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CNC MACHINE CONTROL FOR HIGH TOLERANCE AEROSPACE PRODUCTION

A Thesis by

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Bachelor of Science, Wichita State University, 2021

Submitted to the Department of Industrial, Systems, and Manufacturing
Engineering and the faculty of the Graduate School of
Wichita State University
in partial fulfillment of
the requirements for the degree of
Master of Science

May 2024

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CNC MACHINE CONTROL FOR HIGH TOLERANCE AEROSPACE PRODUCTION

The following faculty members have examined the final copy of this thesis for form and content, and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Industrial Engineering.

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ABSTRACT

This research is motivated by the needs for advanced processes and control methods for CNC machines in the aerospace industry. Generally, more metal is removed from a workpiece than what is remaining in the machine after processing. This requires use of all types of tooling, cutters, drills, spindles, drive systems, actuators, controls, processes, etc. Countless decisions by analysts, engineers, planners, machinists, and managers, and the complex physics that govern machine tool movement, accuracy and repeatability demand post-machining quality control measurements be implemented. The ex-situ nature of the typical quality control systems increase cycle time and costs. In-situ quality control is proposed here as an alternative to reduce cycle time and cost, while increasing quality. For this purpose, a (CNC) machine tool was equipped with direct computer control coordinate measuring software and high accuracy contact probing. This special CNC is validated for its capability for self-health monitoring and in-situ part quality control. The validation conforms to international standards for performance evaluation of commercially available coordinate measuring machines (CMMs). The capability of the CNC system to perform CMM-type measurements is demonstrated via a case study. The equivalency between part dimensional measurements obtained directly from the use of the CNC machine tool as a CMM and from part dimensional measurements performed using commercially available CMMs is established via a correlation study. The self-health checks were run for a period of one-year and the measurements are analyzed statistically using standard SPC methods.

PREFACE

This thesis research is intended to advance the aerospace machining professions and provide new education topics for Wichita State University's Department of Industrial, Systems and Manufacturing Engineering, as well as any other colleges within the University that find relevant information for education.

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LIST OF ABBREVIATIONS/NOMENCLATURE

CMM	Coordinate Measurement Machine
CNC	Computerized Numerical Control
CTE	Coefficient of Thermal Expansion
SPC	Statistical Process Control
TCP	Tool Center Point

LIST OF SYMBOLS

“	Inch
μ	Micro

CHAPTER 1

INTRODUCTION

1.1. CNC Capability Needs

Aerospace structures comprise of millions of metallic components at large-scale product size. “Large” is referencing commercial industry planes that at minimum fit the “narrow body” description and any product that exceeds these volumes. The Boeing 737 and Airbus A320 are considered in this description. In today’s production environment, these parts are made requiring such difficult machining capabilities that research is being conducted to find alternative methods of physically modifying the products. Currently milling operations of large CFRP structures are primarily executed by conventional machining systems in portal design that cause very high investment cost due to the large dimensions of the workpieces and special heavy foundations to carry the machine weight (Möller, et al., 2017). High rates of production are also needed at all CNC machining centers to supply the factories with enough components for assembly. New programs and products being introduced to production systems often must be conforming from the start and for the entire life cycle, because there is no time to iterate through quality components of a new process (Schwneke, et al., 2008). *Repeatable* machines are critical to achieving these production rates with internal machine fabrication and conforming quality. When a machine is relatively controlled and repeatable, it then needs to become *accurate* enough to hold a Tool Center Point (TCP) that allows the physics of the machine tool to only consume one-third of the true position tolerance of the feature created. If a six-thousandths true position feature is being created in a product, the entire machine tool system should be limited to two-thousandths of mechanical deviation using all its required orientations for work. This minimal

deviation requirement is what drives machine tool builders and sellers to continue pursuing control methods for repeatability and accuracy.

1.2. Problems With CNC Accuracy

Machine tool accuracy with a CNC control is a culmination of many systems interacting to place a tool tip in a perfect center location of space. Physically, a machine tool is subject to error in its design, construction, and daily use. “Machine accuracy is directly related to the systematic geometric errors of the machine tool, fixture errors, part clamping distortion, part cutting distortion, tool and spindle deflection, machine tool thermal deformation, etc.” (Gu, Agapiou, & Kurgin, 2017). The machine can also be subject to accuracy error caused by programmed commands and block processing modes. “High accuracy means that the error between the target curve and actual trajectory is small as a result of generating a program based on a chord error for the target curve and moving a machine tool with the program” (Otsuki, Sasahara, & Sato, 2019). Process error can sometimes create machine accuracy error if programming is not considerate of the working volume and measurement strategies. For example, assuming that tooling and part datums are perfectly flat and contacting at any arbitrary point on the workpiece can lead to statistically incorrect probing data. Basic XYZ probing measurements used to offset the working parameters can lead a machine program pattern into a volume that deviates from setup conformance because of only one point that does not match the tooling and part contact assumption. Other individual measurements that are included in process error can be workpiece thickness and workpiece flatness. If in situ measures are not put in place to combine these two specifications, then a flatness added to a thickness can exceed working envelope at the time of machining, even with two conforming supplier quality measurements off the machine prior. Additionally, physical kinematics is constantly changing direction and

magnitude of forces throughout a machine tool system while in motion. This is unavoidable for any company attempting to be profitable because production time is increased if kinematic motion forces are minimized. “The dynamic error of CNC machine tools, which often exceeds the quasi-static error at high-speed machining, becomes the main reason affecting the machining error of the sculpted surface parts” (Lyu, Liu, Liu, & Zhao, 2020). A constant and dynamic error on machine tools, which is impossible to eliminate in some manufacturing systems, is due to dimensional changes of the machine and the workpiece. “Thermal error is generated on account of the thermal expansion and distortion caused by the change of structure element and environment temperature” (Lyu, Liu, Liu, & Zhao, 2020). For CNC accuracy error, it can be concluded that expertise of many academic subjects and technical skills are required to compensate a machine tool into aerospace machining tolerances. Any of the discussed causes can consume an entire tolerance for a machine process, easily, at a *large* 5-axis machine tool.

1.3. Research Objectives

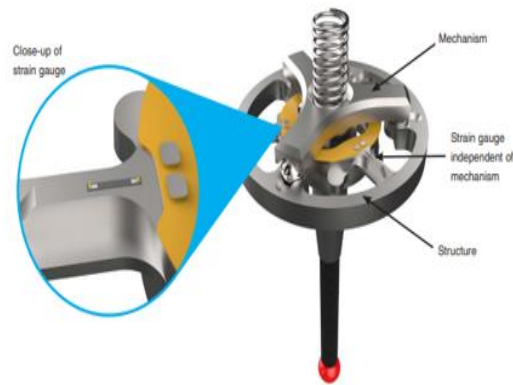
1.3.1. Preliminary Concept of Control

With these factors contributing to the accuracy problem of a CNC machine system, there must be methods to avoid any physical-perfection assumptions and prevent accumulation of error in the system. The design of a scale-feedback system is one major contributor to control, which allows movements as small as .0001” (in) to be counted along any of the linear axes of travel in a machine. To be able to return a system to an indicator tick on a scale to the accuracy of .0001” is how referencing during cycles and homing prevents error from accumulating. Additional assumptions of physical perfection are eliminated with the ability to measure control surfaces and part surfaces. The research to be conducted herein will utilize dynamic probing equipment and software to find physical error between theoretically perfect and actual points of a workpiece

or tooling. With the ability to reference scale position counters and probed physical locations that feed XYZ coordinates of interest, the research can move into the first ideas for CNC control.

This begins with physical measurements of the machine scales vs. the probed points found by secondary measurement systems. A Renishaw strain gauge probe system is accurate to an order of magnitude below the scales of a machine. Figure 1. Renishaw RMP600 Specifications shows the sensitivity values of a typical Renishaw probe system. These sensitivities are up to an order of magnitude smaller than the machine accuracy of a given drive (Note that Renishaw sensitivity is as small as .00001 in vs. machine accuracy = .0001 in).

2D lobing in X, Y	$\pm 0.25 \mu\text{m}$ (10 μin) – 50 mm (1.97 in) stylus length $\pm 0.25 \mu\text{m}$ (10 μin) – 100 mm (3.94 in) stylus length
3D lobing in X, Y, Z	$\pm 1.00 \mu\text{m}$ (40 μin) – 50 mm (1.97 in) stylus length $\pm 1.75 \mu\text{m}$ (70 μin) – 100 mm (3.94 in) stylus length



Stylus trigger force (typical minimum)	OMP400	OMP600	RMP400	RMP600	MP250
XY plane	0.06 N, 6 gf (0.22 ozf)	0.15 N, 15 gf (0.54 ozf)	0.09 N, 9 gf (0.32 ozf)	0.20 N, 20 gf (0.72 ozf)	0.08 N, 8.0 gf (0.29 ozf)
+Z direction	2.55 N, 260 gf (9.17 ozf)	1.75 N, 178 gf (6.03 ozf)	3.34 N, 341 gf (12.01 ozf)	1.90 N, 194 gf (6.83 ozf)	2.25 N, 229 gf (8.09 ozf)

Figure 1. Renishaw RMP600 Specifications.

It is proposed to utilize a Renishaw probe system to transform the machine tool into a highly accurate measurement system, effectively making it an “on-board” or “in-situ” coordinate measuring machine (CMM) that can detect tool and workpiece points while fabrication is taking place. This enables a point to be measured while knowing that the error in the measurement system is less than that of the machine system, meaning the measured point is the best accuracy to be expected out of a system attached to the machine. The goal of this research is to use this probing capability to correlate physical machine characteristics to measurable values of deviation. For example, success in this research can possibly lead to, “Closed Door Manufacturing,” which is a minimal human intervention machining strategy (Guiassa, Mayer, Balazinski, Engin, & Delorme, 2014). To begin, the machine system alone must be controlled, so a Tool Center Point (TCP) measurement process needs to be created and validated for deviations, then an electrical compensation process following the validated numbers. Once the machine kinematics are at the required repeatability and accuracy for product conformance, tooling and product characteristics can be located by the machine with confidence. This is only possible if the machine tool system undergoes the same qualification process utilized to validate commercially available CMMs. We intend to apply industry CMM standards to the machine tool and correlate measurements with multiple certified measurement systems used in the aerospace industry. To further eliminate deviation in the machining process, parts and fixtures will be measured with the CMM correlated machine. Deviations can be turned into offsets of the working coordinates within the Numerical Control (NC) program. The concept of probing to find a workpiece or fixture is not new to the industry, but the requirement for CMM correlation prior is. It is important to note that machine operators will be introduced to new practices given the success of this research. Keeping the workforce in mind is critical for any new technology and

processes to work correctly. “The correct interaction between the workforce and the various enabling technologies of the 4.0 paradigm represents a crucial aspect of the success of the smart factory.” (Valentina, Valentina, Salvatore, & Riemma, 2021). The next milestone is to find statistical correlation in product feature measurements using the machine and CMMs. To make a conforming aerospace product, the entire envelope of a part must also fall within the one-third tolerance requirement. Thermo-elastic effects (i.e., thermally induced material growth) becomes a relevant variable as the envelope of the part increases with distance along the X, Y, or Z drives. Every material has a different expansion rate per degree of temperature change called the Coefficient of Thermal Expansion (CTE). A CNC machine system is made of many different materials, which causes individual expansions of the machine components in any shop that does not control ambient temperature or fluid temperatures. A study of temperature effects on parts and machines will be conducted as one aspect of CNC machine control to produce aerospace parts. When a study for relevance and approach to measuring materials is finished, a control process for the Coefficient of Thermal Expansion (CTE) in a machine system will be created and validated as another variable of control.

The final process for control will be combining known errors in the machine system and fitting all physical deviations into one best average volume. Machine accuracy, tooling / part volume specification, CMM correlation, and CTE all attribute to physical XYZ errors on an aerospace product. The major milestone of the research is to address these known variables and validate the control of each. This will be followed with further research into the ability to make more accurate measurements with a machine tool and decrease the tolerance maximum that is statistically proven true. The advancement in these processes drives businesses to accurately purchase work packages and be a reliable supplier in the aerospace supply chain. It is also

desired that the research conducted challenges the engineering of machine tools and measurement devices across the globe to reach a new standard of control.

CHAPTER 2

Literature Review

2.1. CMM Qualification Standards

Unless stated explicitly, all direct quotes that appear under this section are from Michal Holub, Robert Jankovych, Ondrej Andrs, Zdenek Kolibal, 2018, “Capability assessment of CNC machining centres as measuring devices,” *Measurement*, Vol. 118, pp. 52-60.

Machine fabrication of products is system of checks and balances between devices doing work and devices that validate specifications that are to be met. Quality is the upmost important factor in an aerospace manufacturing system because of the complex products that are required for air travel, and the high consequences for inadequate components on aerostructures. As engineering advancements continue, demand for aerostructures does too. This forces factories to begin productivity initiatives while also signing up for higher tolerance machine work – two different goals, that without new and specialized processes, could negatively impact the other. A concept that is not widely implemented in the aerospace industry, is the validation of features using a machining center. “From the perspective of a specific example of engineering, it maybe the implementation of automated measurement of the workpieces during the machining process, which will significantly shorten or even eliminate standard measurement non-machining operations.” This concept is not meant to replace the checks and balances of aerospace manufacturing, but instead allow machines to potentially measure required specifications that are low enough tolerance for a machine to meet the resolution, in the goal of offloading repetitive work from CMM’s, so they can be used on the products that are becoming more advanced. “Small and medium-sized products are checked mostly with tactile probes on CMMs. The

requirements for accurate CMMs are increasing along with the requirements for more accurate products.” There are also special requirements for measuring large aerospace products, which have physical and productivity difficulties. “Mobile measurement devices are preferred for measuring of large workpieces, mainly due to the expensive and time-consuming transportation of the product from the point of machining to the large CMM, which need not be in the immediate vicinity of production premises.” If a product is not able to be measured in the machine tooling setup, there are extra steps added to the production of the product.

Transportation – the product must now be moved through the factory and will require floorspace for staging/measuring. This is a violation of LEAN practices in production because of non-value-added work and the quality risks associated with movement of products. Quality and productivity both beg the invention of a different conformance verification method. “The alternative way of checking the longitudinal dimensions of workpieces is to use the workpiece touch probe directly on the machine. These probes are frequently found within the standard machine tool equipment as one of the main benefits of deployment.” The touch probes are equipped on machines but are not certified standard measurement devices. For a device to be certified to measure, it must have a calibration certificate and be used in a validated measurement process. “Accuracies of measuring equipment and their uncertainties are referred to in the calibration certificate of the equipment,” “Furthermore, in the case of complex and time-consuming measurements, good ambient conditions must be ensured to achieve the best quality of the measured data.” The machine must be certified as a measurement device before it is able to produce quality data in the factory. A disadvantage for the machine tool is, that it is attempting to produce data straight from the factory floor. Often machine tools are performing some of the most physically complex and highly coordinated work in a business. “The overall accuracy of the machine is influenced by

several factors; the authors (referenced in (Holub, Jankovych, Andrs, & Kolibal, 2018)) divide them into errors resulting from geometry and kinematics, temperature errors, errors from the forces acting during machining, errors from the preparations and the adjustment of work-pieces.” This list is unique to a machine tool, while CMM’s can avoid most of these error-inducing situations. The intended measuring machine needs a metric for confidence in accuracy. This metric is referred to as the Volumetric Accuracy. “Volumetric accuracy of the machine, which is determined by volumetric deviation, has a predicative value for the machine geometric accuracy throughout the entire workspace. Volumetric accuracy is affected by both the quality of machine design, manufacturing and assembly, and the level of compensation methods deployed.” “After the inspection and evaluation of the machine tool, it will be possible to state to what length tolerance the workpiece touch probe can be used on the machine tool to achieve a “safe” inspection of longitudinal dimensions.” Fortunately, measurement device verification has become a field of expertise that advances far past machine measurement verification, so there are industry standards to be referenced. “The second possible approach is to use a combination of the method described in (ISO 22514-7) and a comparison of statistically processed measurements with the workpiece touch probe and the laser interferometer (standard length).” The laser interferometer is a standard CMM device used in the aerospace industry but must be a certified piece of equipment for the test to be valid. The experiment setup described in this literature is as follows:

“The machining centre is equipped with the workpiece touch probe OMP400, RENISHAW, s.n.52T988, with repeatability of 1µm, which is deployed in the experiment to measure the test part. To verify the achieved position, we utilized the laser interferometer XL-80 RENISHAW with environmental unit XC-80 RENISHAW measuring the temperature, pressure, and humidity.

Technical specifications XL-80 and XC-80 are described in the following table (Table 1). Furthermore, temperatures were measured at selected points of machining centre by the system TESTO Saveris with six temperature probes. Among the controlled points are the individual machine axes X, Y and Z, as well as the headstock, air, and the workpiece. Figure 2. Test workpiece -left, Measurement cycle - middle, Measurement test – right shows the testing details.

TABLE 1. LITERATURE REVIEW 1 LASER AND COMPENSATOR SPECIFICATIONS

Laser interferometer XL-80		Environmental compensator XC-80	
Item	Specification	Item/resolutions	Specification
Measurement accuracy	± 0.5 ppm	Material temperature	± 0.1 °C
Linear resolution	1 nm	Air temperature	± 0.2 °C
Maximum travel velocity	4 m/s	Air pressure	± 1 mbar
Dynamic capture rate	50 kHz	Relative humidity	$\pm 6\%$ RH

M. Holub et al.

Measurement 118 (2018) 52–60

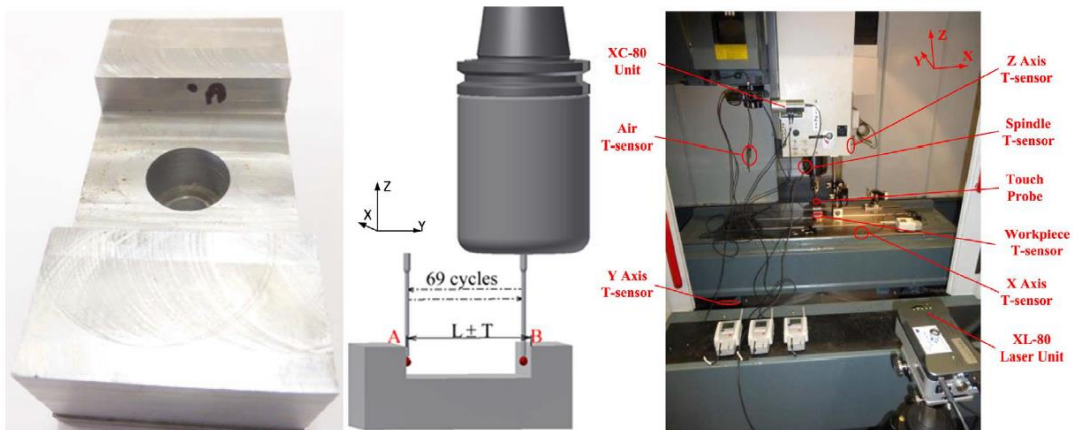


Figure 2. Test workpiece -left, Measurement cycle - middle, Measurement test – right.

The intention of this experiment is to find the confident accuracy of the machine tool with a touch probe inside of a specified volume.

The experiment then intends to manufacture a slot and validate the machine's ability to measure the slot vs. an interferometer laser. The slot engineering is specified as $L=41.940 \pm 0.0075\text{mm}$. After manufacturing of the slot, the interferometer used in the experiment measured the slot dimension at $L =41.93813\text{mm}$. This is the target value for the machine to measure repeatedly.

Czech Metrology Institute gave a certified L measurement target:

“The measurement itself was carried out using the laser interferometer RENISHAW XL80, s.n. 56H160 at Czech metrology institute (CMI). Determining the length of the groove (internal dimension) was set from repeated measurements. The measured dimension was set at $41.9384 \pm 0.0005 \text{ mm}$.” This certified dimension was then measured by the machine probe, with 69 total samples, in the setup shown below in Figure 3. Chart of accuracy measurement test of the machine tool

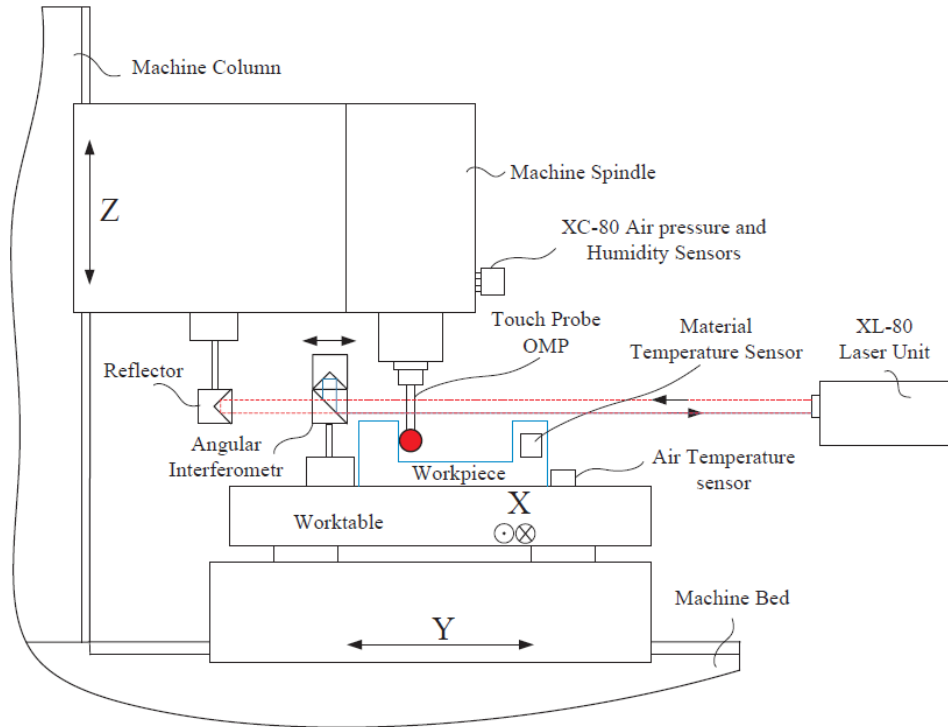


Figure 3. Chart of accuracy measurement test of the machine tool.

“A concurrent measurement of workpiece with the laser interferometer and workpiece touch probe OMP can eliminate the errors that might arise e.g. as a result of thermal expansion of the workpiece or machine.” Temperature was reported to be rising throughout the study, thermal expansion caused growth of the measurement systems, machine, and certified slot through the experiment Figure 4. Temperature profile on the machine MCV 754

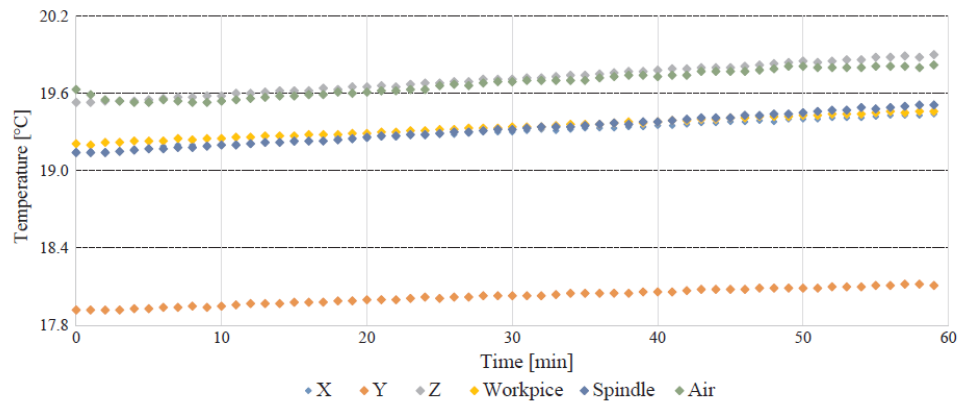


Fig. 6. Temperature profile on the machine MCV 754.

Figure 4. Temperature profile on the machine MCV 754.

The results of the first trial for this experiment are shown below

TABLE 2. RESULT OF ANALYSES OF MEASUREMENT WITH TOUCH PROBE WITHOUT CORRECTION

x_1	41.9198	x_{16}	41.9201	x_{31}	41.9201	x_{46}	41.9207	x_{61}	41.9203
x_2	41.9200	x_{17}	41.9203	x_{32}	41.9204	x_{47}	41.9203	x_{62}	41.9198
x_3	41.9198	x_{18}	41.9205	x_{33}	41.9201	x_{48}	41.9202	x_{63}	41.9210
x_4	41.9201	x_{19}	41.9204	x_{34}	41.9201	x_{49}	41.9207	x_{64}	41.9205
x_5	41.9196	x_{20}	41.9198	x_{35}	41.9205	x_{50}	41.9201	x_{65}	41.9204
x_6	41.9199	x_{21}	41.9203	x_{36}	41.9202	x_{51}	41.9203	x_{66}	41.9200
x_7	41.9200	x_{22}	41.9198	x_{37}	41.9206	x_{52}	41.9204	x_{67}	41.9203
x_8	41.9202	x_{23}	41.9202	x_{38}	41.9198	x_{53}	41.9199	x_{68}	41.9210
x_9	41.9202	x_{24}	41.9204	x_{39}	41.9201	x_{54}	41.9206	x_{69}	41.9204
x_{10}	41.9203	x_{25}	41.9196	x_{40}	41.9201	x_{55}	41.9204		
x_{11}	41.9203	x_{26}	41.9207	x_{41}	41.9205	x_{56}	41.9204		
x_{12}	41.9201	x_{27}	41.9203	x_{42}	41.9206	x_{57}	41.9206		
x_{13}	41.9202	x_{28}	41.9201	x_{43}	41.9204	x_{58}	41.9202		
x_{14}	41.9203	x_{29}	41.9198	x_{44}	41.9205	x_{59}	41.9205		
x_{15}	41.9197	x_{30}	41.9204	x_{45}	41.9203	x_{60}	41.9207		
T	= 0.015 mm				x_e	= 41.93813 mm			
s_g	= 0.000303 mm				\bar{x}_g	= 41.9202 mm			
C_g	= 1.65				C_{gk}	< 0			
									incapable

As shown in the bottom right of this table, prior to the methods of the research author, the machine was not able to validate the measurements made by the interferometer laser in the setup.

Following the first test, the author was able to invent an error compensation method that ultimately resulted in a capable measuring process:

TABLE 3. RESULTS OF ANALYSES OF MEASUREMENT SYSTEM CAPABILITY WITH CORRECTION

x_1	41.9372	x_{16}	41.9378	x_{31}	41.9379	x_{46}	41.9385	x_{61}	41.9379
x_2	41.9375	x_{17}	41.9380	x_{32}	41.9381	x_{47}	41.9380	x_{62}	41.9379
x_3	41.9374	x_{18}	41.9378	x_{33}	41.9379	x_{48}	41.9380	x_{63}	41.9386
x_4	41.9376	x_{19}	41.9379	x_{34}	41.9378	x_{49}	41.9380	x_{64}	41.9381
x_5	41.9372	x_{20}	41.9377	x_{35}	41.9381	x_{50}	41.9378	x_{65}	41.9382
x_6	41.9373	x_{21}	41.9378	x_{36}	41.9377	x_{51}	41.9379	x_{66}	41.9378
x_7	41.9377	x_{22}	41.9376	x_{37}	41.9380	x_{52}	41.9381	x_{67}	41.9380
x_8	41.9376	x_{23}	41.9378	x_{38}	41.9377	x_{53}	41.9377	x_{68}	41.9387
x_9	41.9379	x_{24}	41.9380	x_{39}	41.9379	x_{54}	41.9382	x_{69}	41.9383
x_{10}	41.9379	x_{25}	41.9375	x_{40}	41.9378	x_{55}	41.9380		
x_{11}	41.9380	x_{26}	41.9380	x_{41}	41.9382	x_{56}	41.9380		
x_{12}	41.9377	x_{27}	41.9381	x_{42}	41.9382	x_{57}	41.9383		
x_{13}	41.9377	x_{28}	41.9377	x_{43}	41.9383	x_{58}	41.9378		
x_{14}	41.9378	x_{29}	41.9376	x_{44}	41.9382	x_{59}	41.9382		
x_{15}	41.9372	x_{30}	41.9381	x_{45}	41.9379	x_{60}	41.9385		
$T = 0.015 \text{ mm}$				$x_e = 41.93813 \text{ mm}$					
$s_g = 0.000305 \text{ mm}$				$\bar{x}_g = 41.9379 \text{ mm}$					
$C_g = 1.64$				$C_{gk} = 1.42$				capable	

The correction algorithms are not explicitly defined but are not of interest in the future experiments of this thesis research. Instead, deviations from the experiment method will be stated for the intention of proving unique thesis research:

1. Error scaling algorithms (outside of machine scale parameters) on the machine will not be included as component of the measurement process.
2. A linear interferometer laser is used in the research above, thesis research will be conducted using a certified laser tracker (scaled to linear interferometer measurements) that is traceable to NIST and certified as a CMM.
3. A series of certified CMM devices will be included in the Thesis Machine CMM Correlation study.
4. Machine scales and temperature compensation will be included on a 5-Axis CNC machine.
5. Measurement points will be in cartesian coordinates (XYZ) and correlation in 3-Dimensions will be evaluated.
 - a. This CMM certification will be 3D in hopes that hole patterns can be certified on the machine tool

2.2. SPC of Machines

Unless stated explicitly, all direct quotes that appear under this section are from Grzegorz Bomba, Artur Ornat and Piotr Gierlak, 2021, “Geometric Measurements on a CNC Machining Device as an Element of Closed-Door Technology,” *Sensors*, Vol 21, pp. 1-23. (Grzegorz Bomba, 2021)

To implement a production process such as “lights-out” or “closed-door,” a company must have confidence in the process and a way to quantify this confidence. This article discusses an aerospace manufacturing process in a machine tool and the possibility of measuring with the machine tool from a statistical confidence perspective, using Statistical Process Control (SPC). As mentioned previously throughout this thesis research, measurements at the machine tool have benefits to productivity, quality, process control, throughput, cost margin, and more. A visual

explanation to why research in topic is significant to industry is shown below in the figure constructed by the author Figure 5. Manufacturing using the standard machining process and CDT

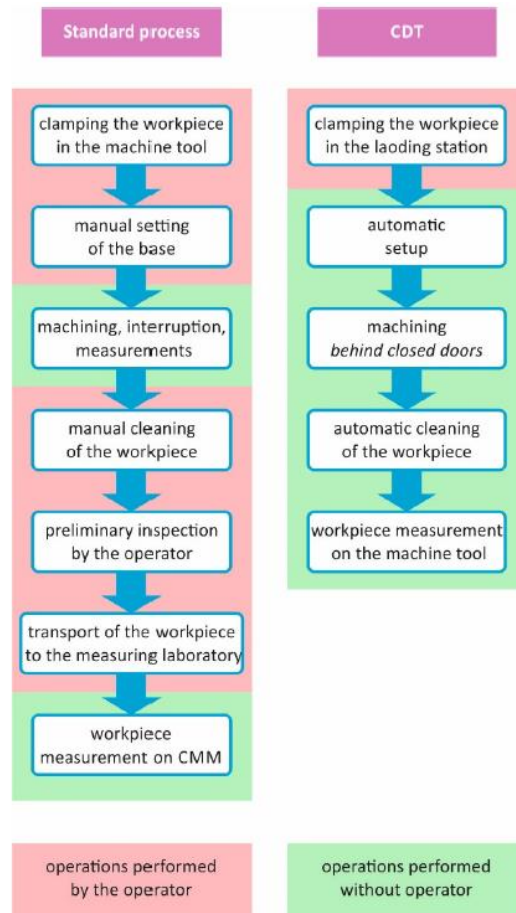


Figure 5. Manufacturing using the standard machining process and CDT.

Seeing the processes compared in this way makes the controlled machine measurement process seem obvious to implement, but there are elements that we are intending to research in this thesis such as robot part loading or cleanup processes. Only the machine measurement vs operator inspection / transport of workpiece / CMM measurement is of interest, and specifically

how SPC can be used to prove the machine measurements are controlled. “SPC is a set of techniques and statistical methods used to evaluate the process stability. The purpose of SPC is to prevent nonconformities by detecting and signaling process faults. SPC responds to the ineffectiveness of traditional quality control.” The goal is to find control metrics that keep the measurement process in control on every part and every measurement cycle. Since the goal is to prove the capability of a machine measurement system, a higher resolution object must be used to conduct the test with respect to the ratio of measurement standards. Certified artifacts are commonly used to do this. “The measured object was the Mitutoyo reference ring with an internal diameter of = 86.999 (mm) Figure 6. Measuring the diameter of the ring gauge on a machine tool with a standard touch probe. The data regarding the reference ring axis and diameter as well as its face surface in relation to the machine reference system were entered into the measurement program.”

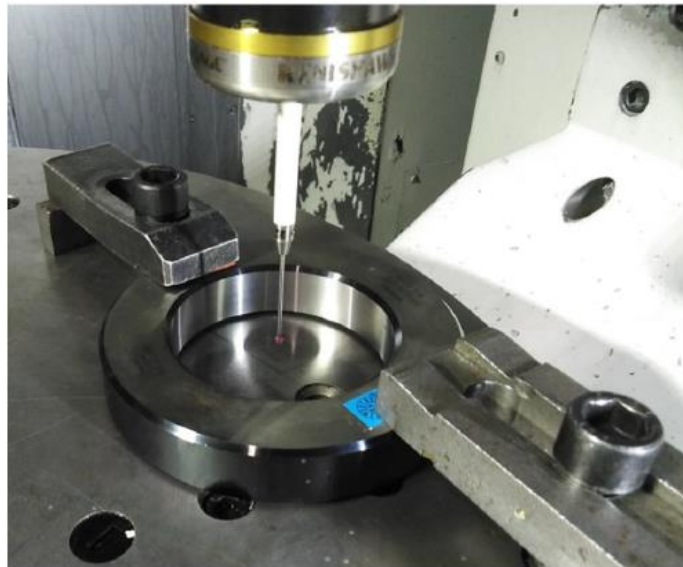


Figure 6. Measuring the diameter of the ring gauge on a machine tool with a standard touch probe.

Probe calibration cycles are ran using an artifact, such as this one shown. The master ring and a test rod validate the XY and Z axes calibration. Locating the XY center of the master ring and the Z height are explained here in the figure provided by the author. “First, the position of the reference ring axis in the machining tool coordinates was established (Figure 7. Setting the master ring gauge on the machine). X0 and Y0 for the workpiece coordinate system were assumed and determined at the location of the established ring axis. Similarly, the coordinate of the position of the ring base surface was assumed as Z0.

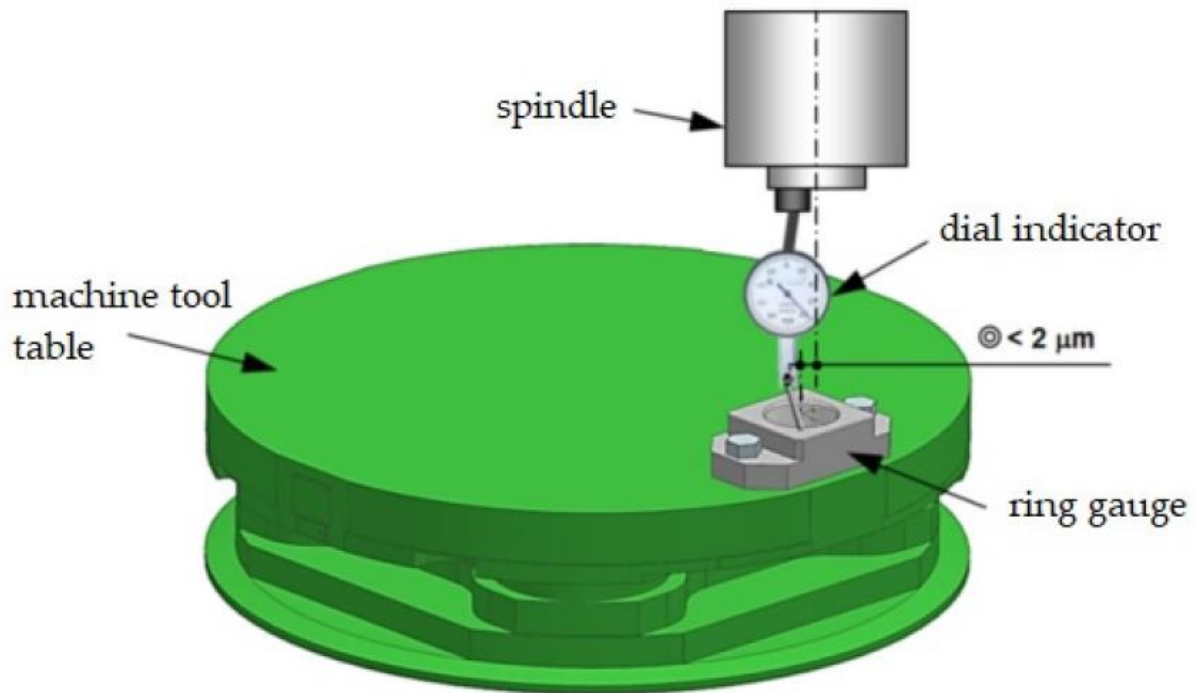


Figure 7. Setting the master ring gauge on the machine.

This method displayed is a machine drive location measurement using a dial indicator and a Z surface establishment using a probe touch cycle. Important to note, machine measurements located by the calibration ring and the XYZ nominal values of the reference ring.

Once established in a location, calibrations of Renishaw standards for the probe devices were followed. These calibrations are standard for Renishaw and do not reflect a unique setup of the probe devices related to the research. Measurements for R&R of the process proceed following the nominal locations established. Obtaining measurements is conducted below.

Sequence 1 is displayed below for Z measurements. “Sequence 1 involved the measurement of the base surface coordinate Z. In sequence 1

(Figure 8. Sequence of measurement of the ring base surface coordinate Z), the Z coordinate of the base surface was measured and defined as Z_0 for the position of the workpiece coordinate system.”

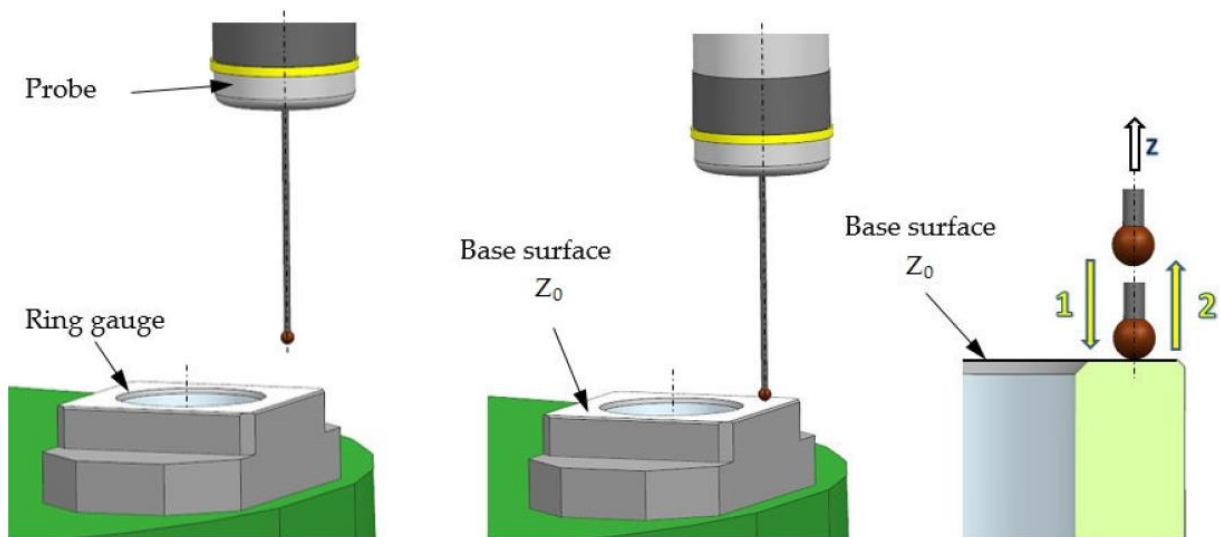


Figure 8. Sequence of measurement of the ring base surface coordinate Z.

Sequence one is an R&R test of the probe system to trigger at the same nominal Z value that was established by the machine on the ring gauge with a test rod. Sequence 2, “Sequence 2 involved the measurement of the Z coordinate, as in Sequence 1, as well as the measurement of

the position of the ring axis TP and of the ring diameter. In the first phase, sequence 2 included elements identical to sequence 1.” “measurements of the diameter – and the TP position of the measured diameter axis was carried out (Figure 9. Sequence of measuring the position of the ring axis TP and diameter phi value).”

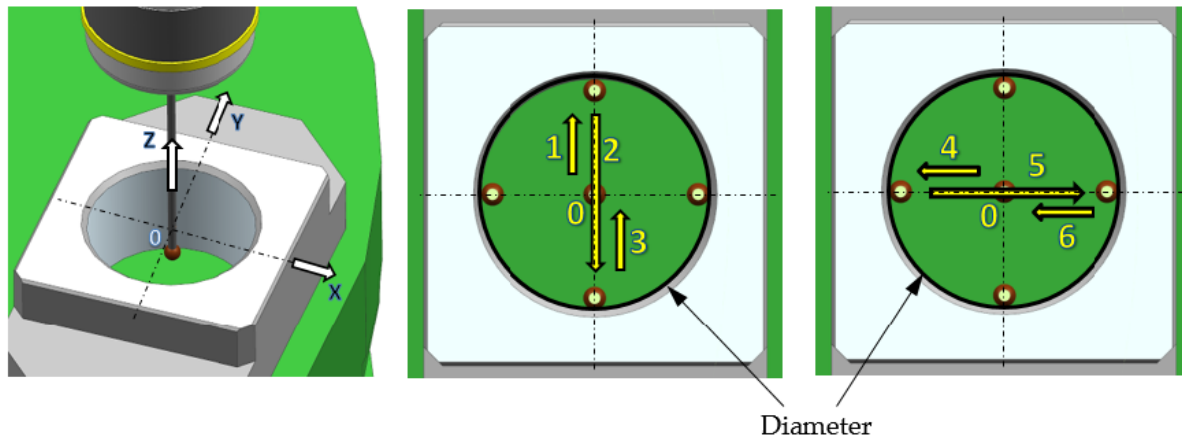


Figure 9. Sequence of measuring the position of the ring axis TP and diameter phi value.

Sequence 3, “Sequence 3 involved the measurement of the Z coordinate, the position of the ring axis TP and the ring diameter including an approach of the probe from the machining tool replacement point. Sequence 3 was analogous to sequence 2 with one difference. Each measuring cycle started with an approach from the coordinated of the machining tool replacement point (moves 1,2,3, and 4 – Figure 10. Sequence of the probe approach (a) Movement from the machining tool replacement point to the measurement area; (b) Back to the machining tool replacement point).”

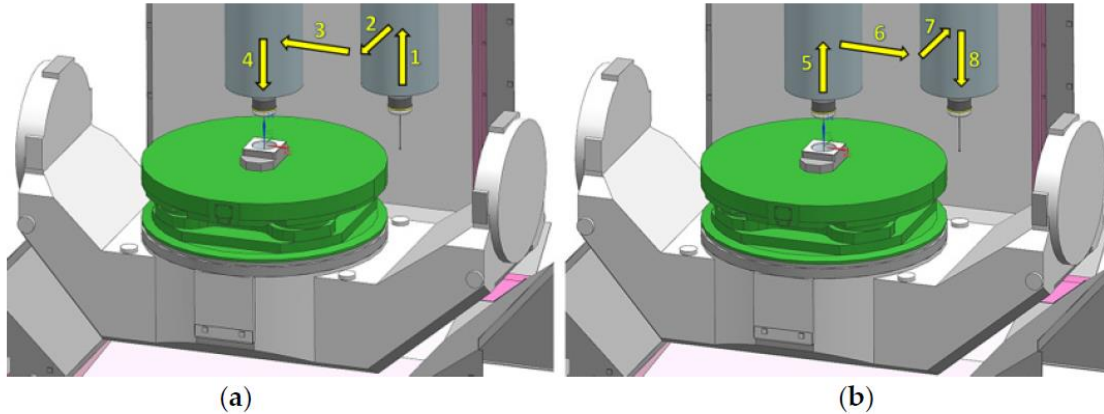


Figure 10. Sequence of the probe approach (a) Movement from the machining tool replacement point to the measurement area; (b) Back to the machining tool replacement point.

All sequences are a different R&R movement of a machine with a probe attached to the spindle. Here is the differentiating approach from the research conducted within the thesis and this article being reviewed. A machine within its own movements and system is repeatable up to capabilities that are beyond any statistical situations, due to the machine design and physical controls that prevent a machine from accumulating physical deviation. While referencing a machine tool to its own measurements is important for control within the system, the strategy of introducing a validated “artifact” is the path being explored within the thesis research. This artifact is not part of the machine system, but instead a separate system that is intended to evaluate the machine tool system and the deviations from certified measurements that are obtained from a machine tool carrying a Renishaw RMP600 touch probe.

In conclusion, there is an instance in the reviewed literature that is similar to the thesis research, where the Renishaw RMP600 probe is mounted in the machine tool spindle in order to receive XYZ location readings that are reliant on the machine tool drive readouts.

Difference in thesis research:

Our approach includes thermal compensation to account for differential thermal growth of workpiece and the machine tool scales. Thermal growth is especially important when the workpiece and machine tool scales are at different temperatures and made of dissimilar materials, which is the case discussed herein the thesis research.

1. Thermal growth within the machine tool system is not mentioned a source of deviation that is to be validated, which the thesis research is intending to evaluate and validate.

Thermal growth deviation within the workpiece is not mentioned within this article and is a topic of research in the thesis being constructed.

2.3. Thermal Errors in Machine Tools

Unless stated explicitly, all direct quotes that appear under this section are from R. Ramesh, M.A. Mannan, A.N. Poo , 2000, “Error compensation in machine tools — a review Part II: thermal errors,” *International Journal of Machine Tools and Manufacture*, Vol 40, pp. 1257-1284.

Thermal error within machine tool systems, as stated previously, is one of the dynamic errors in a physical system that is unavoidable. Controls can be used to ensure production environments are favorable for preventing thermal growth in parts, but eliminating heat within machine components while work is being completed is not feasible. “Relative movement between the various elements of the machine causes heat to be generated at the contact zones and it is this heat that leads to the deformation of the machine elements.” (Ramesh, Mannan, & Poo, 2000). Experts in machine design have come up with a number of preventative methods to minimize thermal error by using materials with relatively low CTE coefficients (concrete, epoxy,

fiber plastics) to construct dominate machine axis and components. (Kim, Jeong, & Lee, 1997) (Kim & Kim, 1997) (Spur, Hoffmann, Paluncic, Benzinger, & Nymoen, 1988) (Sugishita, et al., 1988) (Tanabe, Takada, & Tsutsumi, 1986). While all design strategies for minimizing thermal expansion and deformation of structures are valid methods to prevent thermal error, the practices are not being researched in this thesis. Firstly, to identify sources of thermal error within a machine tool system, some of the common significant contributors include: Bearings; Gear and hydraulic oil; Drives and clutches; Pumps and motors; Guideways; Cutting action and swarf; External heat sources. (Ramesh, Mannan, & Poo, 2000) These referenced heat sources are examples of the unavoidable thermal errors during production and movement of a machine tool that is performing work. A visual representation of the listed errors and resulting effects within a machine system are visualized below:

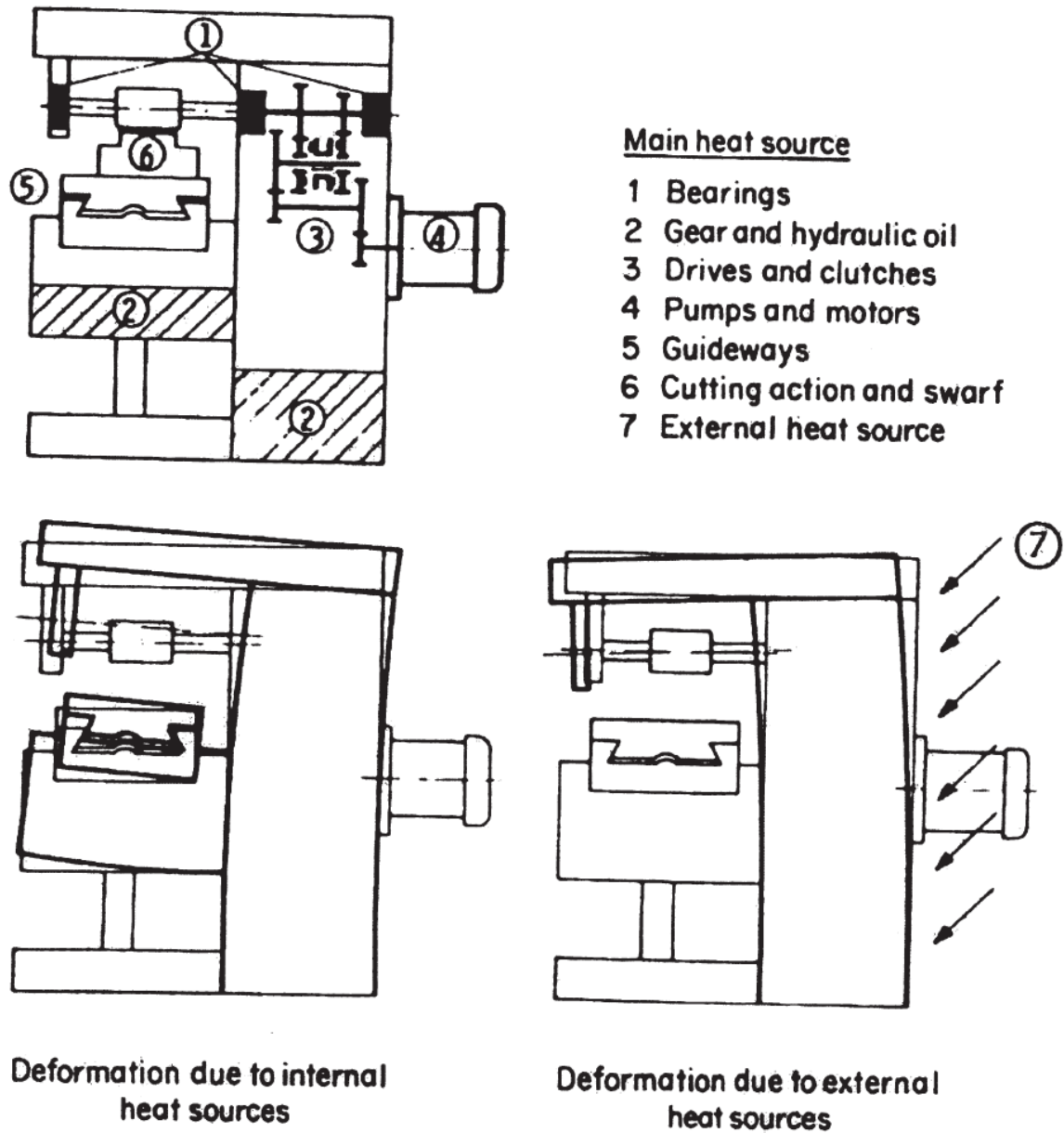


Figure 11. Thermal Deformations of a Machine System (Week, 1984).

(Ramesh, Mannan, & Poo, 2000) defines thermal errors into two categories, PITE and PDTE. These are called Position Independent Thermal Errors and Position Dependent Thermal Errors. “These errors effectively change the machine offsets and are known as position independent

thermal errors (PITE).” “The second category of errors deals with those that change as a function of axis position as well as temperature. They effectively alter the linear positioning of the machine and are known as position dependent thermal errors (PDTE).” (Ramesh, Mannan, & Poo, 2000) PITE are entire-system/component encompassing errors. PITE errors can be understood for example as thermoelastic errors of a machine tool, which if is introduced to the machine system at a high rate of change can result in inaccuracy of the system. PDTE error examples include thermal expansion differences in a machine tool system vs. a product that has a different CTE expansion coefficient. A machine tool system with a dominant steel axis will not expand linearly as much as a part with an aluminum chemical composition per Degree F / inch. This PDTE example is said differently by (Allen, Postlethwaite, & Ford, 1997) as “A PDTE will produce component errors if the change in linear positioning of the machine does not match the change in linear positioning required by the thermal expansion of the component.” This example explains positioning systems vs. machine components, but the same applies for part expansion, whichever metal component needs to be positioned accurately in respect to. To address very simply, thermal expansion within machine components and the relevant measures, (Ramesh, Mannan, & Poo, 2000) states, “The mechanism of heat transfer across the machine tool joint shows that conduction is the only significant mode of heat transfer.” Expansion within machine joints and axis are dependent on the mechanical forces that are acting on the machine’s contact joints. The dynamic mechanical forces are dependent on where the major structure of a machine is currently positioned. In summary, the machine joints are not experiencing uniform thermal or mechanical loading while machining is taking place, and thermal elements are introduced to the system (Ramesh, Mannan, & Poo, 2000). “This nonuniformity in the contact pressure causes variation in the contact resistance that in turn causes variation in the heat flux. The resulting heat

flux generates thermal contact stresses that alter the existing pressure distribution.” (Ramesh, Mannan, & Poo, 2000) “Thus a closed loop interaction is activated which remains in effect until a state of equilibrium is achieved (Attia & Kops, 1981). The production use of this information is based on the “equilibrium” that is reached. Only once a machine is installed and the physical structure is mechanically repeatable can thermal expansion be compensated for. When the system has experienced the working temperatures of the production environment it will reside in, and also has experienced physical requirements for part conformance (endurance testing / cooling system testing / etc.), linear thermal expansion of a machine can be measured. In this point in time, with the system physically constructed and constrained, a measure of deviation can be obtained. This idea will advance to Thesis research objective answers in later.

Using a machine in a thermally unstable environment is the reality that the majority of machine shops face. Seasonal changes, logistics requirements for areas to open doors, part soaking or lack of, no perfectly efficient cooling systems, etc. are some of the many variables for thermal inaccuracy. “One of the most important initial considerations seems to be the need for temperature control. It is imperative to keep the machine tool in a controlled ambient temperature rather than have it exposed to the vagaries of the atmosphere.” (Ramesh, Mannan, & Poo, 2000) This control strategy is the most obvious and still the most difficult to orchestrate in day-to-day production systems. Generalized strategies are named as:

- a) Control of heat flow into the machine tool environment.
- b) Redesign of the machine tool system to reduce sensitivity to heat flow.
- c) Compensation through controlled movement.

“A” and “B” are both impossible for large manufacturers that do not deal with thermal compensation standards or are strictly customers of machines and not directly involved designers of the machines they purchase, so continuing to “C” will progress the literature review being conducted. “It is quite deceptive to believe that real-time correction for thermal deformations could eliminate design defects connected with thermal phenomena.” (Bryan, 1990) To prevent a continuous effort to chase what is perceived as thermal error in a machine, repeatability of a machine through cycles of production temperatures is a requirement. If a machine system will physically displace out of the required tolerances and unsuccessfully locate to reference positions, then thermal compensation efforts will never work – mechanical deviations in the machine system are more significant than linearly controlled thermal growth values. Another aspect of large-scale manufacturing that should be considered as a minimization effort is the cutting heat. “This factor takes precedence over all other sources of heat generation in the case of high-volume production.” (Ramesh, Mannan, & Poo, 2000) Optimizing feeds and speeds of material should be considered so chips receive the heat of cuts and not the component being machined. The absorption of heat into the working part will result in physical XYZ growth of the part that is not being considered. Any error during roughing operations that is not adjusted for in finishing operations will directly apply to deviations of the final product.

The modeling sections of this research by (Ramesh, Mannan, & Poo, 2000) will not be evaluated as the thesis research does not include predictive modeling or error prediction software to address thermal expansion within machine systems. However, the conclusions to these topics should be mentioned as the direction of study is because of findings similar to this research. “Nonetheless, many of the developed models assume that the component errors are already available when actually they have to be obtained by time-consuming and tedious experiments

that invariably prove to be a costly exercise.” (Ramesh, Mannan, & Poo, 2000) Machine systems have many components that are not accessible when a machine is placed into production, and it is certainly understood that extensive studies of a machine that is meant to operate and produce output would not be possible for a team tasked with compensation implementation. “In addition, most of the geometric and master part tests are very time-consuming and hardly any of the analytical methods of modelling describe how these models could be updated.” (Ramesh, Mannan, & Poo, 2000) It is critical for companies to have a continuation of thermal expansion efforts that follow equipment updates and technology advances. For extremely advanced statistical models to become obsolete with a machine update is not financially sustainable for large-scale production systems. The method for obtaining expansion values must be universal (not machine specific models) and repeatable upon changing equipment and technology that is obsolete. “In addition, most of the compensation systems available at present utilise an externally situated computer to perform the task of data acquisition and error modelling/compensation and the compensation values are fed back into the CNC system of the machine tool through the interface.” (Ramesh, Mannan, & Poo, 2000) “However, despite such research, the industrial implementation of these error compensation systems, in particular that for thermal error, is still to be achieved primarily due the unavailability of a viable commercial system.” (Ramesh, Mannan, & Poo, 2000) This is still a relevant statement two decades later. The only universal references for thermal expansion values or resulting strategies are the machine controls. Here in the controls is where the actual expansion values are commanded dynamically or periodically. Many different software exists in its own personalized fashion, often to accommodate a specific machine being sold, but still no thermal expansion process software is commercially viable. For

these reasons, a generalized method is still in development for large scale use. Differences from this literature and the thesis research include:

- Laser interferometer measurements are included as a variable of accuracy in reference to workpieces as well as the machine system.
- Thermocouple measurements are not able to be taken on all components of a machine system, as the research is being conducted on currently in-production machine systems.
- Modeling will not be used to evaluate the significant thermal deviation.
- CMM software is included in the machine system.
- References of certified equipment is being used (as required by new thermal compliance standards developed since this literature)

CHAPTER 3

Research Outline

3.1. Validation of In-Situ Machine Tool Monitoring – Use of the Machine Tool as a CMM

This work was aimed at the development of a procedure to combine production, machine monitoring and part dimensional measurement using computer numerical control (CNC) machine tools equipped with in-situ, self-validated probing systems, to be utilized in the aerospace manufacturing sector. A methodology in which the machine tool completes the required part operations, and then functions as a coordinate measuring machine (CMM) is laid out, to eliminate the need to perform long and expensive ex-situ CMM measurements. The novel, in-situ probing procedure is especially attractive for the completion of automated, daily machine health checks and first article inspections that are regulated by international standards (SAE AS9102B: Aerospace First Article Inspection Requirement, 2014). The advantages are reduced operating cost due to reduced inspection labor/time and part rework requirements, and increased conformance to part quality specifications. The procedure aids in the certification by aerospace quality audit criteria (NADCAP Audit Criteria for Measurement and Inspection, 2013).

To operate the machine tool as a CMM, a high precision spherical probe (Renishaw Rengage, model RMP600 (RMP600 radio machine probe, 2008) is mounted directly on the machine head, to trigger the reading of machine X, Y and Z coordinates, which are taken as the coordinates of the point of interest. The methodology is validated following a case study involving the drilling of holes on a family of aircraft floor beams using a computer numerical

control (CNC) machine tool – a Bavus 5-axis machining center. The holes are located at various locations on the long faces of the floor beams.

A qualification method is applied to verify that the machine tool can be used as a CMM with sufficient accuracy and repeatability, and to ensure that the daily machine performance and first article inspections conducted with the in-situ CMM probing system are accurate. The qualification method is based on the standards that apply to commercial CMMs. That is, standards ANSI/ASME B89.4-1997 (Hook, 2001), including addenda ANSI/ASME B89.4a-1998 and ANSI/ASME B89.4b-2001, and ISO 10360-2:2009 (ISO/TC, 2009). These standards are henceforth referred to as ASME B89.4 and ISO 10360-2.

Qualification of the use of the CNC machining center as a CMM is performed following two procedures. These are: 1) volumetric testing and 2) interim performance evaluation (daily checks).

Volumetric testing involves measuring the displacement of the CNC machine drives using a calibrated instrument of sufficient range, accuracy and repeatability, twice a year. In general, the machine is to be commanded to move its head along several paths, over a volume that matches the regular operating volume of the CMM. The selected paths include space diagonals requiring 3-axis interpolation (p.32 of (ASME B89.4) and p. 8 of (ISO 10360-2)). Presumably, 3-axis interpolation motion is the most inaccurate kind of machine motion (Suh, Kang, Chung, & Stroud, 2008). The machine head is stopped at predetermined distance intervals, to permit several measurements of actual head position along the length of each diagonal. As per the ASME B89.4, for large CMMs of the size and axis aspect ratio of the Bavus CNC machining center, at least ten (10) measurements should be performed on each diagonal (p. 37 of

ASME B89.4). As per the ISO 10360-2, at least five (5) measurements should be performed on each diagonal, distributed evenly over the length of the diagonal (p. 6-7 of ISO 10360-2).

An interim performance evaluation is used to determine the likelihood that the machine tool, when used as a CMM, is working within its accuracy and repeatability between full volumetric tests. As per the ASME B89.4 and ISO 10360-2 standards, the goal of the interim test is to identify and stop CMMs that are out of accuracy and repeatability, before a significant number of bad parts are accepted or good parts rejected. The interim test should be applied frequently to increase confidence in the CMM's performance. It may be based on measurements made on a test workpiece of the same family that the machine is to test regularly or on measurements made on an artifact specifically designed for CMM testing. After a full volumetric test, ten (10) consecutive interim tests should be conducted, and the mean deviations from the artifact's nominals used to establish a baseline value for the artifact, with the range of deviations taken as an indication of the expected, typical variation from nominals. Deviations from the artifact's nominals should also be within the accuracy and repeatability tolerances of the CMM. Historical data from regular interim tests should be within the range of deviations established by the ten (10) initial interim tests.

3.2. SPC Control of the System

While measurements at a point in time are useful in validation and conformance buyoffs periodically, Statistical Process Control (SPC) has daily benefits to the factory at a machining work center. The previous methods for measuring machine Tool Center Point supply deviations in XYZ through the software used. The software is ran using DMIS code, which is the same code language CMM machines use to drive and measure with probe devices. Having this resolution of data enables us to make control limits and chart results of each machine orientation of

measurement. Machine Engineers care about the entire envelope of movement and overall health of every machine system, but production only needs to be concerned with the kinematic envelope they perform work in. This distinction is a key concept in the methods being developed during this research. The definition of conforming is being narrowed in scope, but controlled to a higher degree of confidence, for the purpose of keeping machines available for production at the maximum percentage of time possible. Each machine will have unique limits of deviation based on the parts produced. It is common that some machines in the factory are used to rough material, while others are held to a higher degree of accuracy to make finish passes. The SPC method will define, and conduct control based on the intended use of the machining center. Advanced statistics are also of interest since the data is available and databased for experimental purposes. Feedback of SPC data to other functional groups outside of Machine Engineering will take place, in hopes that business analyst and project engineers convey the correct capability to customers and suppliers, keeping us capable of the work we sign up to supply and receive.

CHAPTER 4

VALIDATION OF IN-SITU MACHINE TOOL MONITORING – USE OF THE MACHINE TOOL AS A CMM

4.1. Volumetric Testing of the bavius CNC Machining Center

Volumetric testing is adapted from standard procedures described in the background and involves measuring the displacement of the CNC machine drives using laser tracker (API R-50 Radian, serial number 60166) traceable to NIST, twice a year. In general, the machine is to be commanded to move its head along several paths, over a volume illustrated in Figure 12. Illustration of a typical workpiece processed by the Bavius CNC Machining Center and the volume over which the volumetric test is to be applied. This matches the regular operating volume of the CNC machine. To qualify the Bavius CNC machining center for the parts to be produced with it, the volumetric testing involved taking diagonal motion measurements every 14.5 in of machine head travel. This produces a total of 10 measurement positions along each diagonal. The Bavius CNC machining center is compensated for ambient temperature, using a built-in sensor and compensation algorithm (Wu, Tang, Chang, & Shiao, 2012). Therefore, displacement commands represent part lengths at the standard temperature of 68 °F. The drives are set at feed rate equal to the feed rate to be used during the regular operation of the CNC machine as a CMM.

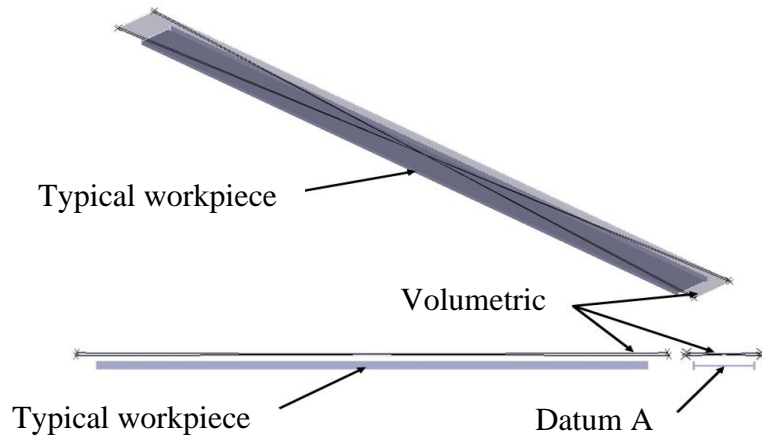


Figure 12. Illustration of a typical workpiece processed by the Bavius CNC Machining Center and the volume over which the volumetric test is to be applied.

The laser tracker's reflector is mounted on the tip of a tool holder inserted in the machine head, while the laser source/receiver unit is held stationary at a convenient location on the machine frame. The laser tracker is compensated for ambient temperature, atmospheric water pressure (air humidity), and atmospheric pressure, using built-in sensors and a compensation algorithm. Therefore, measurement values are true values at 68 °F. The start of each diagonal is taken as the zero-length reference. The difference between corresponding commanded and measured lengths are calculated. The measured length is the cumulated length along a diagonal. That is, the laser tracker is only zeroed at the start of a diagonal. The diagonal motions, and the measurements, are performed four (4) times. The start of each diagonal is taken as the zero-length reference. The difference between the four (4) measured lengths corresponding to the same location along a diagonal are calculated. For each measurement location, the range of the four measured lengths is calculated. The maximum range is taken as the machine repeatability index. This repeatability index can be used to assess machine performance over time. The difference between the most positive error and the most negative error, regardless of measured length, is taken as the machine

accuracy index. Commonly applied industrial practice dictates that this accuracy index shall be at least four (4) times smaller than the smallest tolerance of the dimensions to be measured with the machine.

Figure 13. Results from a volumetric test performed on the Bavius CNC machining center. The plot shows the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center (") shows a plot of the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center, all along the four diagonals defined in Figure 13. Results from a volumetric test performed on the Bavius CNC machining center. The plot shows the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center ("), including all repeat measurements. From Figure 13. Results from a volumetric test performed on the Bavius CNC machining center. The plot shows the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center ("), the repeatability and accuracy indices of the Bavius CNC machining center are 0.0006 in and 0.0012 in, respectively.

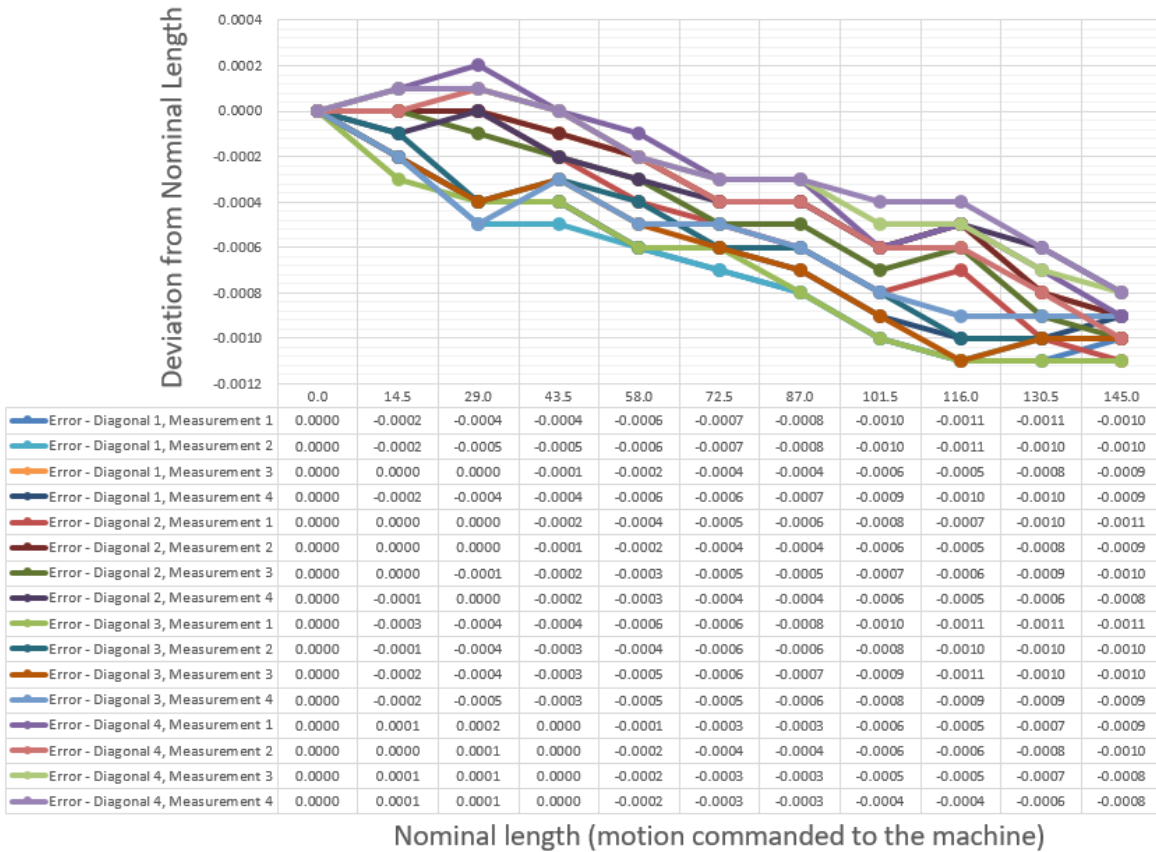


Figure 13. Results from a volumetric test performed on the Bavius CNC machining center. The plot shows the deviation of the measured length with respect to the nominal length vs. the nominal length given as commanded motion to the Bavius CNC machining center ("

4.2. Interim Performance Evaluation (Daily Checks)

Daily checks are adapted from standard interim performance evaluations described in the background, and involve the use of the high precision contact probe (Renishaw Rengage probe RMP600 (RMP600 radio machine probe, 2008)) and a program written in a CNC/CMM software (CAPPS-NC), to command machine motions to the various probing points. The software complies with international standards traceable to the National Institute of Standards and Technology (NIST).

The interim performance evaluation described herein is designed to check the accuracy and repeatability of the X, Y, Z and A drives of the Bavius CNC machining center, which are involved in part processing and measurement. The interim performance evaluation is to be conducted against two specially designed artifacts: A five (5)-sphere calibrated artifact (Figure 14. Schematic illustrating the arrangement of the five (5)-sphere calibrated artifact used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Inset A shows the artifact in regular orientation. Inset B shows the artifact from “behind”, to make all spheres visible. Spheres are labeled TB1 to TB5.) and two (2) calibrated bushings embedded on the hard tool (Figure 15. Schematic illustrating the arrangement of the two (2) calibrated bushings embedded on the hard tool to be used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Bushings are labeled as Bushing 1 (left) and Busing 2 (right). Insets A and B show close, top views of area surrounding the bushings).

These “checks” mimic measurement of location and diameter of holes made by the Bavius CNC machining center on XY and XZ planes of a specific family of parts. The Bavius CNC machining center is utilized to make holes on the XY and two XZ planes of parts of this family. Then, the Bavius CNC machining center is utilized to measure the location and diameter of these holes. The measurements are below the operating envelop of the Bavius CNC machining center. Thus, the interim testing complements the volumetric test measurements described in the previous section, which involved measurement along diagonals located above the operating envelope of the machine.

The five (5)-sphere calibrated artifact (Figure 14. Schematic illustrating the arrangement of the five (5)-sphere calibrated artifact used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Inset A shows the artifact in regular orientation. Inset B

shows the artifact from “behind”, to make all spheres visible. Spheres are labeled TB1 to TB5.) is qualified using a standard CMM (Hexagon 152210-Chrome) traceable to NIST. During the qualification, the artifact is free from loads resulting from clamping against the metrology table. The artifact is glued to the table of the Bavus CNC machining center to keep it free from loads throughout the interim testing. The qualification is conducted in a controlled atmosphere at 68 °F. The artifact is made of the same material (same aluminum alloy) as the parts being processed on the Bavus CNC machining center. This enables thermal compensation, during the interim testing, using the standard procedure deployed by the Bavus CNC machining center for regular part processing. The artifact’s nominals are taken from these qualifications. The nominals are average values of the X,Y, Z coordinates of the five (5) spheres, with local coordinate system as defined in Figure 14. Schematic illustrating the arrangement of the five (5)-sphere calibrated artifact used to qualify the Bavus CNC machining center, by probing with the Renishaw Rengage probe. Inset A shows the artifact in regular orientation. Inset B shows the artifact from “behind”, to make all spheres visible. Spheres are labeled TB1 to TB5..

The two (2) bushings embedded on the hard fixture (Figure 15. Schematic illustrating the arrangement of the two (2) calibrated bushings embedded on the hard tool to be used to qualify the Bavus CNC machining center, by probing with the Renishaw Rengage probe. Bushings are labeled as Bushing 1 (left) and Busing 2 (right). Insets A and B show close, top views of area surrounding the bushings) are qualified using a laser tracker scaled against a linear laser (API XD1LSP) traceable to NIST. The qualification is conducted directly on the Bavus CNC machining center, but the temperature of the machine bed is measured, and the dimensions obtained from the qualification corrected for thermal growth due to temperature deviations with respect to 68 °F. The hard fixture holding the bushings are also made of the same material (same

aluminum alloy) as the parts being processed on the Bavius CNC machining center. This enables using the standard procedure deployed by the Bavius CNC machining center for the thermal compensation. The artifact's nominals are taken from these qualifications. The nominal is the center-to-center distance from bushing 1 to bushing 2, with local coordinate system as defined in **Error! Reference source not found.**

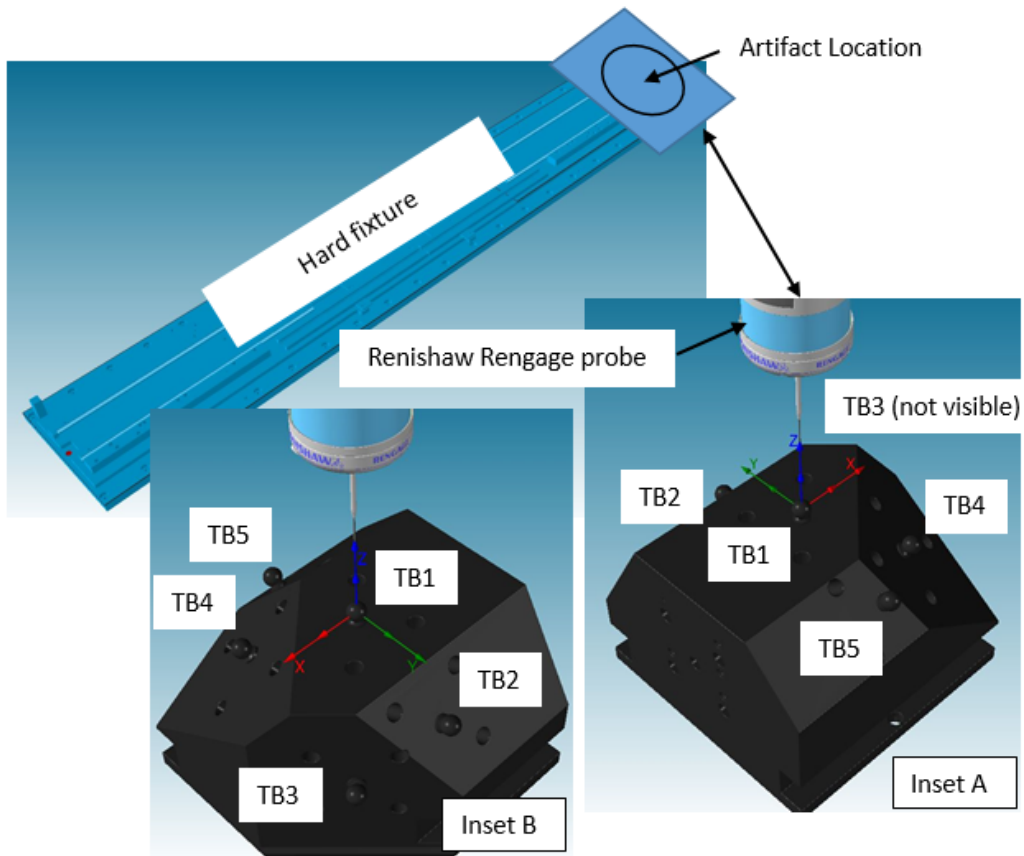


Figure 14. Schematic illustrating the arrangement of the five (5)-sphere calibrated artifact used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Inset A shows the artifact in regular orientation. Inset B shows the artifact from “behind”, to make all spheres visible. Spheres are labeled TB1 to TB5.

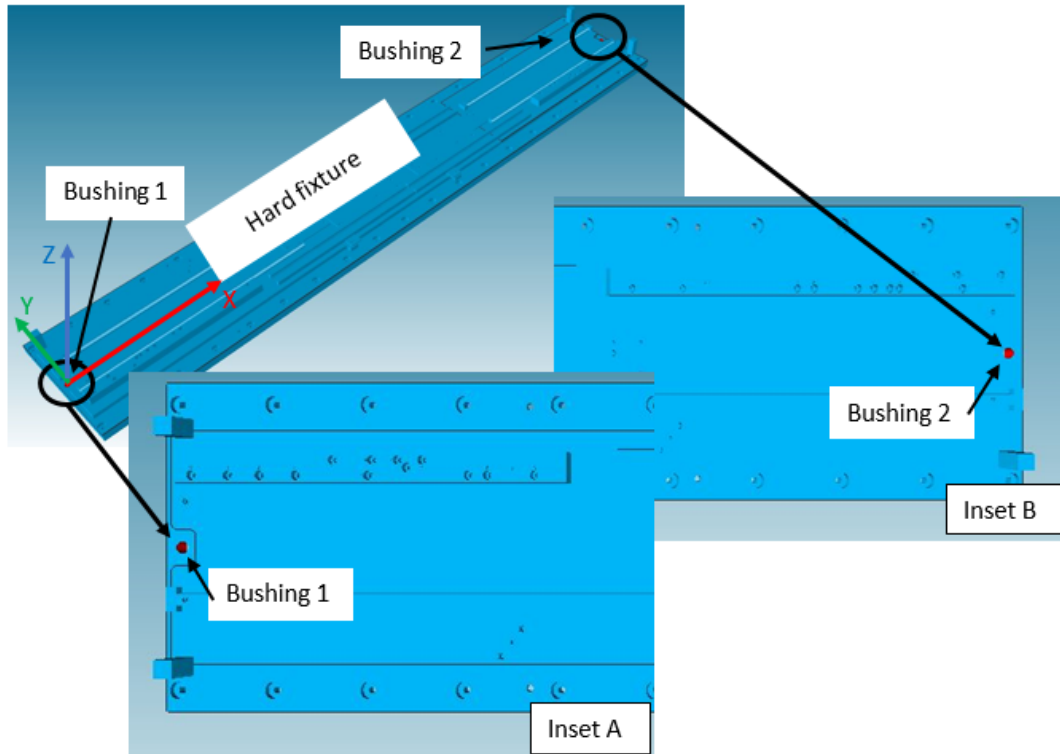


Figure 15. Schematic illustrating the arrangement of the two (2) calibrated bushings embedded on the hard tool to be used to qualify the Bavius CNC machining center, by probing with the Renishaw Rengage probe. Bushings are labeled as Bushing 1 (left) and Busing 2 (right). Insets A and B show close, top views of area surrounding the bushings.

4.3. Experimental Configuration

The FAIs involve the use of the high precision contact probe (Renishaw Rengage probe RMP600 (RMP600 radio machine probe, 2008)) and a program written in a CNC/CMM software (CAPPS-NC), to command machine motions to the various probing points. The software complies with international standards traceable to the National Institute of Standards and Technology (NIST). The probing points are selected to define the position of the holes to be inspected. Figure 16. Schematic illustrating the arrangement of the machine bed of the Bavius

CNC Machining Center. Milling floor of the hard fixture (blue), datums and clamps of the hard fixture (yellow) and a generic workpiece (red). shows the probe performing an FAI on a generic part.

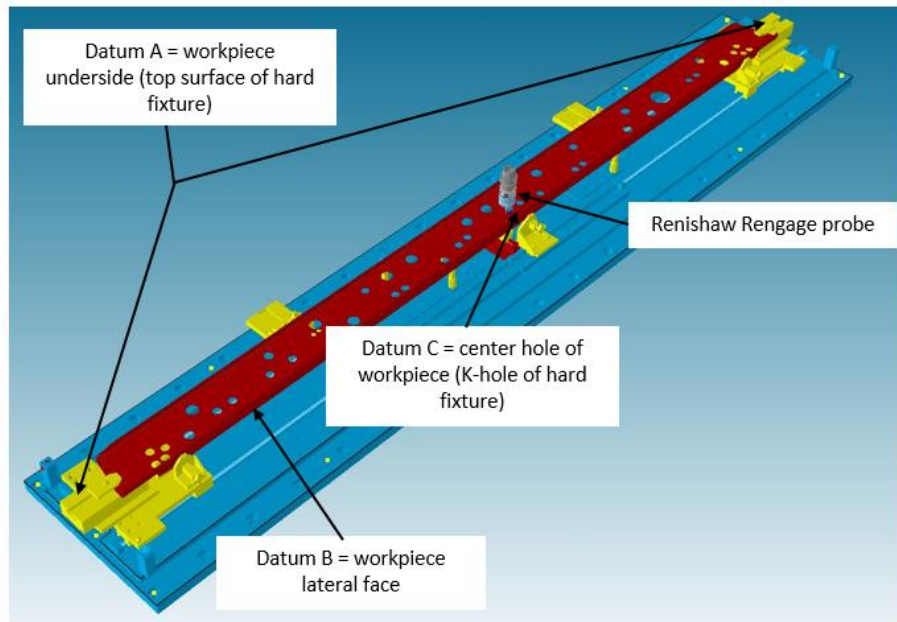


Figure 16. Schematic illustrating the arrangement of the machine bed of the Bavius CNC Machining Center. Milling floor of the hard fixture (blue), datums and clamps of the hard fixture (yellow) and a generic workpiece (red).

The Renishaw Rengage probe is being used to measure the position of all the holes of interest, directly on the machine. Typical holes are on the horizontal or vertical long faces of the part. One beam was processed by the Bavius CNC machining center by drilling holes that are required to be made at the center. The beam was run through an FAI procedure using the Bavius CNC machining center as a CMM, as described in the preceding sections. To validate the measurement procedure, the same beam was subject to measurements using several other standard CMMs and clamping methods. The results from this round robin test are shown and discussed in the following sections.

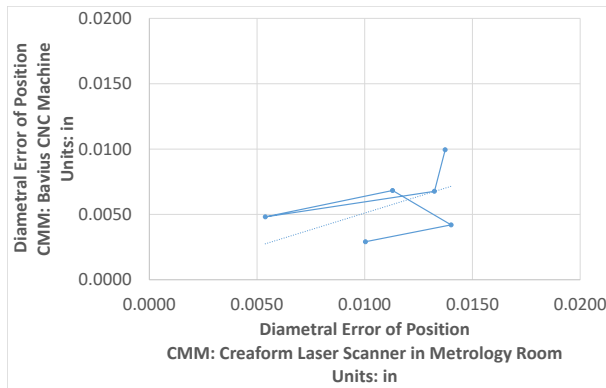
4.4. Experimental Results

Figure 17. A) Relationship between measurements of the diametral error of position using the Bavius CNC machining center as a CMM vs. using a Creaform laser scanner in an environmentally controlled metrology room. B) The error relationship, but after measurement using the Bavius CNC machining center and a Leica laser tracker, without dismounting the beam between measurement runs. Y and X are diametral position errors measured by the two methods compared, respectively. R is coefficient of correlation.

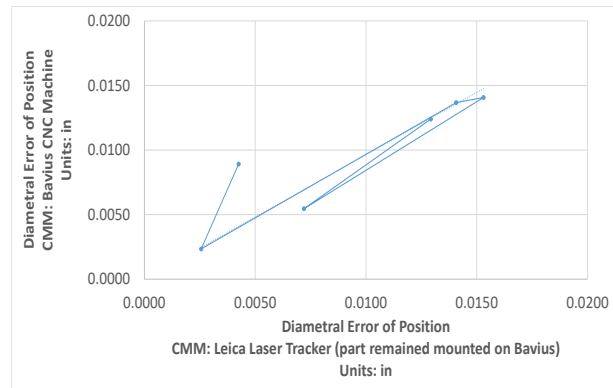
A shows the relationship between measurements of the diametral error of position using the Bavius CNC machining center as a CMM vs. using a Creaform laser scanner in an environmentally controlled metrology room. Figure 17. A) Relationship between measurements of the diametral error of position using the Bavius CNC machining center as a CMM vs. using a Creaform laser scanner in an environmentally controlled metrology room. B) The error relationship, but after measurement using the Bavius CNC machining center and a Leica laser tracker, without dismounting the beam between measurement runs. Y and X are diametral position errors measured by the two methods compared, respectively. R is coefficient of correlation.

B shows the error relationship, but after measurement using the Bavius CNC machining center and a Leica laser tracker, without dismounting the beam between measurement runs with one device or the other. Note the equation of the linear regression line between errors reported by one measurement procedure and the other, and the coefficient of correlation (R), both given in

the figure insets. When the beam is dismantled to be taken to metrology, the regression line fails to explain the relationship between errors measured by the Bavius vs. the laser scanner (R is high, but regression line constant is less than 1). However, when the beam is held on the machine tool and both the Bavius and the laser tracker are used to measure the errors of position, the regression line explains the relationship between the errors reported by these two measurement methods (R is high, and regression line constant is about 1).



A: Regression line $Y = 0.51X$, $R = 0.96$



B: Regression line $Y = 0.96X$, $R = 0.96$

Figure 17. A) Relationship between measurements of the diametral error of position using the Bavius CNC machining center as a CMM vs. using a Creaform laser scanner in an environmentally controlled metrology room. B) The error relationship, but after measurement using the Bavius CNC machining center and a Leica laser tracker, without dismantling the beam between measurement runs. Y and X are diametral position errors measured by the two methods compared, respectively. R is coefficient of correlation.

Moreover, as evident from Table 4. Results from round robin tests. Regression line and coefficient of determination between position error measurement procedures. Y and X are diametral position errors measured by the two methods compared, respectively. R is coefficient of correlation., the regression line is found to explain the relationship between the position error

measured by the Bavius CNC machine only when the part remains mounted on the it for the measurement run following the alternative method.

TABLE 4. RESULTS FROM ROUND ROBIN TESTS. REGRESSION LINE AND COEFFICIENT OF DETERMINATION BETWEEN POSITION ERROR MEASUREMENT PROCEDURES. Y AND X ARE DIAMETRAL POSITION ERRORS MEASURED BY THE TWO METHODS COMPARED, RESPECTIVELY. R IS COEFFICIENT OF CORRELATION.

Test Set	Comparison between:	Regression line	R
1	Bavius CNC Machine vs. Creaform Laser Scanner in Metrology Room	$Y = 0.5X$	0.94
2	Bavius CNC Machine vs. Leica Laser Tracker (part remained mounted on Bavius)	$Y = 1.0X$	0.98
3	Bavius CNC Machine vs. Creaform Point Probe (part remained mounted on Bavius)	$Y = 0.6X$	0.99
4	Bavius CNC Machine vs. FaroArm Contact Point Probe (part remained mounted on Bavius)	$Y = 0.8X$	0.96
5	Bavius CNC Machine vs. Bavius CNC Machine (part remounted between measurement runs)	$Y = 0.5X$	0.82

4.5. Summary

A CNC machining center was fitted with high resolution contact probing to enable drive position readings triggered by the probing to be utilized for part measurement. Standard volumetric and interim tests that apply to performance evaluation of conventional CMMs were

adapted for performance evaluation of the CNC machining center when it is used as a CMM for automated machine tool health monitoring and for FAIs. Immediate advantages from this operating procedure were obtained on the shop floor, including reduced inspection labor/time and part rework requirements, and increased conformance to part quality specifications.

It was found, by round robin testing following measurement of drilled holes position error by several methods that proper part clamping is critical. Measurements of hole position error using the CNC machine tool itself ensures that part clamping is standard, thus measurements more repeatable.

The proposed use of the CNC machine as a CMM shall be a cost-effective method for metrology inspection whenever the measurement cycle time is a small fraction of the manufacturing cycle time. The method is particularly attractive in the aerospace sector, where low production volume is associated with high machine tool idle time. For these applications, in-situ probing results in minimally disruptive part measurement.

CHAPTER 5

STATISTICAL PROCESS CONTROL: TOOL CENTER POINT DEVIATION

HISTORY

5.1. SPC – TCP Measurements

Tool Center Point is evaluated via “Daily Check Probe Routine” on machines using the DMIS software, certified probe devices, and a certified tooling ball. The objective is to establish a center XYZ location on the machine and attempt to move the machine spindle to all extreme rotary positions while measuring this center XYZ location. An important note to make here is, the machine is not evaluated on its ability to find the zero point (this would be a coordinate measurement capability test), but its ability to minimize deviation while different rotary positions are used to find the established zero XYZ. A standard TCP Process is shown below:

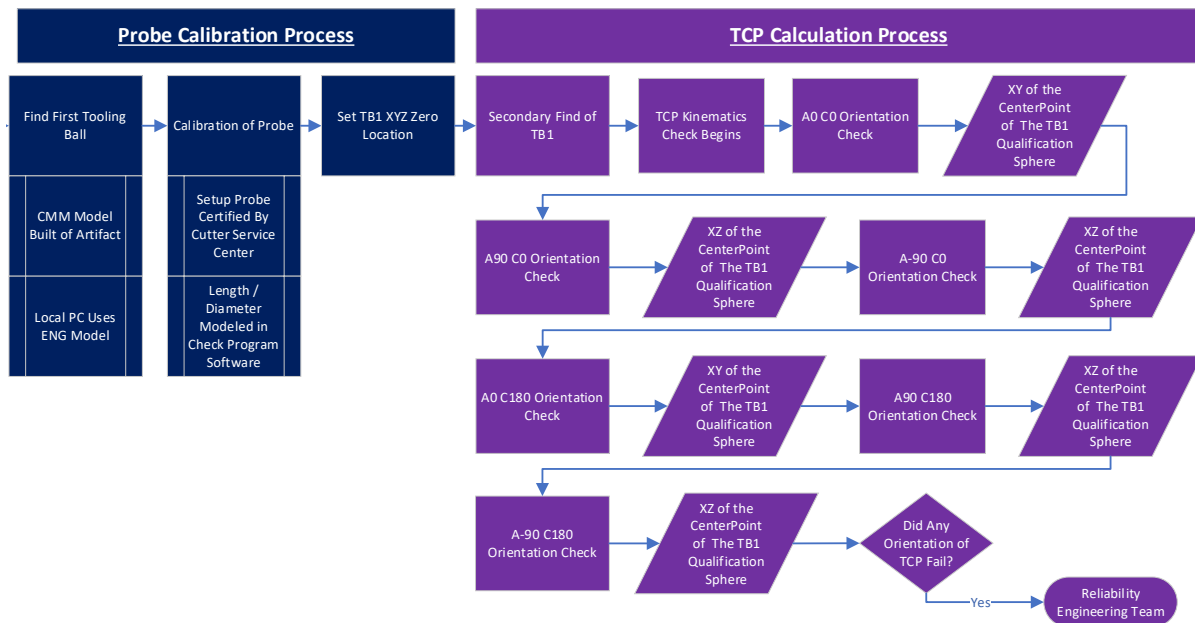


Figure 18. Tool Center Point Program Process.

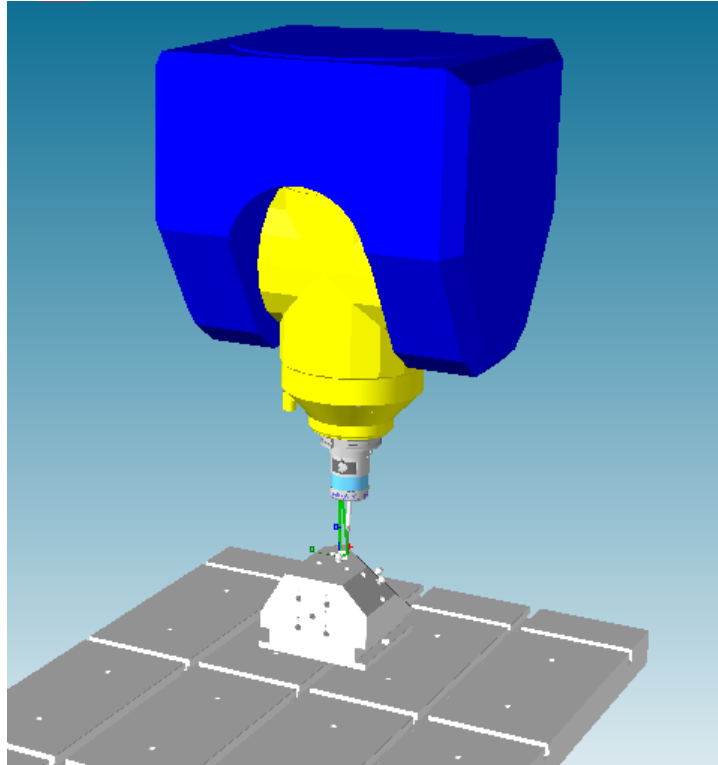


Figure 19. A0C0 Machine Spindle Measurement Orientation.

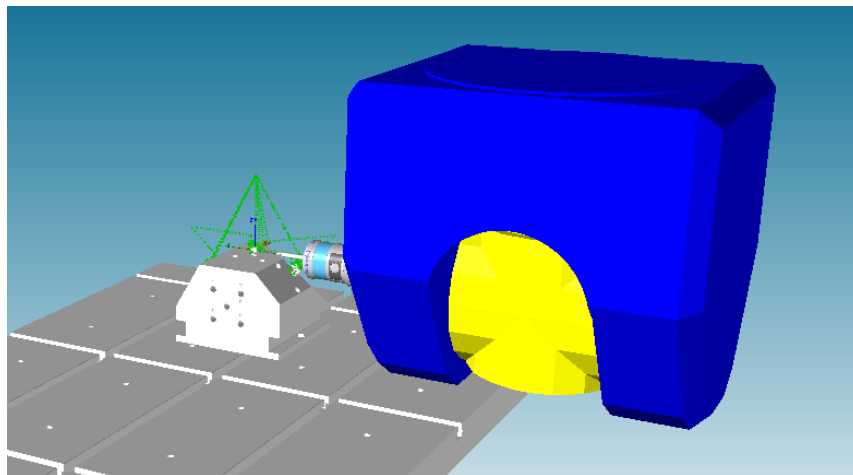


Figure 20. AP90C0 Machine Spindle Measurement Orientation.

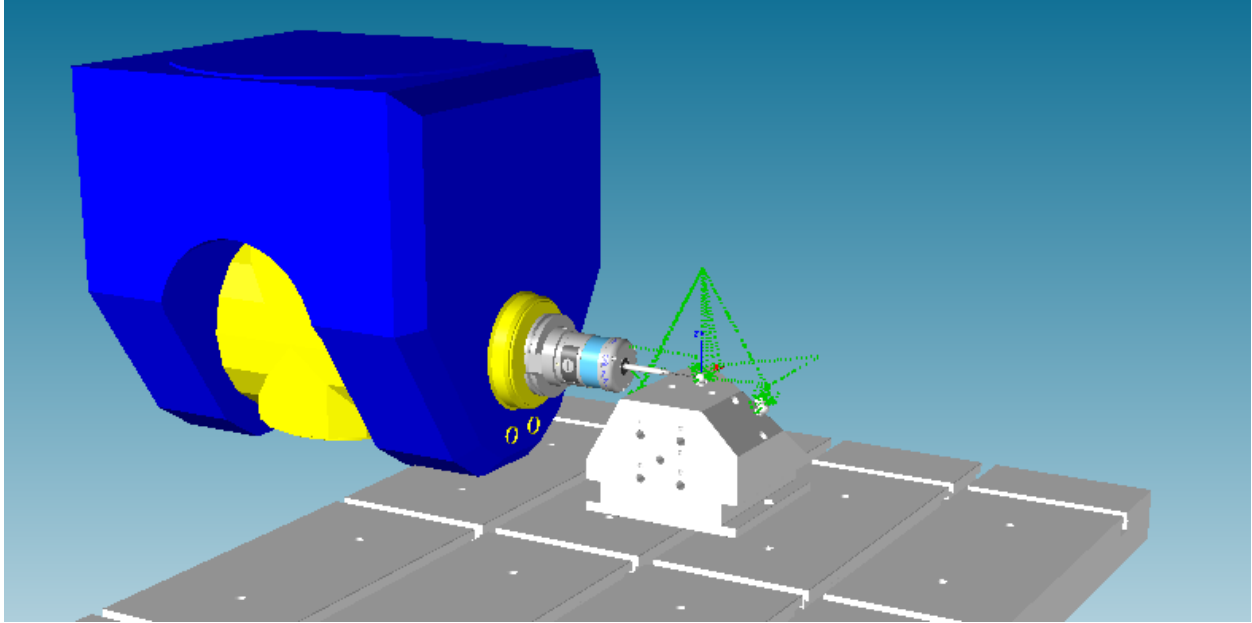


Figure 21. AN90C0 Machine Spindle Measurement Orientation.

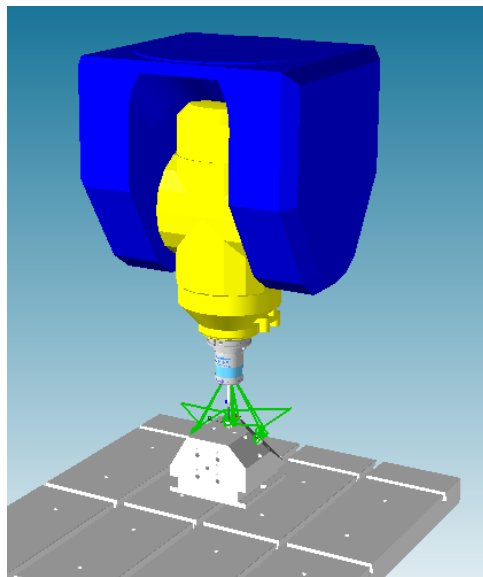


Figure 22. A0C180 Machine Spindle Measurement Orientation.

After the program is ran, XYZ deviations associated to each rotary position can be obtained. A data table can be constructed to represent the “Daily Check,” which will look similar to Table 5. TCP Results Using Daily Check Programs.

TABLE 5. TCP RESULTS USING DAILY CHECK PROGRAMS

Output_label	Report_DateTime	X_DEVIATION	Y_DEVIATION	Z_DEVIATION	True_Position
A0CP180	10/05/2023 08:20:00	0.0004	0.0001	0	0.0008
AP90C0	10/05/2023 08:20:00	0.0005	0.0002	-0.0003	0.0013
AP90CP90	10/05/2023 08:20:00	0.0003	0.0015	0	0.0031
AP90CP180	10/05/2023 08:20:00	0.0001	0.0007	0.0005	0.0017
AP90CP270	10/05/2023 08:20:00	0.0002	0.0008	0.0002	0.0016
AN90CP270	10/05/2023 08:20:00	-0.0003	0.0001	-0.0005	0.0012
AN90CP180	10/05/2023 08:20:00	-0.0008	0.0009	-0.0007	0.0028
AN90CP90	10/05/2023 08:20:00	0.0008	0.0015	-0.0003	0.0035
AN90C0	10/05/2023 08:20:00	0.0011	0	-0.0001	0.0022
A0C0	10/05/2023 08:20:00	0	0	0	0.0001

With this table, data is now available as a physical evaluation of a machine center at a point in time. The thesis research will not dive into measurement standards that are used to obtain tooling ball (multi point centering) center point measurements, but the Tool Center Point process is only possible when certified equipment and certified macro-based measurements are used. True Position is the metric of interest for operations. This metric was mentioned previously in the thesis research as the “one-third” of tolerance allowed by the machine physical kinematics. True Position is compared directly to engineering requirements of 5-axis features and only less than one-third of the engineering tolerance is accepted for production use. If daily check values are acceptable, operations continue and there is no further concern for machine accuracy at that point in time. Machine engineers have a deeper interest in the data obtained from probe routines and the concepts of statistical process control.

5.2. SPC – Databasing Daily Check Data

Machine data storage initiatives work congruently with the Tool Center Point database initiatives for SPC, as Tool Center Point is one of many metrics that should be recorded from a machine tool. The general method for machine data storage is illustrated below in Figure 23. Machine Data Acquisition Architecture. This is a general architecture for machine data, with many specific skillsets required to connect the machine systems and computer-based systems together.

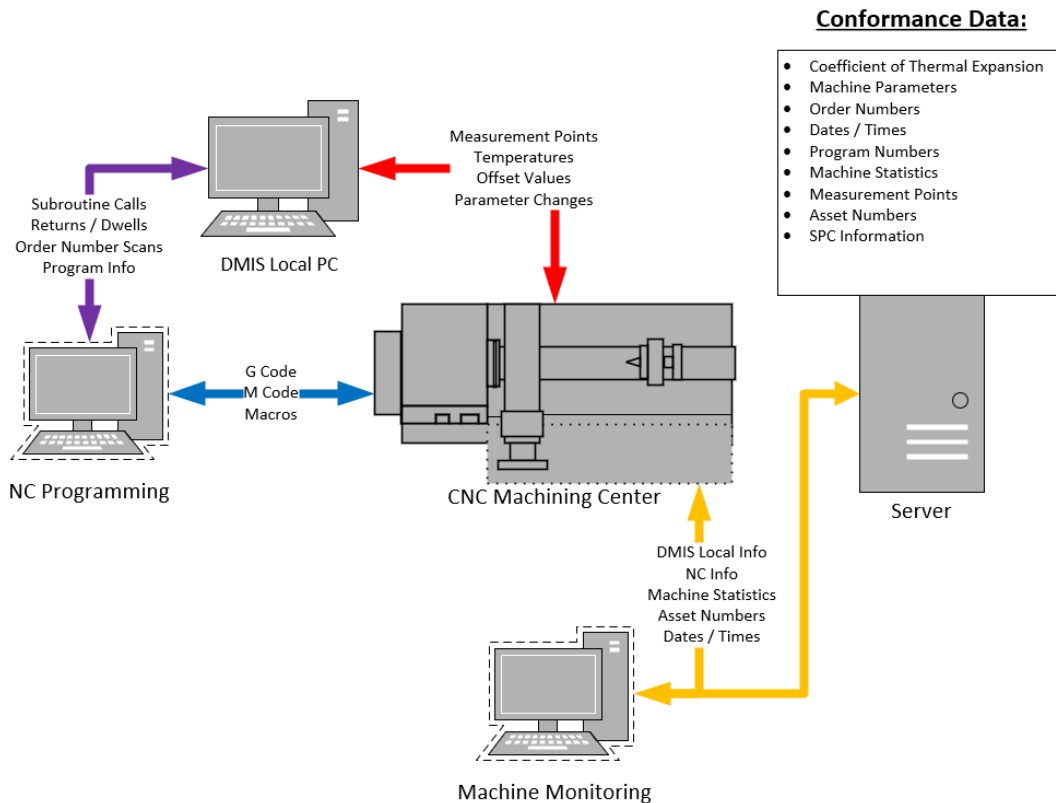


Figure 23. Machine Data Acquisition Architecture.

As shown in the architecture example (Figure 23. Machine Data Acquisition Architecture.), information from the machine tool has many dimensions. This piece of equipment

is a source of Enterprise Resource Planning / Manufacturing Execution System / Quality / Facilities / Simulation / IT / etc. information. The only use focused within this research is the obtaining of Tool Center Point process data.

5.3. SPC – Historical Results from Actual Production System

The Bavius PBZ SC machine tool system is the cell of interest in this SPC study. The TCP process runs every workday on this machine, and there has now been roughly a year of data captured in this machine system without any interjection to the process / program. This is important for the SPC studies because the machine system is being evaluated on its accuracy, which is a daily check to ensure tolerance is being met before production, but also the ability of the machine tool system to be precise while undergoing a full year of cutting/drilling/thermo-elastically expanding through the seasons/wearing/settling/crashing. All of the phenomena mentioned are captured (at the disadvantage of the system) by sampling the machine data and keeping outliers in the study. The machine system precision is victim to incorrect settings, feed rates not being properly set while kinematic checks are run, etc. The intention of the study is to evaluate a machine in the operation situation, which has now been obtained for about one year of production.

First, the strategy for collecting the deviation data is a query from the server architecture shown above in Figure 23. Machine Data Acquisition Architecture. XYZ deviations for any physical orientation measured can be obtained, but it is relevant to note that the machine working orientations are at A-Axis +/- 90 degrees, and C-Axis 0/180 degrees. This helps for deviations and feature fabrication because one of the XYZ directions is now a through-vector, and the deviation direction does not influence the installation location or tolerance usage. However, the true position precision and production-relevant precision will both be shown. Note: This is not a

repeatability test, as studied in literature from this thesis research because the samples are taken on a different day, after different physical events have taken place, and they represent an entirely different physical situation each time a sample is taken. Repeatability would be a test within the system, while controlling all the physical variables mentioned before.

5.4. SPC – Orientation Statistics

5.4.1. A-Axis Positive 90 Degrees (AP90C0)

Query:

COUNT(X_DEVIATION) as X_DEVIATION_COUNT, STDEV(X_DEVIATION * 1000) as X_STD_DEVIATION,

COUNT(Z_DEVIATION) as Z_DEVIATION_COUNT, STDEV(Z_DEVIATION * 1000) as Z_STD_DEVIATION

WHERE Output_Label = 'AP90C0'

TABLE 6. AP90C0 X AND Z DIRECTION DEVIATION

X_DEVIATION_COUNT	X_STD_DEVIATION	Z_DEVIATION_COUNT	Z_STD_DEVIATION
229	1.768	229	2.547

It can be seen in the results (Table 6. AP90C0 X and Z Direction Deviation) that the machine system precision is represented in the X direction with a standard deviation of 1.768 thousandths of an inch, and in the Z direction with a standard deviation of 2.547 thousandths of an inch. This would mean the system will locate 99.7% of samples within +/- .0053” for X direction and +/- .0076” for the Z direction in the orientation of A-Axis +90, per the generally excepted Empirical Rule. It is wise to evaluate this data with different methods, to be sure that

statical rules are not being violated and declared true without validation. The first validation will be a histogram plot, to ensure that the population of data does indeed represent a physical system that has not been changed *significantly* over the time period of data collection. A significant change would be identified in a histogram plot as an entirely separate population of data, where overlapping data points of two curves do not occur. The X deviation direction (obtained via query of X deviation actuals) plot is graphed below (Figure 24. AP90C0 X Deviation Histogram – Bavius.):

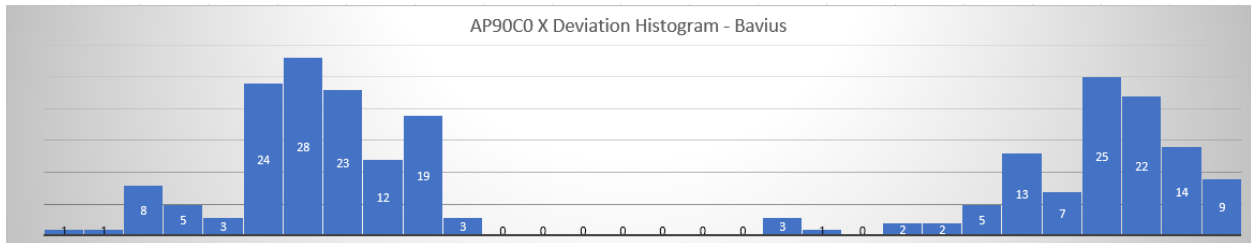


Figure 24. AP90C0 X Deviation Histogram – Bavius.

This result is a statistical representation of two physically different systems. The most important step from here, is to find the population that represents the machine currently. This can be done using the measurement database and sorting results based on timestamp.

X_Deviation Query (to find population):

```

Select (X_Deviation * 1000) as X_Deviation, (Z_Deviation * 1000) as Z_Deviation,
Report_DateTime

where Output_Label = 'AP90C0'

order by Report_DateTime desc

```

Results of this query will be presented in the chronological order timestamp starting at the most-recent timestamp. The values obtained in the timestamp certified query tell us that the deviations obtained most recently belong to the population of data on the left side of the histogram results. The standard deviation test needs to be conducted on physically valid data, so a new query for X deviation data will be constructed.

X_Deviation Query (Valid Population) :

```
Select COUNT(X_DEVIATION) as X_DEVIATION_COUNT,
STDEV(X_DEVIATION * 1000) as X_STD_DEVIATION,
```

```
FROM DATABASE
```

```
WHERE Output_Label = 'AP90C0'
```

```
and X_Deviation < 'MAXIMUM DEVIATION IN RELVANT POPULATION'
```

TABLE 7. AP90C0 X DEVIATION QUERY (VALID POPULATION)

X_DEVIATION_COUNT	X_STD_DEVIATION
126	0.364

What has been discovered here is a physically and statistically valid data range (Table 7. AP90C0 X Deviation Query (Valid Population)), which is smaller than the previous data range (Table 6. AP90C0 X and Z Direction Deviation), but usable for decision making now. The X direction deviations of A-Axis +90 are represented by 126 samples with a standard deviation of .364 thousandths of an inch. This new calculation of the Empirical Rule translates to an accuracy of +/- .001” for 99.7% of all samples that will be obtained while the machine system is in this

physical state. Recall the accuracy evaluation that did not consider the physical system state being +/- .0053” for the X direction. This difference in accuracy confidence has many business and production systems engineering benefits, but the topics will not be expanded on within the thesis research being conducted here. The process for evaluation of the other relevant machine work orientations will be the same. Each physical orientation must be divided into its own statistical evaluation, and sorted by each XYZ direction of space that is considered in the General Dimensioning & Tolerancing of the work piece features.

5.4.2. A-Axis Positive 90 Degrees (AP90C0) Z Direction Evaluation

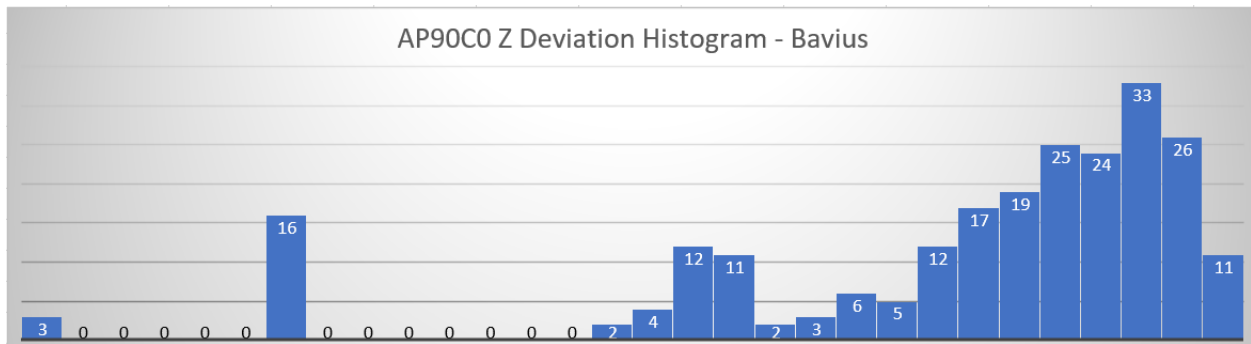


Figure 25. Population Evaluation of AP90C0 Z Direction.

Z distribution (Figure 25. Population Evaluation of AP90C0 Z Direction.) does not appear to be as obvious as the X deviation histogram distribution, but higher resolution of the data can be obtained by adding additional bins to the graph (Figure 26. Population Evaluation of AP90Co Z Direction Higher Resolution.).

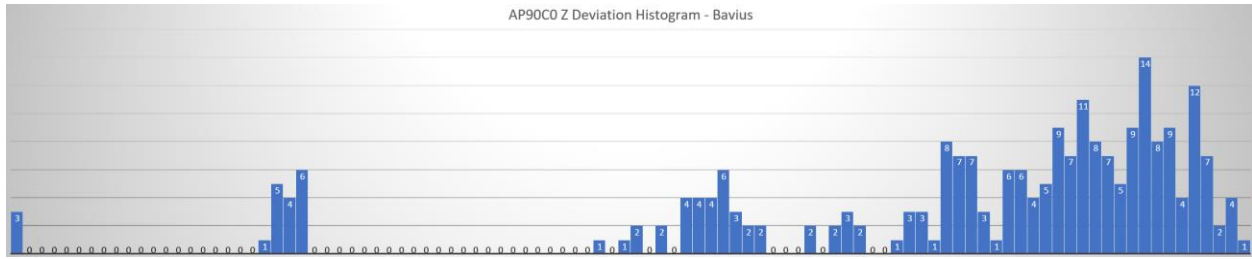


Figure 26. Population Evaluation of AP90Co Z Direction Higher Resolution.

This plot has a similar suggestion to the first, a shift in population is possible, but not as obvious as it was for X deviations. The intersection of the populations is the potentially visualized, here (Figure 27. Potential Population Intersection AP90C0 Z Direction.):

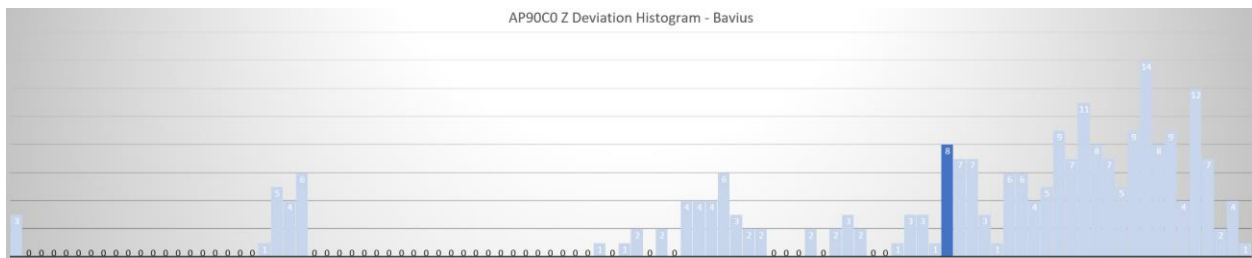


Figure 27. Potential Population Intersection AP90C0 Z Direction.

This deviation value will be the filter for the next query, once the most recent population data is identified.

Z_Deviation Query (to find population):

Select (Z_Deviation * 1000) as Z_Deviation, Report_DateTime

where Output_Label = 'AP90C0'

order by Report_DateTime **desc**

TABLE 8. AP90C0 Z DIRECTION POPULATION IDENTIFICATION QUERY RESULTS

Z_Deviation	Report_DateTime
0.24	2023-07-17 11:06:44
-7.846	2023-07-17 10:55:30

The database suggests a significant change happened between the timestamp values shown (Table 8. AP90C0 Z Direction Population Identification Query Results). Plotting these deviations vs. timestamp values ascending could possibly lead to a visual validation of this situation as well. Plotting deviation in chronological order is shown below (Figure 28.AP90C0 Z Deviation Time Series - Bavius.):

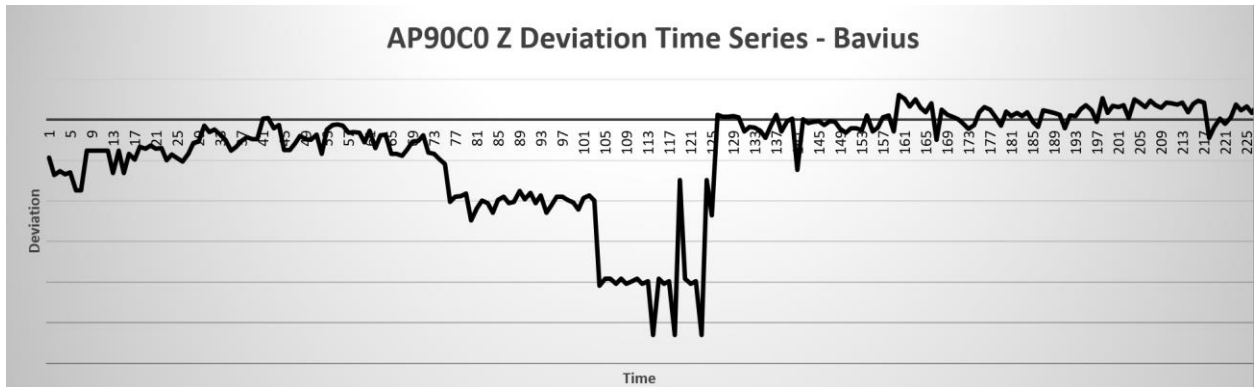


Figure 28.AP90C0 Z Deviation Time Series - Bavius.

This plot suggests the AP90C0 orientation was rapidly corrected physically or electronically within a short period of time. From this point, the population can be evaluated only using values above the special case (the dip in the graph) that was identified as an event:

TABLE 9. AP90C0 Z DEVIATION TIME SERIES DATA (VALID POPULATION)

Z_DEVIATION_COUNT	Z_STD_DEVIATION
171	0.831

The Z Deviation values representing the steady curve of the line are evaluated above (Table 9. AP90C0 Z Deviation Time Series Data (Valid Population)). The behavior of the Z direction appeared to have negative and positive values, as shown in the time series, with slightly less control than the X direction for AP90C0 spindle orientation – the 2nd evaluation still shows an improvement in precision for the machine system, however (prior value was 2.547 standard deviation). Importantly, the histogram plot was not able to distinguish between the older population of deviations and the recent populations of deviations. Instead, the histogram outliers shown plotting on the left side of the graph were simply random deviations while the orientation was out of control. The time series graph shows this trend happening in a way that is more intuitive with time of measurement. The event found in the X deviation histogram and Z deviation time series should have a similar time stamp. If so, speculation can be made for the AP90C0 orientation that an event occurred on a particular day during the year of production. The X deviation timestamps will be searched using the same query as before with X deviations descending. 07-14 is identified as the timestamp date where X deviation changes significantly (between the populations shown previously). A production relevant note in this situation is that 07-14 is a Friday, and 07-17 is a Monday. It is possible that these changes were done electronically or physically by machine engineering and maintenance personnel. Service records in the business would be a validation of this occurring.

5.4.3. A-Axis Negative 90 Degrees (AN90C0) Sample Study

Query:

```
COUNT(X_DEVIATION) as X_DEVIATION_COUNT, STDEV(X_DEVIATION *  
1000) as X_STD_DEVIATION,
```

COUNT(Z_DEVIATION) as Z_DEVIATION_COUNT, STDEV(Z_DEVIATION * 1000) as Z_STD_DEVIATION

where Output_Label = 'AN90C0'

TABLE 10. AN90C0 FULL POPULATION QUERY

X_DEVIATION_COUNT	X_STD_DEVIATION	Z_DEVIATION_COUNT	Z_STD_DEVIATION
231	1.218	231	1.721

X Deviation Population Histogram:

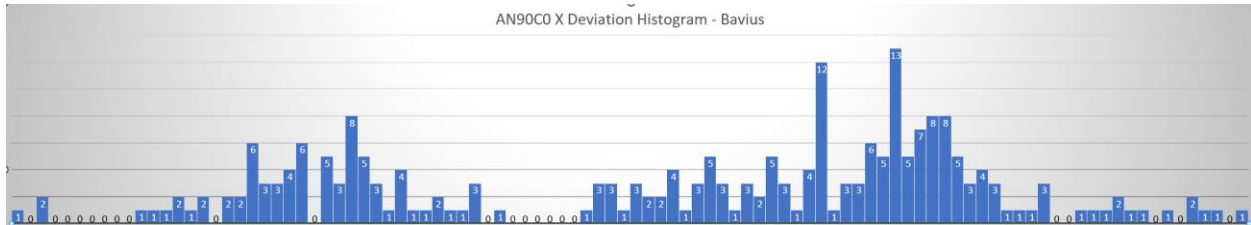


Figure 29. AN90C0 X Deviation Population Histogram.

Z Deviation Population Histogram:

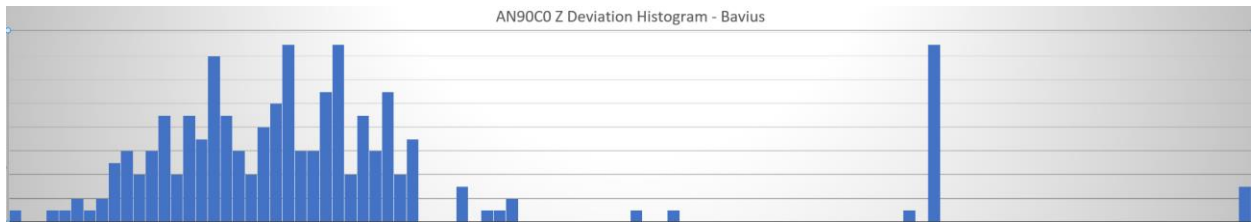


Figure 30. AN90C0 Z Direction Population Histogram.

Two populations found in X Deviation (Figure 29. AN90C0 X Deviation Population Histogram.);

X Population Identified: Right plot identified via timestamp descending

One population found in Z Deviation, with outliers; Time series for AN90C0 Z Direction is shown below:

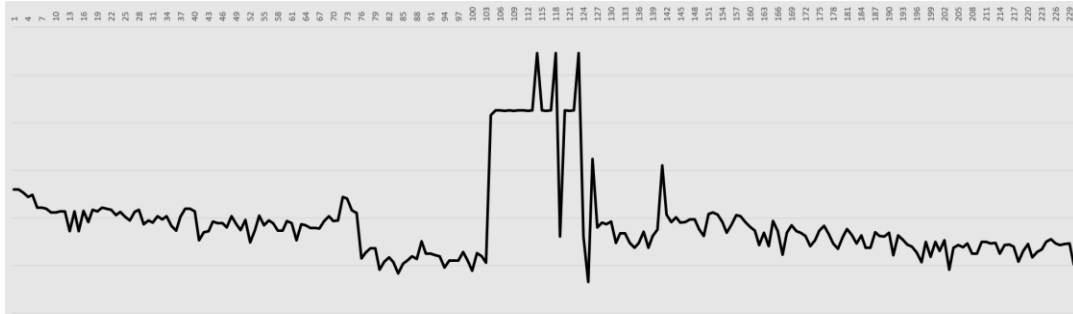
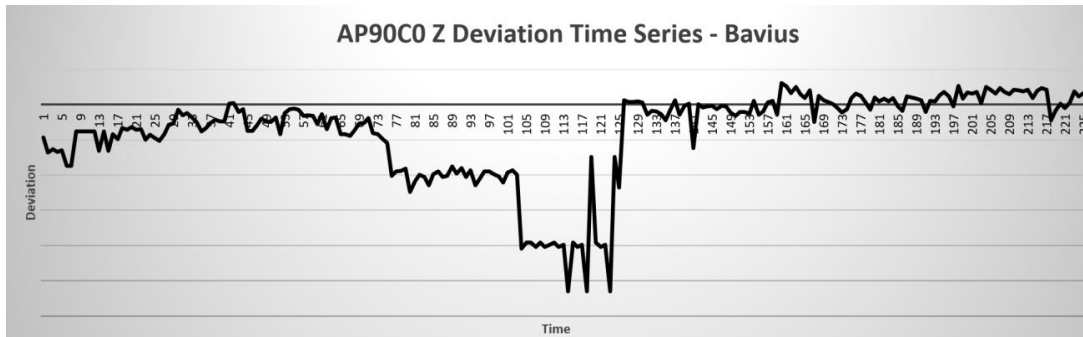


Figure 31. AN90C0 Z Direction Time Series Plot.

Recall the plot from AP90C0 that showed a similar shape and deviation time series:

(Figure 28. AP90C0 Z Deviation Time Series - Bavius.)



This is a situation where the AN90 and AP90 orientations were both influenced by the same event (tuning, settings, crash, component change, etc.). The shape of the graphs could be indicative of a change to the machine system that caused A movements to deviate in the Z direction oppositely, or in other terms, changed the vector of the machine spindle out of normality to the XZ plane when 90 degree rotations are performed. As stated before, identifying the event that occurred on the day of changes to the consistent shape of the graph would be the best place to start. Since two orientations using the same axis (A) have been influenced at exactly

the same points in time, it would be intuitive to start with investigation on A axis changes. An important note in this situation however, is, the system was returned to the state before the plot changes occurred. The impact to production was insignificant because deviations were back to the controlled graph shape of

TABLE 11. AN90C0 Z DEVIATION (CONTROLLED VALUES)

Z_DEVIATION_COUNT	Z_STD_DEVIATION
205	0.709

For AN90C0 and

TABLE 12. AP90C0 Z DEVIATION (CONTROLLED VALUES)

Z_DEVIATION_COUNT	Z_STD_DEVIATION
131	0.613

For AP90C0. Meaning A axis movement orientations were back in control.

TABLE 13. AN90C0 CONTROLLED VALUE X AND Z DEVIATIONS

X_DEVIATION_COUNT	X_STD_DEVIATION	Z_DEVIATION_COUNT	Z_STD_DEVIATION
131	0.637	131	0.613

5.4.4. A0CP180 Orientation Check

```
SELECT  
  
COUNT(X_DEVIATION) as X_DEVIATION_COUNT, STDEV(X_DEVIATION *  
1000) as X_STD_DEVIATION,  
  
COUNT(Y_DEVIATION) as Y_DEVIATION_COUNT, STDEV(Y_DEVIATION *  
1000) as Y_STD_DEVIATION  
  
FROM DATABASE  
  
WHERE PART_NAME = TOOL CENTER POINT CHECK  
  
and Machine_Name = BAVIUS MACHINE NUMBER  
  
and Output_Label = 'A0CP180'
```

TABLE 14. A0CP180 FULL POPULATION QUERY RESULTS

X_DEVIATION_COUNT	X_STD_DEVIATION	Y_DEVIATION_COUNT	Y_STD_DEVIATION
234	1.7	234	4.316

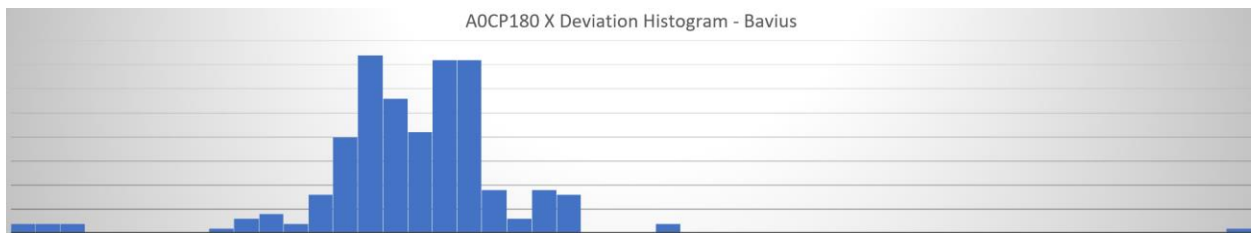


Figure 32.A0CP180 X Deviation Histogram - Bavius.

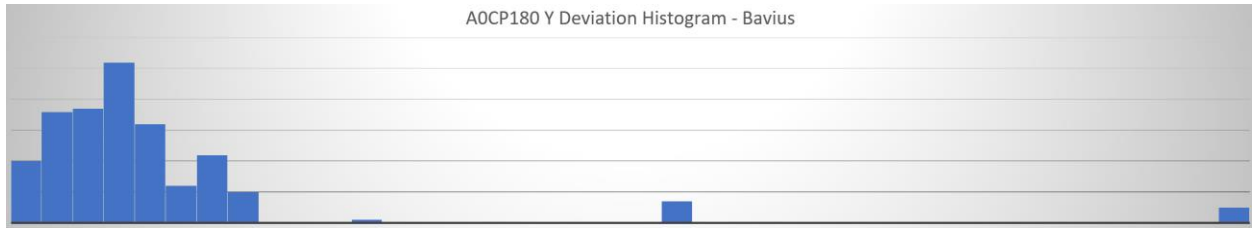


Figure 33.A0CP180 Y Deviation Histogram - Bavius.

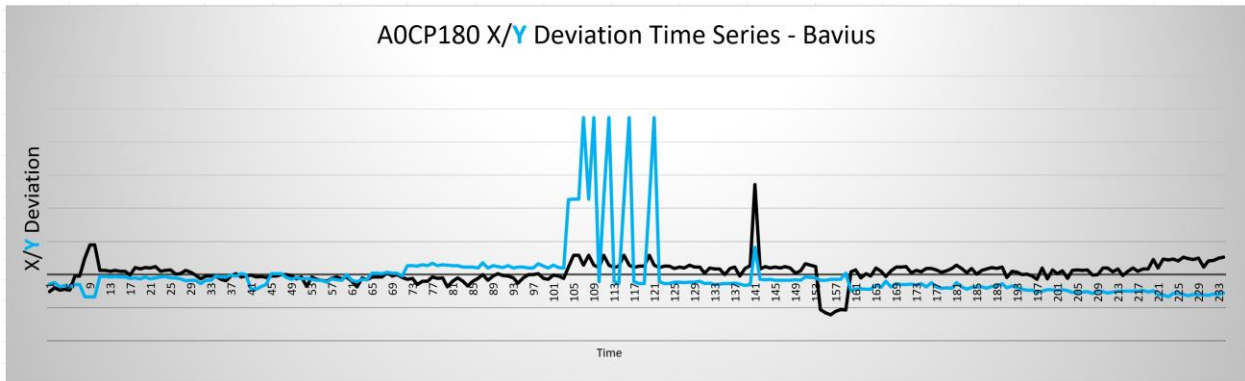


Figure 34.A0CP180 X & Y Deviation Time Series Plots - Bavius.

Query W/ Outliers Removed

TABLE 15. A0CP180 DEVIATIONS WITH TIME SERIES OUTLIERS REMOVED

X_Deviation_Count	X_STD_Deviation	Y_Deviation_Count	Y_STD_Deviation
213	0.986	213	1.29

The difference in capability if SPC techniques were not used would have first been

(Table 14. A0CP180 Full Population Query Results)

X_DEVIATION_COUNT	X_STD_DEVIATION	Y_DEVIATION_COUNT	Y_STD_DEVIATION
234	1.7	234	4.316

(Table 15. A0CP180 Deviations with Time Series Outliers Removed)

X_Deviation_Count	X_STD_Deviation	Y_Deviation_Count	Y_STD_Deviation
213	0.986	213	1.29

This difference is important to distinguish, especially because only 21 sample measurements caused the statistics to misrepresent the population of production data.

To conclude all of the SPC checks for this machine study, here are all of the kinematic orientation capability statistics before and after the SPC process created.

5.4.5. AP90C0 Capability Difference Using SPC

(Table 6. AP90C0 X and Z Direction Deviation)

X_DEVIATION_COUNT	X_STD_DEVIATION	Z_DEVIATION_COUNT	Z_STD_DEVIATION
229	1.768	229	2.547

Table 7. AP90C0 X Deviation Query (Valid Population)

X_DEVIATION_COUNT	X_STD_DEVIATION
126	0.364

Table 9. AP90C0 Z Deviation Time Series Data (Valid Population)

Z_DEVIATION_COUNT	Z_STD_DEVIATION
171	0.831

5.4.6. AN90C0 Capability Difference Using SPC

Table 10. AN90C0 Full Population Query

X_DEVIATION_COUNT	X_STD_DEVIATION	Z_DEVIATION_COUNT	Z_STD_DEVIATION
231	1.218	231	1.721

Table 13. AN90C0 Controlled Value X and Z Deviations

X_DEVIATION_COUNT	X_STD_DEVIATION	Z_DEVIATION_COUNT	Z_STD_DEVIATION
131	0.637	131	0.613

5.4.7. A0CP180 Capability Difference Using SPC

Table 14. A0CP180 Full Population Query Results

X_DEVIATION_COUNT	X_STD_DEVIATION	Y_DEVIATION_COUNT	Y_STD_DEVIATION
234	1.7	234	4.316

Table 15. A0CP180 Deviations with Time Series Outliers Removed

X_Deviation_Count	X_STD_Deviation	Y_Deviation_Count	Y_STD_Deviation
213	0.986	213	1.29

5.5. SPC – Formulation of Statistics and Equations

SPC in this thesis research is not establishing process capability or control limits as a means of finding control and statistically establishing limits/tolerances. Instead, SPC is being used simply to track machine accuracy within the kinematic envelope of work and comparing to specification limits. These specification limits are referenced from engineering feature tolerances and applied to the machine tool via one-third concept mentioned previously in the research. (Pyzdek, 2003) represents the process capability index with this formula:

Process Capability Index:

$$C_p = \frac{T}{ND} = \frac{USL - LSL}{UCL - LCL} = \frac{T}{6\sigma}$$

Equation 1. Process Capability Index

The component of process capability that is being used for comparison in the thesis research SPC is USL (Upper Specification Limit). The USL value is defined by the one-third engineering feature tolerance and used in the SPC module as the nonconformance limit vs. TCP Process measurements that are obtained. These TCP measurements can also be distributed statistically, commonly recognized by a Gaussian distribution or normal distribution curve. Another difference from using the (Pyzdek, 2003) equation to distribute TCP measurements is the LSL (Lower Specification Limit). The LSL is zero (0.000”), so it is easier to think of this as a Lower Boundary (LB), as (Grau, 2009) identifies. To summarize, USL is being used as an engineering-referenced hard-limit for TCP deviation, and LSL is considered a boundary representing 0.0000” of TCP deviation for any system being evaluated using this process.

5.6. SPC – Tool Center Point Data Use Cases

As a functional example for Tool Center Point Process data, familiarize with the process for obtaining deviations and think of each orientation check as an independent measurement from the other orientations. What begins to formulate is a population of data for this exact orientation on this piece of equipment. The TCP orientation metric is of interest to operations because it is a representation of machine accuracy, so it is desirable to see the value each day before any product machining is attempted. For machine engineers it is also desirable to create a trend for the metric, to enable SPC methods and other advanced statistical studies that discover significant machine characteristics. See the process shown and the SPC chart shown below for a specific machine orientation (A+90 Degrees, C 0 Degrees) in Figure 36. SPC Plotting Example AP90C0 Orientation.

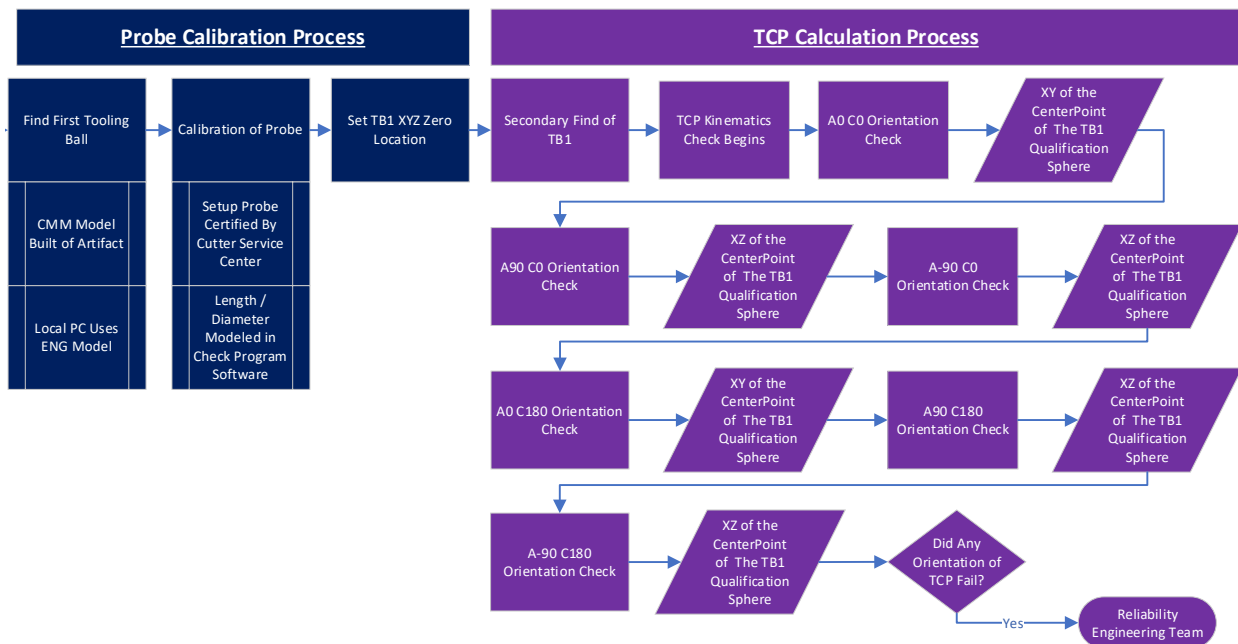


Figure 35. Tool Center Point Program Process.

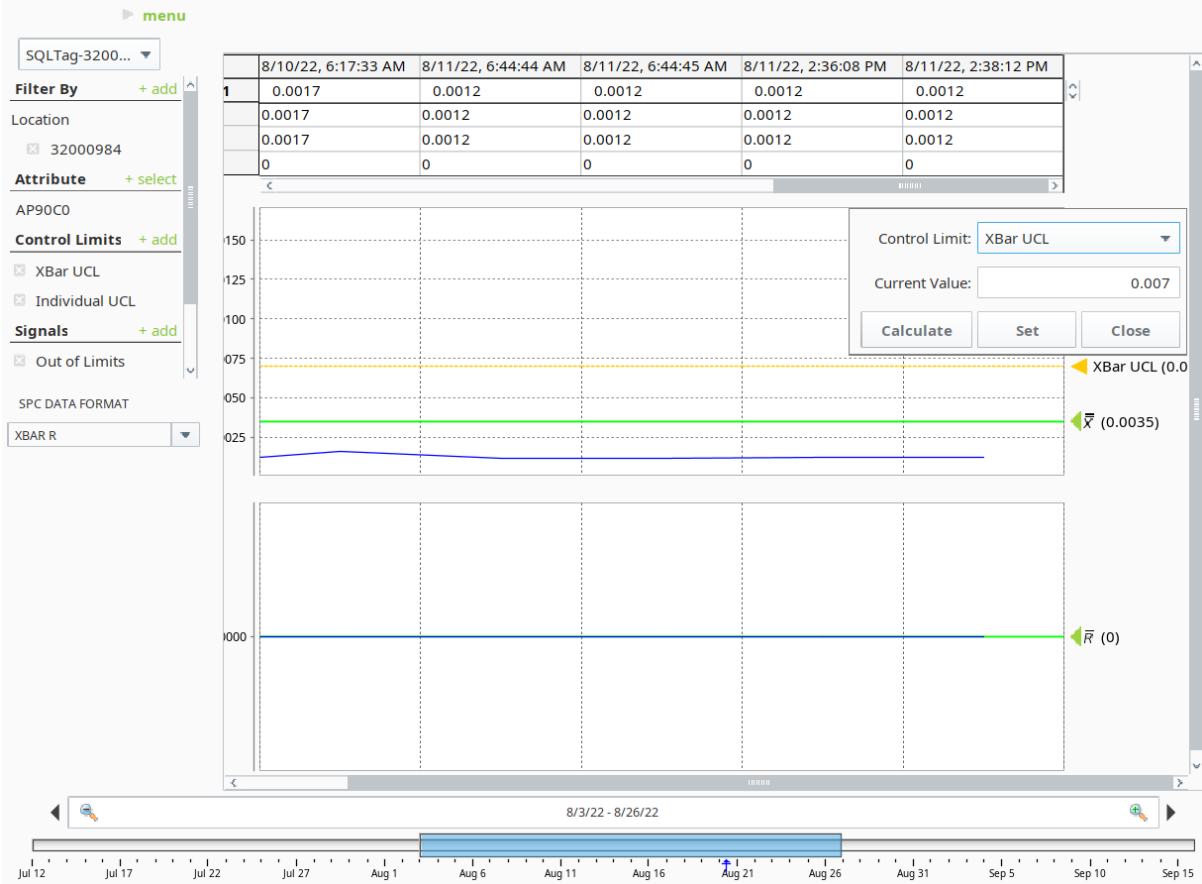


Figure 36. SPC Plotting Example AP90C0 Orientation.

Shown above (Figure 36. SPC Plotting Example AP90C0 Orientation.) is an example of a controlled orientation after the Tool Center Point Process is used, the machine data architecture collects the DMIS information, and the SPC module is populated with the data. This machine was granted permission to perform work on the day where this orientation data was obtained, because the obtained true position (.0012”) is below the orange upper control limit shown on the chart. Now, a real-world example of SPC functioning exactly the way it is designed.

5.7. SPC – Out of Tolerance SPC Example

Any machine equipped with the Tool Center Point Process is known by operations as having a “Daily Check,” which has gained popularity amongst machinist as part of the everyday

start-up procedures for the machine. They are supplied with the deviation numbers and machine engineers translate deviations to them. Eventually, this transformed into an automated visual for any operator to see when they run their machine health check. Machinists are shown their results for the day, and if all orientations displayed are within specified tolerance, they continue. If a machinist finds a case where an orientation is not in tolerance, they have the responsibility to call for help and only continue work when the machine will make conforming features at all orientations. Here is an example of a machine being taken down for Preventative Maintenance servicing on the date 8/5 and being returned to the shop on 8/9. Figure 37. Orientation Check Failure Shown in SPC Module shows the example.

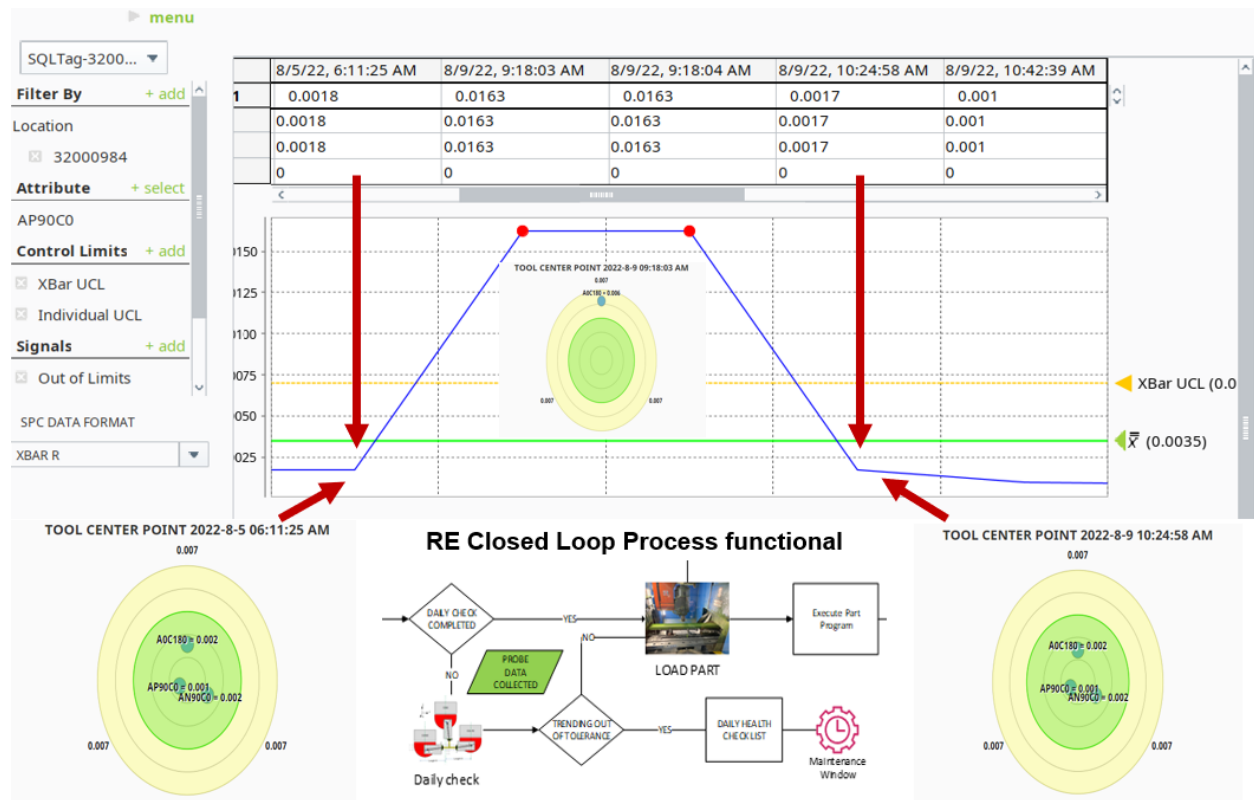


Figure 37. Orientation Check Failure Shown in SPC Module

The machinist had the target shown on 8/5 when the machine was given to maintenance, and once returned to the shop had the 8/9 target shown. This is an important function of the SPC strategy created in the thesis research, because it is a preventative quality initiative. Knowing your equipment is world-class / state-of-the-art when it is purchased does not mean your equipment is staying in the exceptional condition it started in. As mentioned before, the complexity of machine systems and *currently* impossible capability to monitor every component within the physical system means these checks are a valid status of the entire system, and an opportunity to prevent waste in a production system. This SPC orientation failure finding immediately stops the production of nonconforming product, which is often found later during the inspection process while the machine tool continues nonconforming production. The financial and logistical benefits of this stoppage before nonconforming machining happens is obvious. Once operations notified machine engineers and maintenance of the issue, a corrective action process was initiated and the issue was resolved in roughly one hour, as shown in the timestamps of the SPC module. (Figure 37. Orientation Check Failure Shown in SPC Module)

CHAPTER 6

DISCUSSION

6.1. Qualify a CNC as a CMM

A CNC machine can be attempted for CMM qualification if standards match the machine setup. The machine studied in this research makes XYZ linear movements and uses a touch-probe system, so the appropriate standards were referenced for the evaluation. Robots and other measurement devices cannot be referenced to this research but can be correlated to other measurement standards if they exist. Additionally, machine tools do not function in controlled-rooms or CMM areas, they function in the production environment. The thermodynamic section discussed above is entirely in play for a machine attempting to correlate to CMM accuracy. Mechanical deviation and thermal expansion techniques must be used prior to attempting CMM correlation. Artifacts and certified equipment are the only valid equipment in a CMM correlation because a device of a higher magnitude of resolution must specific the authority dimension and location being compared to. If a CNC machine can measure an artifact to the accuracy required by a CMM, then the CNC has successfully passed the artifact test of the standard. Now, in measurement correlation situations, the workpiece is being treated like the machine system in terms of the “physical system” concept. A workpiece that does not have a 100% constraint on all surfaces, will be a different physical system between setups. The same workpiece, same tool, same machine – different physical system as soon as force is released or applied to an area of the setup. This is an important concept to remember when trying to represent the work that a machine has done. The best way to measure a workpiece is exactly the way it was during manufacturing, and this cannot be done if parts are physically different between the CNC and CMM setup. As noted in the research, making a datum scheme that follows the same points is

the best way to eliminate material error and obtain a true evaluation of the CNC system and CMM system. When CNC and CMM both reference the same XYZ points for a datum scheme, they will be in the same coordinate system and in turn give valid deviation data to statistically correlate.

6.2. Machine Accuracy

A machine tool system is subject to the ever-changing culmination of the physics within itself. It is apparent that assumptions will never lead engineers to the correct answer for maintaining perfect machine accuracy. Minimizing the opportunity for physics to act in their nature has proven to be a step in the right direction. From the ground up and through the mechanical structure of a machine, stresses and static loads that are not designed will inevitably present themselves. Monolithic systems should be balanced and hold as little stress as possible for this random movement to be avoided. Through the setup of a machine, if these structures are measured constantly and thoroughly, it is possible to assemble with insignificant amounts of load on the mechanical systems. The correct science of machine building and construction is critical to accuracy. Variables outside of the system are the next subjects of interest. Production environments ideally should be controlled for temperature, but if this is not feasible then machine systems must not have thermal sources rapidly introduced at any point in time, to avoid thermoelastic deviations causing physical shifts in the machine structure. A machine can be constructed to conformance, then thermo-elastically morphed out of this conforming shape. Machine tool builders specify this allowance in temperature change. If this can be avoided, moving a machine accurately is the next concern. Scale feedback systems are a requirement of any machine tool attempting to machine features in aerospace industry structure parts. If a machine does not have measured feedback of movement, the mechanical system cannot be

constantly evaluated. Without scale feedback, a machine is operating on alignment and movement assumptions, which have been identified as detrimental to accuracy success. To this point in accuracy conclusions, only X,Y, and Z have been covered. Rotary systems must undergo their own evaluations of physical accuracy and electronic calibration. Encoder/Scale feedback is also a necessity of rotary systems that are intended to work on aerospace-grade products. Endurance testing the mechanical/electrical/cooling/tooling systems are the last checks before a machine can begin being used. Replicating working conditions and physical situations is wise during these tests, so that the major sources of error discussed before can present themselves before production time.

6.3. SPC of Machine Accuracy

The machine tool system of interest must be physically controlled before statistical methods can be applied. Let's assume the theoretical machine system is accurate and repeatable to the specifications needed for production and machine builder buyoff. The first relevant concept found in this research is the separation of machine orientations for statistical evaluations. Why? A 5-axis movement of a machine system means all three linear axis are moved and two rotary axis are moved to position the tool tip. This measurement is inherently a different physical situation than the origin that the movement started at (XYZ & AC/AB/BC all moved for this one orientation example). Next, the machine tool and certified probe equipment must be chasing a certified feature location or dimension to be a valid reference. The machine cannot travel to a location and declare it has found a feature, then be evaluated for accuracy on its ability to find this point again. The only error introduced to the system between these two measurements is mechanical positioning error, which we have declared are already successfully controlled. The machine must be chasing a point that has been found by a measurement system more accurate

than itself. Linear lasers and laser trackers are popular for this function. The collection of data via certified points and controlled system are valid until the system is changed. Following the change of any part of a machine system, data collection needs to be started from the beginning – if the next collected data following the change falls outside of the distribution of points which represent the previous physical system. Recall the X deviation example for the Bavus PBZ SC machine, where two populations of data existed for the same machine within the last year of sampling. With SPC and the strategy for control limits, there is also not a single answer for machines. Limits should be based on the feature that is being created. In the aerospace industry, engineering designs are the authority source and conformance to the authority source is the only acceptable outcome. Limits should be set on the machine accuracy SPC based on the tolerance being applied to the workpieces. Capability of a machine system is also based on the tolerances present. An unchanged machine tool system that is holding accuracy and repeatability, will be compared to different tolerance windows and score different index values against all tolerances. Finally, the most important use of SPC is to prevent failures. To not forget the reason for studying the subject, it is intended to give a warning about the physical state of the machine system so that work does not take place when the machine is no longer capable.

6.4. CONCLUSION

A CNC machining center was fitted with high resolution contact probing to enable drive position readings triggered by the probing to be utilized for part measurement. Standard volumetric and interim tests that apply to performance evaluation of conventional CMMs were adapted for performance evaluation of the CNC machining center when it is used as a CMM for automated machine tool health monitoring and for FAIs. Immediate advantages from this

operating procedure were obtained on the shop floor, including reduced inspection labor/time and part rework requirements, and increased conformance to part quality specifications.

From the volumetric testing, the machine's accuracy was determined to be within 0.0012 in and the machine's repeatability was determined to be within 0.0006 in. The interim testing confirmed that the tool center point does not deviate more than the accuracy measured by volumetric testing. Measurements of workpiece feature position when using the CNC machine as a CMM (with the installed in-situ probing system) was found to correlate well with measurements using external CMMs, when the workpiece was measured on the machine, without dismounting it. This all indicated that the adaptation of the CNC machine as a CMM for in-situ health monitoring and workpiece inspection performed just as good as external, commercially available CMM systems. The one-year long SPC study indicated that over time, the CNC machine may suffer from performance degradation that requires action from the machinist, engineering, and maintenance teams. When the machine is physically under control, its performance is as good as that determined by the volumetric testing. This performance is affected by the machine head orientation, with the orientation corresponding to zero head rotation being the most accurate.

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