due to limitations in the speed or accuracy of each solution (Renishaw, 2002). Non-contact solutions include calibrated video camera solutions and laser scanning options. Contact probes can be broken into two general groups, scanning and discrete, based on the type of data being taken. Scanning probes are continuous contact probes that sense the part as the probe is moved along the expected contour (Renishaw). Scanning probes are useful in the gathering of high-speed data on a part's form characteristics (Imkamp & Schepperle, 2006; Knebel, 1999). Probe speed plays a significant role in the accuracy of the information and probe wear needs to be taken into account (Wiebush, 2001; Lu, 1992). Discrete probes, or touch trigger probes (TTPs), are the most prevalent technology available (Marsh, 1996; Dove, 2000). They have the advantage of being less expensive than some of the other options and are good when fewer data points are needed, such as measurements for position or size (Renishaw, 2002). The three main TTP technologies available are piezo probes, strain-gage probes, and kinematic resistive (kinematic) probes. The accuracy of each probe decreases respectively, but so does the price and sensitivity. Piezo probes trigger on the contact made between the part and the probe. Strain-gage probes require a specific amount of pressure to be placed on the part to trigger a reading. The final category of probe, which was used during this study, is the kinematic resistive probe.

As of 1996, approximately 98 percent of the probes used on CMMs were touch trigger probes (Shen & Springer, 1998). The original CMM probes were kinematic and, while still popular, they have some known issues with their use (Hocken et al., 1993; Lu, 1992; Shen & Moon, 2001; Shen & Zhang, 1999; Traylor, 1991). The main problem with kinematic probes is what is known as pre-travel, or their lobing error. This error occurs due to the mechanical design of the probe (see Figure 1a). Lobing error is due to the changes in the required pre-travel pressure of the probe as the contact vector rotates around the Z axis of the probe. The lobing pattern is a map of the error the probe experiences due to the different forces required to unseat the probe. As the contact vector rotates until it is in-line with a mechanical rest, the force required to trigger the probe continually increases. This map is approximately triangular in shape and will usually have its points spread at approximately 120 degrees (Lu, 1992; Traylor, 1993; Woźniak & Dobosz, 2003).

As can be seen in Figure 1b, as the stylus contacts the part, the probe is pivoted such that either one or two contacts are lifted out of their seated positions. The orientation of the error map in Figure 1c is the same as the probe orientation in Figure 1b. Because different amounts of force are required to pivot the probe, the amount of realized deflection will alter, resulting in what is called lobing. Although various algorithms and models have been developed to attempt to compensate for lobing (Shen & Springer, 1998; Shen & Zhang, 1999; Lu, 1992), the fact remains that lobing exists.

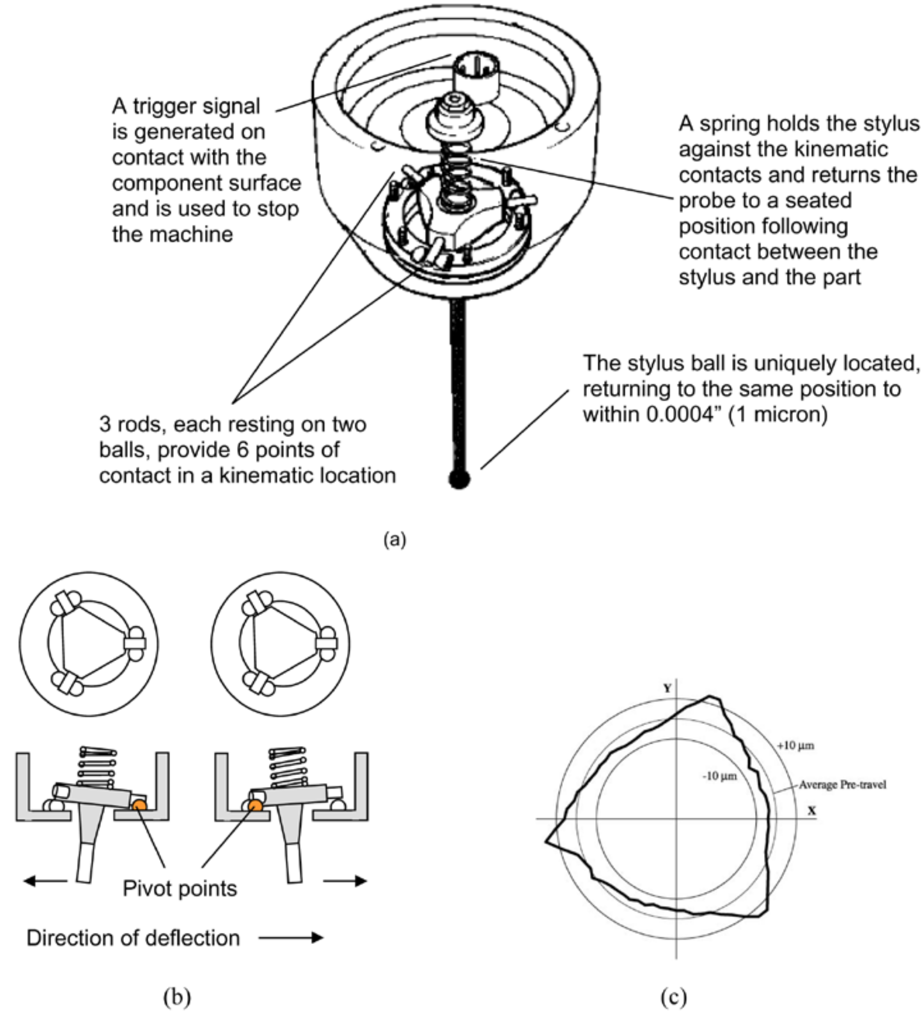
In metrology numerous issues have to be addressed in order to insure accurate, repeatable results. Included in the issues are (a) those factors that affect repeatability and accuracy, (b) the effects of cosine error and (c) the required number of points to be taken on a feature (Marsh, 1996; Lee & Woodward, 1992; Phillips, S. D., Borchardt, B., Estler, W. T. & Buttress, J., 1998; Ramaswami, Modi & Anand, 2007; Wechenmann, Eitzert, Garmer & Webert, 1995; Wozniak & Dobosz, 2005).

With the increased role of the CMM in various areas, the ability to depend on the information given becomes more critical to the enterprise (Adams, 2000; Chalmers, 2002; Ramaswami, Modi & Anand, 2007). Accuracy and repeatability of the measurement can be affected by multiple sources. The primary sources of CMM errors include geometric and kinematic errors in the machine, thermal effects, mechanical loading, and fixturing errors (Dama, 1998). Other sources of error that may not be quite as obvious include the length of the probe stylus, the probe diameter, the probe contact angles, the required probe contact force (Dove, 2000), user errors, humidity, dust, part cleanliness (Knebel, 1998), probe geometry, work piece imperfections, and probe-feature interactions (Elshennawy, 1987).

In Marsh's 1993 study (as cited in Marsh, 1996), it was found that there was a significant improvement in the repeatability of the machine as the number of points taken was increased One of the more prevalent methods of determining a feature based on discrete data points is least squares (Dowling, Griffin, Tsui, & Zhou, 1997; Ramaswami, Kanagaraj & Anand, 2009). In the least squares method, the computer will calculate the minimum variance of each point from a theoretical feature. With the least squares method, the system will be able to give a best guess at what the correct value should be. As can be imagined, the more points that are collected, the better the estimation (measurement) of the actual diameter.

The available literature implies that there is no single answer for the determination of the proper sampling strategy (how many data points to collect). While all authors agree that more points will provide better representations (Choi, W., Kurfess, T. R. & Cagan, J., 1998; Marsh, 1996; Hocken et al., 1993; Ramaswami, Kanagaraj & Anand, 2009; Weckenmann, A., Eitzert, H., Garmer, M. & Webert, H., 1995), the maximum required number varies. The study by Hocken et al.(1993) support between seven and eleven points on a circle as the appropriate number of points, whereas Dowling et al. (1997) suggest that four to eight points will be enough. In his review, Ziemian's 1996 study discusses research that indicates that no more than sixteen points will be needed. Furthermore, in his study of multi-baseline repeatability, Marsh's study (1993) selected between three and ten measurement points on a diameter. For the purposes of this study, a sampling strategy of ten measurement points was selected. This selection was based upon the balancing of time with improved feature definition.

Figure 1. Kinematic Probe Illustration. The existence of probe lobing is due to the three-point design of kinematic probes. Image (a) illustrates the internal parts of a kinematic probe. Image (b) shows that as the probe is forced in a given direction, it can be pivoted onto either one or two of the contacts, resulting in different required forces, as shown in image (c). Images (a) and (b) are derived from Renishaw. Image (c) is reprinted with permission from Brown & Sharpe.



Methodology

As mentioned previously, the goal of this study was the determination of whether various probe head configurations and measurement orientations would have an effect on the CMM's ability to repeatedly measure a feature. The methodology for this study was to measure an inside diameter gage ring in each combination of measurement plane, adaptor style, stylus size and stylus length. The independent variables investigated in this study were the measurement plane, the adaptor style, the stylus length, and the stylus size. The dependant variable was the measured diameter of the gage ring.

The following null and alternative hypotheses, and their associated interactions, were tested. For all hypotheses, an alpha of 0.01 was selected.

1. Ho1: $\mu_{\text{xy plane}} = \mu_{\text{xz plane}} = \mu_{\text{yz plane}}$. There is no difference in the mean measurement of the part based on the measurement plane (measurements in the XY, XZ, or YZ planes) of the part.
2. Ho2: $\mu_{\text{star probe}} = \mu_{\text{indexable head}}$. There is no difference in the mean measure-

ment of the part based on the adaptor style.
3. Ho3: $\mu_{\text{stylus length 1}} = \mu_{\text{stylus length 2}}$. There is no difference in the mean measurement of the part based on the stylus length that is used.
4. Ho4: $\mu_{\text{stylus tip 1}} = \mu_{\text{stylus tip 2}}$. There is no difference in the mean measurement of the part based on the stylus tip that is used.

As seen in Figure 2, the part (gage ring) was oriented along one of three axial planes (XY, XZ, and YZ). Parts oriented on the XY plane were situated such that only the X and Y axes were used to obtain the points, because all points were taken the same distance from the top surface of the ring. Parts oriented on the XZ and YZ planes were situated such that the axes listed in the orientation were the only ones used (for the XZ plane, only the *X* and *Z* planes were manipulated).

As parts are moved from one measurement plane to another, the probe orientation was moved as well. The two methods used to achieve this were: 1) the use of a star probe adaptor and 2) the use of an indexable head (see Figure 3).

Increased stylus lengths have the potential of magnifying CMM measurement errors. Due to this possibility, two lengths were chosen in this study which represent the shortest length currently available for the machine and a longer stylus that incorporates a single shank extension.

The size or diameter of the stylus also has the potential to induce measurement errors. Stylus size selection is often made based on the surface of the part being measured, as smaller probes are more susceptible to irregular surfaces. However, as the size of the stylus tip increases the weight of the probe could induce an error. The tips that were selected for this study were a small spherical stylus tip and a disk shaped tip that is actually a slice of a larger sphere. During this research, the temperature was recorded during the data collection periods, but not controlled. However, if the temperature change had exceeded two degrees Fahrenheit during a run, that run would be performed again. A two degree change was chosen because the thermal expansion of two degrees is sufficiently small such that it is outside the CMM's measuring capability.

The machine used for this study was a Brown & Sharpe MicroVal PFx Direct Computer Controlled (DCC) Coordinate Measuring Machine. The software available allowed for program inspection routines and the automatic collection of the data. A Renishaw MH20i indexable head with a TP20 extended force probe module and Renishaw's basic tip kit were used as the selected probing hardware. Prior to the beginning of the research, the machine was calibrated and received a certification from Brown & Sharpe's service department. Also, all other use of the CMM

Figure 2. Selected Ring Orientations. Each ring is oriented on a separate CMM plane that has been designated by the two axes that are moved during the measurement process.

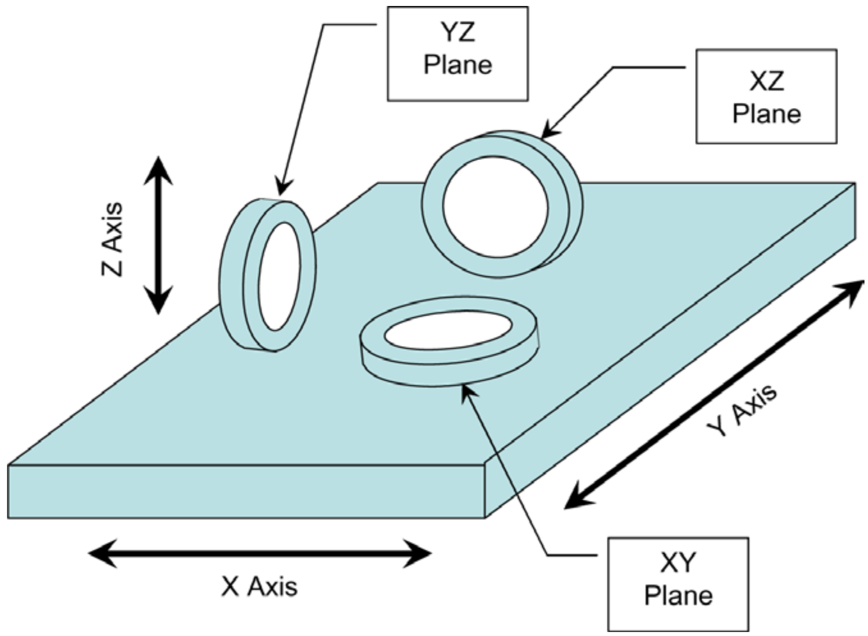
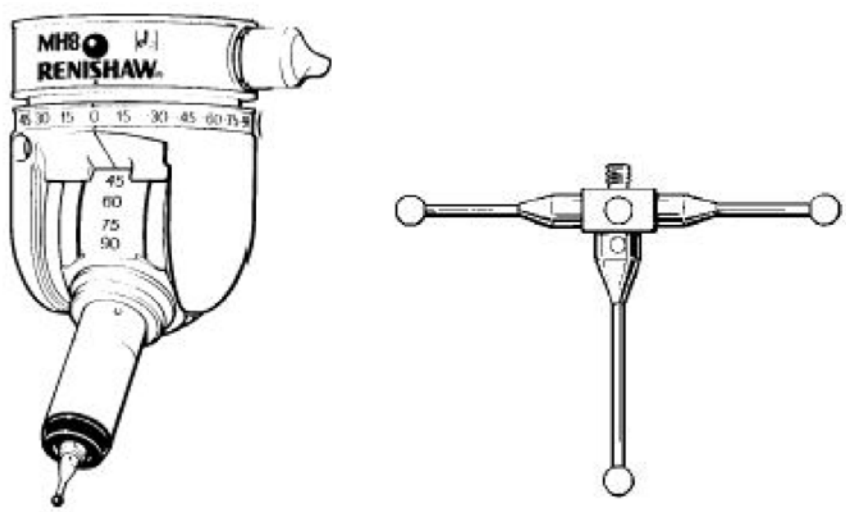
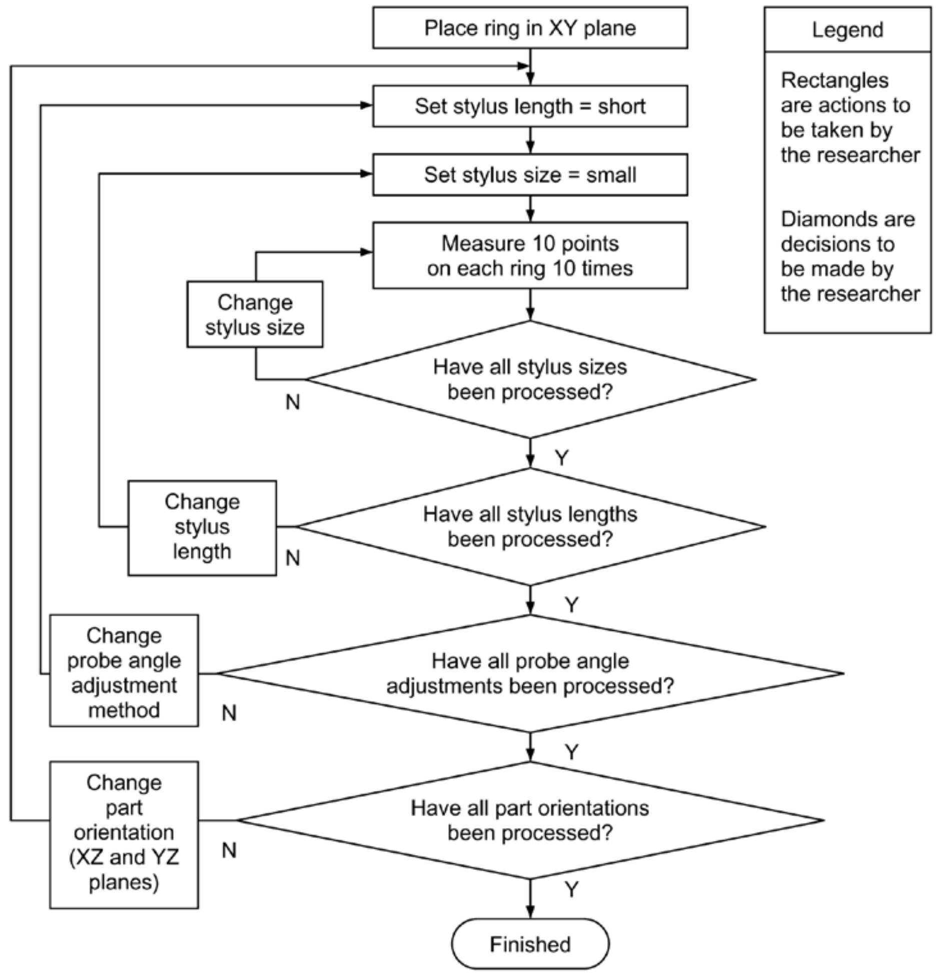


Figure 3. Adaptor Styles. The image on the left is an indexable probe head. The image on the right is a star-adaptor that would be used with a non-indexable probe head. Reprinted with permission from Brown & Sharpe.



was suspended until after the data for this research was collected to protect the CMM from possible abuse through misuse.

Figure 4. The Data Collection Sequence. As each variable was addressed, the collection sequence progressed down one level until all variables had been addressed without moving the part. At that point, the part was adjusted and the sequence was repeated.



Because external sources of variation would have brought the validity of any conclusions into question, various precautions were taken to help limit the impact of any extraneous sources. Among these efforts were climate control, vibration control and part variation issues. Because all CMMs are constrained by their volumetric accuracy, movement of the part between data collection runs could inadvertently introduce volumetric inaccuracies into data sets (Piratelli-Filho & Di Giacomo, 2003). The chosen method of accounting for this possible issue was to keep the locations of the part (gage ring) as static as possible and moving the part only when absolutely necessary. By sequencing the variables in the pattern shown in Figure 4, the movement of the parts within the area of the CMM was minimized. For example, based on Marsh's methodology, the parts were not moved between the data collection runs for the small and large stylus lengths. This minimized the effects of volumetric inaccuracies between most variables (Marsh, 1996).

The actual data collection was done automatically by the CMM. The researcher developed two programs that allowed the system to automatically collect data on each variable group with a minimal level of user intervention. When the program was finished, the stylus length, stylus size, or adaptor style was altered as required, per the flow shown in Figure 4. Based on Marsh's (1993) methodology, all measurement combinations were done before advancing to the next adjustment to minimize temperature variations among the variable groups (Marsh, 1996).

Prior to each physical probe configuration, the probe was re-qualified to account for changes in the probe tip location. Previous observations have noted that the qualification process can produce varying stylus diameters. Because calculations are being made during the qualification process, some level of variation was expected.

Multiple analysis techniques have been used to examine the results of the study. Descriptive statistics were run on all data, and average diameters were calculated for each probe head configuration combination.

An ANOVA analysis technique was used to evaluate the hypotheses presented. ANOVA was selected due to its ability to make multiple comparisons without accumulating the effects of alpha (α). In the case of this study, the ANOVA allowed for a simultaneous comparison of each of the variables, including all interactions. Specific attention was paid to the various interactions, because they would indicate which combinations of variables either encouraged or discouraged use.

An α of .01 was selected for this research. The logic of picking this alpha level was two-fold. First, it was desirable to minimize the chances of incorrectly accepting a false alternative hypothesis (Type I error). Because the α level had been reduced to .01, or a one-in-a-hundred chance, the possibility of making a Type I error was reduced. In addition, the power of the test was increased by placing 10 data points in each cell of the ANOVA, reducing the chances of falsely accepting an alternative hypothesis (Type II error). A larger data set size could have been selected, but the additional increase in power could not be justified in light of the potential negative effects, specifically, the identification of insignificant differences due to extreme sample size and the additional processing time which would potentially allow for more temperature variation.

Results

The observations were reported to 1/100,000th of an inch (five places past the decimal point). To aid in the analysis process and to help insure that any differences were visible, all of the temperature adjusted points were analyzed in SPSS as 1/1,000th of an inch (thus, 3.60124 was processed in SPSS as 1.24). Also, the variable being affected for each hypothesis was given a short name (see Table 1).

A brief look at the box plots in Figure 5 shows that there seems to be some differences in the amount of variance for the measurement plane, adaptor style, and stylus size variables. This visual inspection is supported by SPSS' test of homogeneity (see Table 2), which show statistical differences in variances for the independent variables, with the exception of the stylus length.

As can be seen in Figure 6, the observations approximate a normal distribution that is skewed to the right (the tail is on the right). This visual observation is further quantified through the skewedness value that was calculated in SPSS. Although the skewedness value in this instance is greater than one, it is not excessively so and the assumption that the data is not drastically skewed can be made. The same can be said for the kurtosis of the distribution (see Figure 6). Figure 6 also shows that the distribution is somewhat high, but that the kurtosis value is only 1.162. The implication of the kurtosis and skewedness values is that while the data may appear abnormal, it is not exceedingly so to where it is detrimental to the study.

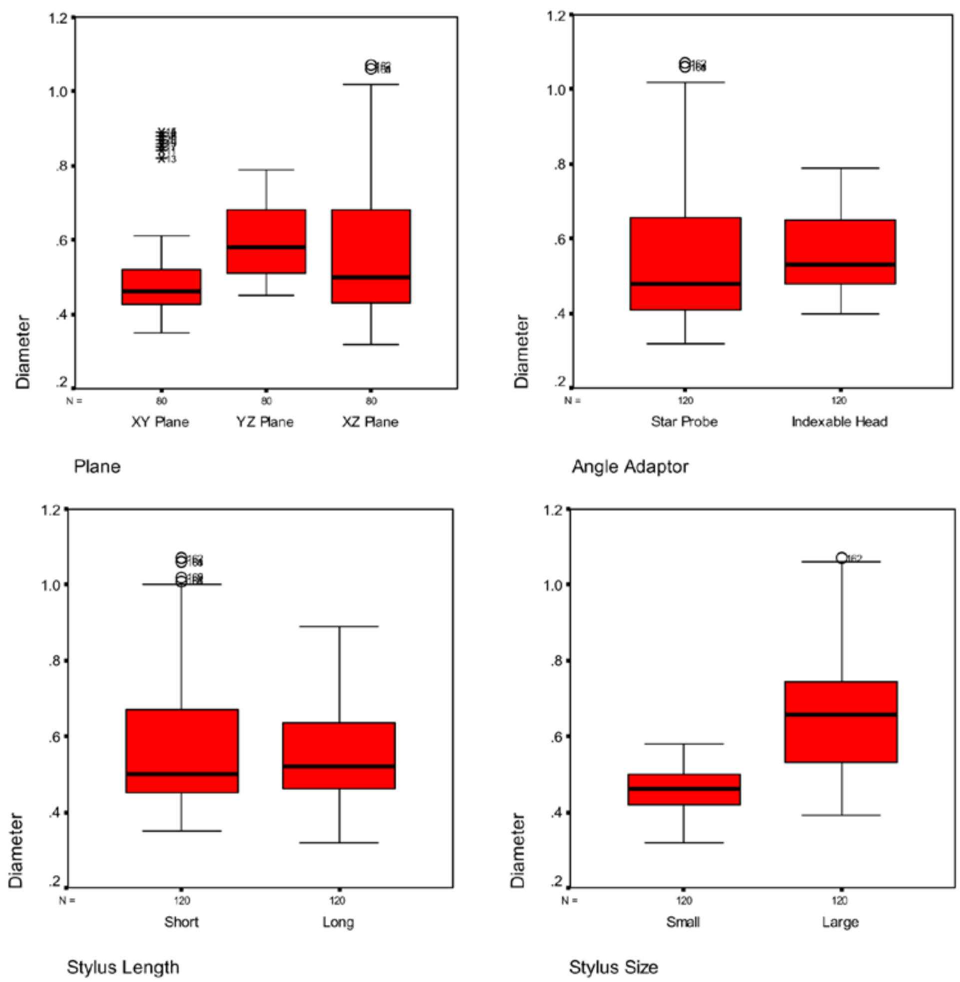
Hypotheses Testing Results

The first, second, third and fourth hypotheses investigated the CMM's ability to report the same measurement based upon: 1) the effects of the measurement plane, 2) the effects of the adaptor style, 3) the effects of the stylus length and 4) the effects of the stylus size. Ten measurements were taken for each measurement plane, stylus size, stylus length, and adaptor style combination. The analysis shows that there is a statistically significant difference in measurements between the various planes, stylus lengths and stylus size. However, the analysis of the second hypothesis fails to show that there may be a statistically significant difference

Table 1. Hypothesis Variable Coding. The following table shows the SPSS variable names given for each hypothesis being tested.

Hypothesis	SPSS Variable	Description
1	Plane	Measurement plane being investigated (XY, XZ, YZ)
2	Adaptor	Probe angle adjustment used (star probe, indexable head)
3	Length	Length of probe stylus (short, long)
4	Size	Probe stylus size (small, large)

Figure 5. Box-plots of the Variables. The figure contains the box-plot output from SPSS, showing the amount of variability for each group of data. Indications above some of the plots are data outliers.

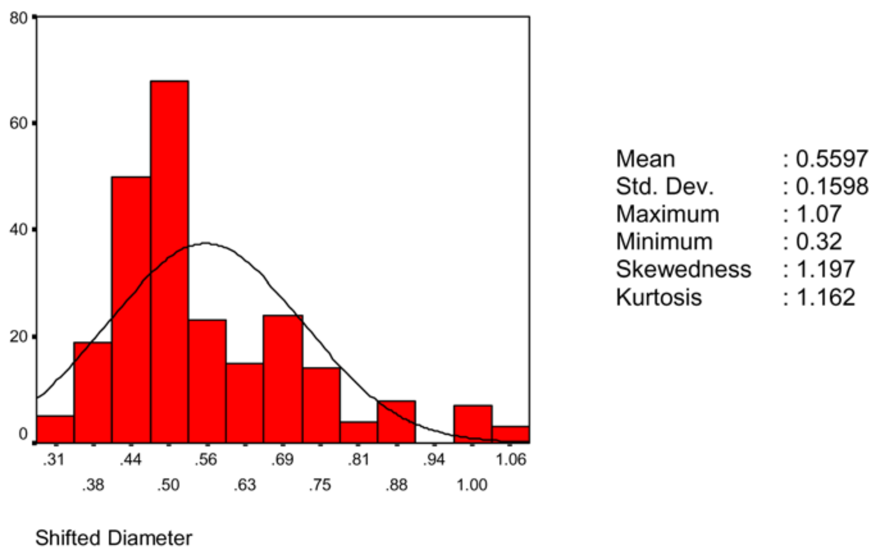


in measurements between the various adaptor styles.

Table 2. Homogeneity of Variance. The following table is a list of the results from SPSS' test for homogeneity for the independent variables.

		Levene Statistic	df1	df2	Sig.
Measurement plane	Based on Mean	10.98948	2	237	0.000
Adaptor style	Based on Mean	37.94873	1	238	0.000
Stylus length	Based on Mean	6.1533	1	238	0.014
Stylus diameter	Based on Mean	62.69586	1	238	0.000

Figure 6. Data Distribution. The figure above is a histogram of the data collected during the study. SPSS has overlaid an approximation of a normal distribution curve for the data set shown.



The fifth and sixth hypotheses investigated the effects of the interaction between the measurement plane and adaptor style as well as the interaction between the measurement plane and stylus length. The analysis shows that there is a statistically significant difference in measurements for both interactions.

The seventh, eighth, ninth and tenth hypotheses investigated the effects of the interaction between the 1) measurement plane and stylus size, 2) adaptor style and stylus length, 3) adaptor style and stylus size and 4) stylus length and stylus size. The analysis fails to show that there may be a statistically significant difference in measurements for any of the interactions.

The eleventh, twelfth and thirteenth hypothesis investigated the effects of the interaction between the 1) measurement plane, adaptor style, and stylus length, 2) measurement plane, adaptor style, and stylus size and 3) measurement plane, stylus length, and stylus size. The analysis shows that there is a statistically significant difference in measurements for the interactions.

The fourteenth hypothesis investigated the effects of the interaction between the adaptor style, stylus length, and stylus size. The analysis shows that there may not be a statistically significant difference in measurements for the interaction.

The fifteenth hypothesis investigated the effects of the interaction between the measurement plane, adaptor style, stylus length, and stylus size. The analysis shows that there is a statistically significant difference in measurements for the interaction.

Based on the results from the ANOVA table (see Table 3), the adaptor and approximately half of the interactions show that there is no significant difference in the measurements between levels. The measurement plane, stylus length, stylus size, and the remaining interactions do show a statistically significant difference. These results indicate that the coordinate metrologist should be careful about measuring the same feature multiple times with different probe head configurations or across multiple planes.

Conclusions

The purpose of this research, as stated previously, was that without a clear understanding of how probe head configurations would affect any measurements taken by a CMM, researchers, managers, and quality assurance experts would not be able to make accurate, informed decisions during the probe head configuration process. As previously discussed, this analysis was not meant to be a traditional repeatability study, but was intended to be an investigation into the common research assumption that the part could be moved between measurement planes without inducing an effect on the measurements being taken.

There is a statistical difference in measurements between levels for the measurement plane, stylus length, and stylus size. This should tell both the researcher and the coordinate metrology practitioner that care will be needed when making decisions about the selection of orientation, stylus length, and stylus size when repeatedly measuring the same feature.

For practical applications this means that if a feature is to be used as a datum, and that datum is to be measured using multiple stylus sizes and lengths, or in multiple planes, the results would be different. A shift in measurements would mean that the diameter would be different; however, it may also mean that the location of that center point will be different. If the latter were the case, then the relative location of the datum would change, resulting in the theoretical movement of the measurement datum.

These results have shown that the measurement plane, stylus length, and stylus size will result in a significant amount of variation when they are changed. However, the adaptor style can be changed without inducing a difference. As researchers are faced with decisions concerning the effects of selecting adaptor styles, they can be relatively confident in switching between indexable heads and star adaptors as needed. However, when testing other variables, the alteration of the measurement plane, stylus length, or the stylus size must be considered because it has been shown that they will induce different results on their own, without changing anything else.

The implications of these are of importance to quality assurance experts and researchers alike. However, it may be the researcher more than the practitioner who will be impacted by these results. This is because manufacturing quality requirements probably do not require the user to repeatedly re-measure the same feature using multiple probe head configurations, whereas the researcher could easily find the need to re-measure the same feature multiple times, in multiple orientations, while investigating the results of various variables.

As shown in the results of the ANOVA table (see Table 3), the selection of different measurement planes, stylus lengths and stylus sizes will induce significant measurement variations for the same feature when any single variable is altered. Additionally, the interactions of (a) measurement plane and adaptor style; (b) measurement plane and stylus length; (c) measurement plane, adaptor style, and stylus length; (d) measurement plane, adaptor style, and stylus size and (e) measurement plane, adaptor style, stylus length, and stylus size will all result in significant measurements variations for the same feature.

These results have the potential of incurring significant issues for researchers, because it means that they will have to be careful with the assumptions that are made when researching a specific effect. Because of these results, researchers will have to attempt to determine whether any observed changes in their research are due to these effects, or to the changes they are inducing. For example, if research is being done on the effectiveness of a new algorithm or sampling strategy, the researcher will need to design the experiments so that the effects of the probe head configuration could be partitioned out.

It should be noted, however, that these results cannot be expanded beyond

Table 3. SPSS ANOVA Results. The following is the output from SPSS for the data collected. A significance that is less than .01 results in the rejection of the null hypothesis.

ANOVA Table

Dependent Variable: DIAMETER

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	5.905a	24	.246	262.926	.0000
Intercept	4.223E-04	1	4.223E-04	.451	.5025
TEMP	3.203E-04	1	3.203E-04	.342	.5591
PLANE	.207	2	.104	110.637	.0000
ADAPTOR	2.716E-04	1	2.716E-04	.290	.5906
LENGTH	1.250E-02	1	1.250E-02	13.360	.0003
SIZE	3.167E-02	1	3.167E-02	33.849	.0000
PLANE * ADAPTOR	1.986E-02	2	9.931E-03	10.613	.0000
PLANE * LENGTH	.203	2	.102	108.701	.0000
PLANE * SIZE	2.912E-03	2	1.456E-03	1.556	.2134
ADAPTOR * LENGTH	2.686E-04	1	2.686E-04	.287	.5927
ADAPTOR * SIZE	5.152E-03	1	5.152E-03	5.506	.0199
LENGTH * SIZE	2.730E-06	1	2.730E-06	.003	.9570
PLANE * ADAPTOR * LENGTH	.133	2	6.659E-02	71.159	.0000
PLANE * ADAPTOR * SIZE	9.675E-02	2	4.838E-02	51.699	.0000
PLANE * LENGTH * SIZE	.697	2	.348	372.409	.0000
ADAPTOR * LENGTH * SIZE	1.382E-03	1	1.382E-03	1.477	.2256
PLANE * ADAPTOR * LENGTH * SIZE	.263	2	.131	140.348	.0000
Error	.201	215	9.357E-04		
Total	81.3026	240			
Corrected Total	6.105785	239			

[a] R Squared = .967 (Adjusted R Squared = .963)

the use of a B89-calibrated Brown & Sharpe CMM using a TP20 extended force probe body. This limit, as previously stated, is because the extended force probe body required higher probing pressures that result in a lower repeatability. While this repeatability has been assumed to be negligible for this study, it does have to be acknowledged.

Recommendations For Further Research

Based on the conclusions, implications, and lessons learned from this research there were six recommendations for further research developed which are: 1) the inclusion of additional levels to some of the existing variables to determine if a multiple regression model is feasible, 2) the inclusion of multiple part sizes with the existing probe head study, 3) the inclusion of different probe modules with the MH20i probe head, 4) to replicate this study across multiple machines other than the MicroVal PFx, 5) to introduce various machine movement speeds into the research and 6) to further explore the interactions that occur between the adaptor style and the stylus size.

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