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Final Report

Virtually Guided Certification of CNC Machine Tools via Virtual Twin	
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I. EXECUTIVE SUMMARY

The goal of this project "Virtually Guided Certification of Computer Numerically Controlled Machine Tools via Virtual Twin" is to demonstrate virtual certification of machine tools at suppliers for successful manufacture of specific parts to significantly reduce the time and cost of first article inspection and cost avoidance due to placement of parts at suppliers who cannot produce them on their machine tools.

This report covers technical progress on the project overall. Each section covers a major segment of the project statement of work, given below:

I.A STATEMENT OF WORK

A brief statement of work for the above described activities is listed below.

Task 1. Program Management

Task 2. Research Module 1: Virtual Twin Methodology Development

- a. Design and Development of Machined Part Artifacts
- b. Methodology to transfer Virtual Twin errors to actual part
- c. Methodology for Temperature Assessment
- d. Building block artifact validation of the Virtual Twin
- e. Representative Small Part, Medium Part, Large Part validation of the Virtual Twin certification
- f. Temperature Studies

Task 3. Software Tool Development

- a. Develop Virtual Twin App using Spatial Analyzer Software Development Kit
- b. Embed Missouri S&T machine tool kinematic error model in Virtual Twin App
- c. Identify visual representation of Virtual Twin predicted part errors most appropriate for procurement process
- d. Create standard reports for characterization of machine tools

Task 4. Characterization of Industry

- a. Machine tool measurement events of at least 8 machine tools of various size scales
- b. Standard reports for supplier on the accuracy of their machine tool
- c. Report to supplier on predicted accuracy of their machine tool to make small, medium, large part artifacts
- d. Analysis of the state of industry and the opportunities to improve

Task 5. Implementation / Business Case / Training

- a. Development of usable Virtual Twin metrics
- b. Practical assessment of implementation of Virtual Twin technique in production
- c. Assessment of cost of Virtual Twin technique
- d. Assessment of monetary impact of Virtual Twin technique
- e. Draft OEM/Supplier Virtual Twin specification
- f. Supplier Virtual Twin training

II. PROJECT REVIEW

The US aerospace industry ($220B in annual sales [1]), America's leading manufacturing export worldwide, had $86 billion in export sales and contributed a positive trade balance of $47.1 billion in 2011 [2], which is the largest trade surplus of any manufacturing industry. According to a recent study by the US Department of Commerce, the aerospace industry supports more jobs through exports than any other industry. This industry directly employs about 500,000 workers in scientific and technical jobs across the nation and supports more than 700,000 jobs in related fields [2]. However, this industry is increasingly being threatened by new international competition and must advance its manufacturing capabilities to remain competitive. In the author's judgment, one of the key opportunities for new competition to replace US aerospace manufacturing is the failure of the industry to produce aircraft to schedule. Boeing's 787 was three years late entering production due to manufacturing challenges where the selected suppliers were unable to produce airworthy parts. At the same time, the resources utilized to remedy these manufacturing problems delay the development of other aircraft platforms, creating a performance gap for the competition to exploit. Airlines, however, operate to very tight margins and, thus, cannot afford these delays, forcing them to purchase aircraft from alternate sources if US-sourced aircraft are not available on time to meet their business needs. To avoid future production delays due to the complex aerospace manufacturing supply chain, it is essential that a digital certification tool that accurately certifies a supplier's ability to produce airworthy parts is implemented.

The fabrication of large aerospace parts has a long lead time between the digital part definition and the certified manufacturing process. Many of the manufacturing decisions early in the process are based on experience, rather than quantitative data. However, a digital certification of the manufacturing process may reduce cost and mitigate startup delays. As shown in Figure 1, typically, after digital definition of the part, the part is sent to a pool of suppliers for a quote. The pool is based on past experience, and the winning supplier is selected based only on price and capacity. After contracts are in place, the supplier designs the tooling, manufacturing plans, and material order to make a first article. Typically it is only after 6-12 months of time and cash investment that a first article is generated by which the process can be certified. In too many cases it is at this point that it is discovered that the supplier cannot make the part to print, often for a combination of factors. The parts have to be corrected or rejected, and the first article is repeated in an attempt to certify the manufacturing process. When the problem is driven by a limitation in the manufacturing capability of the supplier, the OEM must move the work to another supplier, restarting the 12 months cycle, or reconfigure designs to accommodate the incorrect part. These problems can be avoided by removing the experiential element in selecting of the supplier pool, and replacing that decision with a digital certification process.

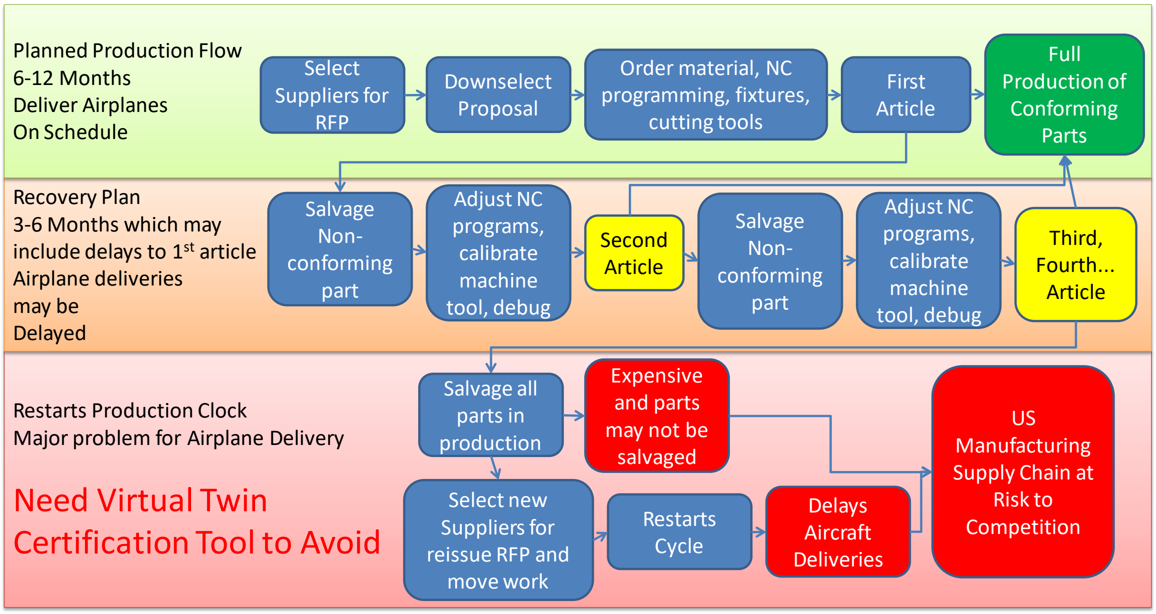

Figure 1: Traditional Machined Part Certification via First Article Inspection.

This MxD program provides a unique opportunity to develop tools that can certify a supplier's manufacturing process capabilities for a digital part via a machine digital twin prior to placing the work at that supplier as shown in Figure 2. For instance, small parts may be suitable for many discrete suppliers while very large part may only be suitable for a handful of suppliers due to their equipment capabilities. By virtually certifying the risk of each supplier to the specific parts being made, the request for quotes can be targeted to suppliers which can fabricate a successful part. At the same time, by providing a digital, certifiable, metric to assess suppliers, the US supply chain as a whole will be better able to make sound decisions in equipment acquisition and processes improvement.

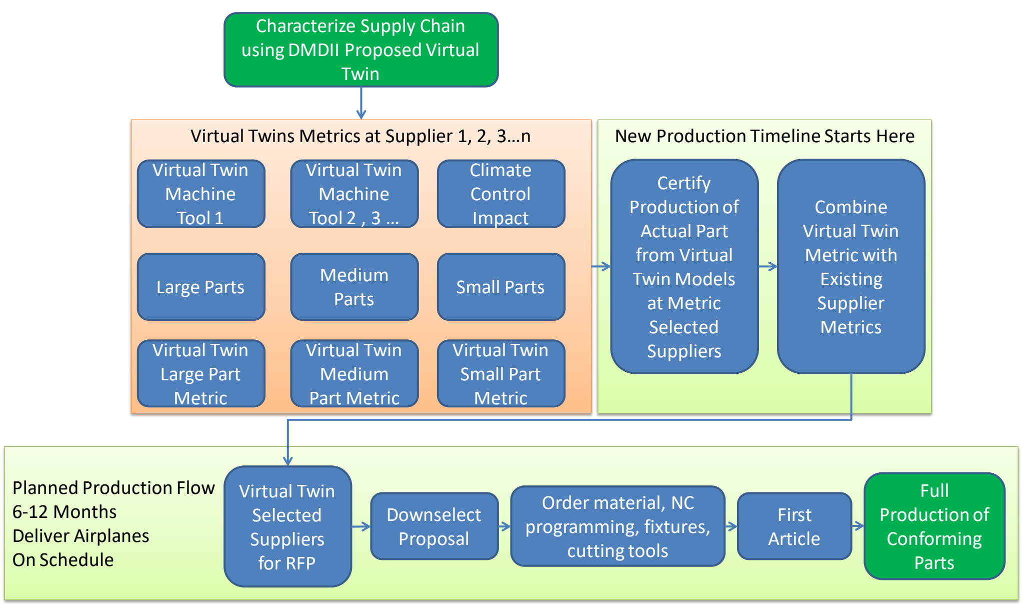

Figure 2: MxD Proposed Machined Part Certification via Virtual Twin.

OEM's and Tier 1's will use this tool to determine which suppliers to send Request for Quotations (RFQs) to during the outsourcing of work in the supply chain. OEM's, Tier 1's and SME's will all use the tool to sort out their existing equipment as to whether it needs service or replacement to be competitive for manufacture of parts.

III. METRICS

The metrics for improvement for this program are shown in Table 2.

Table 2: Project Performance Improvement Metrics

Metric	**Present State (Baseline)**	**Future State (Project Goal)**
Business Metrics	**Unsuitable Machines Allowed to Bid on Part Packages (100%)**	**Unsuitable Machines Allowed to Bid on Part Packages (20%)**
Technical Metrics	• **Calibration requires a week.** • **Analysis report not given.** • **No method for virtual certification.**	• **Calibration requires one day.** • **Analysis report will be provided.** • **Better than 80% of part error predicted by virtual certification**

IV. TECHNOLOGY OUTCOMES

This section covers the overall technology system, system requirements, system architecture, technology features and architecture, and software development.

IV.A System Overview

Part dimensional errors in machining arise from a number of sources including kinematic errors in the machine, machine dynamic errors, tool deflection, tool wear, and thermal distortions in the part or machine caused by temperature variations during the machining process. While the effect of some of these sources requires a complete machining plan in order to assess (e.g., tool deflection cannot be determined before the tools have been selected by the process engineers), others can be determined *a priori* with minimal knowledge of the machining plan (e.g., kinematic errors can be used to determine tool positioning error at any point in the workspace.) Of the sources that can reasonably be evaluated during the early planning stage, kinematic error and sensitivity to ambient temperature change are the most impactful.

This work builds on methods for rapidly measuring and constructing high fidelity models of machine tool error kinematics developed by Boeing and Missouri S&T over the past 7 years [4, 5, 6]. Measurements are acquired by a laser tracker (i.e., a laser interferometer on a two axis gimbal) that measures the XYZ position of an optical target attached to the machine tool spindle. As illustrated in Figure 3, the machine is jogged to a random point cloud where measurements are taken. Repeating the procedure with a different length optical target tool yields a second set of data from which the position and orientation of the machine tool can be inferred at each of the measurement points. A statistical optimization modeling framework is used to construct a high fidelity model of error kinematics from the data set. For example, while any coordinate frame with origin $p=\begin{bmatrix} p_x & p_y & p_z \end{bmatrix}^T$ and XYZ axes oriented in the $n=\begin{bmatrix} n_x & n_y & n_z \end{bmatrix}^T$, $o=\begin{bmatrix} o_x & o_y & o_z \end{bmatrix}^T$, and $a=\begin{bmatrix} a_x & a_y & a_z \end{bmatrix}^T$ directions, the coordinate frame can be compactly represented in the transformation matrix, $T=\begin{bmatrix} n & o & a & p \\ 0 & 0 & 0 & 1 \end{bmatrix}$, and an XYZCB machine tool, for example, can be represented by,

$$T_{nom}=T_X(q_X)T_Y(q_Y)T_Z(q_Z)T_C(q_C)T_B(q_B) \quad (1)$$

where q_X, q_Y, q_Z, q_C, and q_B are the axis commands, T_X, T_Y, T_Z, T_C, and T_B track the motion of each axis, and T_{nom} gives the position and orientation of the spindle face from which machining paths can be generated. In the modeling framework developed by Boeing and Missouri S&T, the inaccuracies of each axis are captured in a model of the form,

$$T_{\text{model}}=T_X(q_X)E_X(q_X)T_Y(q_Y)E_Y(q_Y)T_Z(q_Z)E_Z(q_Z)T_C(q_C)E_C(q_C)T_B(q_B)E_B(q_B), \quad (2)$$

where E_X, E_Y, E_Z, E_C, and E_B are the geometric errors of each axis. In contrast with the nominal model, (1), which contains simple linear and rotational motions of each axis, the error kinematic model, (2), contains complex, high-order 6-DoF motions that capture the actual behavior of the machine motion through guideway bending or twisting, axis sagging, bearing race noncircularity, and small misalignments.

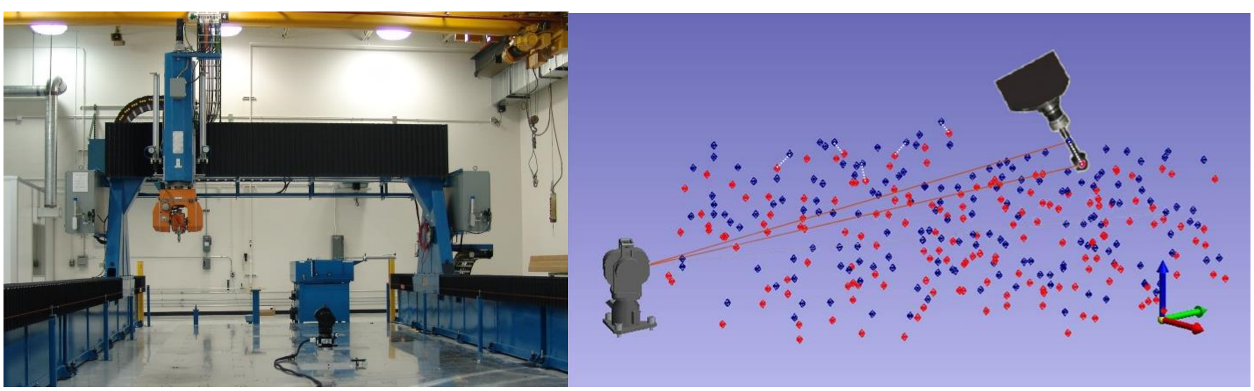

Figure 3: Large 5-axis machine tool at Boeing production facility (left) and point cloud measurement (right).

Depending on the size of the machine and other factors, the measurements and modeling typically can be completed in 8-24 hours (a reduction from 1-2 weeks, typical, for very large 5-axis machine measurement using classical methods.) In previous work, the above modeling method was used to support an advanced calibration method. That method has been employed on more than one hundred machine tools across Boeing production facilities and elsewhere, and was the winner of the Defense Manufacturing Excellence Award in 2009. Here, the modeling method is used for a different application, the creation of a virtual twin of the machine tool. An overview of this process is shown in Figure 4.

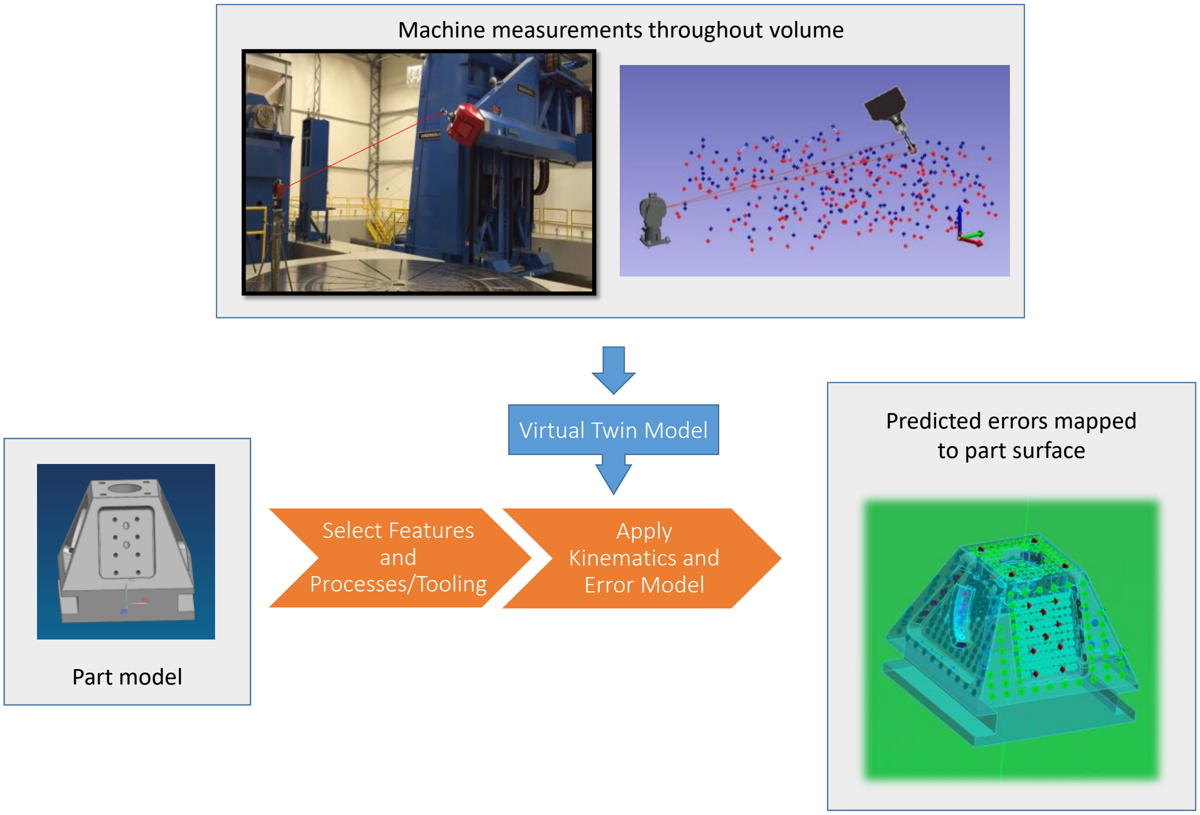

Figure 4: Overview of virtual twin analysis.

IV.B System requirements

This section discusses the requirements to use this system to virtually certify a machine tool. For more detailed requirements, refer to the draft specification in Appendix F.

To build the virtual twin of a machine tool, the following equipment and conditions are required:

- CNC motion control allowing point to point motion and dwell
- Laser tracker and target which can measure 3D position
- Trained personnel to take machine measurements
- Machine definition, which includes the machine axis configuration, negative and positive travel limits, and kinematically relevant link lengths and offsets
- Machine modeling software, available for license through the Center for Aerospace Manufacturing Technology at Missouri S&T.

To use the virtual twin to map errors onto either a standard part to create metrics, or a specific part, the following is required:

- Spatial Analyzer, Ultimate or better, 2018 or newer, from New River Kinematics
- Virtual Twin Analyzer developed in this project, licensable from the Center for Aerospace Manufacturing Technology at Missouri S&T
- Machine virtual twin from measurements
- Digital model of the part to be analyzed
- Approximate manufacturing plan for the part to be analyzed

IV.C System Architecture

IV.D Software Development, Features, and Modes of Operation

The goal of the Virtual Twin Analyzer software is to allow the user to map the geometric errors from a machine tool onto the CAD representation of a machined part. Virtual Twin Analyzer is a package that is used concurrently with SpatialAnalyzer (SA) by New River Kinematics. The software allows the user to import machine definitions and measurement data, as well as the CAD of the part of interest. The user can then specify where in the machine space the part will be machined, what areas will be inspected (via assigning control points in the software), and assign the types of machining processes to part surfaces. After the CAD part, tooling, and points have been applied to the surfaces that the user wants, the user can run operations. The software then determines, then uses the machine definition and measurement data to determine what errors are expected on the part surface based on the positioning of the machine and the machine Virtual Twin. These errors are then displayed on the part surface. Figure 5 shows the layout of the process. Figure 6 shows an example of one of the reporting options within the software. This figure shows a histogram of the errors over all analyzed surfaces of a test part.

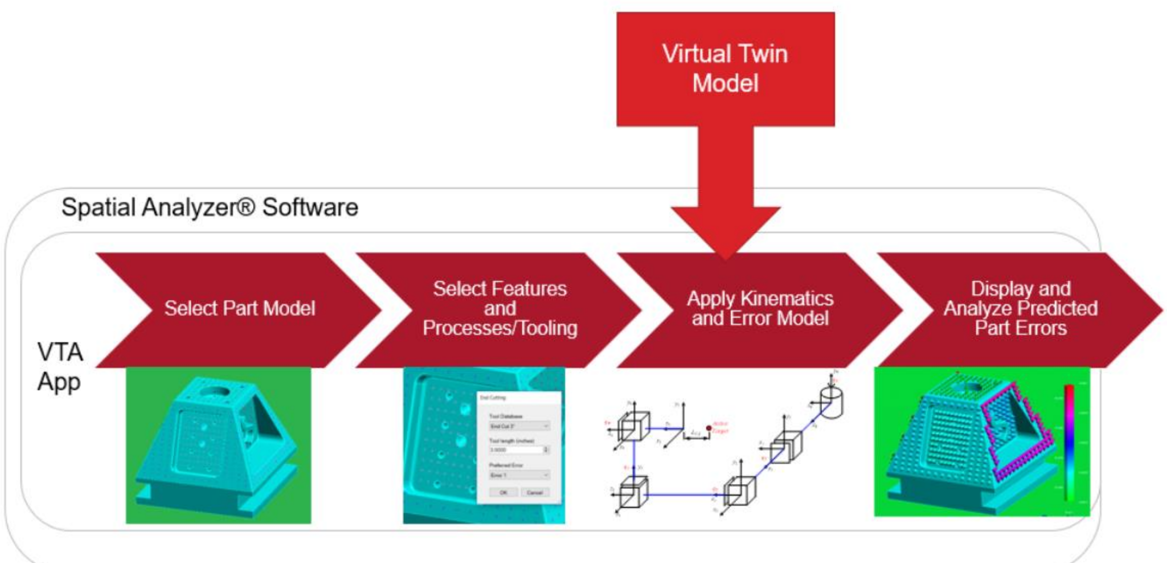

Figure 5: Layout of Virtual Twin Analyzer process.

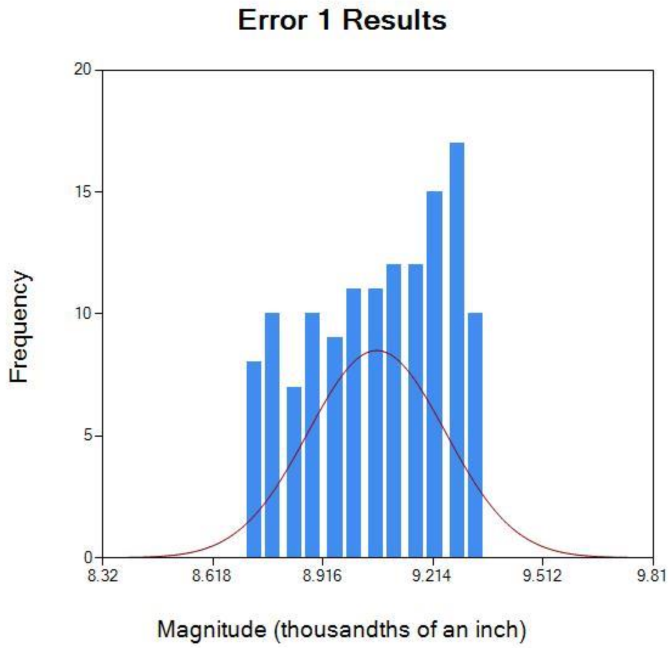

Figure 6: Histogram example.

Four different types of errors are shown for each machine. These are the two arm configurations showing the error vector completely for each evaluated point and then a normal error set for each of the arm configuration error sets. The user can observe the errors in the 3D workspace of SpatialAnalyzer. Any time after operations have been run, the user can export the resulting data to a .csv file. Also, the user has the option to show and hide different error groups, and generate frequency plots of the errors such as the one shown to the right. Virtual Twin Analyzer gives the user the option to create a quick report within SpatialAnalyzer of some statistical and error information.

Virtual Twin Analyzer offers the user many tooling options such as: end cutting, side cutting, drilling holes, kellering, complex surface operations (for multiple tooling orientations), and custom tooling (for individual points on a surface). The user also has the ability to create evaluation grid points, click points or import points of their own from SA. In addition to the computation of tooling and point errors, Virtual Twin Analyzer provides the user many other functions. These additional functions include creating the machine workspace table, importing a CAD model of the machine and workspace itself, and moving the part around within the workspace to an exact location with a transformation dialog. Details of the features of the VTA software can be found in the user manual included in Appendix D.

IV.E Use cases

i) Use Case 1: Supplier management

"As a procurement agent at a major OEM, I would like to be able to better assess supplier capability through a metric rather than relying only on experience."

Broad use by OEMs and suppliers to correctly match machined products with capable suppliers. An OEM would use the tool to provide a useful metric for machine accuracy to a procurement agent.

ii) Use Case 2: Troubleshooting tool for failed first and second articles

"As a design engineer, I would like a tool to better assist a supplier who is producing noncompliant parts so that the issue can be corrected faster."

"As a supplier, I would like a tool to find problems leading to non-conforming articles more quickly."

Virtual Twin technology can quickly assess whether machine accuracy explains a nonconformance and can uncover mechanical issues with a machine during assessment. This can speed up the troubleshooting process when first or second articles fail.

iii) Use Case 3: Equipment management

"As an equipment engineer at an OEM, I need a tool that can assess whether a machine tool can make parts adequately or requires repair, calibration, or replacement."

"As a supplier, I need a tool that can assess whether a machine tool can make parts adequately or requires repair, calibration, or replacement to remain competitive."

OEM's, Tier 1's and SME's will all use the tool to sort out their existing equipment as to whether it needs service or replacement to be competitive for manufacture of parts. A full volumetric analysis of a machine can reveal whether it is too worn to be repeatable, and the model of the errors that is generated can determine whether the machine accuracy needs improvement through repair, mechanical alignment, or compensation.

V. ACCESSING THE TECHNOLOGY

V.A Background Intellectual Property

This technology requires two pieces of background intellectual property to function. The first is a piece of software that accepts a machine definition and measurements and returns a machine model. Missouri S&T developed a piece of software serving this purpose at private expense prior to this project. See IP assertion in Appendix H. This software can be licensed via the Center for Aerospace Manufacturing Technology. The second required background intellectual property is the metrology software Spatial Analyzer developed by New River Kinematics. The Virtual Twin Analyzer is built as a plug in for this commercial software.

V.B Technical and Systems Requirements

Refer to draft specification in Appendix F.

VI.INDUSTRY IMPACT & POTENTIAL

The Virtual Twin technology is broadly applicable to all kinds of machined parts, but will have the most impact on the Aerospace industry where part tolerances are critical. The US aerospace industry ($220B in annual sales [1]), America's leading manufacturing export worldwide, had $86 billion in export sales and contributed a positive trade balance of $47.1 billion in 2011 [2], which is the largest trade surplus of any manufacturing industry. Use case 1 is targeted at proper placement of machined parts, which has been a critical issue in past products. Boeing's 787 was three years late entering production due to manufacturing challenges where the selected suppliers were unable to produce airworthy parts. At the same time, the resources utilized to remedy these manufacturing problems delay the development of other aircraft platforms, creating a performance gap for the competition to exploit.

Applying the Virtual Twin technology to equipment decisions (use case 3) is another large market. In 2014, $4.94 billion dollars was spent by US manufacturers on metal cutting tools (Reference [3]). For all US manufacturers, not just aerospace, these enormous capital decisions determine their profitability. For small business machine houses, it determines their very existence. The ability to make quantitative decisions between purchasing new equipment and upgrading/maintaining existing equipment is enabled by the proposed Virtual Twin certification.

The team is not aware of any comparable software to the Virtual Twin Analyzer, which is able to map the geometric errors of a machine tool directly onto a machined part surface. For use case 1, a procurement agent relies on experience and simple qualitative metrics. For use case 2, an engineer or supplier may bring in an outside service provider to assess a machine using traditional methods, although this does not provide information on how any machine errors that are found impact the part. Traditional assessments also tend to include multiple instruments that assess machine axes individually, taking more time. Such a service could also be used for use case 3. There are many such service providers that would be competing with this product if it was offered as a service. However, these metrology service providers may be good partners to apply the Virtual Twin Analyzer and associated technology.

VII. TECH TRANSITION PLAN AND COMMERCIALIZATION

VII.A Overall transition

The primary strategy to transition this technology into the MxD US manufacturing supply chain is to create practical metrics that OEM's, Tier 1's, and SME's can all use to evaluate the suitability of a machine tool on the shop floor for production of specific parts. To deliver this capability, the determined the costs through actual events at the suppliers, and developed a draft specification that can be used by each level of the supply chain to implement the Virtual Twin Certification process for their business.

A training package will be developed to complement the hands-on training of the events. This training package will include training for providers of the service, suppliers, procurement agents and engineers at OEMs. This training consists of a series of videos covering machine tool measurement, modeling, and using the developed software for several types of analysis. A draft specification was also developed to guide the implementation of the software.

The team will also partner with New River Kinematics (makers of the Spatial Analyzer software VTA is based on) to include the VTA software and market to their customer base. The inclusion of the software producer, metrology equipment manufacturer (API, Hexagon), and metrology service providers (API, and others), allows the team to have a realistic representation of the costs of implementation and support from stakeholders at all levels. This also gives a pathway to market to a large, established, customer base and a clear means to support these evaluations at suppliers at a lower cost.

VII.B Software transition:

There are essentially two pieces of software: first, the “Virtual Twin Analyzer” (VTA) which is the application for Spatial Analyzer that applies tooling to the machined part and calculates the machine errors mapped to those surfaces.

The second is the software that processes the machine tooltip measurements into a model of the machine errors. The machine modeling is somewhat outside the scope of this program, but is nonetheless necessary for the VTA software to work, so the team has developed several strategies towards providing a commercially viable solution.

1. The current implementation for machine modeling is also available for licensing from Missouri S&T. The Center for Aerospace Manufacturing Technology (CAMT) at Missouri S&T can provide support for measuring a machine and modeling it using this software, although the software is not a complete commercial solution.

2. The team is also partnered with API outside of this project to develop a commercial code to collect machine information, generate and collect measurements, and build a machine model.

3. The team will clearly define the inputs and outputs for the VTA software so that any measurement method and machine model can be integrated with VTA.

The VTA software is in the process of transferring to a C# based code, which is more user friendly and easier to maintain. The software will be supported and maintained by the Center for Aerospace Manufacturing Technology at Missouri S&T, and can be licensed directly through CAMT as well. The team will be using the training described above to initially market the software. Demand for the software will also be driven by the business case and draft specification developed in this program.

VII.C Barriers to Adoption

The primary barriers to adoption of this technology are unfamiliarity with the machine measurement and modeling techniques and the added cost of machine evaluations to build a large data base of machine metrics. To address the unfamiliarity with the technology, the team developed a series of training videos. Additionally, the team has worked with API, a metrology service provider, outside this program and plans to work with them to be able to provide this technology to suppliers. To address initial cost, the team plans to focus on use cases 2 and 3 initially, which do not require as much initial investment and move towards use case 1 as the OEM's and suppliers become more familiar with the technology and its benefits.

VIII. WORKFORCE DEVELOPMENT

The US aerospace industry is at a unique juncture as approximately 65% of the engineering workforce is eligible for retirement. This group is heavily weighted to being responsible for bringing technology into the organization or acting as the gatekeepers to implementation. The exodus of this knowledge base is a significant risk to the US aerospace industry and has the industry scrambling to prepare. The current system of assessing the manufacturing capability of suppliers hinges on the expert judgment of the OEM engineers making source selection decisions. At the same time, experts at our suppliers who craft responses to OEM RFQ's are retiring, thereby reducing the supplier's ability to anticipate problems prior to first article manufacture and posing a significant risk to the US supply chain. By generating a data-based system with appropriate metrics for evaluating suppliers, new engineers both at the OEMs and their suppliers can be educated with real data on the effect of their decisions.

Educational Module and Plan: Our methodology will only be valuable in the long term if we educate the industry. During site visits, we trained the personnel (i.e., maintenance personnel, machine operators) at our customer's facilities. In addition to the graduate students and post-doc that worked on this project, we included several undergraduate students in the site visits and other research activities.

IX. CONCLUSIONS & RECOMMENDATIONS

This program has created a technology which aides OEMs in selecting appropriate machines and suppliers for machined part packages, troubleshoots existing placements producing nonconforming parts, and provides information about machines which is useful for making decisions about repair and replacement. The program developed a draft specification to guide the user in applying the technology to virtually certify machines, as well as a software application, and training videos.

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XI. APPENDICES

Appendix A: LIST OF DELIVERABLES

1. Short training videos
2. Workshop (Held in Chicago May 2019, slides in Appendix G)
3. Virtual twin Analyzer software tool
4. Draft Specification (Appendix F:)
5. Report on State of the Industry (Appendix E:)
6. Final Report (This document)

Appendix B: DEMOS

Refer to demonstration videos, which are a deliverable of this project.

Appendix C: VALIDATION AND TESTING

1. Plans

The efficacy of the virtual twin method for kinematic errors was quantitatively evaluated through machining studies. The machining studies were performed on a research machine tool at Boeing in St. Louis. The machine tool is in a temperature controlled facility to eliminate the effect of thermal distortion; it has been well characterized dynamically, and it has an advanced calibration scheme that virtually eliminates all measureable kinematic error. In the first study, a group of “building block artifacts” will be machined, in which the part is of a very simple geometry and a specific source of machine kinematic error is emulated through a set of engineered erroneous calibration tables.

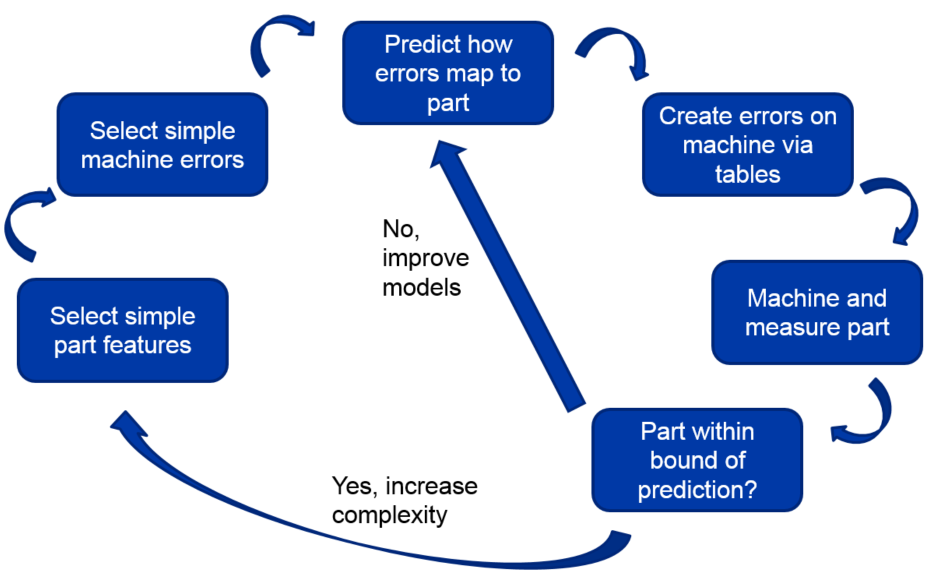


Figure 7: Planned validation approach.

2. Results

The material for all machining tests in this section was aluminum. For the first tests, milling a simple block, a ¾” ball nose cutter was used with 0.100” depth of cut at 300 inches per minute and a spindle speed of 28,000 rpm were used. The introduced error was sinusoidal to be easy to distinguish from any process noise and was introduced on the Z axis (into the part) depending on machine travel in the X direction (along the length of the block). The period was set to 4” and the amplitude was started at 0.050” and reduced until it was difficult to measure (0.001”). Figure 8 shows the test block after machining with the 0.050” amplitude error in the Z direction. This error can easily be seen with the naked eye. Figure 9 shows the indicator reading over the block after machining without induced error as a baseline. Figure 10 shows the indicator readings for tests at all amplitudes plotted together. Figure 11 shows the indicator reading for the 0.005” amplitude test plotted against the nominal error, which has a standard deviation from the nominal curve of 0.0001”. The difference between the two is small, particularly when compared to the noise from the indicator on the baseline measurement. Figure 12 shows the same comparison for the 0.001” amplitude test, which has a standard deviation from the nominal curve of 0.0002”. These results show promising error mapping.

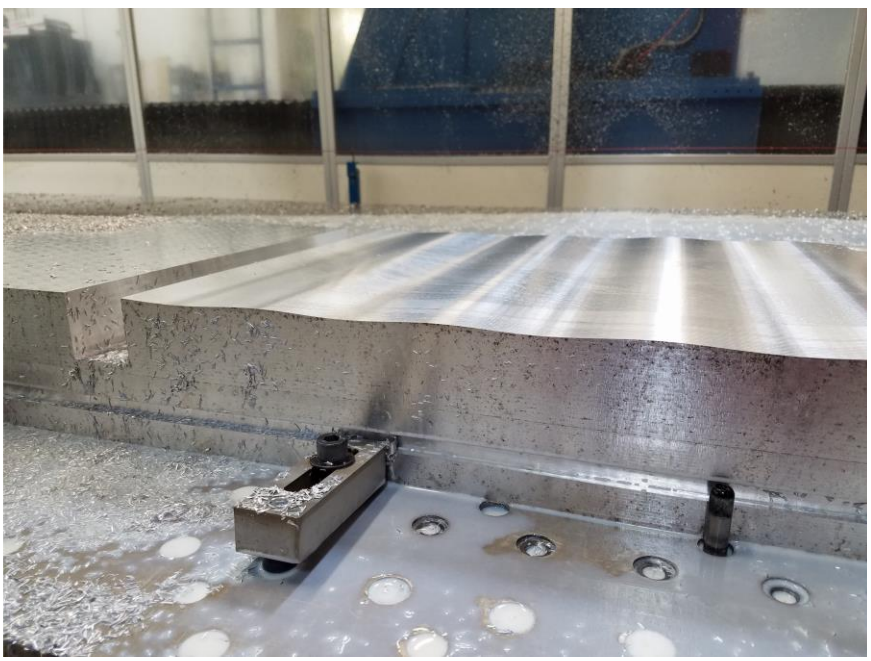


Figure 8: Test block with sinusoidal error milled into the surface.

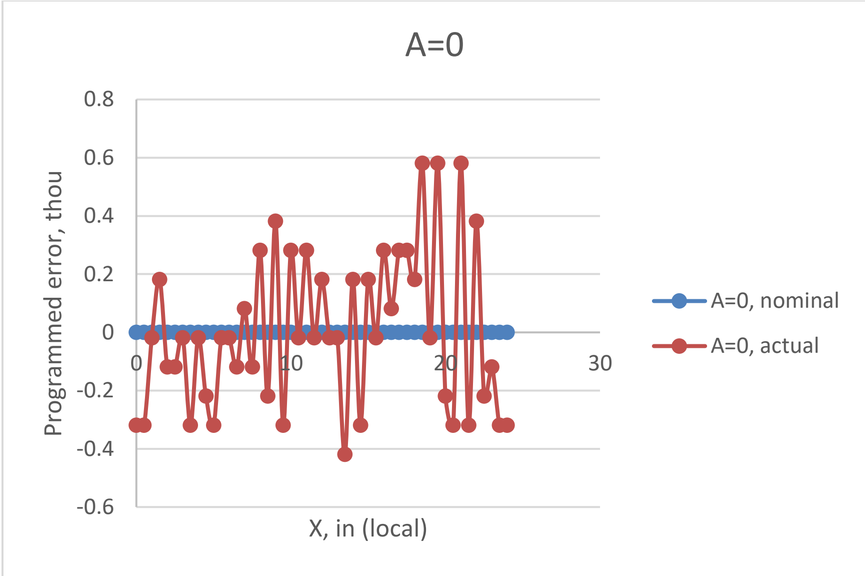


Figure 9: Indicator reading over prepped block, no introduced errors.

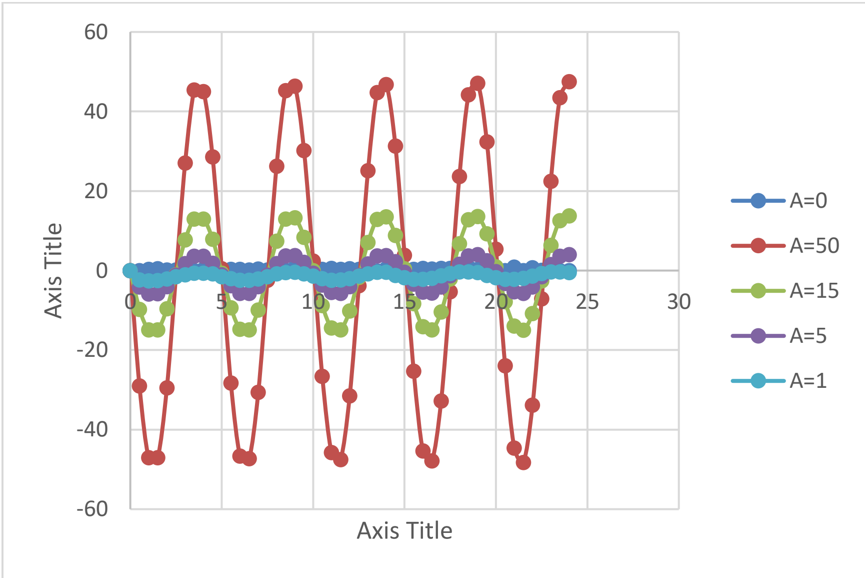


Figure 10: X dependent sinusoidal errors in the Z direction, labelled by amplitude.

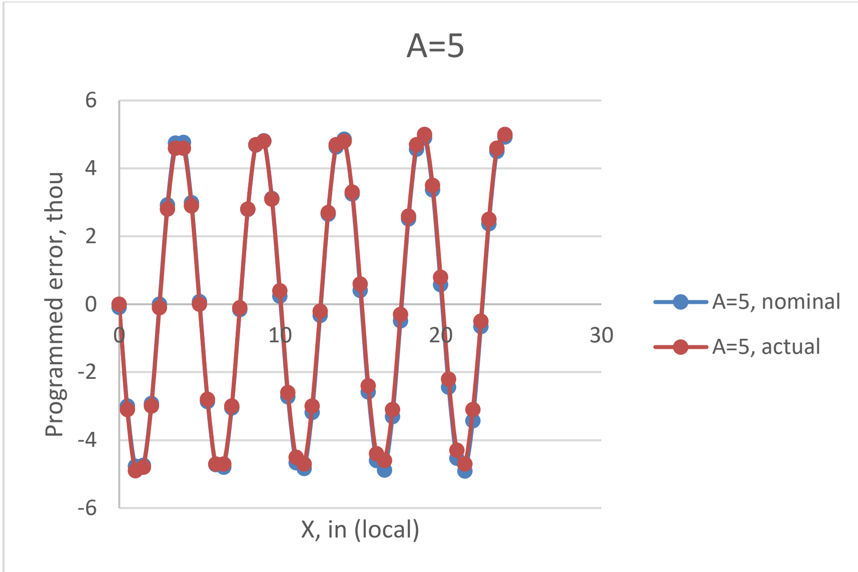


Figure 11: Programmed error plotted with measured error.

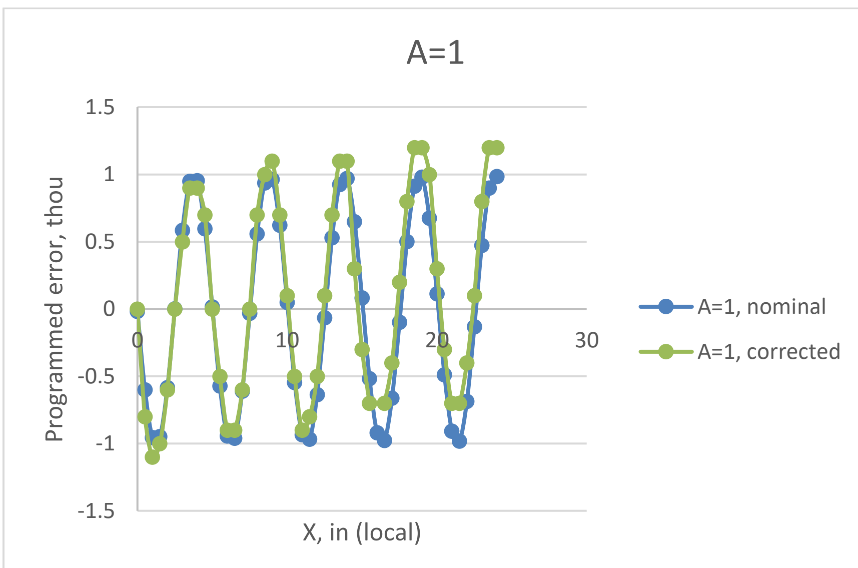


Figure 12: Programmed error plotted with measured error.

Next, errors were introduced in two directions. Rather than milling the top surface of the block, the edge was milled, creating a lip so that an indicator could be used to check errors in both the Y and Z directions. A ¾”-120 end mill was used with 0.100” depth of cut, a feed rate of 100 inches per minute, and a spindle speed of 28,000 rpm. The feed rate was reduced in this test to avoid chatter. The error in the Z direction has a period of 4” and used amplitudes of 0.030” and 0.005”. The Y error had a period 1.4x larger than the Z error and an amplitude 70% of the Z error. After machining, the errors are measured using an indicator as in the previous tests. The indicator is stopped at 0.50” intervals and read manually and recorded. Figure 13 shows the errors in the Z direction for two different tests (amplitude=0.030” and 0.005”) and Figure 14 shows the errors in the Y direction. Figure 15 shows the comparison of the two error test to the previous test for the Z direction at an error amplitude of 0.005”, showing good alignment between the two tests.

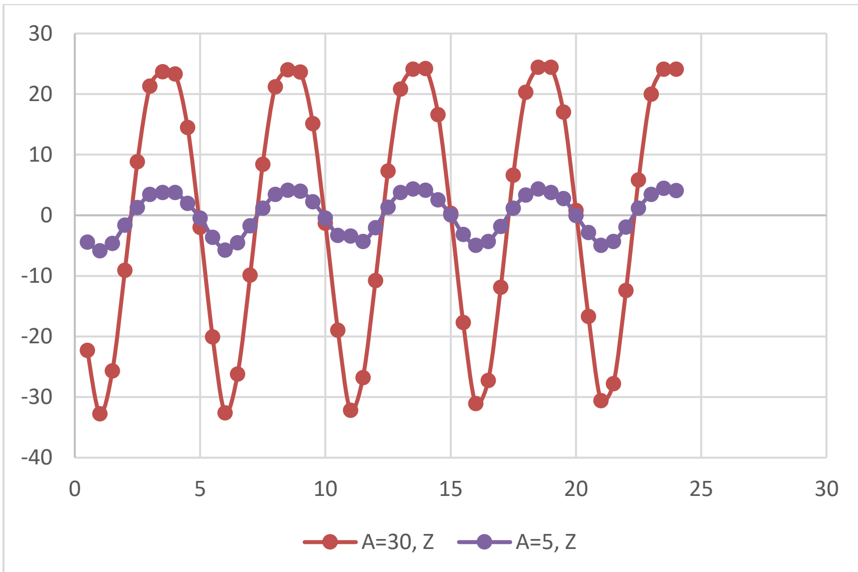


Figure 13: Error in Z direction (measured via indicator) for two different amplitudes.

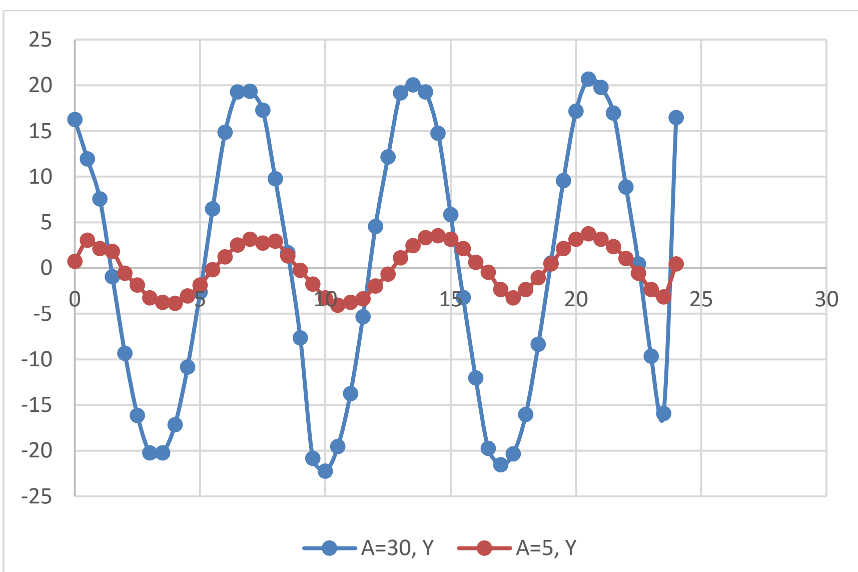


Figure 14: Error in the Y direction for two different amplitudes.

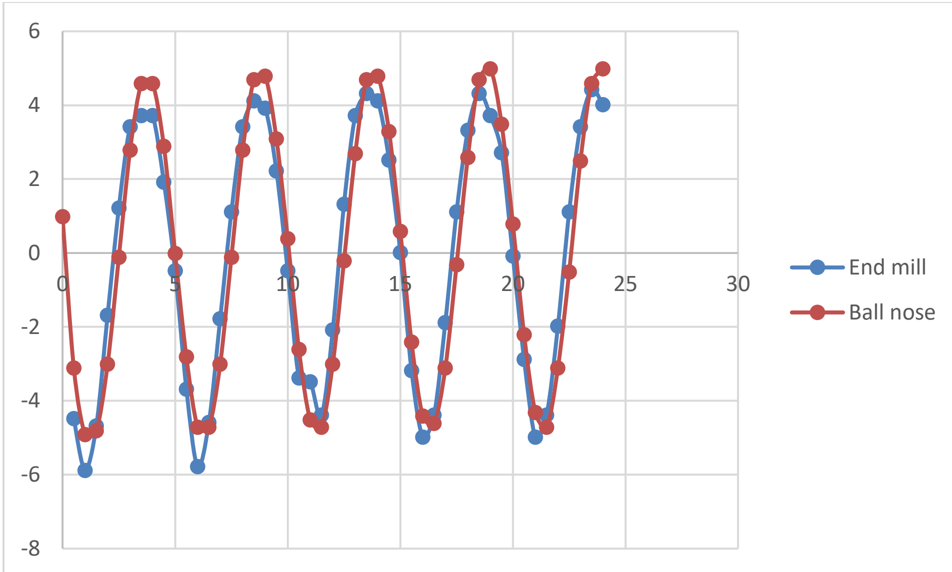


Figure 15: Comparison of single error test (ball nose cutter) with two error test (end mill).

The final "building block" machining test cut a simple "v" shape keeping the B axis of the machine at an angle. Cutter, speeds, and feeds were kept the same as the previous test. Errors were measured using a digital indicator containing a glass scale with data collected using LabView and a data acquisition card. First, the part is cut and scanned with the indicator/contraption with no introduced error. Then error is introduced on the B axis depending on travel in X (along the part). The amplitude of the error is 0.075 degrees with a period of 4". Assuming the tool is approximately 5", this gives an expected error on the part of 0.016". Finally, error is introduced on the Z axis depending on the position of B with an amplitude of 0.050" and a period of 5.5°. Figure 16 shows the result of the part scan for the three tests. Comparing the two test runs to the initial baseline, the run with error introduced on the B axis deviates by approximately 0.015", which matches reasonably well with the expected amplitude for this tool length. The sinusoid is also clearly visible in the scan data. For the run with error on the B and Z axes, the sinusoid in the B axis is less clear as it seems to be interacting with the error on the Z axis. The Z axis error depends on the B positions, which only fluctuates 10 degrees throughout the span of the part, so it does not show a visible sinusoid since it is not changing as much over the length of the part. The overall magnitude of the deviation from the baseline is approximately 0.040" at the largest area, located near the point of the part shape (the middle of the graph).

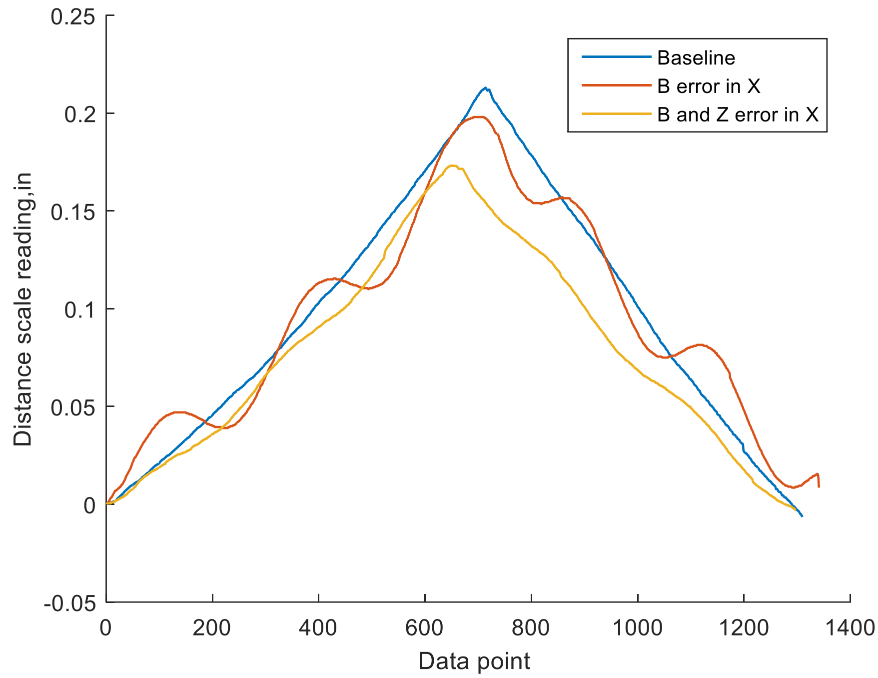


Figure 16: Errors measured during rotary axis experiments.

After the building block tests described above were completed, this machine was taken out of service for a retrofit. The rotary axes and spindle of the machine were replaced, which reduced the machine's geometric errors. A test part designed before this retrofit was programmed and machined, then scanned and compared to the predicted errors from the software tool developed in this program. The figures below show the blue light scans of the machined part compared to the software output for each surface. Notably, the overall errors on the part on critical surfaces were at most 0.0075" and the software tool predicts errors up to 0.0064", both of which are significantly lower than the errors on this machine prior to retrofit. These errors are small enough that blue light scanning may introduce enough error to make comparison difficult. The general trends of the major surfaces match, at least within the accuracy of the scanning equipment used. To better validate the software tool, this experiment can be repeated with larger errors introduced on the machine. A coordinate measuring machine can also be used to better measure along the curved surfaces in the pockets and to locate the holes, providing a better comparison to the analysis from the VTA software.

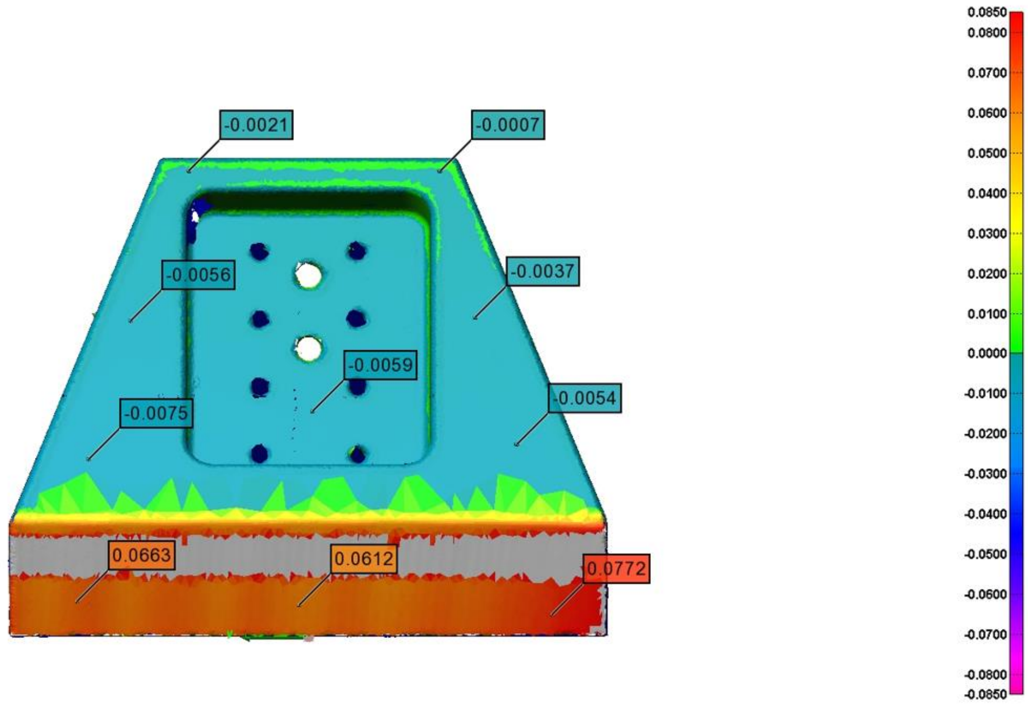


Figure 17: Scan of machined part, face 1.

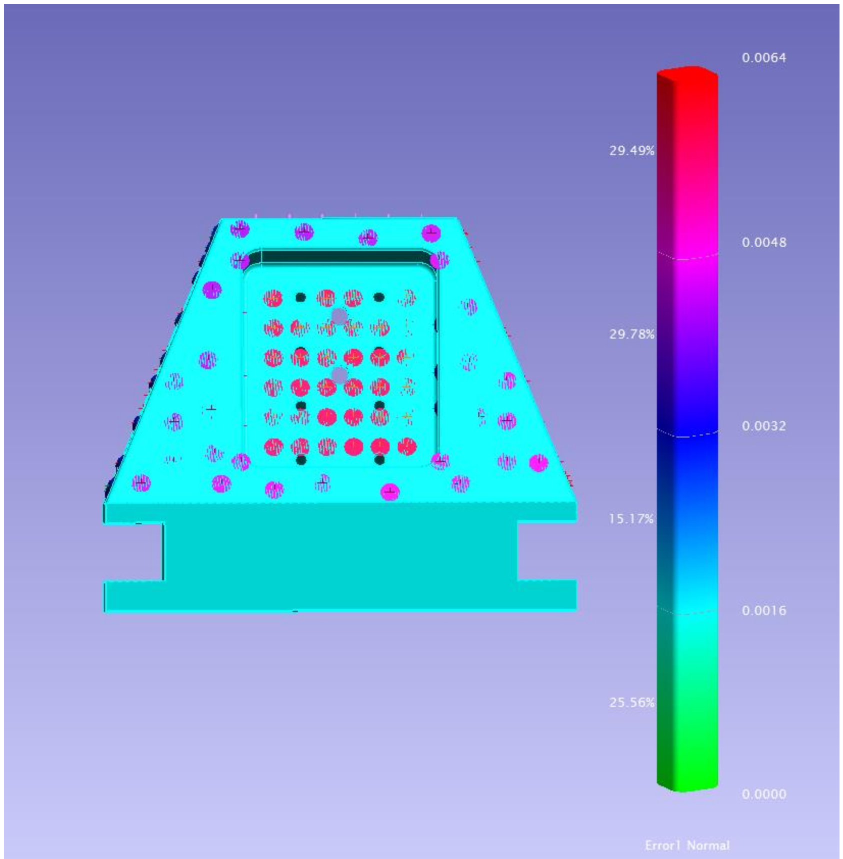


Figure 18: VTA prediction for face 1.

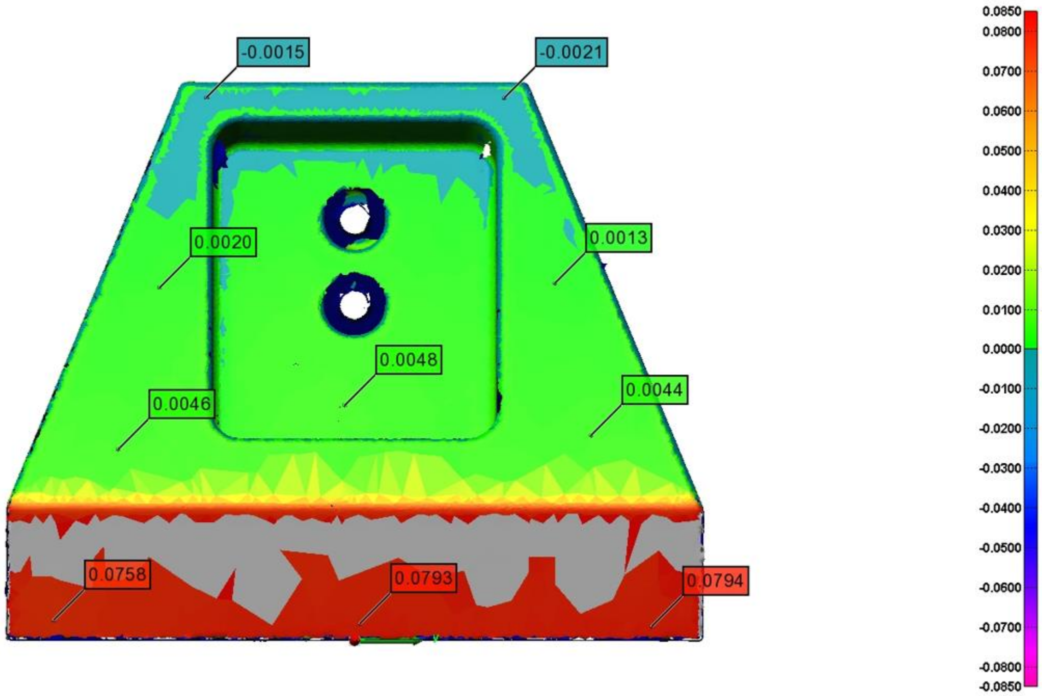


Figure 19: Scan of machined part, face 2.

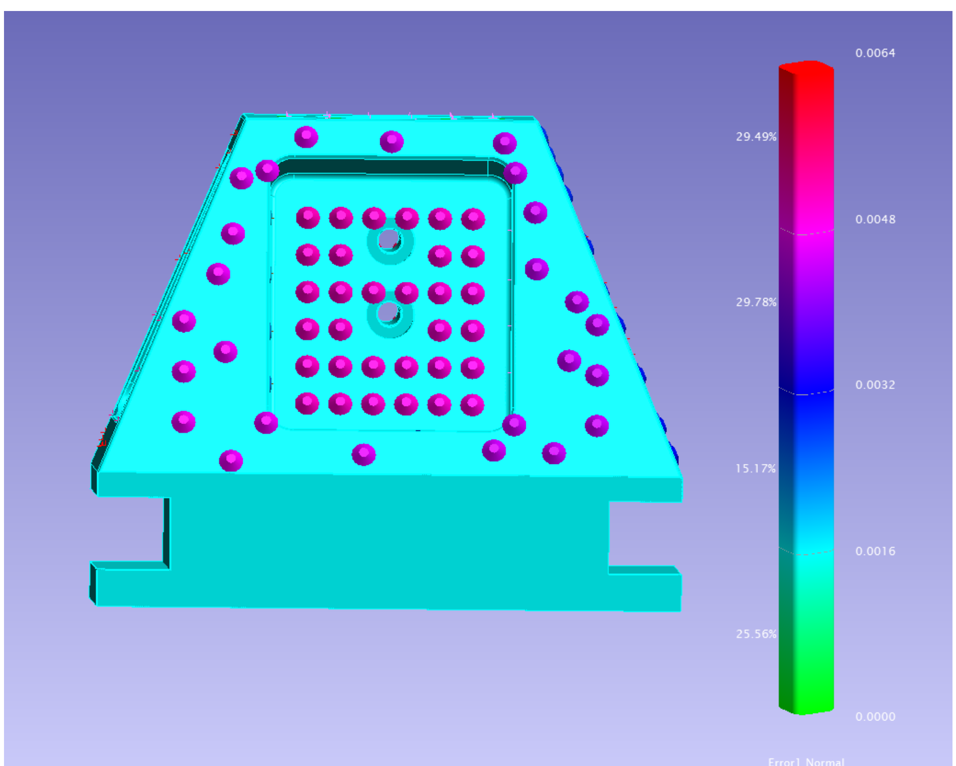


Figure 20: VTA prediction for face 2.

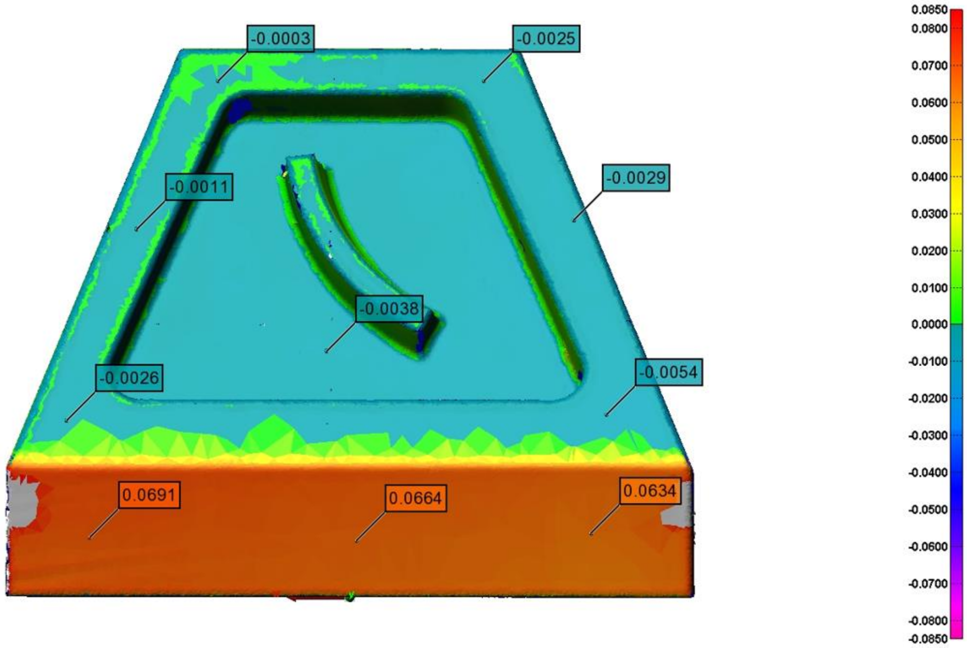


Figure 21: Scan of machined part, face 3.

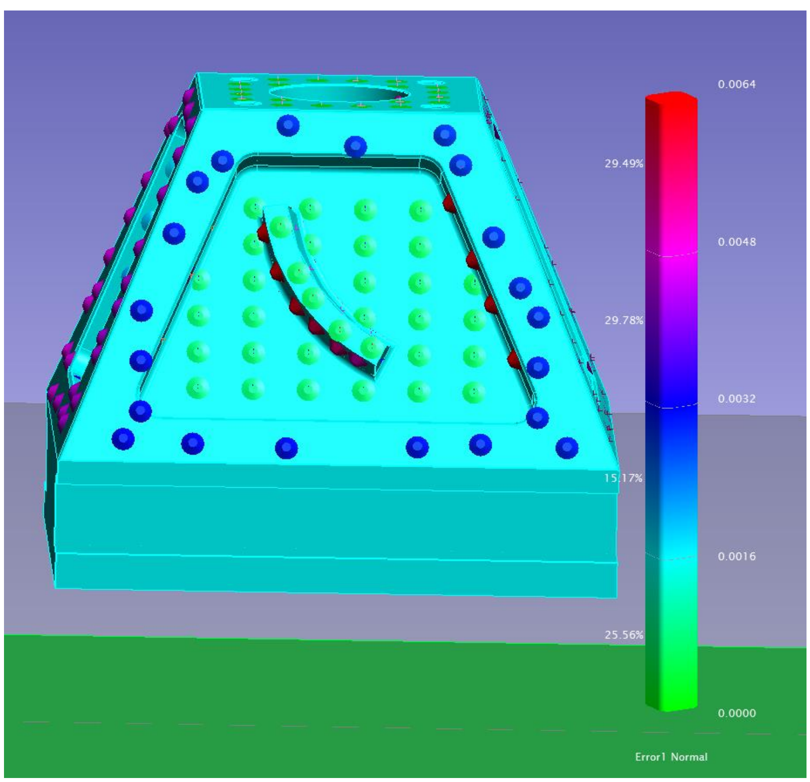


Figure 22: VTA prediction for face 3.

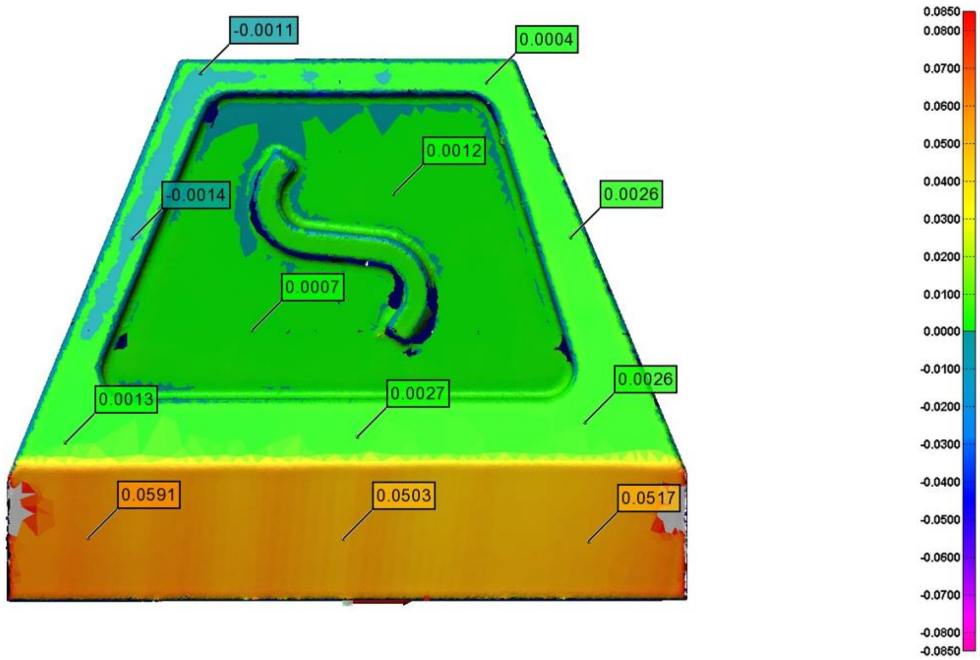


Figure 23: Scan of machined part, face 4.

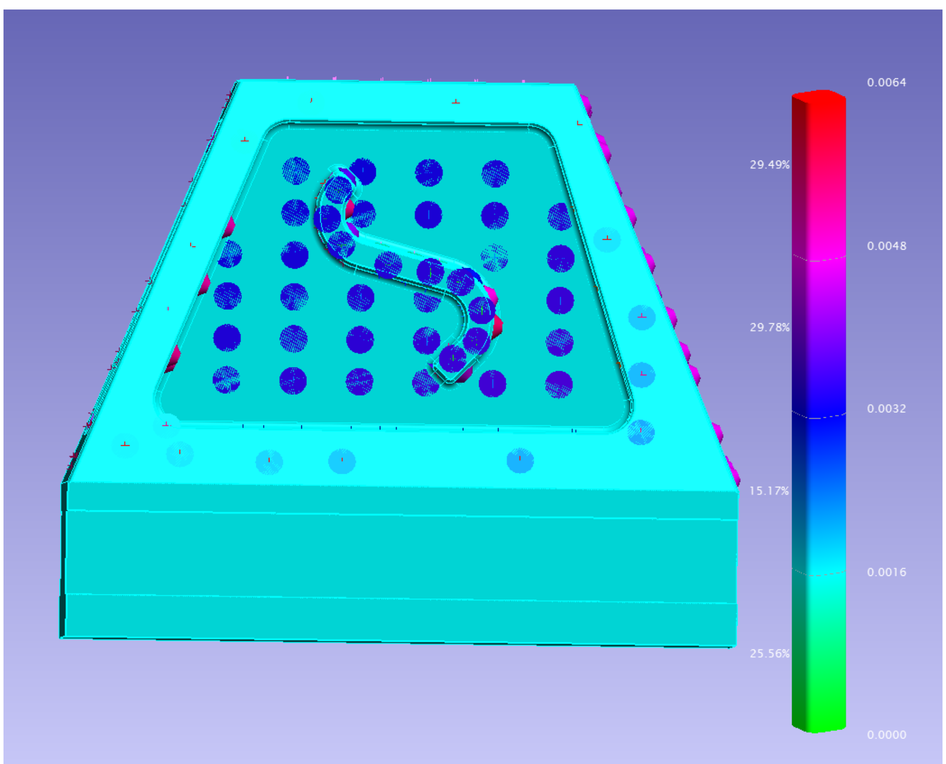


Figure 24: VTA prediction for face 4.

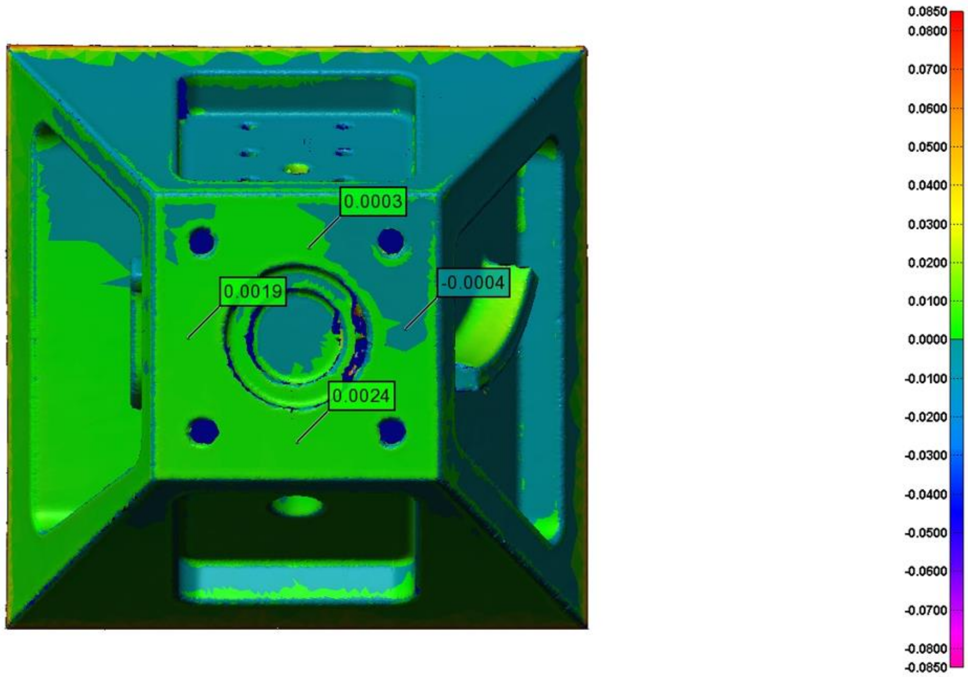


Figure 25: Scan of machined part, top.

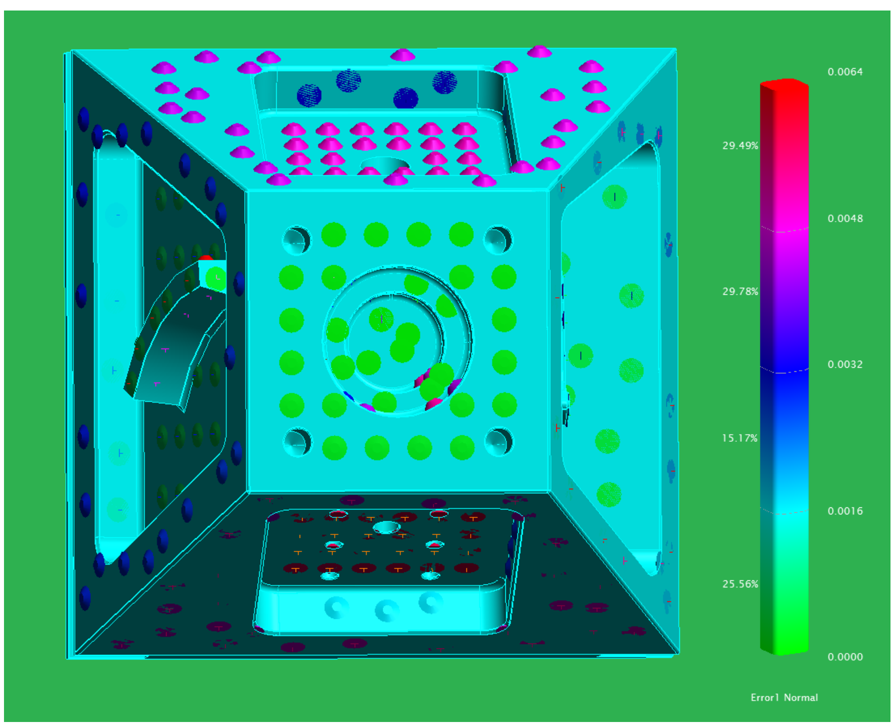


Figure 26: VTA prediction for top surface.

Appendix D: MACHINE TOOL THERMAL ERROR ASSESSMENT

Although some high value machine tool assets are housed in temperature controlled facilities, the majority of machine tools are located in facilities where the ambient temperature can change significantly throughout a day, especially in summer months. With a coefficient of thermal expansion for steel of 12 µm/m°C, thermally-driven distortion of the machine kinematics can quickly become significant, especially for large parts that may span meters in length with tolerances on the order of 10s of microns. While the academic literature reports some successes in predicting thermal distortion of the kinematics, the methods require detailed finite element modeling of the machine tool and installation of a large number of thermocouples [7, 8]. The method employed by Boeing and Missouri S&T is to characterize and bound the thermal sensitivity of the machine tool by measuring rate of change of the tool position relative to fixed points on the machine table as a function of ambient temperature change. These measurements can, again, be rapidly acquired using a laser tracker and can be performed during the kinematic error measurements if there is sufficient ambient temperature change during the measurement event.

The experiments described here used a 3-axis machine tool in a closed area with multiple thermocouples and spherically-mounted retroreflectors (SMRs) for measurement of temperature and position. The closed area is artificially heated and the response of the machine is monitored. The experiment is repeated twice to verify results. Figure 27 depicts schematics of thermocouple distributions on the 3-axis experimental machine tool in the first and the second experiments. Figure 28 and Figure 29, respectively, show the schematic and real distribution of SMRs on the machine tool. The SMRs locations are kept the same between the two experiments for comparison.

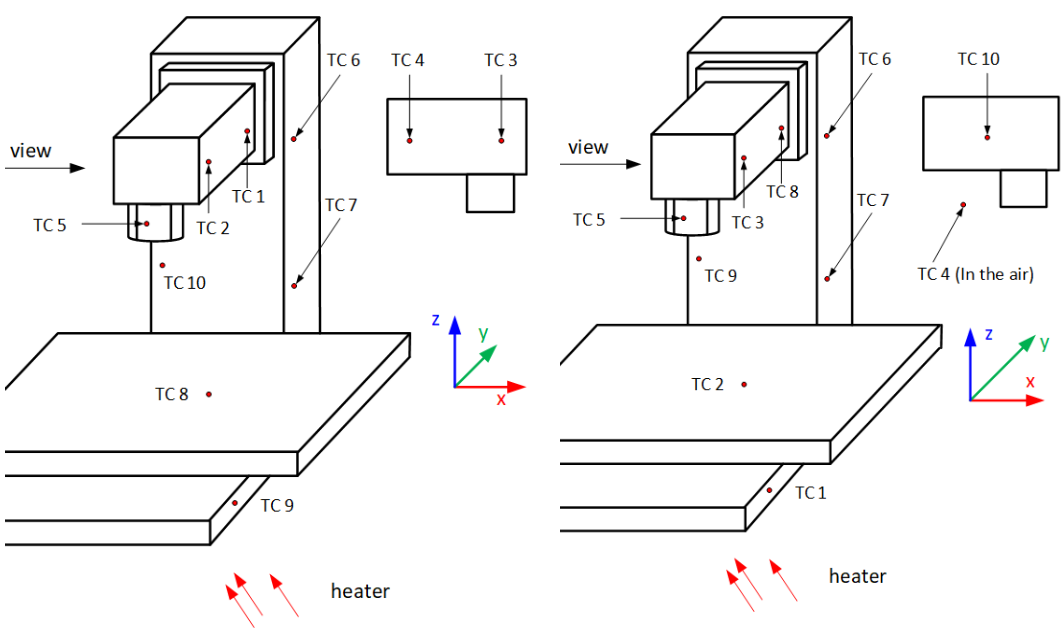


Figure 27: Thermocouple distribution on Randall's machine tool in (a) the experiment 1 (a) experiment 2

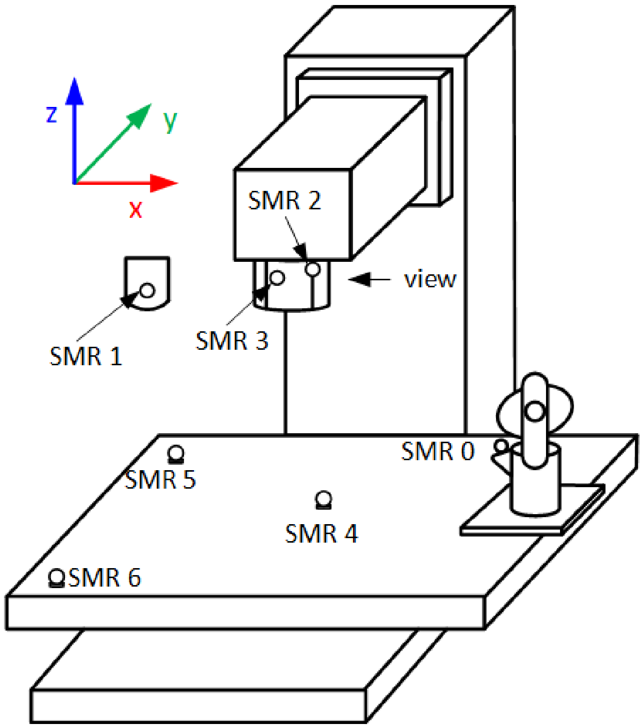


Figure 28: Schematic of SMRs distribution (Identical in experiment 1 and 2)

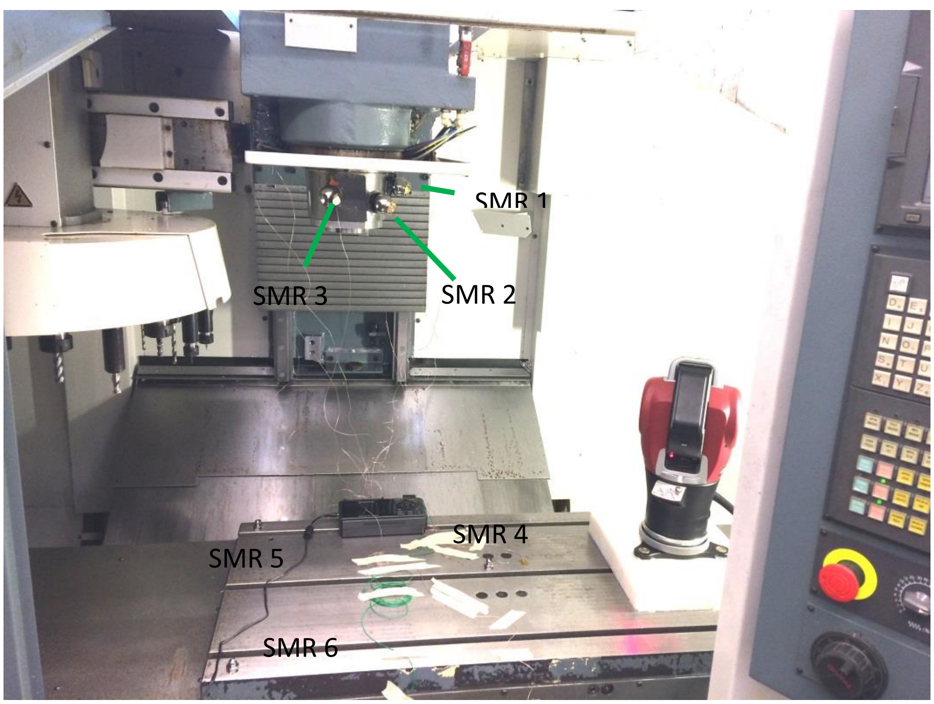


Figure 29: SMR distribution on the experimental machine tool (Identical in experiment 1 and 2).

The sampling periods in both experiments are 2s. The temperatures recorded in the two experiments are shown in Figure 30.

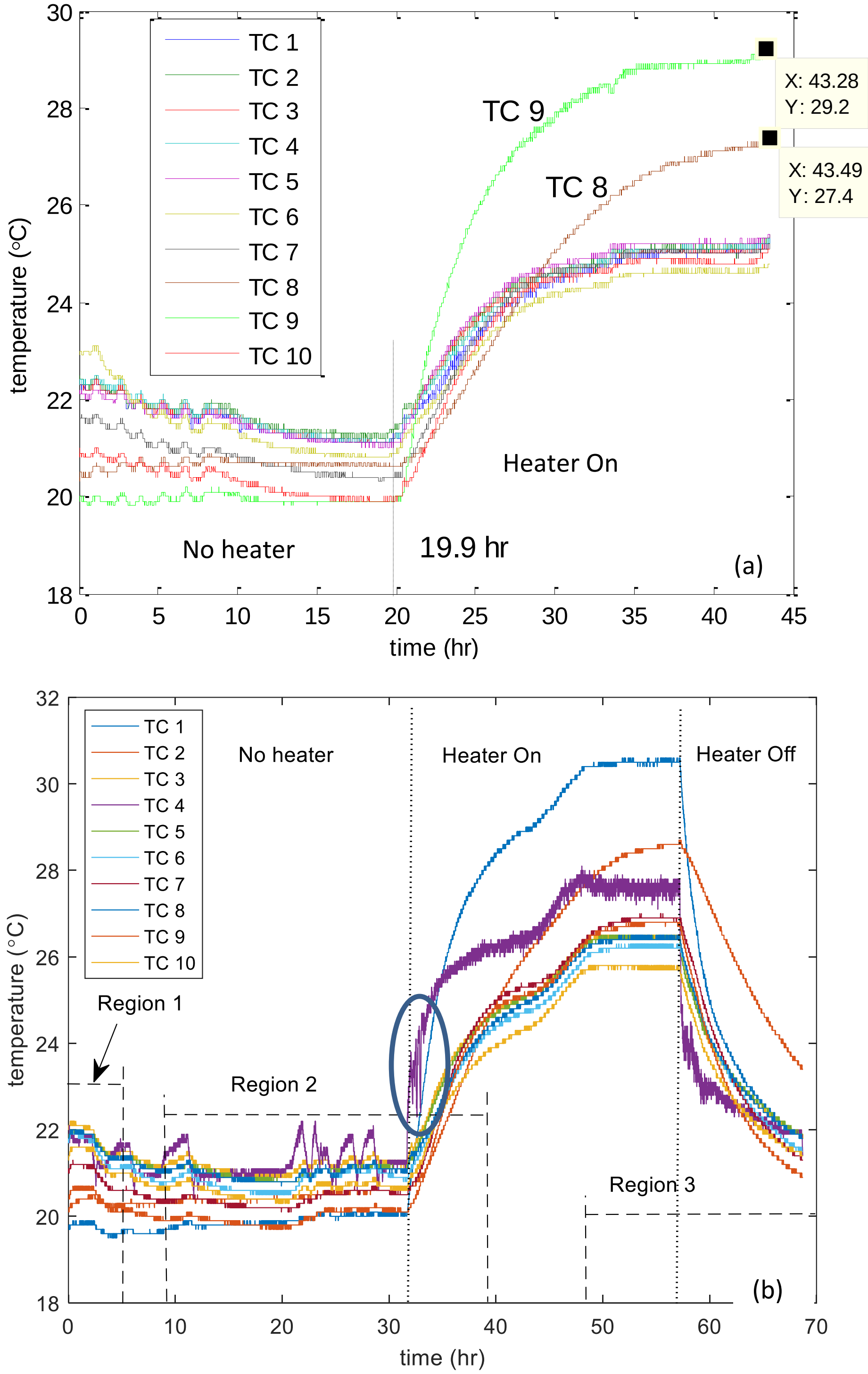


Figure 30: Thermocouple measurement data in (a) experiment 1 (b) experiment 2

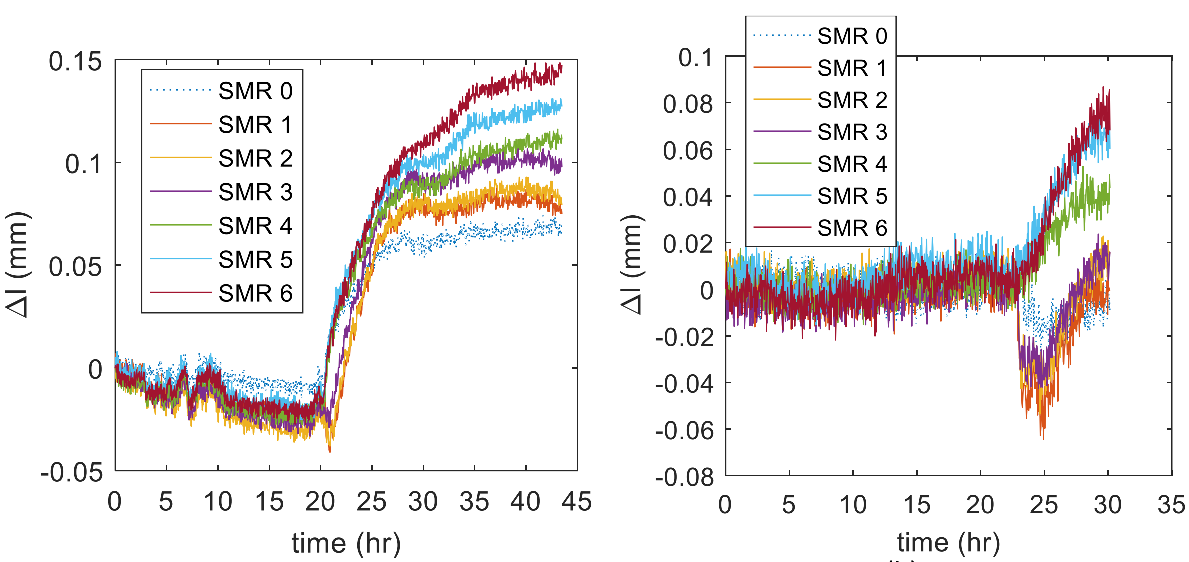
As shown in in Figure 30, in the first experiment, the heater was turned on at 19.9 hr and the temperatures continued rising up until reached their maximum values. In the second experiment, the heater was turned on in the middle of the experiment and turned off after the temperatures reached and stayed at their maximum values for a while. The areas labeled as ‘Region 1’, ‘Region 2’ and ‘Region 2’ correspond to the time when all data, including both temperature data and SMRs position data, are recorded completely. In other words, some data were lost in regions that are not labeled. Those time are specified in Table 1. Note that thermocouple 4 shows more fluctuating data than the other thermocouples, which is due to that thermocouple 4 is exposed in the air and more sensitive to change, i.e., responds faster and has larger magnitude to ambient temperature, while the other thermocouples are attached on machine tool surfaces and less sensitive to the air temperature change.

Table 1: Staring and Terminate time of regions 1, 2 and 3 as labeled in Figure 4

Region	Starting time (hr:mm)	Terminate time (hr:mm)
Region 1	0	5:00
Region 2	8:50	39:00
Region 3	48:06	67:00

Position Measurement Results

Observe that in Figure 30 (b) that region 2 in the second experiment has a similar temperature profile as the first experiment as shown in Figure 30 (a). Thus, we compare the measurement data in between the first experiment and region 2 in the second experiment. Figure 31 (a) and (b) depict the distance variations measured in experiment 1 and region 2 in experiment 2, respectively.



(a) (b)

Figure 31: Distance variations of all seven SMRs in (a) experiment 1 (b) region 2 of experiment 2

Figure 31 (a) demonstrates the existence of ADM shift in experiment 1, i.e., API-owned LT, since distance variations of all SMRs are equally changed relative to time although in different magnitude. Figure 31 (b) shows when the temperature is stable, the distance variations are dominated by noise, which demonstrates that the ADM shift of our refurbished LT does not exist when temperature is stable. It shows, however, that distance variations of SMRs 4, 5 and 6, have different profiles compared to that of SMRs 0 – 3. Since SMR 0 is on home position which is less affected by temperature change, it is reasonable to assume at this stage that the ADM shift still exists although not significant (~0.025 mm). The movement of SMRs 4 – 6 induced by machine tool deformation may counteract the effect of the ADM shift such that their distance variation profile may look different from the other SMRs. Figure 32 (a) and (b) depict the ADM shift measurements and estimates in experiment 1 and region 2 of experiment 2, respectively.

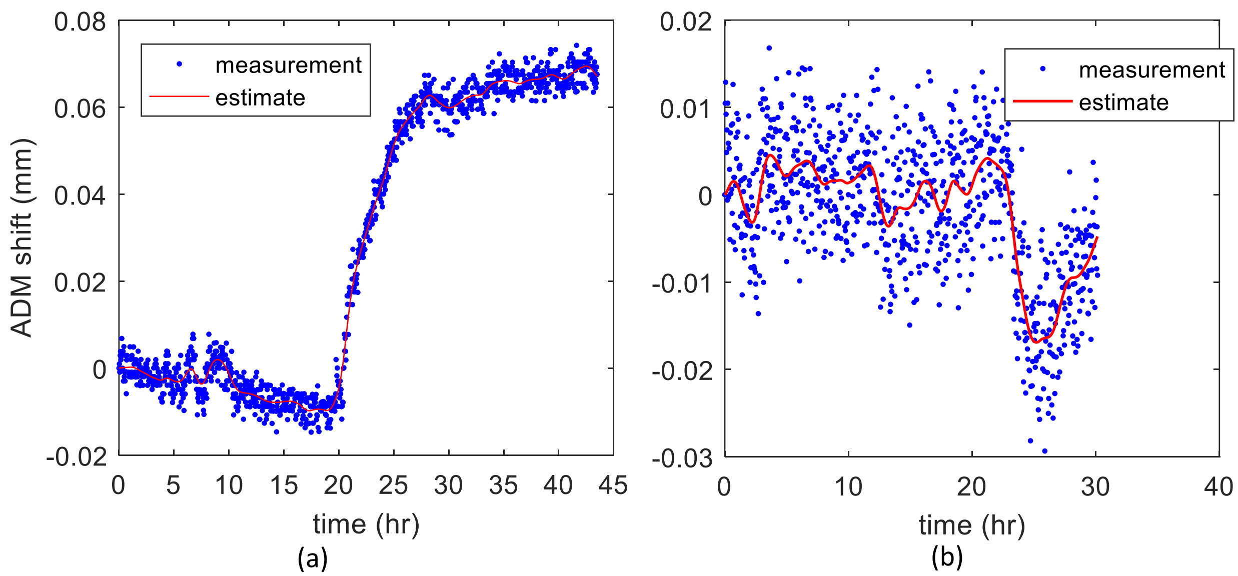


Figure 32: ADM shift measurement and estimate in (a) experiment 1 (b) region 2 of experiment 2

Figure 33 (a) and (b) depict the azimuth angle variations of all seven SMRs measured in experiment 1 and region 2 of experiment 2, respectively.

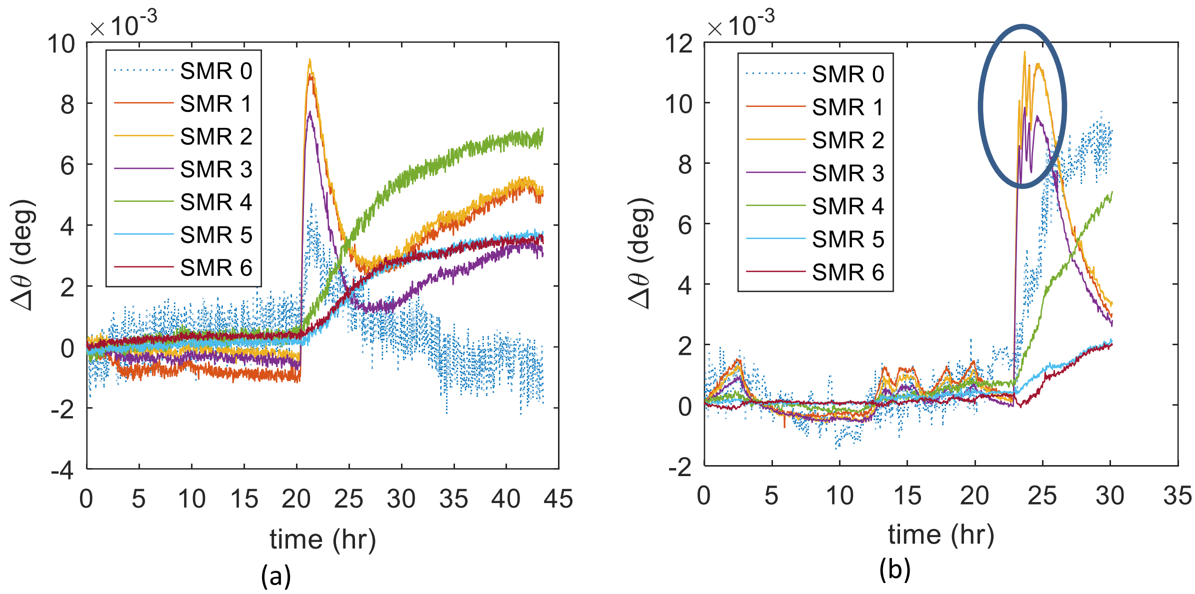


Figure 33: Azimuth variations of all seven SMRs in (a) experiment 1 (b) region 2 of experiment 2

Two observations are made from Figure 33. First, conspicuous jumps are observed in both experiments and those jumps only exist for SMRs 1, 2 and 3, i.e., SMRs on the spindle. In other words, from the perspective of azimuth angle variations, horizontal movements of SMRs 1 – 3 are different from that of SMRs 4 – 6. Second, observe from Figure 33 (b) and Figure 30 (b) that the circled spikes in the jumps in azimuth angle variations of SMRs 1 – 3 correspond to the circled spikes in the air temperature change. This indicates that the movements of SMRs on the spindle may arise from some deformation that is more sensitive to air temperature instead of machine tool surface temperature.

Two conclusions are made. First, the deformation that results in azimuth angle variations, or equivalently, horizontal movements, of SMRs 1 – 3 may be different from the deformation that results the horizontal movements of SMRs 4 – 6, the 'spikes' appear in the azimuth angle variations may result from the thermally instable 'C' structure of the machine tool. Second, the former one is more sensitive to air temperature change while the latter one is more related to machine tool surface temperature. For further conclusion, we look at Figure 34 (a) and (b) that depict elevation angle variations of all SMRs in experiment 1 and region 2 of experiment 2, respectively.

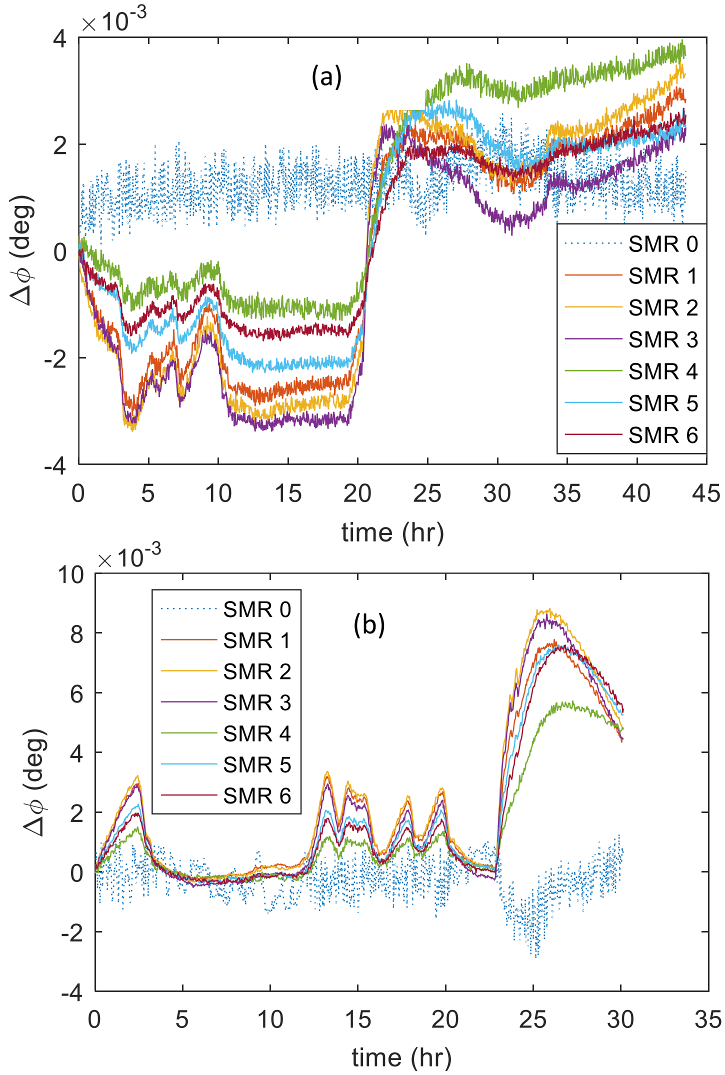


Figure 34: Elevation variations of all seven SMRs in (a) experiment 1 (b) region 2 of experiment 2

It is observed in Figure 34 that in experiment 1, all SMRs have similar elevation angle variation. This also occurs in region 2 in experiment 2. Based on these observations, different from azimuth and elevation angle variations of all SMRs may arise from the same type of deformation.

Machine Tool Table Thermal Expansion

One way to determine whether the machine tool is deformed is to evaluate the distance between two SMRs or the area of a triangle consisting of three SMRs. Since SMR 4, 5, and 6 are all on the x-axis table, we compute the area of the triangle consisting of them. For the triangle shown in Figure 35, the cross product of two vectors is used to compute its area, i.e.,

$$S(t)=\frac{\left|(\mathbf{AB})(t)\times(\mathbf{AC})(t)\right|}{2}\ . \quad (2)$$

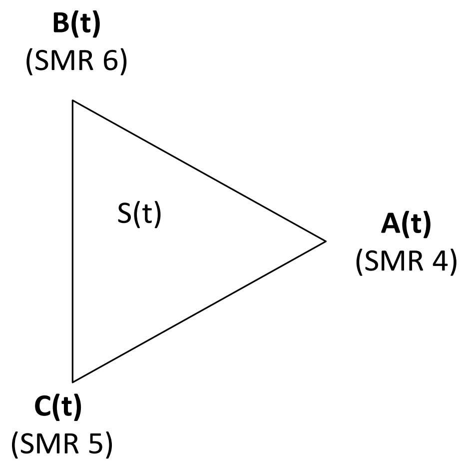


Figure 35: Triangle composed of SMR 4, 5 and 6.

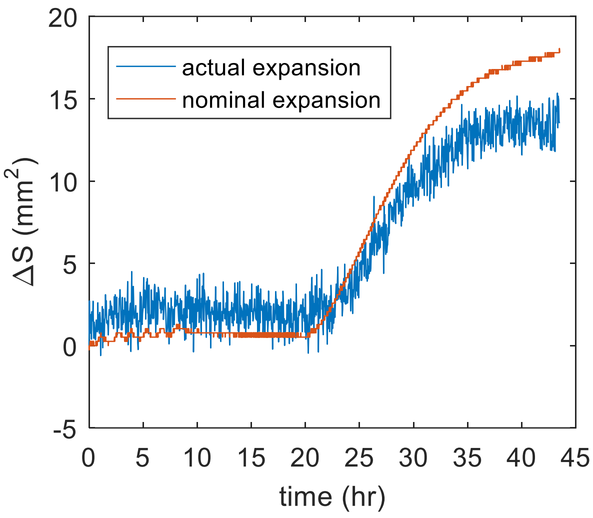
The computation consists of three steps. First, output positions of SMR 4, 5 and 6 in Cartesian coordinate. Second, use the formula (2) to calculate the area of triangle ABC with respect to time and compute the actual expansion $\Delta S_a(t)$ where

$$\Delta S_a(t)=S(t)-S(0) \quad (3)$$

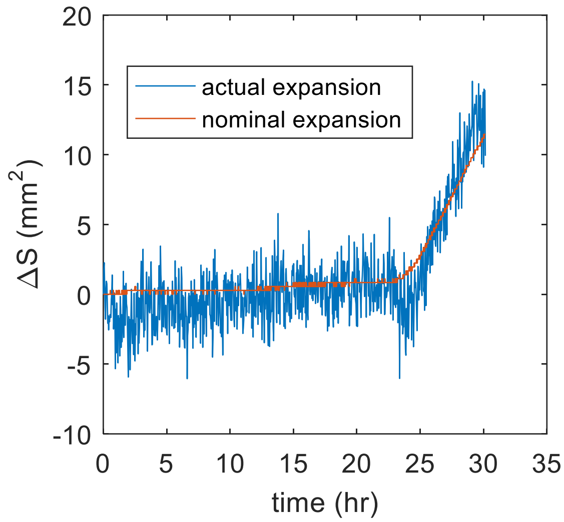
Third, compute the nominal expansion $\Delta S_n(t)$ of the triangle ABC using area expansion theorem, i.e.,

$$\Delta S_n(t)=\alpha_A \Delta T(t) S(0) \quad (4)$$

where $\alpha_A = 24\times10^{-6} K^{-1}$ is the coefficient of area thermal expansion of steel. Figure 36 depicts the nominal and actual thermal expansion of the triangular area consisting of SMRs 4, 5 and 6 for experiment 1 and region 2 of experiment 2.



(a)



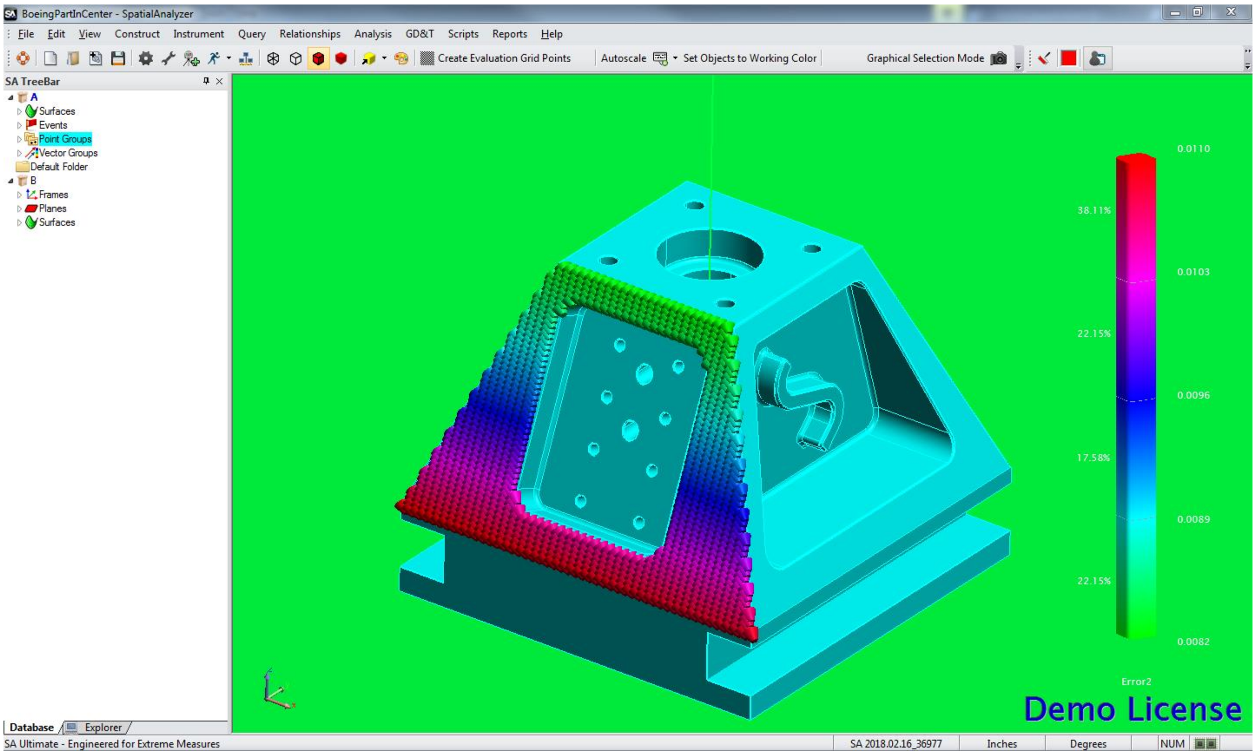
(b)

Figure 36: Nominal and actual thermal expansion of the triangular area composed of SMRs 4, 5 and 6 for (a) experiment 1 (b) region 2 of experiment 2

Figure 36 demonstrates that the actual area thermal expansion computed based on the laser tracker measurements basically agrees with the nominal area thermal expansion computed based on area expansion theorem. This indicates that a large portion of the variations in the measurements of SMRs 4, 5 and 6 arises from the x-axis table thermal expansion. The slight discrepancy between actual and nominal expansion may result from several aspects. First, the actual area expansion coefficient is very likely to be different from the nominal area thermal expansion coefficient. Second, thermal effect of the hot glue around the nests where SMRs are seated is not considered. Third, area expansion theorem assumes there is no constraint around and under the table, whereas in reality the x-axis table is constrained underneath. Last, elevation angle error in the LT is not considered.

Appendix E: VTA USER MANUAL

Virtual Twin Analyzer



User Manual

The Boeing Company,

Missouri University of Science and Technology

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Table of Contents

Welcome

Welcome to Virtual Twin Analyzer. As the user, you are about to begin using software that has been developed from groundbreaking research. Not only do you have the opportunity of taking part in this great software but you also get to use it in conjunction with SpatialAnalyzer from New River Kinematics. Their software is used across many industries and is a leader in virtual spatial analysis and visualization.

1. Introduction

Virtual Twin Analyzer is a package developed to aid in the analysis of robotic machines. It is used specifically for five and six axis machines which are analyzed using the software. Virtual Twin Analyzer uses existing SpatialAnalyzer software to visualize the errors that are present when performing machining on a computer aided design (CAD) part. This is extremely beneficial in determining the accuracy of machines.

Virtual Twin Analyzer has the capability of performing many tooling operations. These tooling operations include standard tooling operations: “end cutting”, “side cutting”, “drilling thru holes”, and “kellering”. Virtual Twin Analyzer also includes the capability of making “custom” points by changing the operation type for specific points. Virtual Twin Analyzer includes the adding of “complex” surface tooling which will determine the tooling properties based on proximity to a specific point. This allows for the tool to work around the boundaries of the part being machined and match the tooling to work into tight spaces.

Virtual Twin Analyzer gives the user much more than just a visual aid though. With Virtual Twin Analyzer’s simple report and error histogram generation the user can view results in a graphical and numerical manner without having to work directly with the data. This information is presented in a way that is ready for final reports. If the report generation of Virtual Twin Analyzer is not detailed enough or fit to the needs of the user then they have the ability to quickly and easily select the information that they would like to export to a Comma Separated Value (.csv) file ready to be viewed and manipulated within Excel or any other data analysis and manipulation software.

With the use of Virtual Twin Analyzer, one can efficiently generate and view information about the machining of a specific part on a specific machine. Virtual Twin Analyzer can handle thousands of evaluation points, tooling vectors, and error vectors making the analysis of a part and machine open and understandable to all viewers.

2. Installation Instructions

To install Virtual Twin Analyzer you should first review the system requirements and recommended system properties and ensure that your system meets them. These can be seen below.

System Requirements

-NET Framework 4.0

-SpatialAnalyzer by New River Kinematics

Recommended System Properties

-4 GB RAM (Random Access Memory)

-1 GB Free Hard Drive Space

-SpatialAnalyzer 2018

Next, you should locate the **"VTA_Installer.exe"** file located in the installer package you received. You should run the installer and step through the windows that are presented to them making adjustments as needed. If you are not an administrator on your computer, you will need to have an administrator run the installer and install Virtual Twin Analyzer.

Creating a Virtual Twin Analyzer Shortcut

To create a Virtual Twin Analyzer shortcut—if it's not already created—you should navigate to the folder where the files were installed and right click on the "Virtual Twin Analyzer.exe" file. You should then hover the mouse over the "Send to" option and select "Desktop (create shortcut)" from the drop down list. This will create the shortcut on the desktop.

Updating Virtual Twin Analyzer

To update Virtual Twin Analyzer, you should first navigate to the old version of Virtual Twin Analyzer and delete the entire folder that holds the program files. Then you should run the new Virtual Twin Analyzer installer to install the new software.

Note: If you would like to keep multiple versions of Virtual Twin Analyzer, simply create a new folder when installing rather than using the default saving location.

3. VTA Fundamentals

One of the best parts of the Virtual Twin Analyzer software is that VTA will guide you through the process and help you along the way. Virtual Twin Analyzer was designed with ease of use in mind the whole time. This led to the development of a guided user control system and basic necessary functions. With the basic functionality you can begin to understand VTA without a steep learning curve like many other programs' analysis and CAD programs.

4. Basic Functions

In this section we will discuss all of the buttons that you must call in order to complete one full analysis of a specific part and machine. These buttons in order are "**Connect To SA**", "**Browse for Machine Files**", "**Create Table Plane Representation**", "**Browse for CAD File to Machine**", "**Add Evaluation Grid Points**", "**Add Surface Tooling**", and "**Run Operations**".

Connect To SA

Once you have installed Virtual Twin Analyzer, the first thing you need to understand is the importance of connecting to SA. Since VTA exists outside of SpatialAnalyzer, you must first connect the two together so that any command performed in VTA will also be performed in SA. The first time that you start VTA you will be prompted to browse for the version of SpatialAnalyzer that you would like to run. The default installation location for SpatialAnalyzer is "C:\Program Files (x86)\New River Kinematics\SpatialAnalyzer (Version)\SpatialAnalyzer.exe". Once you have defined what version of SpatialAnalyzer to run, VTA will save this data and refer to it in the future to start SpatialAnalyzer automatically if you don't already have SpatialAnalyzer open.

If you have SpatialAnalyzer open already, Virtual Twin Analyzer will attempt to make a connection automatically and you will be prompted with a "Connected Successfully" message from Virtual Twin Analyzer.

Browse for Machine Files

Once a connection with SpatialAnalyzer has been established you will be required to select machine files before continuing any further along in the application by selecting the "Browse for Machine Files" button. These files are the robot file which includes: the machine configuration and the measurement file that includes measurements taken for the machine.

When you select the “Browse for Machine Files” button, the dialog for machine files will open. This dialog gives you the option of selecting files individually or by selecting the machine folder. VTA will try to determine what each file is based on the naming convention of the files. If VTA is successful in determining a match for each file, you will prompted asking for verification that the correct files and type are selected.

Note: VTA uses the naming convention that the robot file will have, “**robot**” somewhere in its name, and that the measurement file will have “**measure**” somewhere in its name. This is done to help prevent any possible errors from the wrong files being read and it is suggested that you adopt this naming convention as well.

You have the ability to reselect machine files at any time during the running of the application. This can be particularly helpful if you would like to compare the errors of two machines.

Create Table Plane Representation

After selecting the files that you would like to use, you must then either create a table or import the machine tool CAD model (see “Browse for Machine Tool CAD”). To create a representation of the workspace, you will be prompted with the table creation dialog. This dialog has default values for a machining table that is 250”x100”. The table can be created as either a quadrilateral shape or a triangle by inputting the coordinates of the corners of the table. It is recommended that you create the table in the XY plane only keeping the Z values set to 0.

Once the values for the table are set, select the “Create Table” button and a table will be created using the coordinates specified. If at any time you would like to leave the table creation dialog, simply select the “Cancel” button or close button in the top right hand corner of the dialog.

Browse for CAD File to Machine

The next step to complete is importing a CAD model that you will be applying the machining to. Upon clicking the “Browse for CAD File to Machine” button, you will be prompted to select the CAD file that you would like to machine. To see a list of CAD files supported by SpatialAnalyzer see the section “Direct CAD Access” in the SpatialAnalyzer User Manual. Once you have selected the part and accepted it, SpatialAnalyzer will begin the process of importing the CAD part.

When SpatialAnalyzer is done importing the part, you will have full access to SpatialAnalyzer and will either be prompted to “Pick surfaces to dissect (ENTER when done)” or the part will be dissected automatically (if running SA version 2018.07.1). While picking surfaces to dissect, it is vital that you select **ALL** of the surfaces that were imported with the part. Failure to do so will result in the deletion of surfaces from SA. To make sure you select all the surfaces in SA, it is recommended that you use the "SA TreeBar" on the right side of the SA user interface. Imported surfaces that need to be dissected will be located in A/Surfaces/(Your Imports Here). After selecting all the surfaces, SA will dissect, recolor, and rename the surfaces.

Note: The process of importing and dissecting surfaces can take some time depending upon the size and complexity of the part. When SA is finished with this step, the next dialog, "Transform Part" will open.

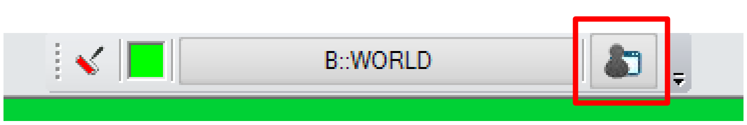
Move Part

Transforming the part to the right location is vital to the delivery of correct data. During this step, you should transform the part to the exact location on the table that you will be machining the part at. This can be done in any number of transformations and can be reset to the original position at any time. All transformations are relative to the original position. This means if you enter X: 100 for your transformation, perform this transformation, then enter X: 110, and perform this transformation, the object will only move 10 more inches from the last position (or 110 inches from the starting spot in the x direction). You also have the option of using SA to move the object by dragging graphically by selecting the "Graphically" button. Once you are satisfied with the position of the part, select "Done". You can recall the "Move Part" form at any time by clicking the "Move Part" button on the right side of the Virtual Twin Analyzer program.

Add Evaluation Grid Points

To begin the process of evaluating points on the part, select the "Add Evaluation Grid Points" button. A message will explain to you how to add points to surfaces using a button located at the top of the SA interface named "Create Evaluation Grid Points". Select the surfaces to apply points to and then hit the enter key on the keyboard. A dialog will appear asking you to input points in the "u" and "v" directions. **Note:** Avoid adding too many points to a single surface or all surfaces combined. Please see the section "Recommendations for Best Performance".

Note: If the SA interface does not have the "Create Evaluation Grid Points" button, you should first verify that you have the VTA SA profile installed. Select the "User Interface Profiles" button located on the "Color / WCF Toolbar" provided by SA (see image below).



Note: If you are unable to see the "Color / WCF Toolbar", right-click on the edge of the SA interface (one of the gray bars). Then select "Color / WCF Toolbar" from the list. This will show the toolbar.

Next, select the option "C#Profile" from the list of available existing saved profiles. If the profile is not located in this dialog you must add it manually. To do this, open up file browser on your computer and navigate to the Virtual Twin Analyzer program folder. In this folder there will be a file named "C#Profile.saprofile". Copy this file to the Templates folder located at "C:\Analyzer Data\Templates. Then you should be able to select this profile as an option and the button necessary for adding points should appear.

Navigate back to the message that appeared earlier and click "OK". The evaluation points have been successfully added if control is returned to the Virtual Twin Analyzer main form.

Add Surface Tooling

The final step in the process of preparing the part for analysis is to "Add Surface Tooling". You will be prompted with the "Add Surface Tooling" dialog box with the options to perform any of the following options: "End Cutting", "Side Cutting", "Drilling Thru Holes", "Kellering", "Complex Surfaces", or "Custom Tooling". Each of these options will open another dialog box that will ask you for information relating to the tooling you have selected such as tool length, tool radius, and orientation of the tool. After you have made valid inputs for the tooling operations, you will be prompted to select the surfaces you would like to perform the tooling on. If you would like to add custom tooling to points, you must also add regular tooling to that surface for it to be evaluated.

End Cutting

An end cut will be performed with the tool always perpendicular to the surface.

Side cutting

A side cut will be performed with the tool parallel to the surface. All tooling orientations that are not parallel to the surface will be corrected if a correction can be made automatically.

Drilling Thru Holes

Virtual Twin Analyzer will attempt to match the selected surface to a cylinder. If it is able to successfully match the surface to a cylinder, the drilling operation will be performed.

Kellering

The kellering operation will be performed similar to a side cut but the tool orientation will remain set at whatever is input and no cuts will be deemed impossible or corrected.

Complex Surfaces

The complex operation will ask you for points you would like to be control points. Each of these points will have a tool length and orientation assigned to it and all points on the surface will be assigned tooling based on proximity to these control points.

Custom Tooling

Custom tooling will take any point that has already assigned tooling to and replace that tooling with tooling that is independent of the surface that it is assigned to. To remove the custom tooling on a point, add surface tooling on top of the point's surface.

Run Operations

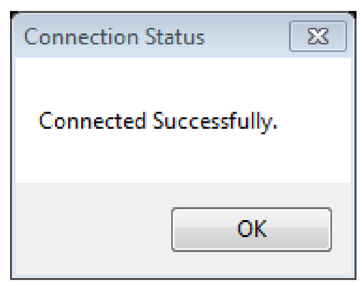
After tooling and points have been added to their respective surfaces, the operations can be run on these points. First, a check will be run to see if there are any surfaces and/or points that have tooling assigned, and no points and/or points but no tooling assigned. You will be notified if this exists and the surfaces and points will be highlighted. Next, SA will begin by creating the tooling vectors for the points and the error kinematics calculations will be performed. The error vectors will be populated within SA. VTA will notify you if there were any tooling corrections or impossible tooling vectors along with what type of inverse kinematics were used for the calculations. Finally, the "Show/Hide Errors" dialog will be shown and the desired errors can be shown.

5. Basic Functions Walkthrough

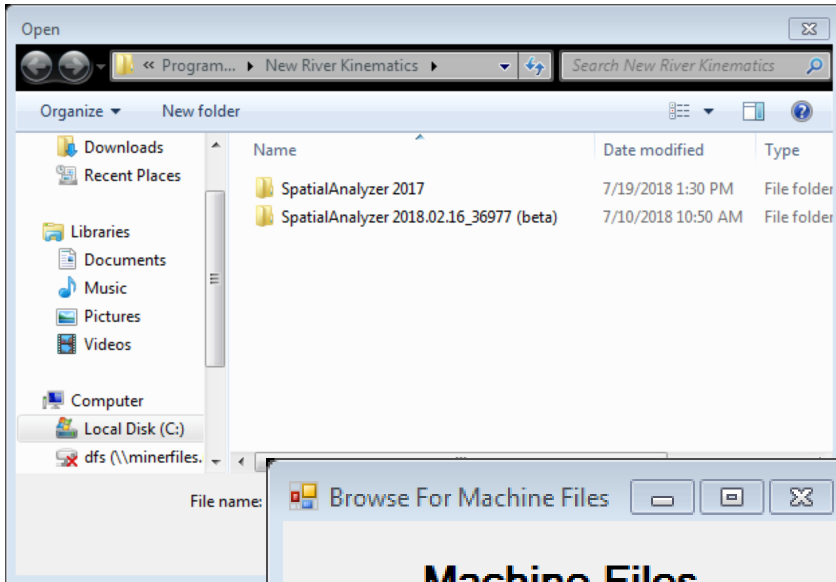
This section of the VTA Manual will guide you through the basic functions of the VTA Application and perform an operation for a specific set of machine files and a test part.

Connect To SA

If you have SpatialAnalyzer open when you start up Virtual Twin Analyzer, a connection will be attempted. You should be informed of your connection results by a dialog like the one on the right.



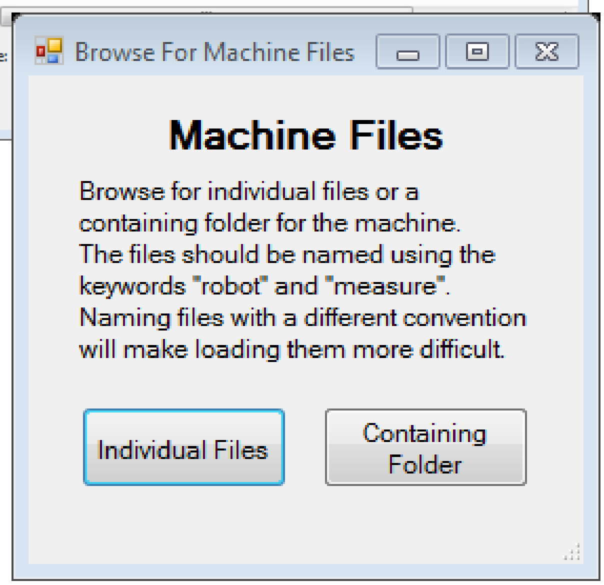
The first time that Virtual Twin Analyzer is opened and SpatialAnalyzer isn't already open, a prompt will tell you to browse for the version of SpatialAnalyzer that you would like to run by default with Virtual Twin Analyzer.



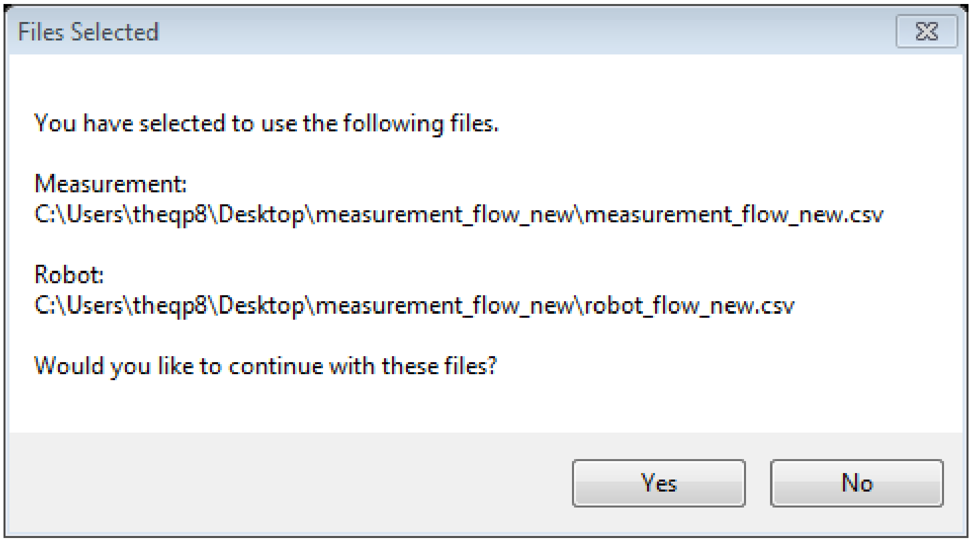
Next, the dialog to the right will open and you will need to navigate to the SpatialAnalyzer version that you would like to run by default with Virtual Twin Analyzer. Once inside the program folder, select the SpatialAnalyzer.exe file. Spatial Analyzer will open and you must "Connect To SA".

Browse for Machine Files

Next you should select the "Browse for Machine Files" button which will present the dialog on the right to you. We will select the "Individual Files" button for this walkthrough; however, you can choose the "Containing Folder" button as long as you have both files in the same folder. You will be given another message that tells you to "First browse for the machine measurement file; then browse for the robot file."



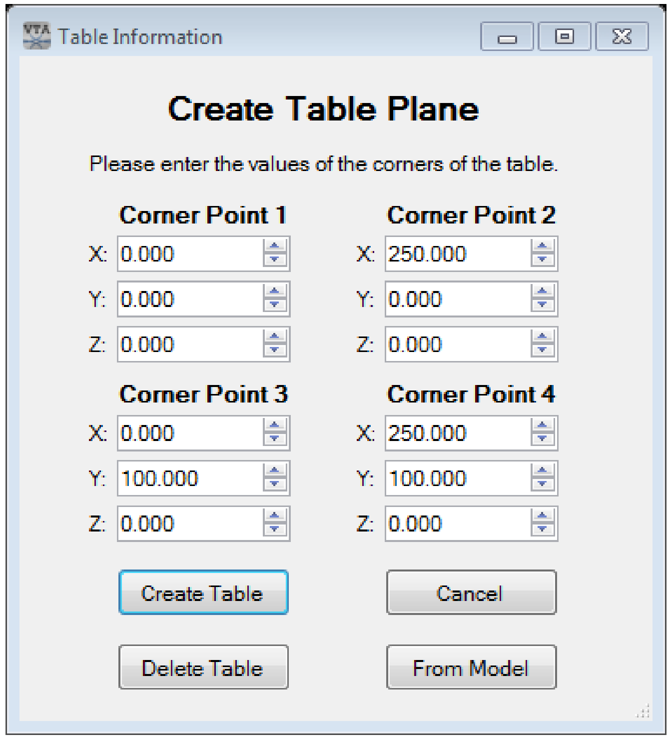
After selecting the two machine files to use, a dialog will appear asking you to verify the two files selected. This dialog can be seen below.



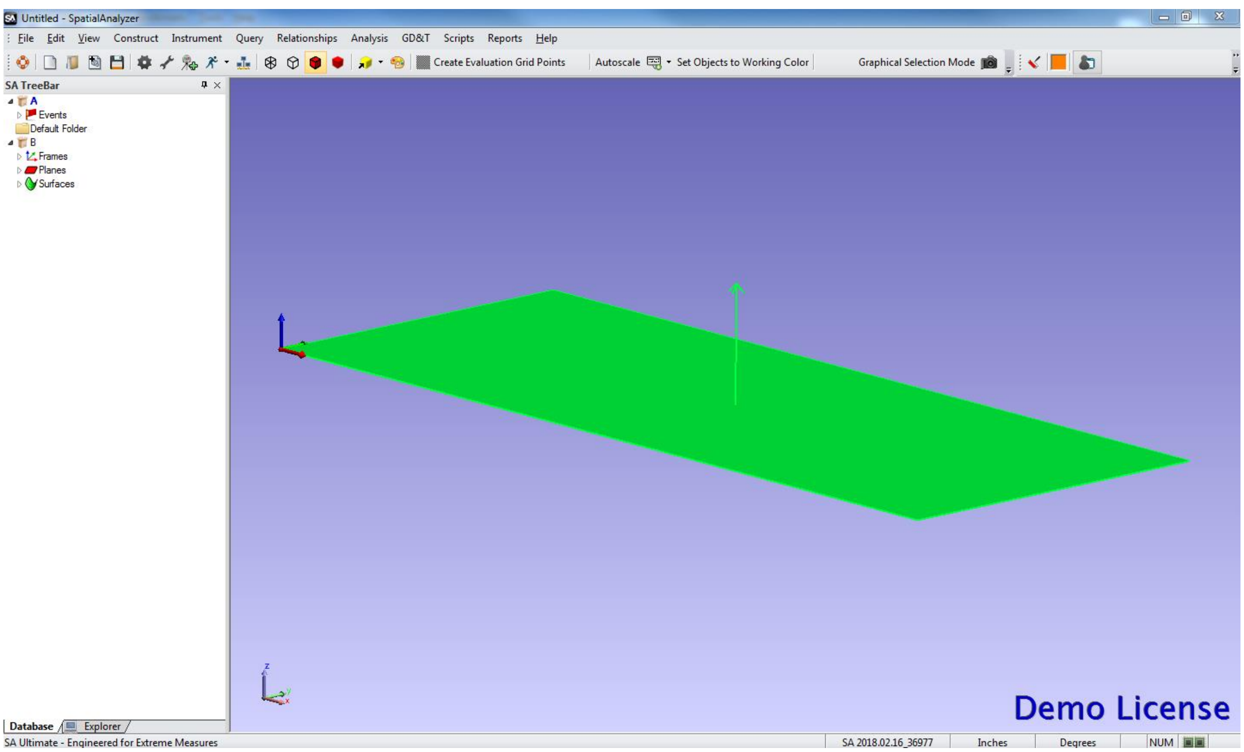
Selecting "No" on this dialog will take you back to the Virtual Twin Analyzer program and selecting "Yes" will set the two files as the machine files to use in the analysis and return you to the main screen. The next step that is now available is to "Create Table Plane Representation".

Create Table Plane Representation

Next we will begin to interact with SpatialAnalyzer by creating a plane in SpatialAnalyzer. This is done by clicking the "Create Table Plane Representation" button. The dialog on the right will open up and you can input any parameters into the corner points of the table. We will just create the default table here which is a 250"x100" table. The table can also be created from the machine limits by selecting the "From Model" button.

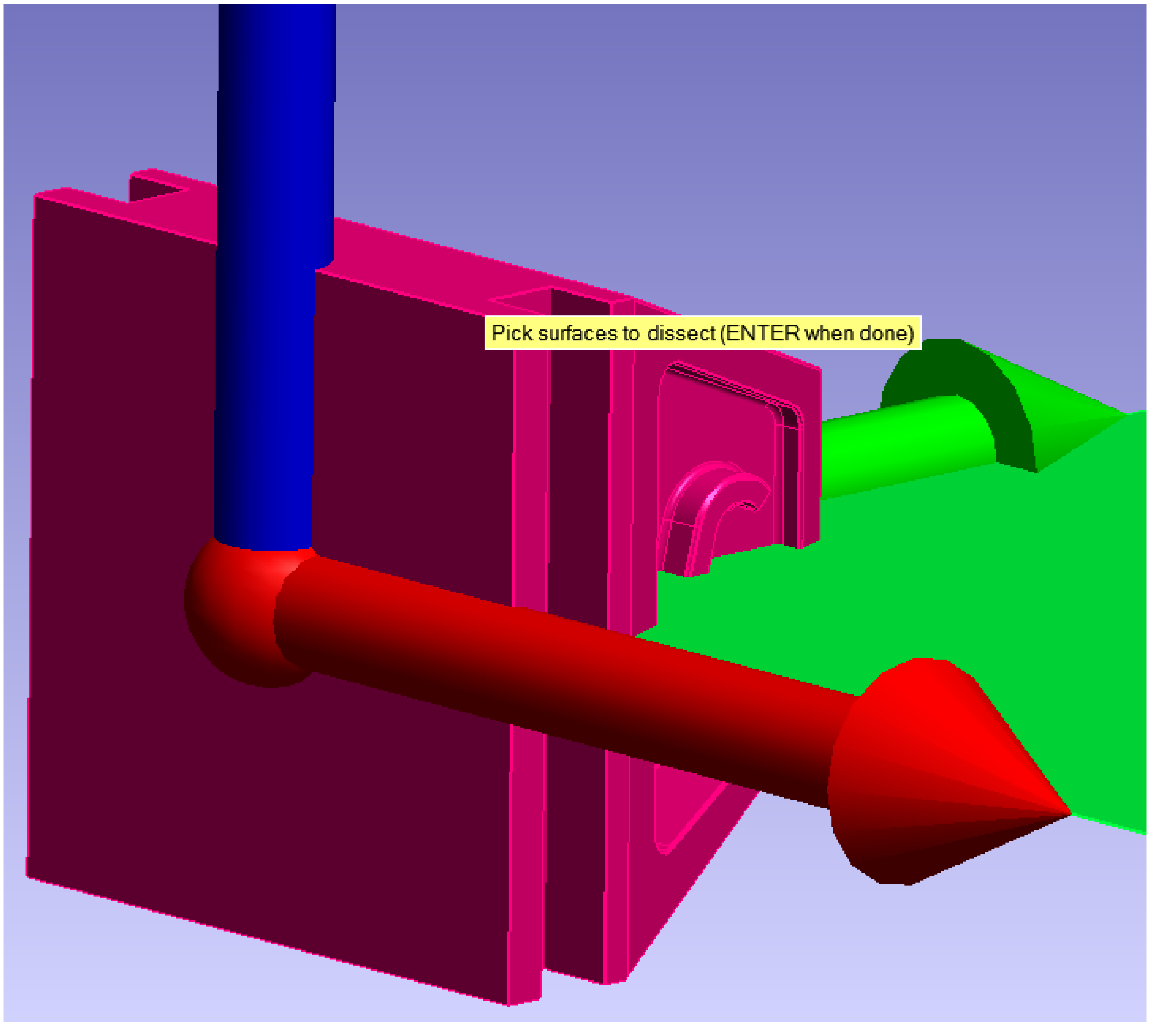


The created table can be seen below in the picture of the SpatialAnalyzer workspace. The table is colored by default to green every time but any experienced SpatialAnalyzer user can change this at any time.



Browse for CAD File to Machine

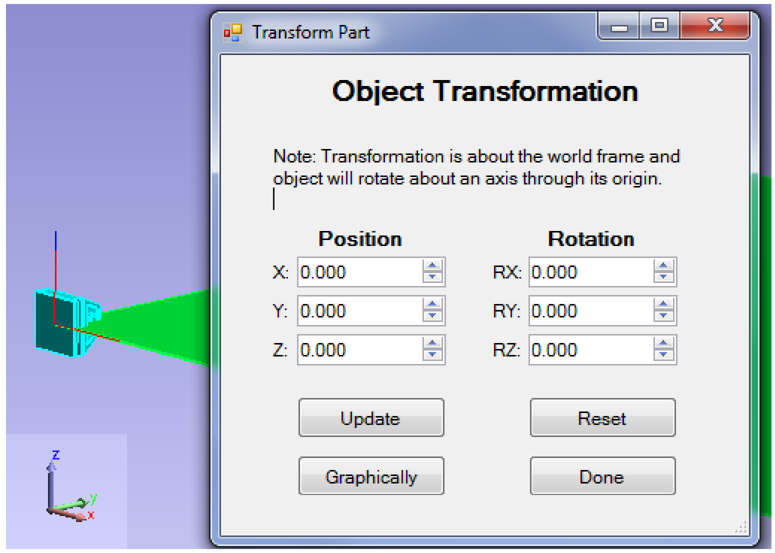
The next action that is needed from you is the selection and importing of the CAD file that you would like to machine. You will again be prompted with a browsing dialog from which you will select the CAD file. Once you select "Open" on the file dialog, SpatialAnalyzer will begin importing the CAD file. When it is done importing the CAD file, you will be prompted by SpatialAnalyzer to "Pick surfaces to dissect (ENTER when done)." This can be seen in the image below.



Spatial Analyzer will begin dissecting the surfaces and renaming them to a standardized name for Virtual Twin Analyzer to use. Once SpatialAnalyzer is done dissecting the surfaces, control will be returned to the Virtual Twin Analyzer application and the "Object Transformation" dialog ("Move Part" button) will be called automatically.

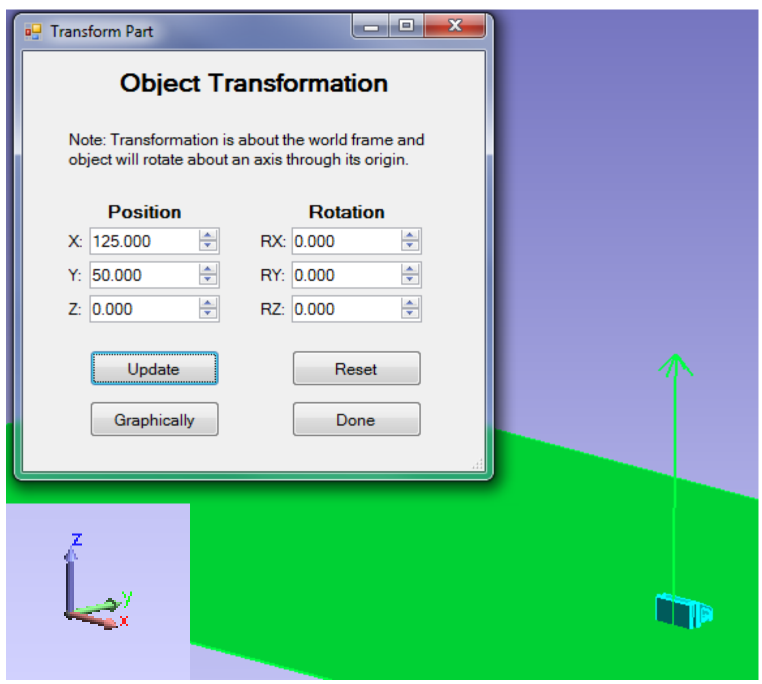
Move Part

The “Object Transformation dialog will be called automatically after the completion of the “Browse for CAD File to Machine” function is finished. It is important to take note of the starting location of the part in relation to the coordinate frame. This is the axis that the part will be rotated about after it has been moved. Imagine the coordinate frame that you see at the start of this function moving along with the part without rotating. To help visualize this we will perform two separate transformations.



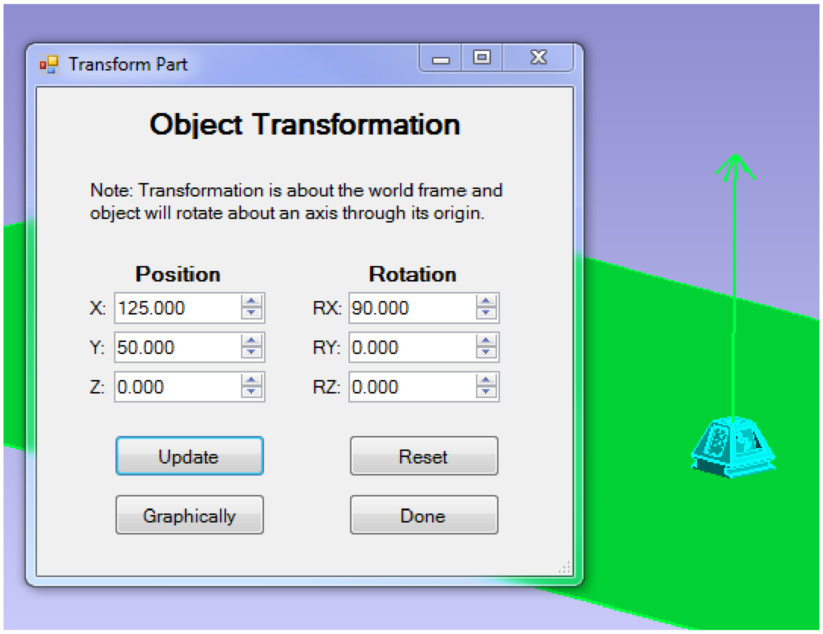
The first will be a translation by 125” in the x direction and 50” in the y direction.

As you can see by the picture on the right, the object was moved to the center of the table (remember the table is 250”x100”). Now let’s remember that any rotation that will be performed now will be about a coordinate frame located on the part in the same location as before the transformation. Next we will perform that rotation to help visualize what we are talking about.



Rotate the part 90° about the x axis.

This action will rotate the part in the same location that it is currently in without moving the part anywhere. Notice how the values for X and Y are not changed from before because these are translations relative to the world frame which is where we started. Also notice that the part did in fact rotate by 90° about the X axis but stayed in the same place on the table. You will find that these transformations become very intuitive as you use Virtual Twin Analyzer.

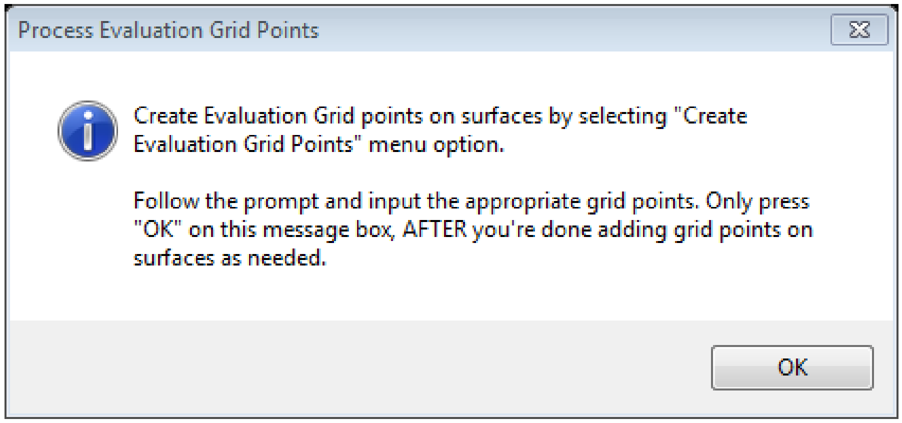


Two other options remain. These are resetting the part to its starting position when this dialog was opened (picture 1 in this section) and moving the object by dragging it graphically in SpatialAnalyzer. When dragging the part graphically within SpatialAnalyzer, simply click and move the object with the mouse and rotate it using the mouse as well. When finished transforming the object, click the "Done" button and the objects position will be saved.

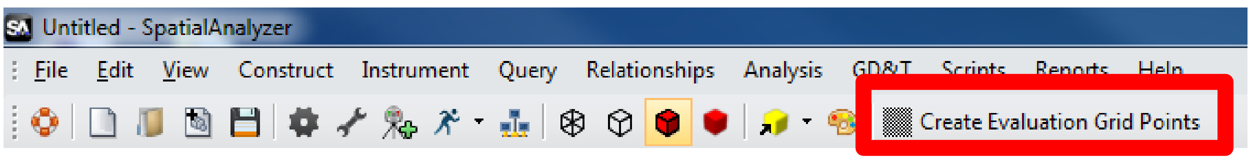
Add Evaluation Grid Points

The next step in our walkthrough is to "Add Evaluation Grid Points" to the surfaces that we would like to analyze. In this example, we will add points to 5 surfaces so that we can demonstrate some of the different tooling operations that can be applied. A message will appear informing you on how to add the grid points to surfaces. **DO NOT** click the "OK" button on this message until you have added all your grid points. If you click "OK" before the points are added, the function will be exited and no points will be added. Then you must navigate to the "Create Evaluation Grid Points" button in SpatialAnalyzer where you will be prompted by SpatialAnalyzer to select the surfaces that you would like to add points to. Finally, return to the message where you can click "OK". Let's give it a try. The steps can be seen below.

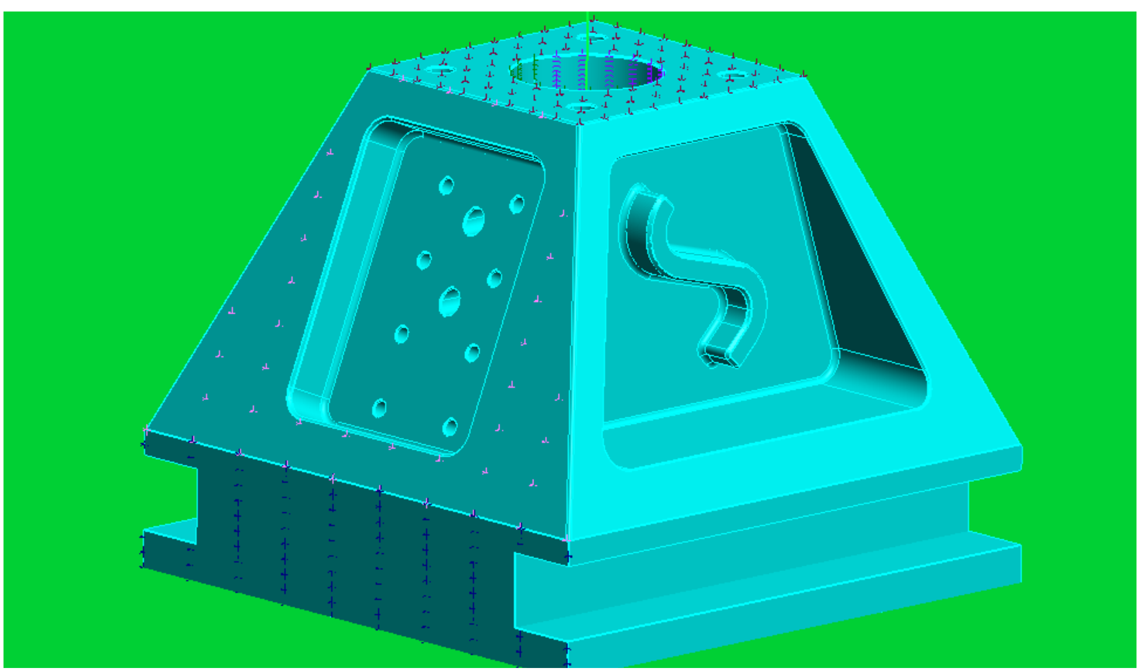
First, the message to the right will appear. **DO NOT** click “OK” until finished adding points. Clicking “OK” will exit the “Add Evaluation Grid Points Command” before you can add points.



Next, navigate to the “Create Evaluation Grid Points” button on the SpatialAnalyzer toolbar and click it to select the surfaces you would like to add points to. The button should be found near the center of the toolbar. See the marked picture below.



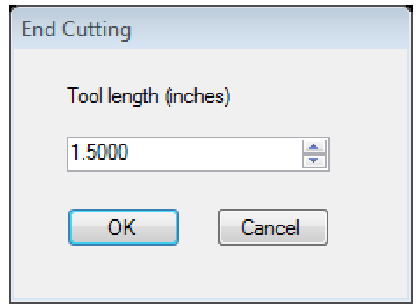
Next you will be prompted by SpatialAnalyzer to “Select Surfaces (Enter when done)”. The surfaces that you select will be highlighted when you are picking them but the highlighting will disappear when you hit “Enter”. Now we must tell SpatialAnalyzer how many points we would like to add to each surface. For this example, I will do 10x10 on each surface. The added points can be seen below.



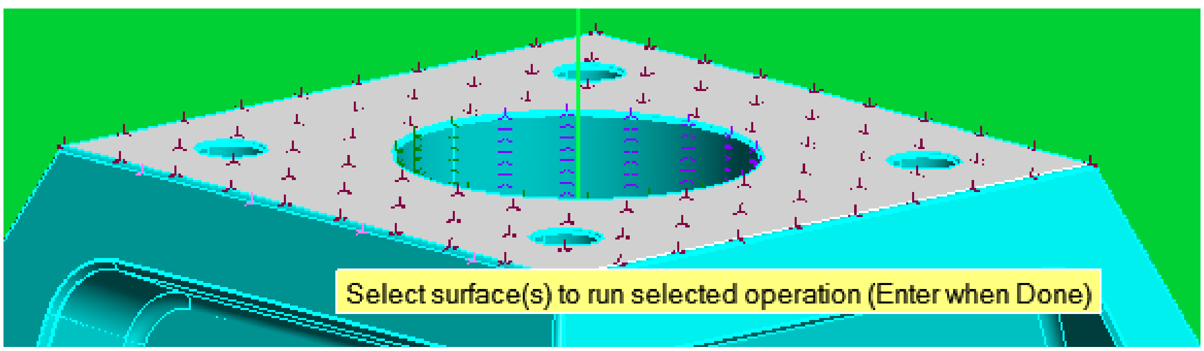
Add Surface Tooling

The final step before we can run the operations and view error vectors is to “Add Surface Tooling”. To view all the tooling options, see the section on “Add Surface Tooling” in the “Basic Functions” part of this chapter. To add tooling to surfaces, select what type of tooling that you would like to apply. Then, depending on the tooling type input the parameters for that tooling, select “OK” in the dialog and then select the surfaces you would like to add the tooling to. **Note:** For the drilling function you do not input any tooling parameters as the tooling is based off of the selected surfaces.

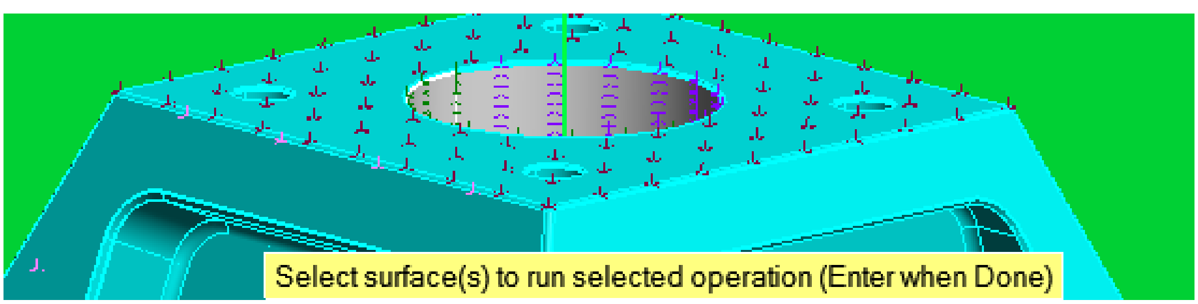
First let’s apply “End Cutting” with a tool length of 1.5” to one of our surfaces by selecting the “End Cutting” button, inputting the tool length, and then selecting the surface in SpatialAnalyzer. The “End Cutting” dialog can be seen to the right.



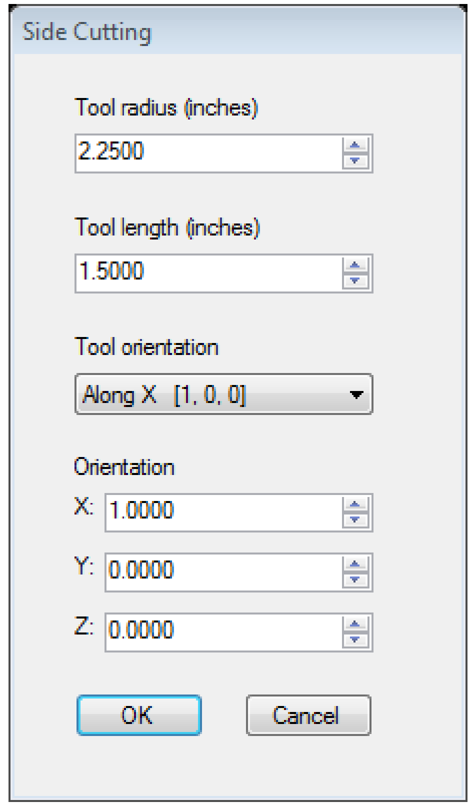
Next we will select the surface. This can be seen below. “Enter” once that surface is selected.

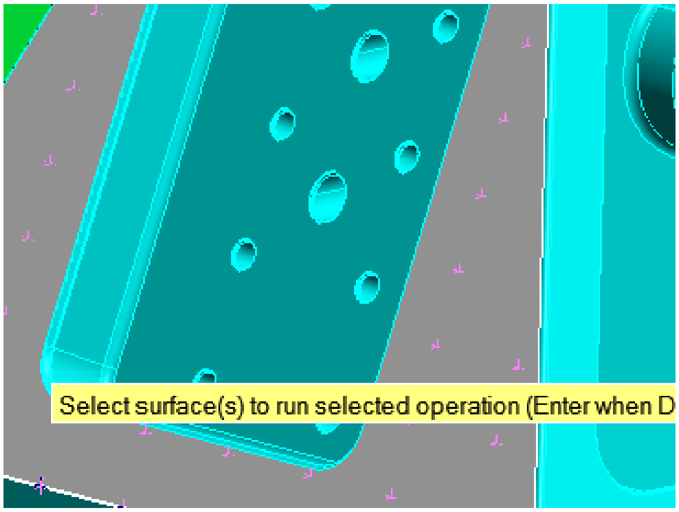


Next let’s apply drilling to the hole that is located on the top of the part. This selection process is quite straightforward. Simply select the two surfaces after selecting the “Drilling Thru Holes” button. Notice how these surfaces are highlighted below.



Next, let's apply a side cut to the angled surface on the side of the part. We will set the tool length, radius, and orientation on this one. The side cutting dialog can be seen to the right. As always, we will select the surface that we want to apply the tooling to. The selected surface can be seen below.

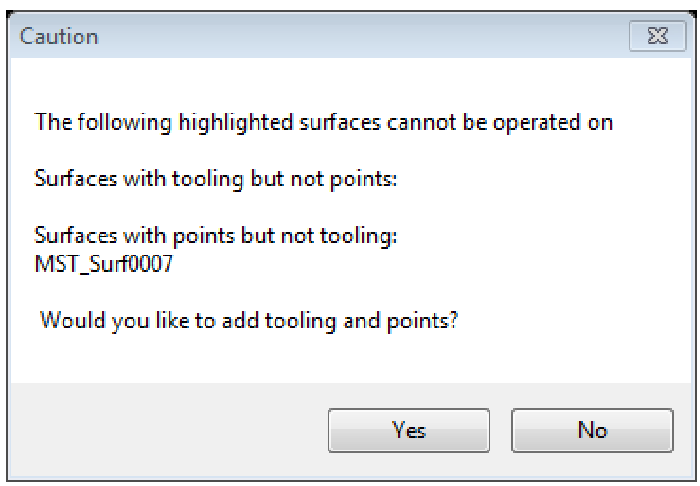




For now, let's not add any tooling to the last surface and we'll see what happens in a little bit.

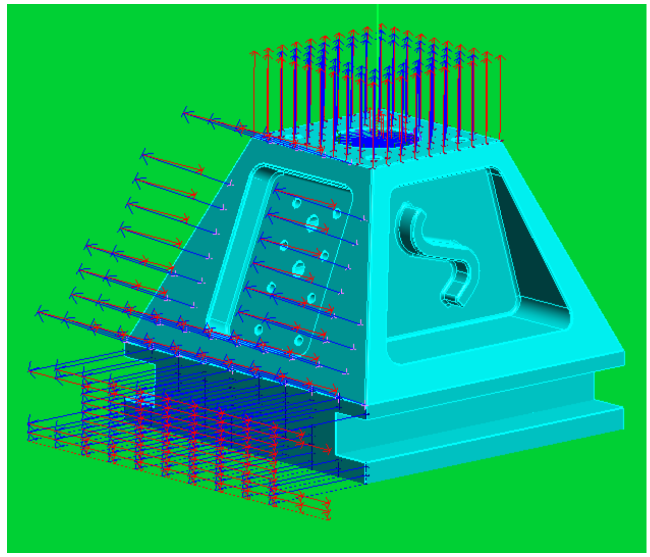
Run Operations

It's time to do some calculations and let Virtual Twin Analyzer and SpatialAnalyzer really do some work. Let's begin by clicking the "Run Operations" button. We'll get a message informing us about the surface with the points but no tooling assigned. The exact message can be seen to the right and the surface is highlighted. For now we will select "Yes" and add a side cut to the surface with the same tooling properties as the other surface that we just applied side cutting to.



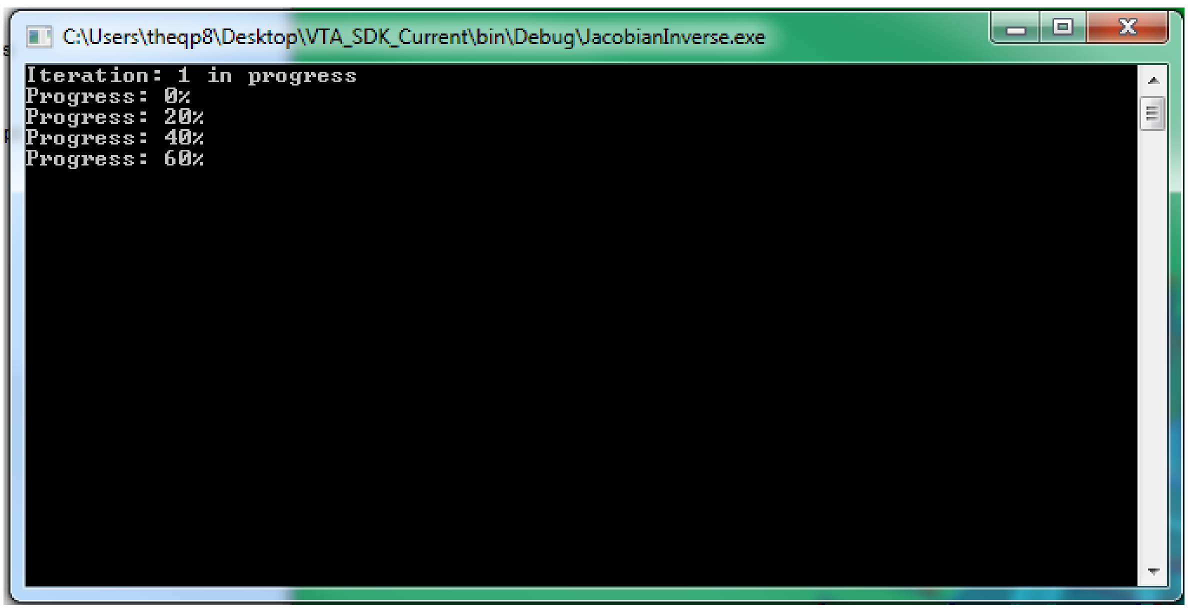
Note: Selecting "No" on the message above would have run the operations on just the surfaces that have both tooling and points, and ignored the other (MST_Surf0007).

Now when we run the operations, the surfaces will first populate themselves with the tooling vectors based on the tooling operations applied to the surface and points. This population of vectors can be seen in the image to the right.



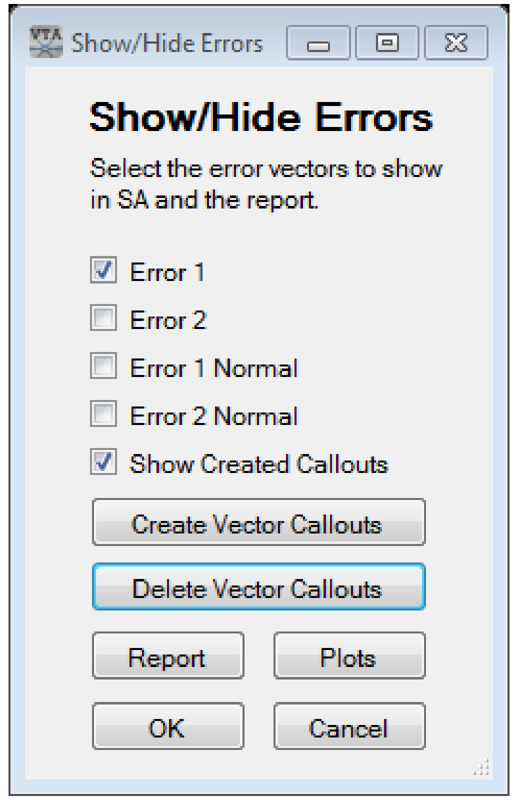
Note: Depending on the number of points and operation type that you have chosen, this process can take some time within SpatialAnalyzer. If there is an issue running the operations either within Spatial Analyzer or with Virtual Twin Analyzer, you will receive an error message.

Next, a window will open showing the calculation iterations and the progress that has been made so far.



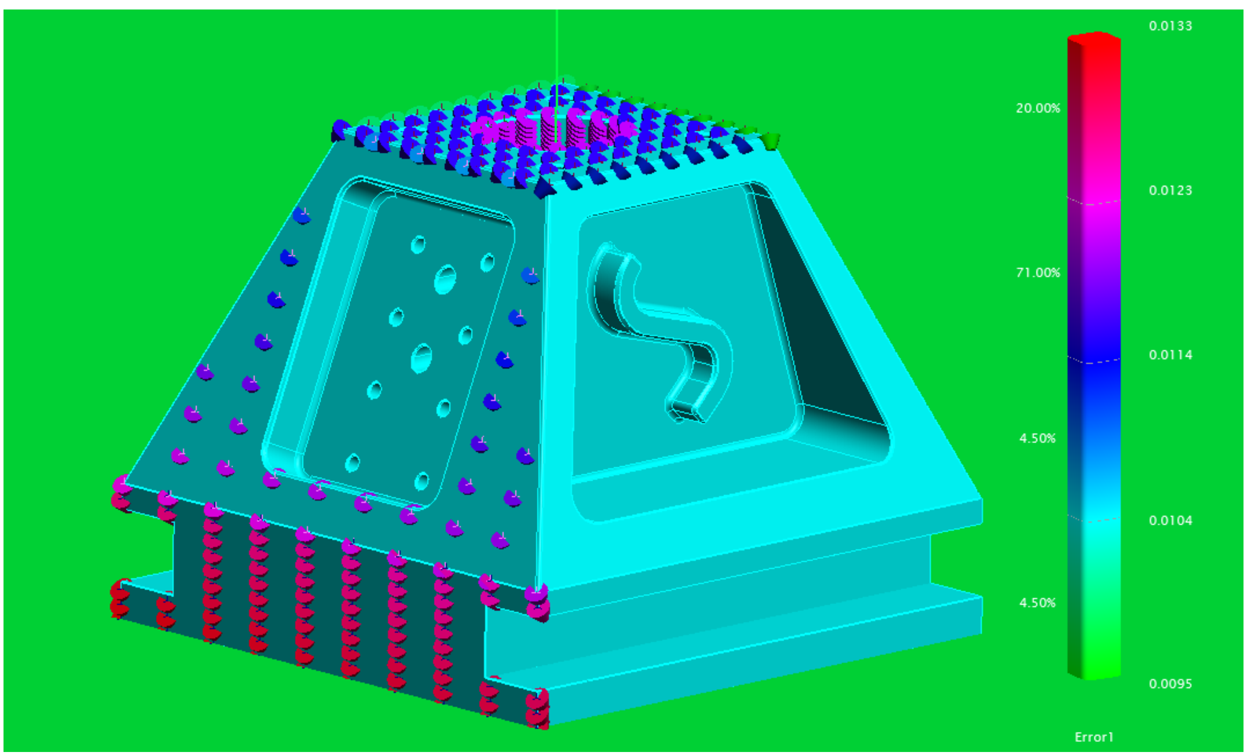
Finally, the error vectors will be populated within SpatialAnalyzer and a message will appear informing you what inverse kinematics were used. A new dialog will open after you select “OK” on the message.

The "Show/Hide Errors" dialog allows you to select what errors you would like to view and the plots that you would like to generate. This dialog can be seen to the right. For now, we will select the "Error 1" checkbox. The results for "Error 1" can be seen below.



Within SpatialAnalyzer, the colorization for the magnitude of the errors can be seen on the right side of the SpatialAnalyzer workspace. This also includes the distribution of errors in four even ranges/groups. These visual results can give a quick idea of how the errors are spread.

New updates have added the option to create vector callouts and show them on the part based on the angle error between the correct tooling orientation and the actual tooling orientation. Simply select the create vector callouts and select the vectors you would like to create callouts for.



VTA Advanced

Congratulations, you now understand the basics of the Virtual Twin Analyzer application and you are ready to increase your knowledge of the application and begin learning the advanced functions and more that you can do with the program. In this chapter you will learn about the optional functions that you can run in the application and will be given a walkthrough on using them.

6. Advanced Functions

Now that you have a basic understanding of the VTA program and the core functionality of it you can begin to analyze data with the advanced VTA functions. These include "**Browse for Machine Tool CAD**", "**Add Evaluation Click Points**", "**Manage Points**", and "**Reports and Errors**".

Browse for Machine Tool CAD

This function replaces the need for you to perform the "Create Table Plane Representation" function. Upon clicking the "Browse for Machine Tool CAD" button, you will be prompted to select the CAD part you would like to import as the machine tool workspace. SA will import the machine tool as a "Mesh Object" meaning it cannot be evaluated like a part surface. After the import, the "Machine Tool Transformation" dialog will open. It is vital that you move the machine tool so that the world frame will coincide with the machine tool base frame. This makes the location in SA correspond to the actual machine location.

Note: The transformation is performed about the world axis.

Add Evaluation Click Points

Similar to the "Add Evaluation Grid Points" button, the "Add Evaluation Click Points" button allows you to add evaluation points to the surfaces of your part. You will be prompted within SA to "Pick Location (Enter when done)." You should then click the part location that you would like to add the point to and continue clicking on all the locations that you want points until you are finished adding points. When you are finished adding points, hit the "Enter" key on the keyboard. SA will place the points on the surfaces and control will be returned to Virtual Twin Analyzer when finished.

Note: Not clicking on a surface when adding points will result in no points being added. Points must be placed directly on a part surface.

Manage Points

The manage points function is really three separate functions grouped together. These functions allow you to "**Read Point Information**", "**Delete Points**", and "**Import Points**".

Read Point Information

During your usage of Virtual Twin Analyzer, you may find that it becomes difficult to recall exactly what tooling you have applied to a surface, or after running operations you may find large errors on a surface and need to check to make sure that you have applied the correct tooling information. To read point information, you should click the "Read Point Information" button.

You will be prompted within SA to "Select points to get information about (Enter when done)". After you have selected the point(s) you would like to get information about, a dialog with information for the first selected point will appear, giving the known information about the point. Each point's information will be given until all the points are completed.

Delete Points

Over time, you may find that you no longer want to evaluate points that are in the program, or that the points got added by mistake. To remove these points from the program select the "Delete Points" button. You will be prompted within SA to "Select points to delete (Enter when done)". After selecting all the points to delete and pressing "Enter", the points will be removed from SA and the VTA program.

Hint: To delete all of the points on a surface or a large number of points, you may find it helpful to press "F2" on the keyboard to open up the "Target/Point Selection" dialog within SA. From here you can select many points at once but should use caution.

Import Points

If you commonly work with the same part and want to evaluate similar points each time that you work with the part, you may find it helpful to import points from SA into the VTA program. This can be done by selecting the "Import Points" button and selecting the points within SA that you would like to import.

Note: Points must be near or on the surface that you would like them put onto, since SA will only locate the points based on their proximity to the surfaces.

Hint: To select an entire group of points use the "F2" select similar to that of the "Delete Points" command.

Reports and Errors

The “Show/Hide Errors” dialog opens automatically after the operations are run, but you can return to the dialog at any time by clicking the “Reports and Errors” button. In the “Show/Hide Errors” dialog you can easily switch the different error vector groups to show within SA. You can also select the “**Report**” button which will show a report to you or select the “**Plots**” button which will open up the “**Generate Error Plots**” dialog.

Report

In the “Show/Hide Errors” dialog, you can select the “Report” button and a simple SA report will be generated with the selected errors shown on the report. This report can be exported to an Excel or a pdf file and can be printed. This report can also be saved within SA for future reference. This report is also saved when the SA workspace is saved.

Generate Error Plots

One of the great features of VTA is quick and easy visualization of the error data. VTA creates some very handy error histogram plots with little to no input in a manner of seconds. These plots are great for viewing results quickly and could even be used in reports.

When the “Generate Error Plots” dialog opens, you will see that you have a few options on what you would like to see. You can select the number of columns (or evenly sized sections) that you would like your errors broken up into. You can also select whether or not you would like to see gridlines on your plots. Once you are ready, click the “Generate” button to create the error histogram plots.

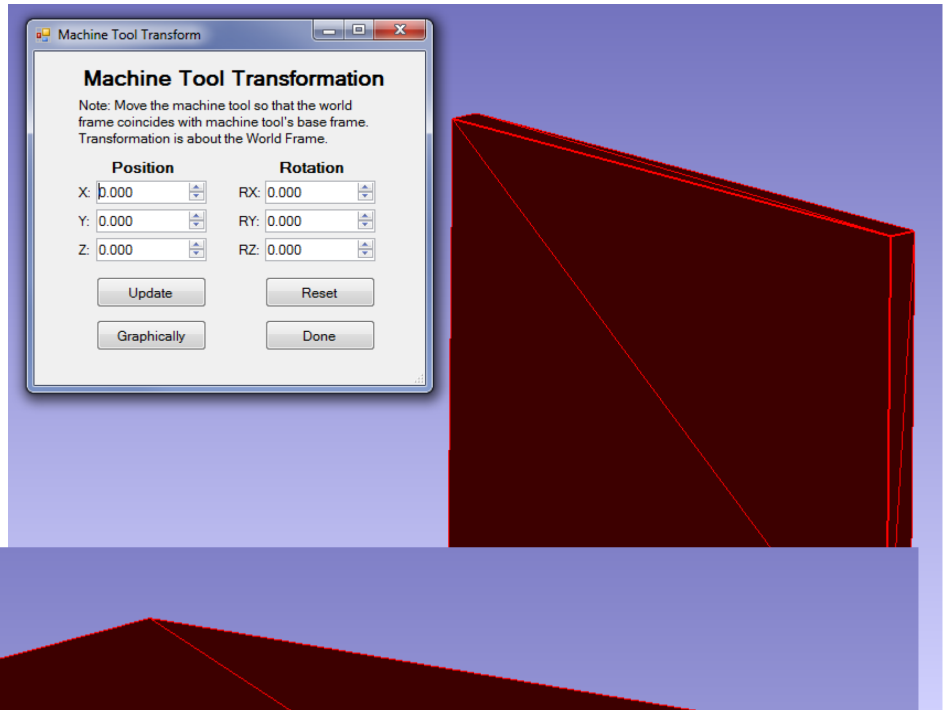
The plot is generated and you will see a scaled normal distribution curve to help visualize how well your data fits a normal distribution. Also, in the upper left hand corner you have the “Save Chart” button which will ask you where you would like to save the chart and the name you would like to give it. The chart is saved as a .jpeg file and can be accessed outside of the Virtual Twin Analyzer software to put in reports.

7. Advanced Functions Walkthrough

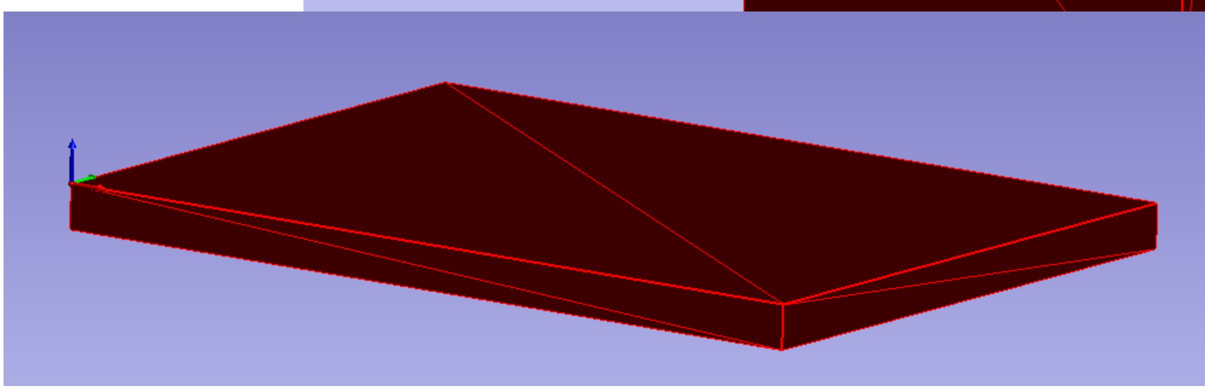
This section of the VTA Manual will guide you through the advanced functions of the VTA Application and perform an operation for a specific set of machine files and a test part. We will begin the walkthrough after the first two steps of the “Basic Functions Walkthrough” section (“Connect to SA” and “Browse for Machine Files”).

Browse for Machine Tool CAD

Upon selecting the “Browse for Machine Tool CAD” button instead of the “Create Table Plane Representation” button, you will be prompted with a file browser for the machine tool to import. Once the file is imported, you will be asked to transform the machine tool to the correct orientation and location to align the machine tool base frame with the SpatialAnalyzer frame. The imported machine tool can be seen to the right along with the “Machine Tool Transformation” dialog.



The necessary transform will be performed to transform the machine tool to the correct location and

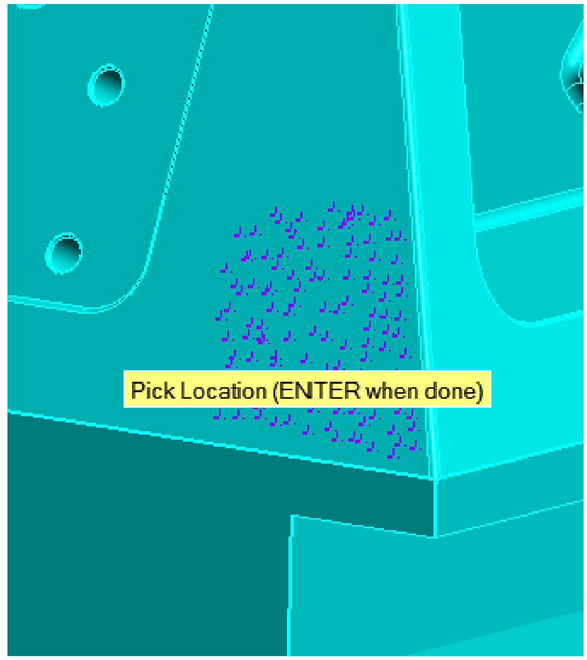


orientation. For the specific machine being used the correct orientation can be seen below. Here we used a very simple machine tool representation but a more complex one may be used and can be as specific as desired.

Similar to before, we will import a CAD file that we would like to machine. The specifics can be seen in the “Browse for CAD File to Machine” step of the “Basic Functions Walkthrough”. We will also move the part similar to what was done before in the “Move Part” step of the “Basic Functions Walkthrough”.

Add Evaluation Click Points

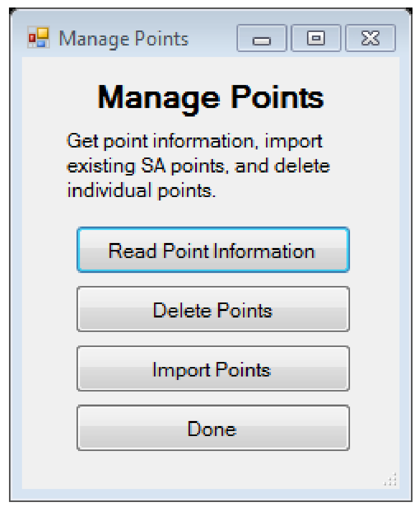
The next step in our process is adding the evaluation points for the object. Instead of adding a grid of points on an entire surface we will now add click points to a specific section of a surface.



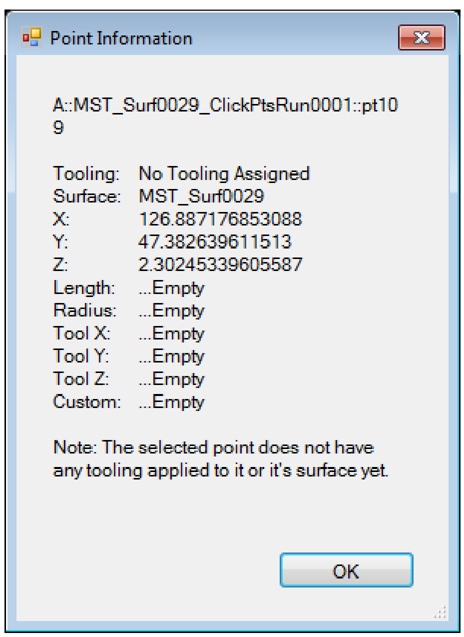
Note: Click points can be added in conjunction with grid points and importing points as well, but we will keep it simple for this walkthrough and only add click points. We will be prompted by SpatialAnalyzer to "Pick Location (ENTER when done)". For this example, we want to examine a specific section of the part more thoroughly and we will add a bunch of points to the one section. This can be seen in the picture on the right. Then SpatialAnalyzer will add the points and control will be returned to Virtual Twin Analyzer.

Manage Points

The next advanced function we will look at is the "Manage Points" dialog. This is accessed by clicking the "Manage Points" button on the main form. Doing so will open the dialog seen to the right.



Let's click the "Read Point Information" button and read the information about a point that we just added. The "Point Information" dialog will be shown to you with the available information. There isn't any tooling information yet because we haven't added any tooling to the surface that the point is on.



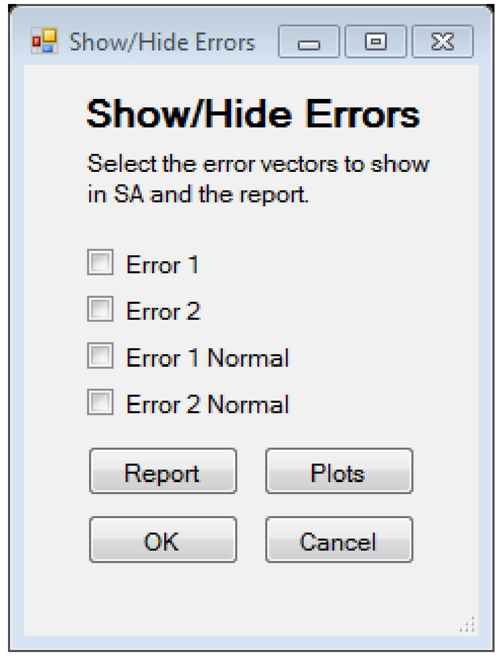
Next, let's delete an extra point that got added to the object when we were adding click points. We will do this by selecting the "Delete Points" button on the "Manage Points" form. Then we must select all the points we want to delete from SpatialAnalyzer.

Finally we could add more points to the project using the "Import Points" button but we will not perform this operation here.

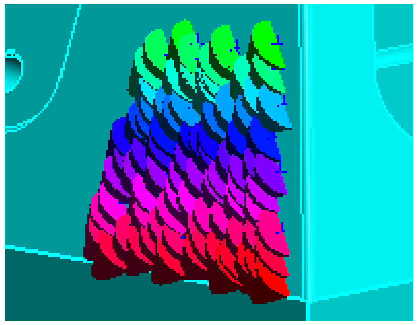
We will add an end cut using a tool with the length of 2.5" to the surface with the points and run the operations similar to these steps in the "Basic Functions Walkthrough".

Reports and Errors

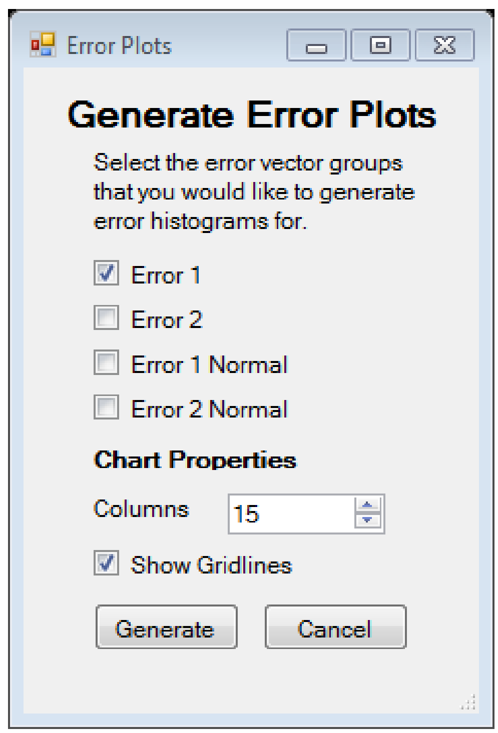
The "Reports and Errors" dialog is opened automatically on the completion of the "Run Operations" command. However, this dialog can be called at any time after running operations by simply clicking the "Reports and Errors" button on the main Virtual Twin Analyzer form. This dialog can be seen to the right.

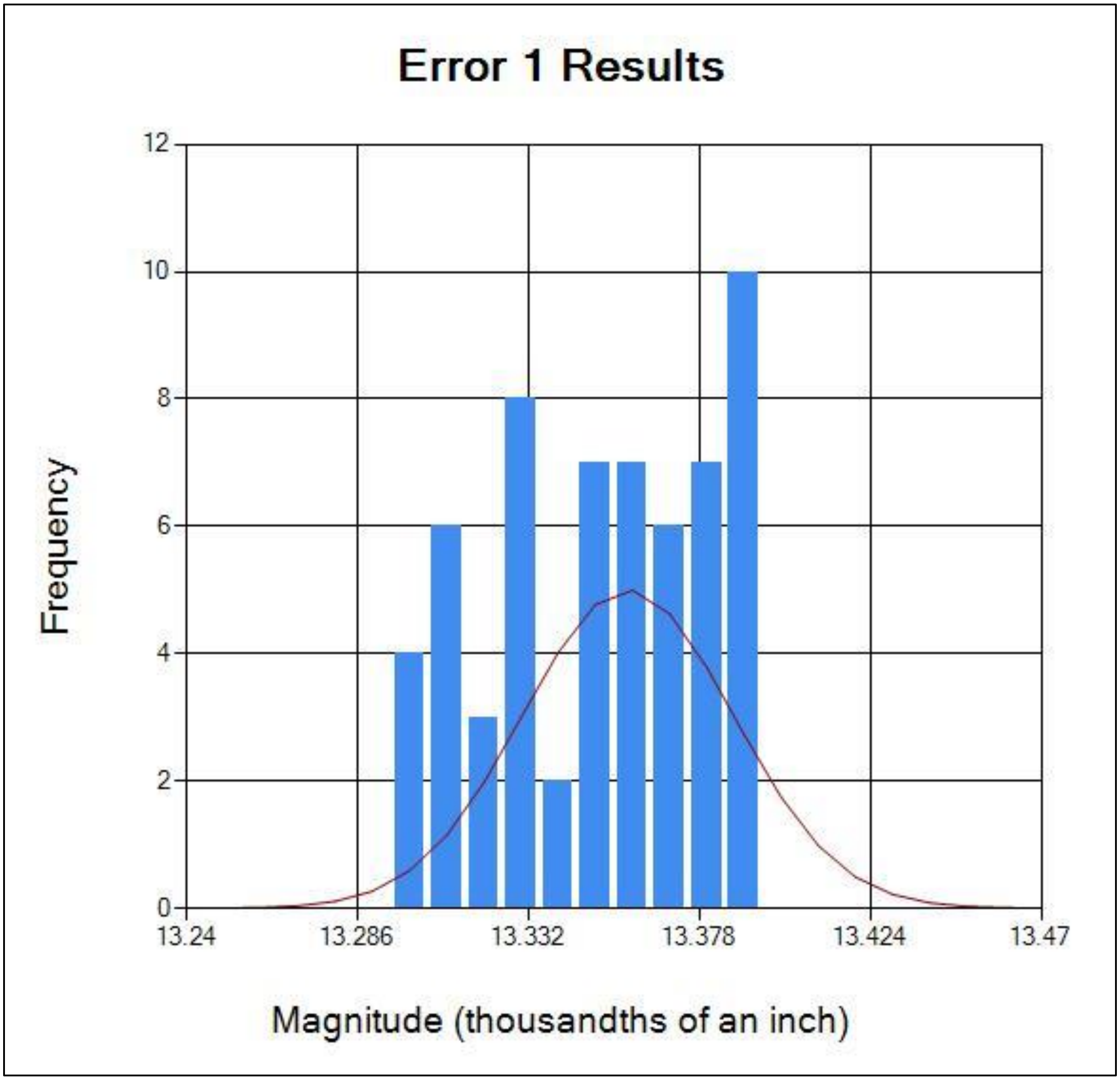


First, we will select "Error 1" to show these error vectors. We can now view the errors in SpatialAnalyzer. Clicking the "Report" button now will generate a quick report within SpatialAnalyzer. This report will only include the selected errors ("Error 1" in this example) along with the number of errors that aren't in the machine workspace, some quick statistical information about the errors, and all of the errors in the selected groups ("Delta" section), and the associated color within SpatialAnalyzer.



Clicking the "Plots" button will open the "Generate Error Plots" dialog. In this dialog, you can select all of the error groups that you would like to generate an error histogram for, the number of sections that you would like to break the errors into, and whether or not you would like to show the gridlines on the plot. We will select "Error 1", with 15 columns and we will show the gridlines. These selections can be seen to the right and the generated plot can be seen below.





This plot includes a scaled standard normal distribution curve for the errors that were generated. The frequency of errors can be seen at different intervals.

Note: The normal distribution curve is for reference only. Not all machines and tooling operations will follow a normal distribution curve.

Working with Data

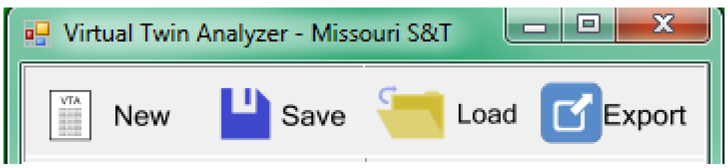
Virtual Twin Analyzer was built with a focus around the data. Every point and surface is kept track of to recall the data later. In this chapter we will discuss how to manage data in Virtual Twin Analyzer and how to use Virtual Twin Analyzer to its maximum potential.

8. Managing Data in Virtual Twin Analyzer

Virtual Twin Analyzer offers four functions to manage the data that you have created. These four functions are the "**New, Save, and Load Files**" functions and the "**Export Data**" function. With these four functions you will be able to save common layouts and progress, redo calculations with a different machine months later, and collaborate with others in your professional field.

New, Save, and Load Files

These three functions can be located at the top of the Virtual Twin Analyzer window and can be seen in the image below.



New Job File

This button will create an entire new job file. This includes the Virtual Twin Analyzer job file and the SpatialAnalyzer workspace. To prevent you from deleting wanted data, you will be prompted, this ensures that you save your data.

Save Job File

The "Save" button is your go to source for saving your progress and project in Virtual Twin Analyzer. First you will be prompted to pick the location and the name of your file. Then Virtual Twin Analyzer will save the project information into that location with the .vtadata extension. Next, a copy of the SpatialAnalyzer workspace will be saved in the same folder under the same name with the .xit or .xit64 extension. The results of the save will appear in a dialog.

Warning: Changing the SA file outside of the Virtual Twin Analyzer application will result in errors and potential loss of data. It is recommended that you only ever use Virtual Twin Analyzer to manage this SpatialAnalyzer file. Changing the location of either one of the files will result in a failure to load both files when loading files. If you do want to move the file to another location, make sure to move both the .vtadata file and the .xit/.xit64 file for the project to the same location.

Load Job File

The “Load” button can be accessed as soon as you are connected to SpatialAnalyzer. You must use this button to load Virtual Twin Analyzer project files as failure to do so will result in a loss of data or the loading of only one of the two programs. Once you have selected the “Load” button you will be able to browse for the .vtadata file that you need to open and the .xit/.xit64 file will be opened automatically. The results of the load will appear in a dialog.

Warning: Loading the Virtual Twin Analyzer project file outside of the Virtual Twin Analyzer application could result in the loss of data and possibly the loss of the ability to load the file at all. Loading the SpatialAnalyzer file will **NOT** load the Virtual Twin Analyzer data file. If you would like to view the data, please use the “**Export Data**” function. Load the files from within the Virtual Twin Analyzer application using the “Load” button.

Export Data

The final of the four functions for managing data is the “Export” button. This will open up the “Export Data” dialog. This dialog includes all the options for the data that you would like to export. Selecting the different errors exports the magnitude of the errors only. To perform the export, you must select the CSV file type which will export the data into a .csv file that is Excel ready but can also be read using a text editor or reader. You can then browse to the location and name the file.

9. Recommendations for Best Performance

As with all programs Virtual Twin Analyzer does have its limitations. The most notable of these limitations is in the number of points that can be handled by SpatialAnalyzer and Virtual Twin Analyzer working together. It is recommended that your computer has the following properties.

-Microsoft Windows 7 or Windows 10

-4 GB RAM

-1 GB free disk space

-SpatialAnalyzer 2017 (or newer)

-All SpatialAnalyzer requirements

Point Limitations

Virtual Twin Analyzer has the capability to manage thousands of points. As with any program though, it does have limitations on its capabilities. The **maximum** recommended number of evaluation points that can be handled within the program is 4000 points. This many points can be spread across many surfaces with different operation types without an issue. Adding more than this many points to the program will cause it to slow down significantly and you don't gain much from having 8000 points versus 4000 points or less since most of the error vectors won't be very visible within SpatialAnalyzer.

Note: 4000 points is the standard amount of supported points for Virtual Twin Analyzer working with SpatialAnalyzer on a medium grade computer. Some machines will be able to support many more points while others might not support this many. Ultimately it is up to you to decide how many points are necessary and how many points your system can support.

For the **most efficient** evaluation add 600 or less evaluation points to Virtual Twin Analyzer. When adding less than 600 points, the highest number of points per second can be achieved within SpatialAnalyzer and Virtual Twin Analyzer. 600 points can be evaluated in a few minutes or less.

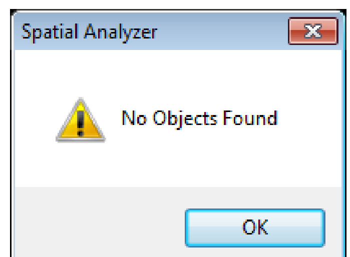
Note: Again, all machines vary and less than 600 points won't always be the most efficient.

Common Errors

As you use Virtual Twin Analyzer, you may find yourself running into some issues with SpatialAnalyzer or Virtual Twin Analyzer itself. Usually these errors come from misuse of the software but sometimes they don't. In this section we will explore some common error messages from Virtual Twin Analyzer and SpatialAnalyzer and what to do when you encounter these errors.

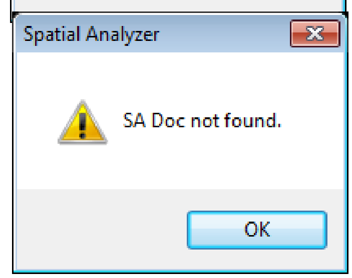
"No Objects Found" or "Object Not Found"

This error is a result of SpatialAnalyzer not being able to find a called upon object from the Virtual Twin Analyzer program. Usually this error occurs after loading a Virtual Twin Analyzer job file and is just a bug within SpatialAnalyzer. However, this error could also be the result of a point, surface, or vector group being deleted from outside of Virtual Twin Analyzer.



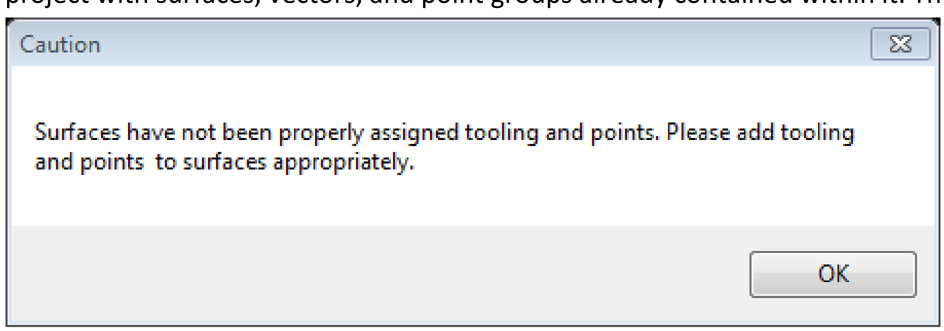
"SA Doc not found", "Table Not Found", "SA Report not found"

These errors occur when generating a report. They are usually the result of loading the job file and then generating a report for the first time. Simply ignore these errors most of the time if the report is generated successfully and contains the part error information.



"Surface Tooling and Points Not Properly Assigned"

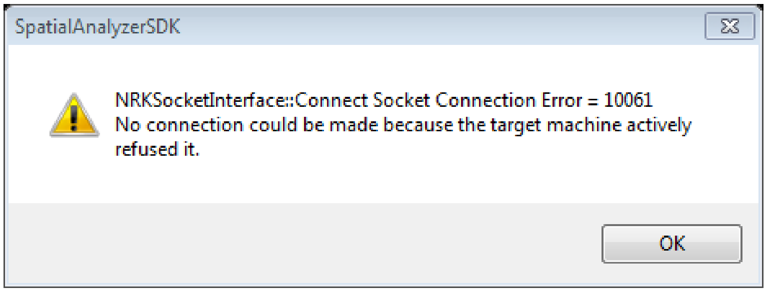
This error occurs during the "Run Operations" section and is a result of points, tooling, and surfaces not matching up. This is most likely an error due to adding points to surfaces and tooling to others. However, this can also be a result of you using a SpatialAnalyzer project with surfaces, vectors, and point groups already contained within it. This can mess up SpatialAnalyzer's internal numbering system, and as a result, associating surfaces to the correct points. This



can also occur if you add surfaces and point groups to the project outside of Virtual Twin Analyzer.

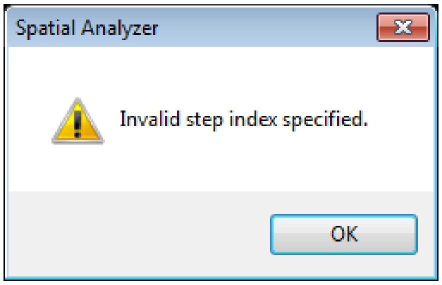
Note: Surfaces, points, and vectors should only ever be added to a Virtual Twin Analyzer project within Virtual Twin Analyzer and not through SpatialAnalyzer.

"NRKSocketInterferace::Connect Socket Connection Error = 10061"



This error occurs when connecting to SA. If this error occurs, you should first make sure that SpatialAnalyzer is open. Then try to "Connect to SA" manually using the "Connect To SA" button. If, after trying to connect manually you receive the error message again, close out of both SpatialAnalyzer and Virtual Twin Analyzer. Then start SpatialAnalyzer and wait for it to load completely. After SpatialAnalyzer has loaded, start Virtual Twin Analyzer and the connection should be available.

"Invalid step index specified"



This error can occur throughout Virtual Twin Analyzer and SpatialAnalyzer. Most of the time, it appears during the "Create Table Plane Representation" step. This warning is completely harmless as long as your table is created successfully.

Appendix E: CHARACTERIZATION OF INDUSTRY

Eight machine tools, both inside Boeing and externally at suppliers, were selected and tool tip data for each machine was collected. The measurement data was used to build the kinematic error model of each machine. The suppliers spanned a spectrum from Tier 1 suppliers such as GKN Aerospace to small businesses such as Steelville Manufacturing and Patriot Machine (women-owned), and also included a machine located at the NASA Michoud Assembly Facility and some machines internal to Boeing. The machines selected for measurement span a range of small, medium, and large workspace.

Each machine was measured at 150-200 quasi-random poses throughout the whole work volume. Each pose was measured twice using an API T3 laser tracker and active target, with the retro-reflector mounted a different distance from the spindle face each time so that both position and orientation information is collected implicitly. These data points were then used to analyze the machine repeatability in the volume and to construct the error model used in the virtual twin analysis. The error modeling is done following the procedure outlined in [3] for the 6-DoF model. This modeling technique is also described in the final report for this program (MxD 15-07-01). An example of the point distribution for a 5-axis machine tool using this method is shown in Figure 37.

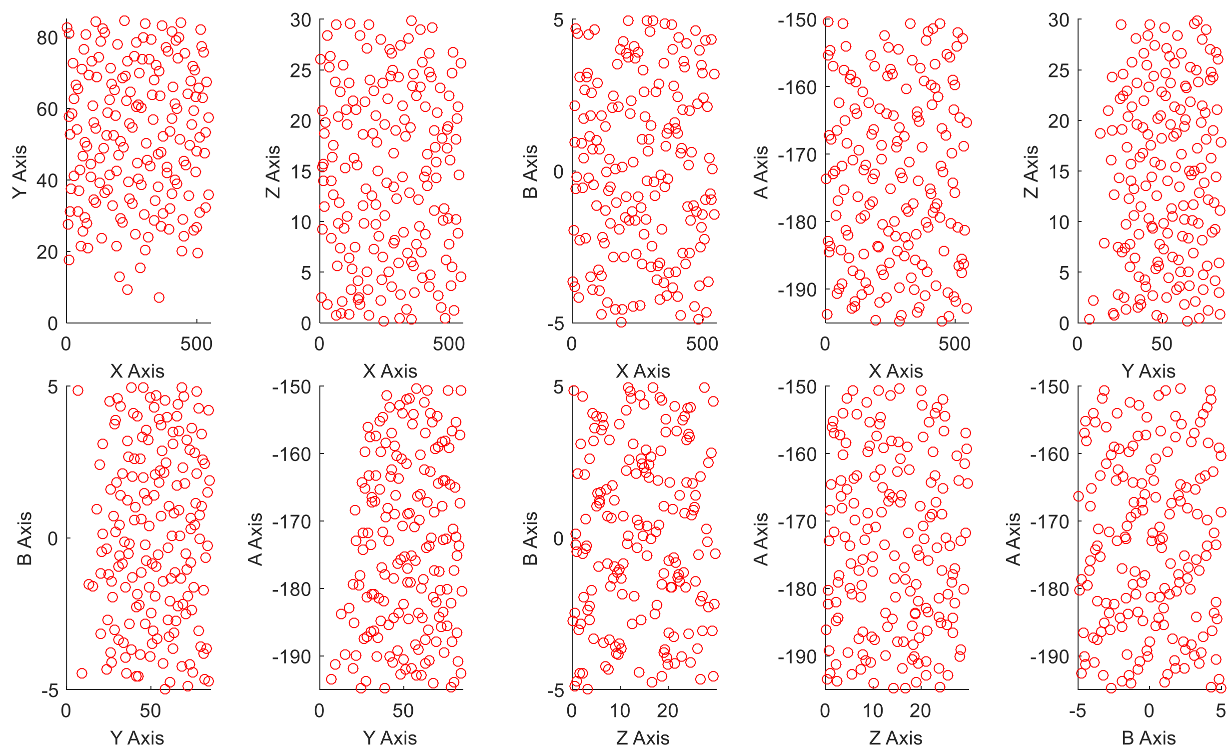


Figure 37: Example point distribution throughout the work volume of a 5-axis machine tool.

The machine data was also used with the VTA software described in a previous section and applied to a metric part designed specifically for this test. The part has angled surfaces and pockets with drilled holes and curved features which are intended to required coordinated 5-axis motion and effectively demonstrate the types of geometric errors that are relevant to aerospace parts. Figure 38 shows the small sized metric part, which is approximately 6”x6”. Figure 39 shows the large metric part, which has the same features as the small part, but is extended to be 12”x36” to represent larger aerospace parts. A medium metric part of 12”x24” is also considered in the analysis.

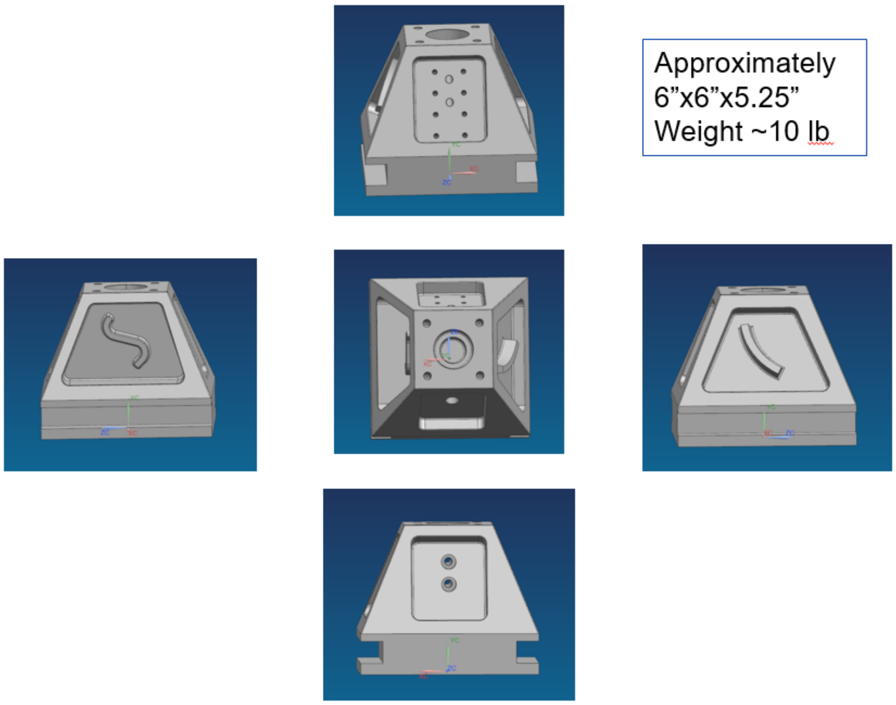


Figure 38: Small metric part layout.

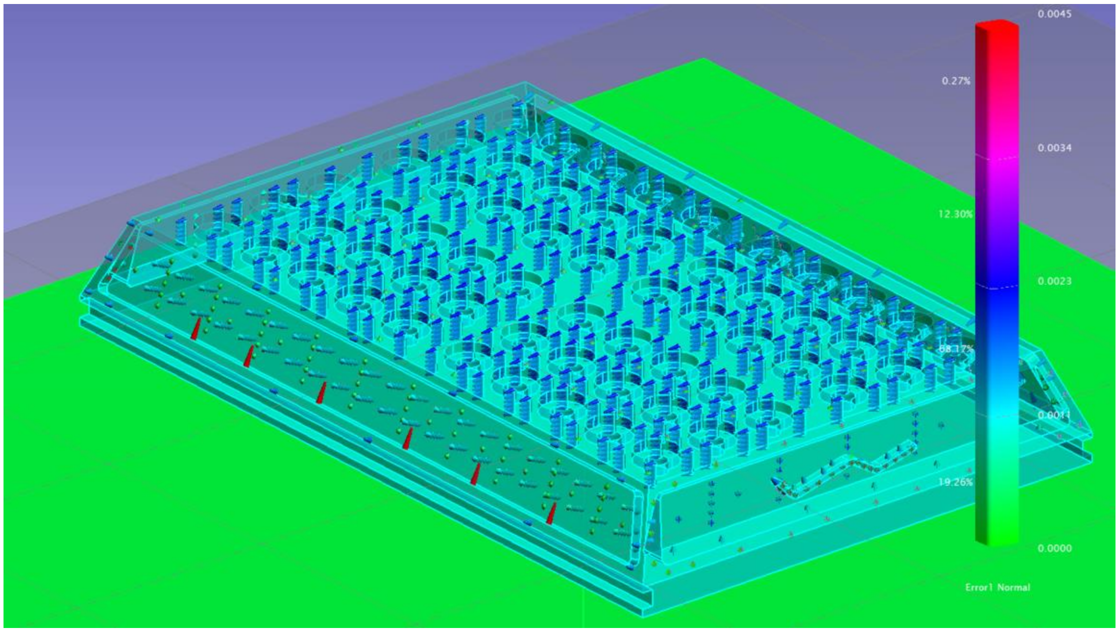


Figure 39: Large metric part example.

For standardization, the part is always placed in the middle of the machine work volume, 10" above the table surface. The same 0.25" endmill with a total length of 5.3" is used as the main tool for all operations on the part except drilling. At this time, analysis of the drilled holes is omitted due to software limitations. The same cutting operations are applied to the part across all machines. Machine 3 has an XYZAB axis configuration with only ±25 degrees of travel on each rotary axis, so it is unable to machine the pockets on this part without multiple setups. Machine 4 has a rotary table, which is currently not a supported configuration in the VTA software, although this feature is planned in future versions.

The mean and maximum error mapped to the part is calculated for the remaining machines. **Error! Reference source not found.** shows the results for all measured machines. If a tolerance of 0.015" is assumed on a typical part, based on the maximum volumetric error observed on the machines, five machines out of eight should have been unable to make the part in tolerance. However, not all geometric errors map to the actual part surface. Based on the small metric part, only two machines would fail to make the part in tolerance. This shows why the VTA software is necessary, and simply looking at the magnitude of the errors on the machine in its work volume is not adequate to predict part outcomes. Figure 40-Figure 47 show the errors mapped to the small metric part for each machine. Many of the tested machines exhibited their worst errors either on the small curves in the pockets, or in the pocket placement itself, both of which are cut at more extreme rotary axis angles. However, some machines, like machine 5 in Figure 43, show a relatively constant error in a single direction (in this case Z). This may cause the tool to predict more error than would realistically map to the part because this doesn't take into account the standard practice of touching off of the part with the machine to set the zero for the part coordinates. Note that this was added to the software and is included in medium/large metric values.

Table 2: Summary of Machines Characterized.

Machine	1	1'	2	3	4	5	6	7	8
Size	M	M	M	S	S	L	M	M	M
Age	8	8	1	30	5	~30	12	0	6
Mean VE	0.026"	0.007"	0.011"	0.013"	0.007"	0.018"	0.010"	0.003"	0.005"
Max VE	0.065"	0.018"	0.021"	0.024"	0.013"	0.049"	0.025"	0.007"	0.009"
Small metric									
Mean on part	0.0054"	0.0039"	0.0042"	Unable		0.0163"	0.0095"	0.0031"	0.0023"
Max on part	0.0134"	0.0086"	0.0075"	to		0.0398"	0.0217"	0.0054"	0.0048"
Std. Dev from avg	0.0034"	0.0023"	0.0014"	machine		0.0117"	0.0063"	0.0035"	0.0011"
Medium Metric									
Mean on part	0.0042	0.0076	0.0028	Unable		0.022	0.0044	0.0012	0.0014
Max on part	0.0096	0.0099	0.0078	to		0.0045	0.0084	0.0023	0.0037
Std. Dev from avg	0.0023	0.0007	0.002	machine		0.0014	0.003	0.0007	0.0001
Large Metric									
Mean on part	0.0041	0.0041	0.0028	Unable		0.0042	0.0049	0.0013	0.0016
Max on part	0.0099	0.0099	0.008	to		0.006	0.0085	0.0023	0.0037
Std. Dev from avg	0.0022	0.0022	0.0021	machine		0.0012	0.0032	0.0008	0.0009

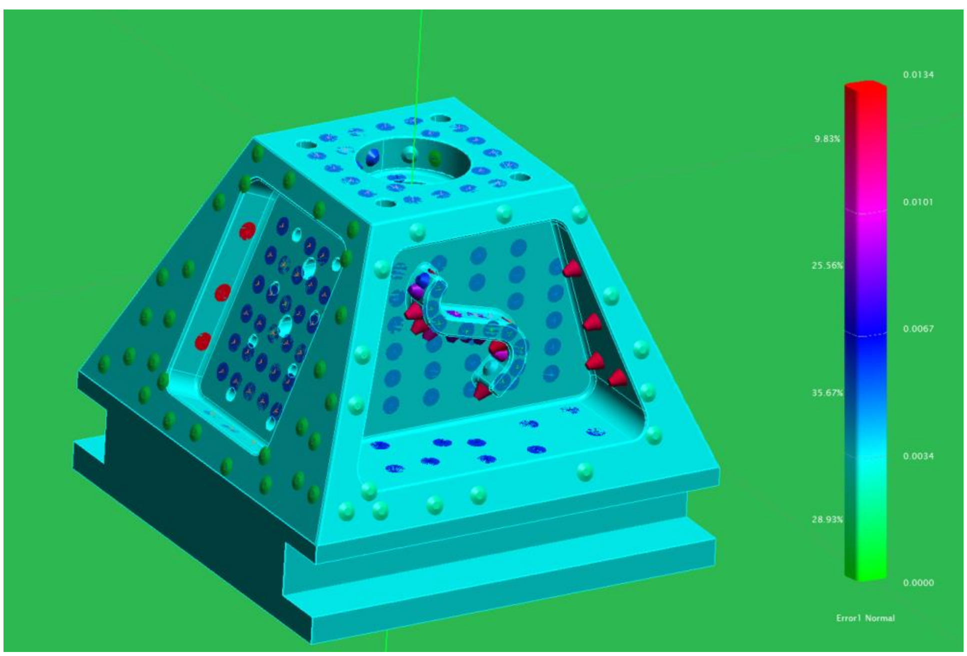


Figure 40: Machine 1

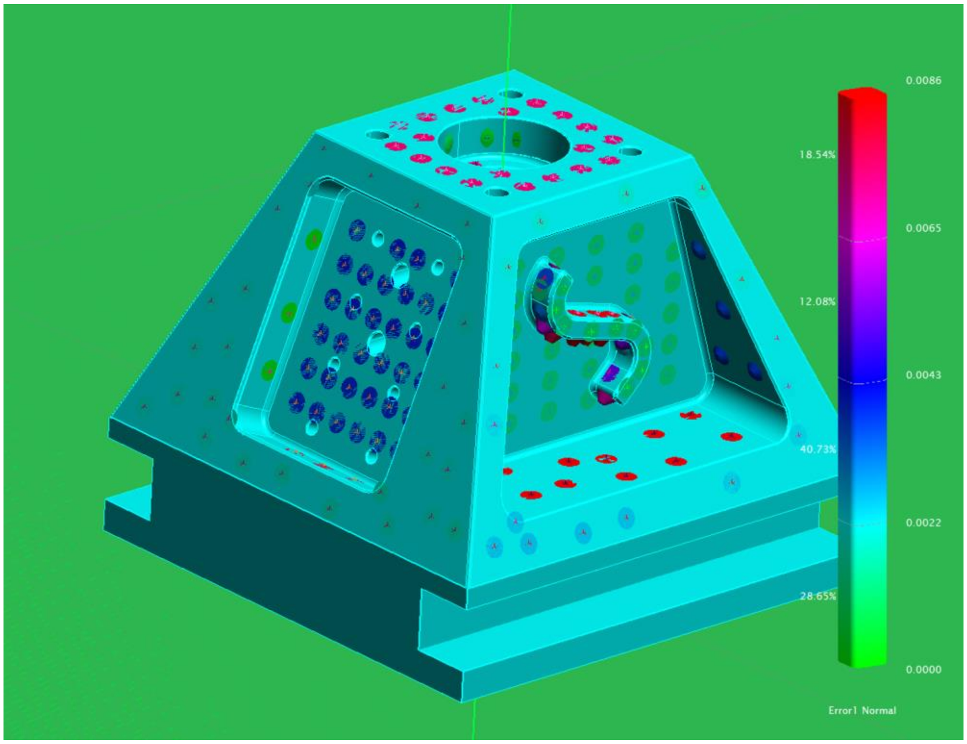


Figure 41: Machine 1 post-retrofit

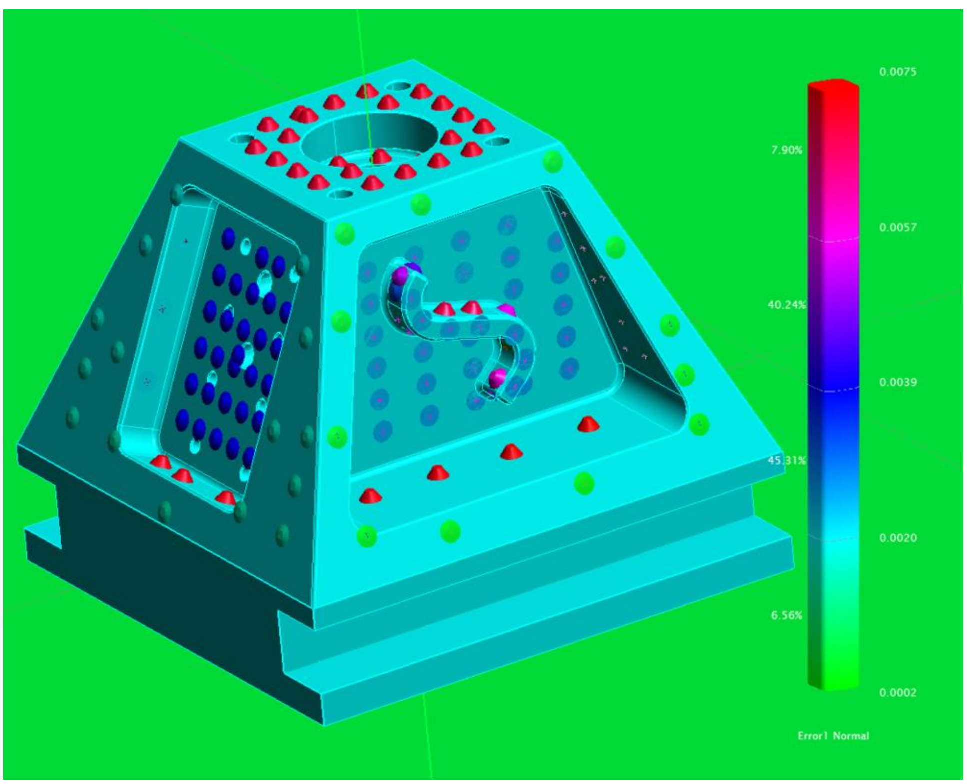


Figure 42: Machine 2

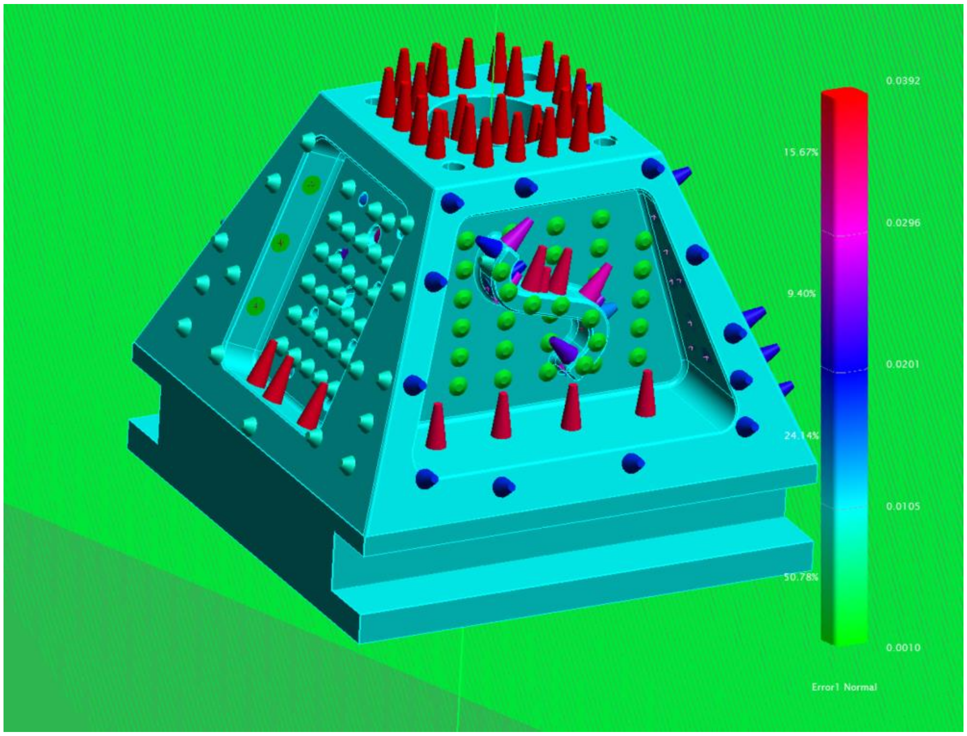


Figure 43: Machine 5

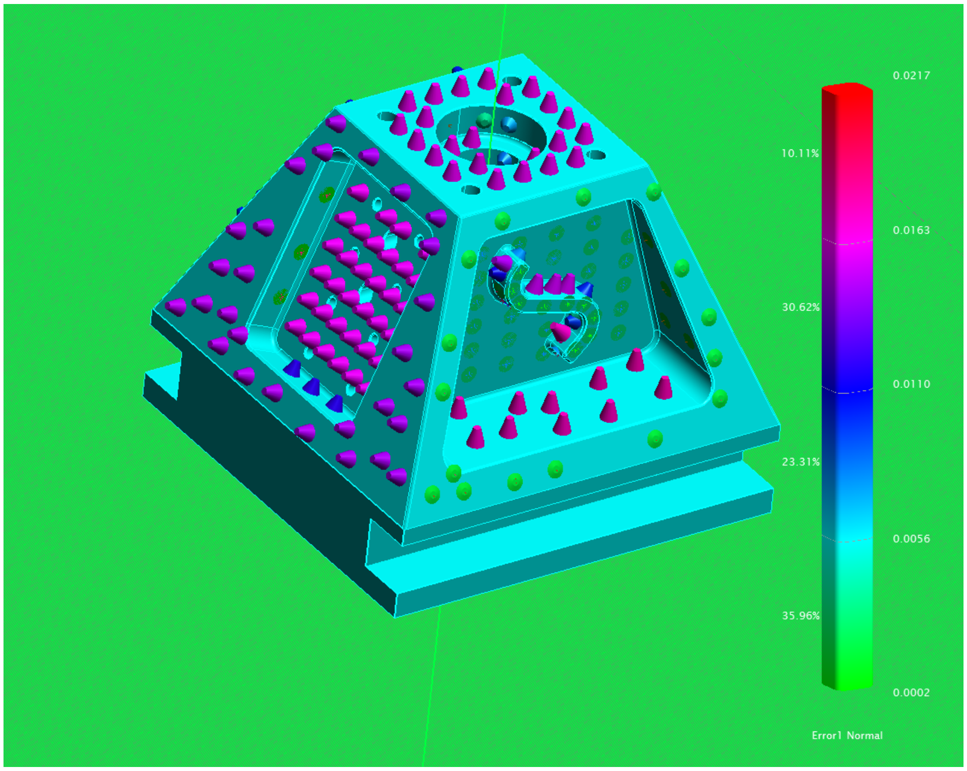


Figure 44: Machine 6

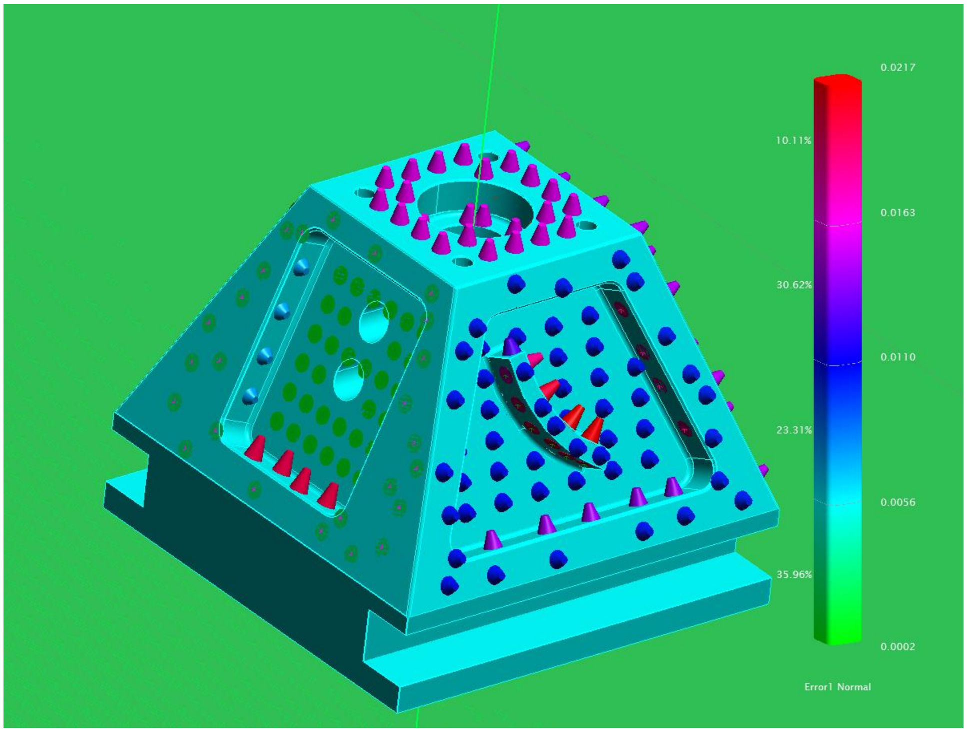


Figure 45: Machine 6

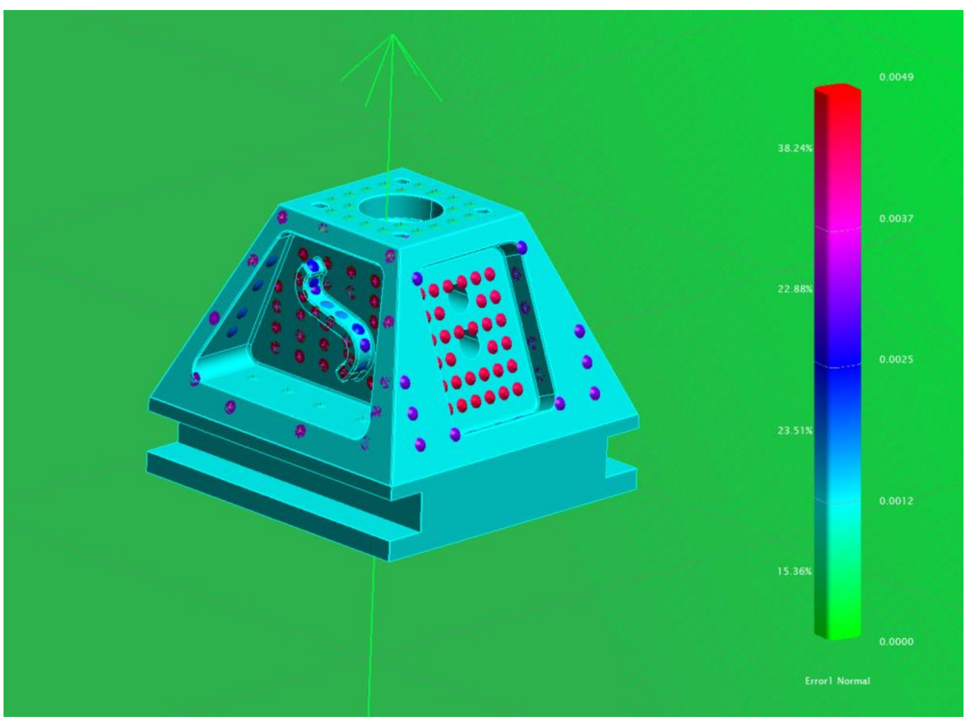


Figure 46: Machine 7

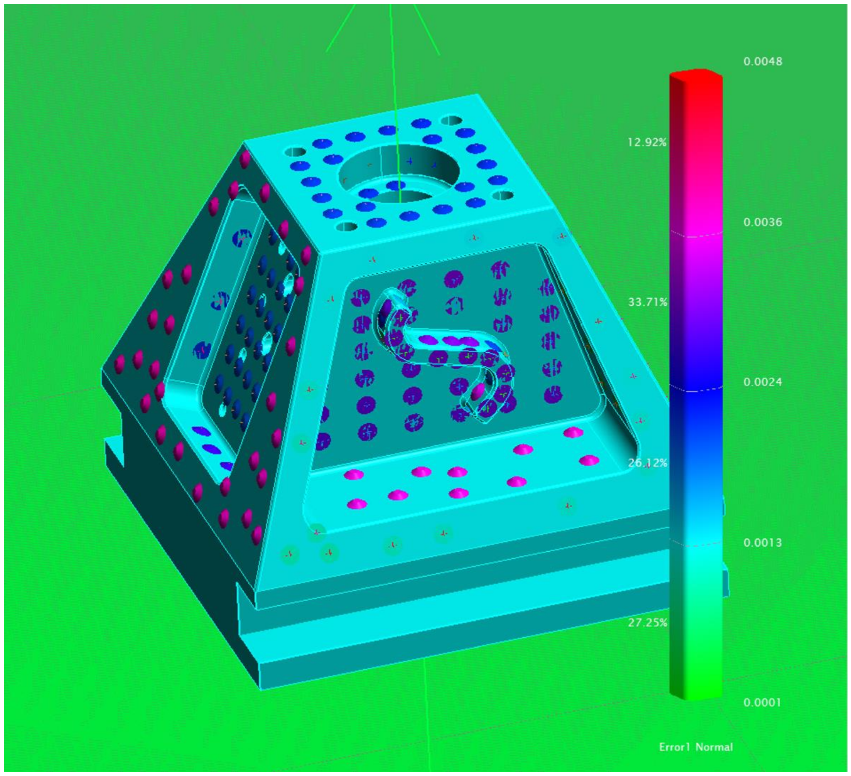


Figure 47: Machine 8

The virtual twin of machine can also be used to determine how much errors vary throughout the machine's work volume, which can determine whether part placement will be an important factor in whether or not a part is produced in tolerance. A sensitivity analysis was performed using machine 1 from the data presented previously. The small metric part was placed on a 5x3x2 grid on the machine bed and the mean, maximum, and standard deviation of the resulting part error were calculated and recorded. For this particular machine, the only direction that was particularly significant was the X direction. The results plotted against the X position are shown in Figure 48-Figure 50. For this machine, sagging in the X axis rail is the dominant error for this part, so positioning that avoids the worst sagging produces a better part.

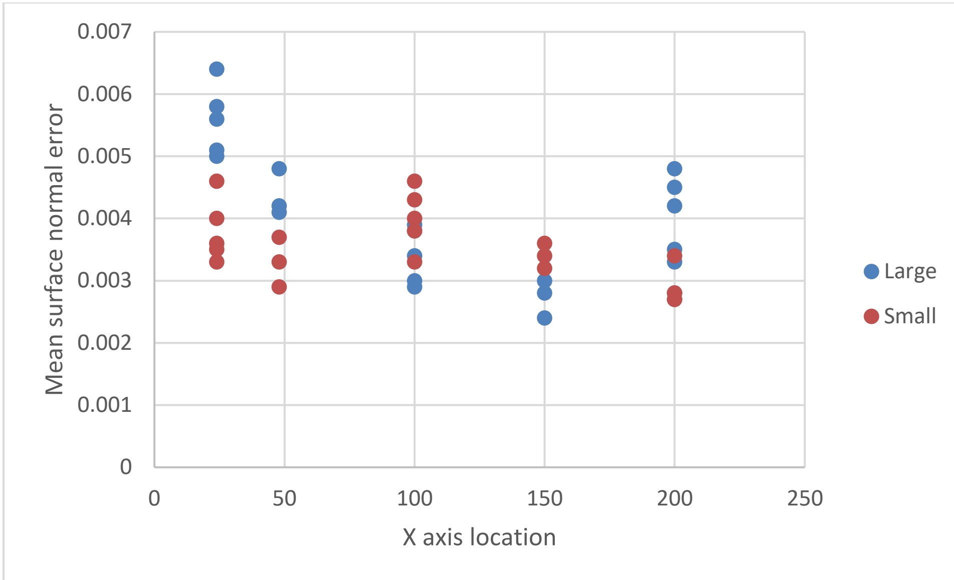


Figure 48: Mean error on small metric part at different part locations.

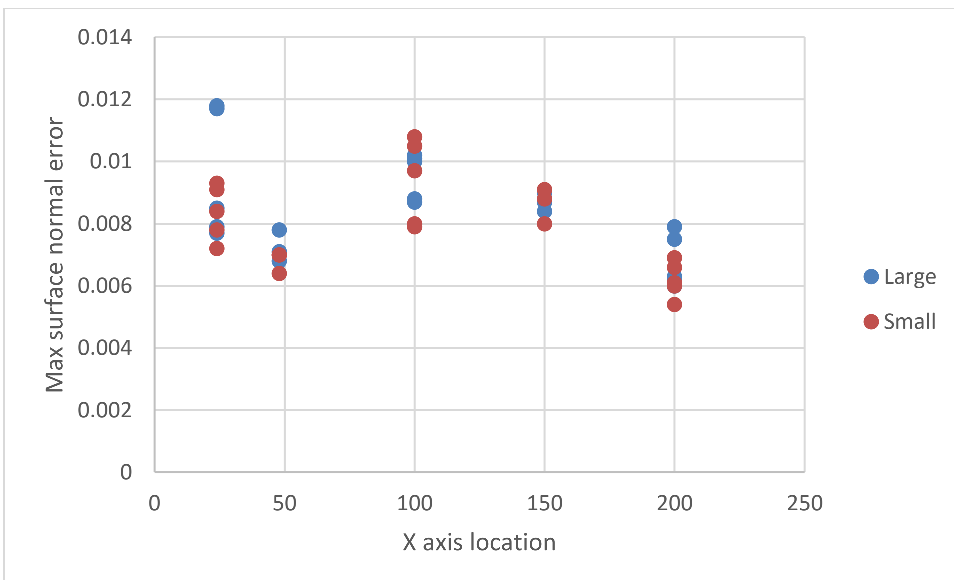


Figure 49: Maximum error on small metric part at different part locations.

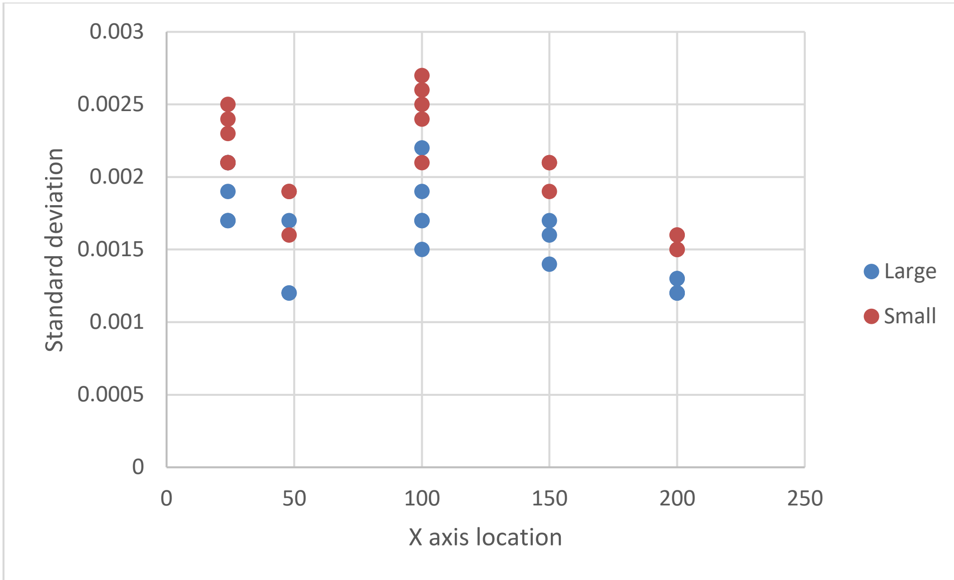


Figure 50: Standard deviation of volumetric error on small metric part at different part locations.

The Virtual Twin Analyzer software includes a built in tool to perform this type of sensitivity analysis and plot it in the machine workspace. Figure 51 shows this analysis for machine 6 in Table 2. This analysis quickly and visually finds the best and worst areas of the machine workspace to place a certain part, as well as giving the user an overall idea of how much machine error varies in the work volume.

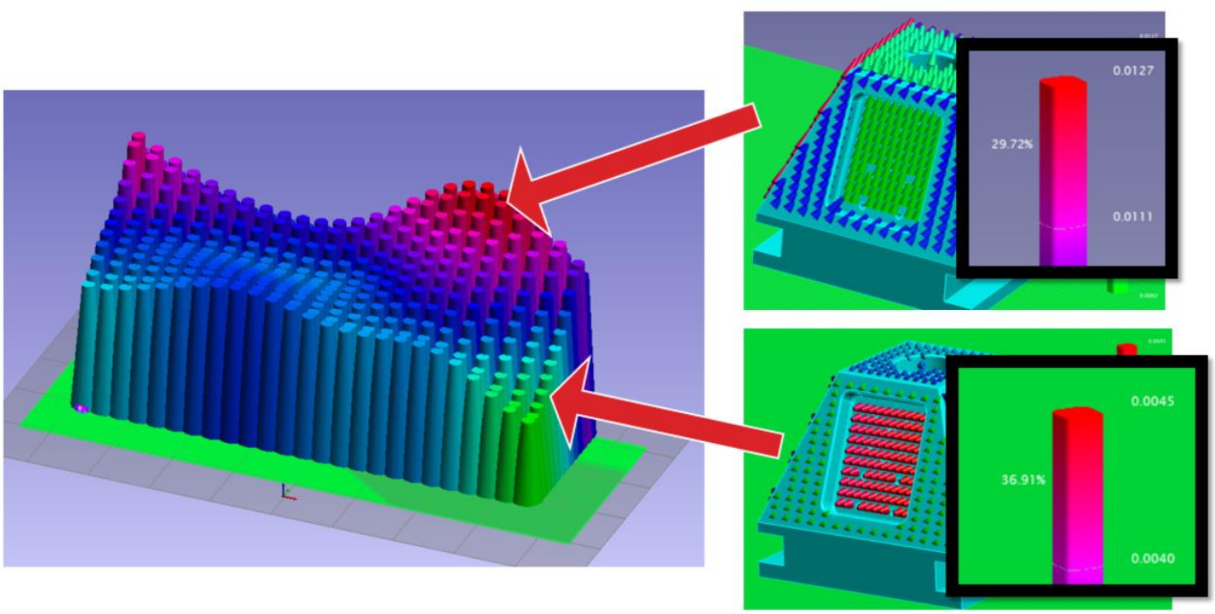


Figure 51: Full volume analysis using small metric part on example machine tool.

An additional evaluation comparing two machines using a generic drilled part that requires more extreme rotary axis angle than the previously evaluated metric parts was also performed. This test compared a lab machine before and after a repair (listed here as 1a and 1b, shown as machine 1 in Table 2) and a supplier machine, listed in this example as machine 2, and in Table 2 as machine 7. The part is 70”x6”x6” and required a +-90^{o} to drill the holes placed along the length. The part is shown in Figure 52. Figure 53 shows the error mapped to the part for machine 1 prior to its repair. The machine has significant position dependent errors on the rotary axes, so there is more than 0.030” of mismatch between the hole placements. A similar drilling test had been performed on this machine under a prior program, and those results are shown in Table 3. While the rotary axis angle was only =-80^{o} in this test, the drilled holes had a maximum error of 0.034”, which is in line with the prediction from VTA. A repair was made to the machine in which the rotary axes were replaced and aligned and data from the machine post-repair was used to run the analysis again, as shown in Figure 54. The part errors are now dominated by the sagging in the rails rather than the rotary axes and there is much less mismatch between the holes. Figure 55 shows the analysis for a different machine (machine 7 in Table 2) which has lower volumetric error, and the part shows very little error, as expected.

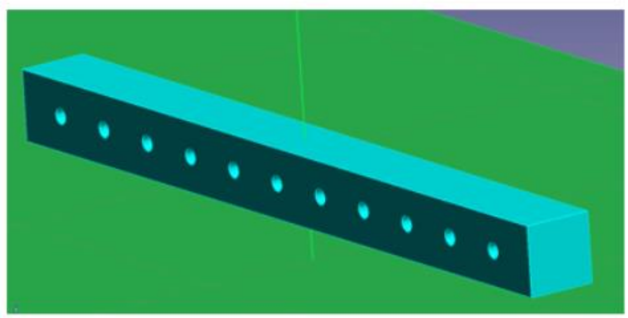


Figure 52: Drilling test example set up.

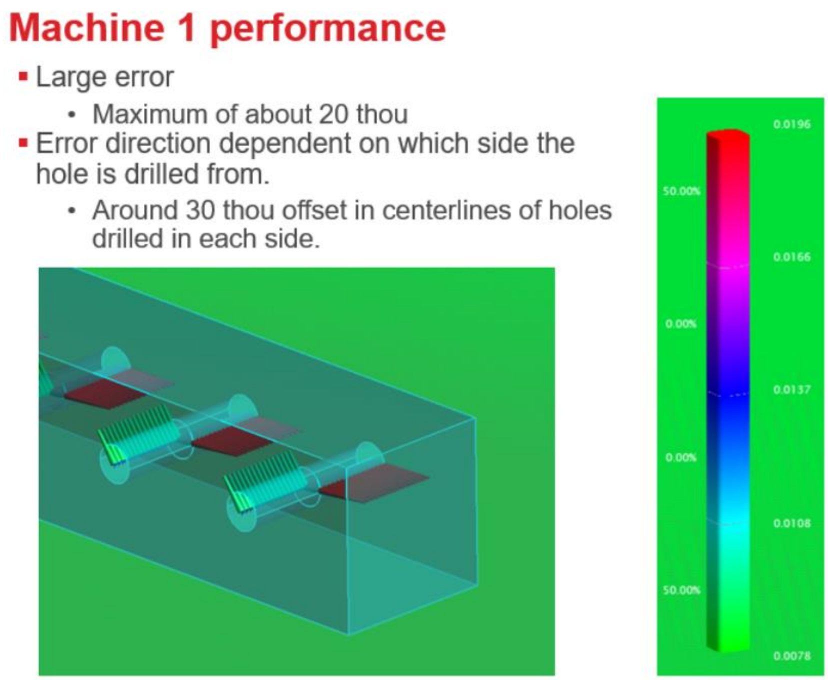


Figure 53: Drilling test results in Virtual Twin Analyzer for machine 1A.

Table 3: Results from actual drilling test on machine 1A.

	Deviation from nominal			
	Factory calibration		**Table-based VEC**	
	Max (in)	**Mean (in)**	**Max (in)**	**Mean (in)**
Drilled, B = 80°	0.0344	0.0098	0.0086	0.0014
Machined, B = 80°	0.0169	0.0094	0.0045	0.0012
Drilled, B = -20°	0.0127	0.0037	0.0091	0.0027
Machined, B = -20°	0.0070	0.0039	0.0029	0.0014

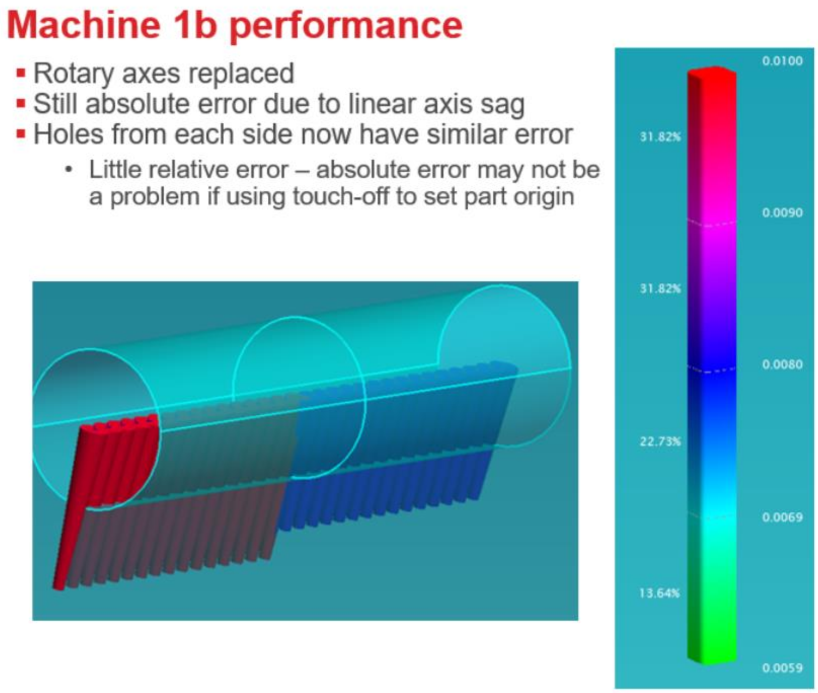


Figure 54: Drilling test results in Virtual Twin Analyzer for machine 1B, post retro-fit.

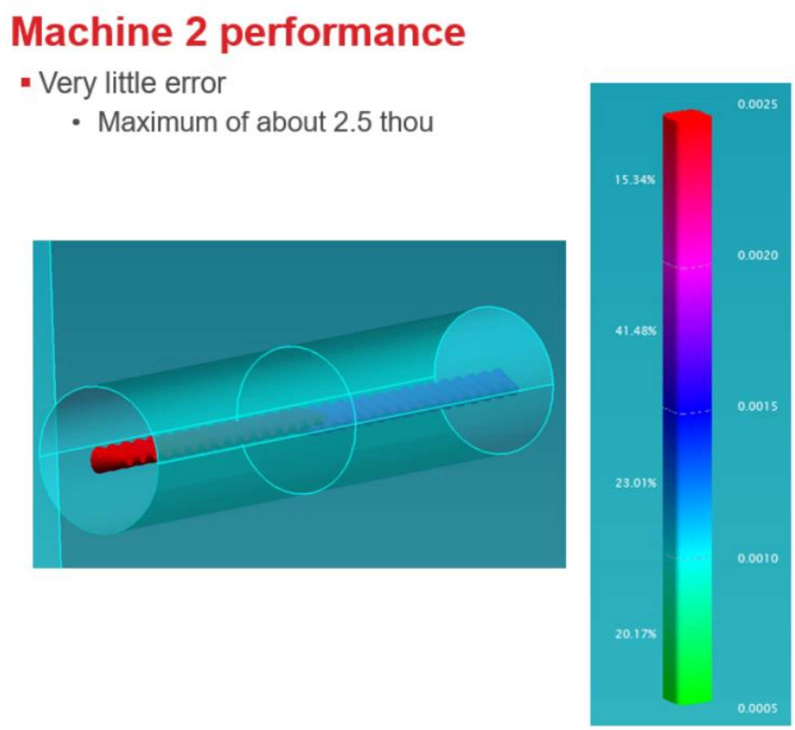


Figure 55: Drilling test results in Virtual Twin Analyzer for machine 2.

Appendix F: DRAFT SPECIFICATION

Cover Page

Standard:
BSSXXXX Rev:
(ORG) DD-MMM-
20XX

WARNING - The Export Control or Intellectual Property language on this page takes precedence over any such language that may appear on subsequent pages of this document.

a.

1. SCOPE

NOTE: Incorporated SSDs: None
Cancelled SSDs: None

This standard establishes the requirements or procedures for qualifying machine tools based on the virtual twin.

WARNINGs may be included throughout this standard. Do not take these WARNINGs to be all inclusive, nor to completely describe hazards or precautionary measures applicable to specific procedures or operating environments.

Non-Boeing personnel must refer to their employer's safety instructions for information concerning hazards, which may occur during operations described in this standard.

1.1 PURPOSE

a. Product Definition Data (part datasets) will identify requirement to certify machines in accordance with BACXXXX Type 1 and this specification.

b. CNC machines qualified in accordance with BACXXXX Type 1 and this specification provide objective evidence that the machine can produce acceptable (acceptable what?) machined hole to hole accuracy requirements in accordance with Product Definition Data. Identification of qualified machines will be recorded in BACXXXX QPL.

c. This specification is used to determine machine tool error based on the virtual twin.

1.2 CLASSIFICATION

This specification is for BACXXXX Type 1 only.

2 APPLICABLE DOCUMENTS

The current issue of the following documents shall be considered a part of this standard to extent herein indicated:

ASME Y14.5-2009 - Dimensioning and Tolerancing
ASME B5.54 - Methods for Performance Evaluation of Computer Numerically Controlled Machining Centers
BAC5114 - Enhanced Process Control for CNC Machining
ISO230 - Test Code for Machine Tools
ISO3070 - Machine Tools - Test Conditions for Testing the Accuracy of Boring and Milling Machines with Horizontal Spindle

ORIGINAL ISSUE: DD-MMM-20XX REV: (ORG) DD-MMM-20XX (ORG) DD-MMM-20XX
Authorizing Signatures on File VIRTUALLY GUIDED CERTIFICATION OF CNC MACHINE TOOLS VIA VIRTUAL TWIN BSS7XXX

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BOEING
SPECIFICATION SUPPORT STANDARD

2. CONTENTS

b. 4 DEFINITIONS

The following definitions apply to terms that are uncommon or have a special meaning as used in this standard:

BACXXXX QPL - Qualified Processors List includes a list of processors and machines that have been qualified in accordance with BACXXXX Type 1, and this specification.

Computer Numerical Control (CNC) - The automation of machine tools via computer-generated commands. Also called Numerical Control (NC.)

CNC Machine - The three dimensional envelope inside which the CNC machine Volume spindle may be used to machine product.

Qualification - The act of performing a series of functional tests, performance tests, and preparation to ensure that the process is capable of producing hardware that meets Engineering requirements.

Qualification Team - Personnel responsible for qualification plan creation, execution and documentation per this specification. Team members will include designated Processor representatives from NC programming, Tooling, Operations, Production Engineering, Quality Assurance organizations, and/or Boeing representatives from Production Engineering, Engineering (Boeing Research and Technology), Supplier Management and Quality.

Processor - Any company or internal Boeing business unit that is qualifying CNC machines in support of Boeing part fabrication in accordance with BACXXXX Type 1.

3. 5 EQUIPMENT

Processor shall adhere to the equipment requirements in accordance with the requirements of this section.

c. 5.1 MACHINE REQUIREMENTS

a. Machine may be open or enclosed for the test.

If an open machine is to be used for the test, take appropriate safety precautions to prevent laser tracker operator injury.

b. Ability to mount LT itself to machine bed or foundation area. LT must be inside the expansion joint for the machine foundation if one is present. In the absence of an expansion joint or separate foundation, the laser tracker should be mounted as close to the area a part would be machined as possible.

(1) Ability to mount active target onto spindle of machine – if there is no spindle on the machine in question, processor can either mount a bracket or it is acceptable to glue a puck for SMR after the last joint. The important thing is to mount after the last joint so that you are seeing all the axis motion.

(2) Mount as close as your end defector or spindle. Ensure all axis motion can be seen.

d. 5.2 LASER TRACKER REQUIREMENTS

a. Processor may use any manufacturer's laser tracker.

b. Processor shall have a procedure in place for the operation of their laser tracker.

c. Laser tracker and any metrology accessories for use in this process shall be calibrated per Processor's internal procedure.

d. Processor may use any manufacturer's software with their laser tracker. If Processor develops their own measurement collection software, adequate testing must be conducted to ensure the software can function equivalent to COTS software.

e. The processor shall establish and maintain a procedure and validation plan independent of the software developer to determine that the software, and subsequent revisions, accomplishes its intended function.

f. Follow OEM suggestion for laser tracker warm-up time.

g. Field checks shall be performed on the laser tracker prior to collecting measurement data.

h. Drift point analysis is required for each survey regardless of environmental conditions, vibration, and stability of the machine area being measured. A record of drift points measured and acceptance tolerance used, before and after measurements, are required as objective evidence.

i. Temperature during survey must be representative of machine's typical operating temperature. Volumetric repeatability should be less than about 0.005". If outside of 3 std deviations when comparing first 10 points of survey at beginning to first 10 reshot at the end of survey, then data cannot be considered accurate.

j. The XYZ coordinate location of the laser tracker relative to the XYZ coordinate location of the machine shall be recorded to establish relativity and allow for repeatability of the program.

e. 5.3 SOFTWARE REQUIREMENTS

There shall be three separate software utilized in this process:

Table 1: Software List

Software: Purpose:

1 Software 1 collects the set of measurement data.

2 Software 2 processes the measurement data into the machine model as described in the procedure.

3 Software 3 is the Virtual Twin Analyzer used to map the machine model onto parts and generate machine accuracy metrics. This software was developed under MxD 15-07-01 and can be licensed through for Aerospace Manufacturing Technology.

a. Processor may use any manufacturer's software for the purpose of measurement data collection. Processor may subcontract to another supplier who will process the data in accordance with this specification.

Measurement collection can be performed with programs other than SA but data analysis will require SA. Processor should only use a different software if they will be subcontracting analysis to another company (e.g. Boeing SM.)

b. Processor has three options regarding machine modeling script:

(1) Processor may write their machine modeling script but must send the script to Boeing SM for approval before using it.

(2) Processor may license available script from Missouri S&T.

(3) Processor may subcontract to a supplier who has access to the script.

c. Processor shall send processed data to Boeing for analysis using the virtual twin software. Processor may license the software from Center for Aerospace Manufacturing Technology at Missouri S&T for their own use and analysis, if desired.

d. Cutter path simulation software is advisable for verifying the measurement program, but not required.

f. 5.4 MODIFICATIONS

The qualification team must agree to and document all modifications to the qualification and include justification for deviations in the qualification plan.

g.

h. 6 PROCEDURE

i. 6.1 MACHINE MEASUREMENT

Written Procedure (Technique) Requirements - Surveys performed following this specification must be done in accordance with a detailed written procedure or instructions for the machine to be tested. The work instructions or written technique must be prepared by the processor personnel performing the machine inspection and must be approved in writing by the Qualification Team (see section X.X) prior to the supplier performing any acceptance inspection. Approval of a written procedure technique does not constitute an approved deviation to the requirements of this specification. Techniques must comply with the general requirements contained in this specification. Each technique must provide the details required to calibrate and perform the inspection and must include as a minimum:

6.1.1 Point Requirements

a. There will be two sets of points:
(1) Set 1 – Will be used for the identification of the model.
(2) Set 2 – Will be used to validate the model.

b. Points must cover full 5-axis joint space with minimal gaps and clustering. Reference example in Figure 1.

c. Points must avoid collision with machine bed tooling or other obstacles.

d. Do not use an evenly spaced grid for measurement point selection. Recommendation: Quasi-random is preferred but any random number generator will suffice.

e. Recommendation: 150-300 points for identification, and 30-50 for validation program, depending on the size and speed of the machine.

f. Validation points must not be contained in the identification point set.

Verification software for the point program is recommended to avoid collision. Operator should run the program without a tool to verify that all points are safe.

Figure 1: Example of Point Layout

j. 6.2 SURVEY PROCEDURE

If the machine undergoing evaluation has not been previously surveyed in accordance with this specification, perform sections 7.1.2.1 & 7.1.2.2. If the machine has been previously surveyed in accordance with this specification, perform sections 7.1.2.1 & 7.1.2.3.

k. 6.2.1 Instrument Set-up

a. Instrument must be on the same foundation as the machine per the requirements listed in Section 5.2.X.

b. Follow manufacturer's recommendation for laser tracker warm-up time.

c. Follow laser tracker manufacturer's recommended calibration procedure. At a minimum, perform a two face field check with an accuracy of < .001°.

d. If machine tool requires a warm-up, perform this check prior to taking any measurements.

e. Load the tool into the machine and perform any required checks to determine tool length or location.

f. Ensure necessary actions are taken to establish XYZ coordinate reference from LT to machine.

l. 6.2.2 Repeatability for First-time Survey

Repeatability of a robot or machine tool is extremely important to the calibration process since the residual error after calibration can never be expected to be less than the repeatability. There is an established process for measuring repeatability in ISO 230-2, or this document will define a procedure for establishing repeatability by means of two Types. Type I is the repeated measurement of a set of random points from the same approach direction. Type II is the repeated measurement of a set of random points from a randomized approach direction which is meant to capture effects such as backlash.

m. Repeatability study need only be performed if machine undergoing evaluation has not been previously surveyed in accordance with this specification.

n. ISO 230-2 describes a procedure for testing the repeatability by measuring a grid of points forwards and backwards. Following the procedure in ISO 230-2 is an acceptable alternative to this specification section (7.1.2.2.)

o. Type I – Perform repeatability by selecting 30-40 points (reference section ___ for point generation procedure). Points shall be measured a minimum of 3 times. Calculate deviation from average of each point. Repeatability shall be reported as an average and as a standard deviation.

p. Type II – Take the 30-40 points from c.) and randomize the order of those points a minimum of two times, creating two new programs in addition to the Type I program. Measure the randomized points. Calculate deviation from average of each point. Repeatability shall be reported as an average and as a standard deviation.

q. After performing repeatability, proceed to section 6.2.3.

r. 6.2.3 Measurements for Repeat Survey

a. Run the identification program with the LT set to measure stable points. The machine should pause for 6 to 10 seconds to ensure stability at each location.

b. At the end of the program, a drift check should be performed by re-measuring the first 10-30 points and evaluating for a deviation of [insert tolerance here.]

If evaluation determines deviation is out of tolerance, repeat survey. But first, verify:

(1) Temperature data from LT weather station to see if temperature change occurred.

(2) No other sources of drift/noise (e.g. vibrations) are present.

(3) LT is passing two face check.

c. Run the validation program with the LT set to measure stable points. The machine should pause for 6 to 10 seconds to ensure stability at each location.

d. Export data file in Comma Separated Value (CSV) format.

s. 6.3 MACHINE MODELING

a. The processor performing to this specification has the option of either following the modeling procedure described in Section 2 of the journal article "Table-Based Volumetric Error Compensation of Large Five-Axis Machine Tools" or they may submit their data to Boeing Supplier Management.

b. For processors who choose to submit their data to Boeing SM, the required pieces of data are as follows:

1) A schematic of the machine, showing the axis ordering and any relevant off-sets between axes as well as positive and negative axis limits. A photograph of the machine is helpful but not required.

2) Datasets as CSV files, including: identification, validation, and repeatability.

3) Any relevant data for tool length or location, and any relevant data for machine base frame if not already include in the CSV datasets.

4) NC programs for each dataset.
5) Model of laser tracker, temperature at start and finish of measurement collection.

6.4 MACHINE EVALUATION USING VIRTUAL TWIN SOFTWARE

Note: This part can be completed by Boeing Supplier Management for suppliers.

a. Processor shall determine whether they will be performing the evaluation internally or if they will seek assistance from Boeing SM. If processor chooses to request evaluation from SM, refer to section ____ for the minimum data required in order for SM to provide evaluation. Otherwise, Processor shall follow bullets b.) through i.) below.

b. Virtual Twin Analyzer Plugin for Spatial Analyzer is needed. Machine model shall be formatted per VTA documentation. Follow software User Guide.

c. Open and connect the software, following instructions in software documentation (VTA User Guide.)

d. Load the machine file. Create workspace using the machine file definition. Load appropriate metric part (which is provided with the software.)

e. Assign points to surfaces for evaluation. Assign appropriate tooling for approximating machining the part. Run a full machine analysis with a grid of X x X x X.

f. Mean, Max, and Standard Deviation will be reported. Include the generated figure in the report.

g. Repeat for other metric part sizes.

h. In the event that some points are outside of machine travel, multiple set-ups may be used in separate reports, or contact Boeing SM for an exception; an alternate part will be provided in that case.

i. Points shall be distributed uniformly on part's surface.

t. 7 QUALIFICATION

u. 7.1 QUALIFICATION TEAM RESPONSIBILITIES

a. The processor shall identify machine to be qualified.

NOTE: Because CNC machine accuracy and capability may be influenced by machine type, age and overall condition, this qualification is CNC machine specific.

b. The processor is responsible for all aspects of qualification including personnel, equipment, and material (e.g., laser tracker, accessories, software, etc.), test execution and documentation. The exception being instances where the processor elects to provide data to Boeing SM and/or qualified sub-contractor per the applicable sections in this specification.

c. The processor shall identify representatives from NC programming, Tooling, Operations, Production Engineering, and Quality organizations if/as required to form a qualification team.

d. Boeing qualification team members will include at least one of the following: machining subject matter expert, Production Engineer, Engineer (Boeing Research and Technology), Supplier Management and/or Quality.

e. The processor shall submit their qualification procedure/plan by written communication to the Boeing qualification team members for approval prior to commencing qualification.

f. The Boeing qualification team members will determine acceptability of processor's qualification procedure/plan.

g. Boeing team member presence during qualification at processor's facility is not required, but Boeing reserves the right to witness qualification activities.

h. All changes to processor's qualification plans/procedures must be provided to Boeing qualification team by written communication for review and approval prior to implementation.

i. After the processor completes qualification activities, the processor shall submit qualification documentation.

j. The Boeing qualification team shall notify the processor with formal written communication of Boeing's approval/disapproval of the processor's qualification results and documentation.

k. Upon successful completion of qualification in accordance with BSSXXXX, as evidenced by Boeing qualification team approval, the processor and qualified machine will be identified in the BACXXXX QPL.

v. 8 REPORTING

w. 8.1 QUALIFICATION DOCUMENTATION REQUIREMENTS

The processor shall retain the following qualification records as defined in the contract or Boeing records management processes:

a. The machine qualification procedure/plan with documentation of approval by the Boeing qualification team.

b. The submitted machine qualification documentation, including evidence of the approval/disapproval by the Boeing qualification team.

x. 8.2 DOCUMENTATION CONTENT

Qualification documentation shall include at a minimum the following information:

a. Identification documentation and photos of machine being qualified (make, model, age, serial number, etc.)

b. Diagrams/sketches/photos of machine being qualified, including laser tracker orientation and location in CNC machining volume.

c. Documentation of laser tracker’s equipment model and certification.

d. Reference to documented machine specific maintenance plans and routine machine tool diagnostic checks in accordance with BACXXXX.

e. List of qualification team members and written acceptance of qualification documentation and results.

f. Evidence that personnel performing the laser tracking set-up and tests are approved to operate the equipment per internal procedure. Additionally, if processor performing the evaluation is a Boeing supplier, that their company is Boeing Coordinate System Measurement (CMS) approved, and/or Nadcap Measurement & Inspection accredited to operate laser trackers.

y. 8.3 REQUALIFICATION REQUIREMENTS

a. Qualified CNC machines operated with routine diagnostic checks and scheduled preventative maintenance (PM) plans in accordance with BACXXXX do not require periodic requalification.

b. At Boeing's request, Processor machine re-qualification may be required to support root cause corrective action for Boeing assembly non-conformances resulting from hole to hole positional variation.

Appendix G: INTELLECTUAL PROPERTY DISCLOSURE AND ASSERTION

SCRA
Applied R&D

Applied Research Center
5300 International Boulevard
Charleston, SC 29418
TEL (843) 760-3200

ATTACHMENT 4

Technical Data/Intellectual Property Disclosure and Assertion Form

In accordance with 252.227-7017, Identification and Assertion of Restrictions on the Government's Use, Release, or Disclosure of Technical Data or Computer Software, identify below all noncommercial and commercial technical data and computer software that you, your subcontractors or suppliers, or potential subcontractors or suppliers plan to generate, develop, and/or deliver in which the Government will acquire less than unlimited rights and assert specific restrictions on those deliverables.

The Offeror asserts for itself and the subcontractors/suppliers/persons identified below that the Government's rights to use, release, or disclose the following technical data or computer software should be restricted:

Technical Data Computer Software To be Furnished With Restrictions*	Basis for Assertion**	Asserted Rights Category***	Name of Person Asserting Restrictions****
Computer Software to be furnished: Machine Kinematic Error Modeling Software	*Developed exclusively at private expense*	*Restricted*	*The Curators of the University of Missouri*

*For technical data (other than computer software or documentation) pertaining to items, components, or processes developed at private expense, identify both the deliverable technical data and each such item, component, or process. For computer software or computer software documentation, identify the software or documentation.

**Generally, development at private expense, either exclusively or partially, is the only basis for asserting restrictions. For technical data, other than computer software documentation, development refers to development of the item, component, or process to which the data pertain. The Government's rights in computer software documentation generally may not be restricted. For computer software, development refers to the software. Indicate whether development was accomplished exclusively or partially at private expense. If development was not accomplished at private expense, or for computer software documentation, enter the specific basis for asserting restrictions.

***Enter asserted rights category (e.g., government purpose license rights from a prior contract; rights in SBIR data generated under another contract; limited, restricted, or government purpose rights under this or a prior contract; or specially negotiated licenses).

****Corporation, individual, or other person, as appropriate.

*******Enter "none" when all data or software will be submitted without restrictions.**

Company The Curators of the University of Missouri
Signature K. Krishnamurthy
Printed Name and Title Dr. K. Krishnamurthy, Vice Provost for Research
Date 5/11/2015

(End of identification and assertion)

Appendix H: PROJECTED PAYOFF

Use case 1:

Potential cost savings vary, but using new programs at Boeing as an example:

- Examining new small programs and an impact rate of 3.75% of total program parts this is a savings of approximately $300k per new (small, <2500 parts) program
- Potential savings of months of time when a part is placed with a capable supplier the first time

Use case 2:

- Can save several months of delays and troubleshooting when the cause of a nonconformance is identified faster. May save further rework and nonconformance.

Use case 3:

- A new machine tool is a multi-million dollar purchase that can make or break a small business. Having accurate information about the current state of equipment and the general state of the industry is invaluable to a small supplier.