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Use of digital tools to simulate the accuracy of subtractive machining processes

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Abstract

The use of Digital tools and IIoT (Industrial Internet of Things) has been a common theme in global research and development over the past decade. This paper describes a newly developed digital environment where the simulation of the machine and machining process can be carried out, with the results indicating the process capability using inspection of a virtual part.

By developing high fidelity digital twins of systems using a process that combines pre-calibration and on-machine data captured from both the machine controller and external sensors, it is possible to use a series of mathematical models to simulate the machining process and develop an accurate prediction model of the machined parts. The digital environment combines models of known and predicted geometric and thermal errors. This process can be used to accelerate product and process development without needing to waste valuable production time or precious materials. It can also be used virtually to validate new machine concepts and de-risk high value manufacturing operations, enabling a much more cost effective and sustainable method of manufacturing machine and process design and development. This paper outlines the approach taken to enable the application of the digital tools developed and focuses on the effect of machine geometric errors in a case study. Preliminary validation is achieved by comparing virtual inspection of the virtual part with CMM data for a test part, showing good correlation of typical feature characteristics.

Keywords: Machine tool, error simulation, digital twin, virtual part production, digitalisation of manufacturing

1. Introduction

The use of Digital tools and IIoT (Industrial Internet of Things) has been a common theme in global research and development over the past decade. For machine tools, simulation of the machine is used in CAM packages to calculate nominal tool paths. Machine tools are complex mechatronic systems with build tolerances, finite stiffness and temperature variations from endogenous and exogenous sources. Models have been created to calculate these effects and, in some cases, compensate for them [1]. Some simulation tools also provide cutting force prediction for complex subtractive processes. Merdol and Altintas [1] integrated a general force model into a process simulation application to predict static cutting forces along a given toolpath. The models have been integrated into commercial software packages such as MachPro [3] to help improve quality and productivity, however the machine path in such simulations is nominal. Soori et al [4] predicted the effects of multiple machine errors sources but only a path profile was compared. Similarly, Lyu et al [5] predicted error on a complex S-shaped profile but did not have machined part comparison. Production capability for a range of parts, features and characteristics is not known unless test parts are produced and inspected. Although case- or error- specific models have been developed in the past, they have not been combined coherently and translated into a virtual part with virtual inspection to provide a general view of cumulative machining errors and feature/characteristic specific analysis for GD&T type capability analysis. This paper describes a digital environment where the simulation of the machine and machining process can be carried out efficiently, with the results indicating the process capability using CMM style inspection of a virtual part.

2. Simulation methodology

This research follows on from previous work on developing modular machine and process simulation [6] but focuses on feature generation and GD&T characteristic analysis and validation. Figure 1 shows a block diagram of the main elements of the modular program. Iso standard G-code programs are parsed and run a virtual machine that incorporates a custom interface to the highly efficient MachineWorks Limited Boolean engine. Stock, tooling, and error data (geometric in this case) are loaded as needed depending on the machine configuration.

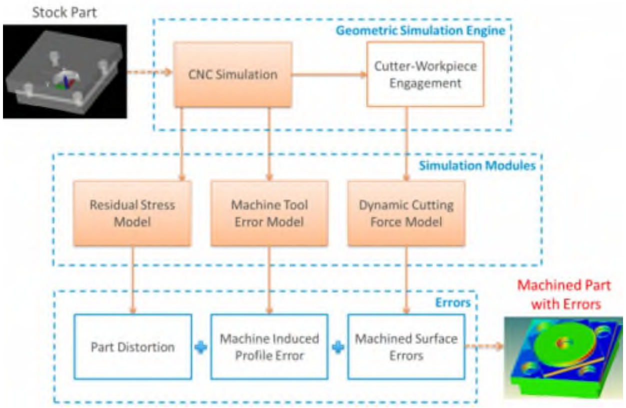


Figure 1. Modular machine and process simulation diagram

2.1 *Error measurement*

The simulation accuracy is dependent on the quality of the measurement data, therefore well-established measurement methods and equipment were used to capture the geometric errors in accordance with the ISO230-2 standard. A Renishaw XM-60 multi-axis calibrator was the primary tool for efficient measurement of the axis motion errors. The squareness between the axis was obtained using a granite artefact.

2.2 *Part detail and CAM setup*

The test parts are based on the ISO 10791 part 7 standard with the size ranging from 150mm to 250mm stock size. The 150 mm part was machined on a small 3-axis milling machine with configuration wX'Y'bZ(C)t using ISO 10791-2 notation [7]. The 250 mm part was machined on a small to medium sized 5-axis machine with configuration wC'A'X'Y'bZ(C)t. Example configurations are shown in Figure 2. The right image from the standard has the X axis moving the column whereas the test machine had the X axis moving the tilt/rotary table.

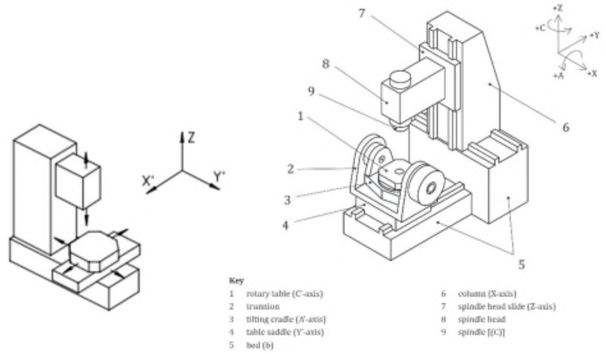


Figure 2. Machine configurations [7].

Figure 3 shows the finished 250 mm part clamped on the CNC machine. Aluminium was chosen to minimise tool wear and cutting force effects thereby reducing uncertainties associated with tool deflection which are still being worked on in the software. The machining parameters were different on each machine due to different operators and tooling availability. The brief was to minimise forces and generate good surface finish during the finishing.

A 0.1 mm axial depth of cut and 0.05mm radial depth of cut was used for the finishing cuts to further minimise cutting force effects. For the 150mm part, which was machined at MTTs facility (the company affiliate), a 16mm diameter, 2 flute cutter was used. The spindle speed was 8017 rpm and feedrate of 4810 mm/min. For the 250 mm part, a 12mm diameter, 3 flute cutter was used. The spindle speed was 5305 rpm and feedrate of 795 mm/min.

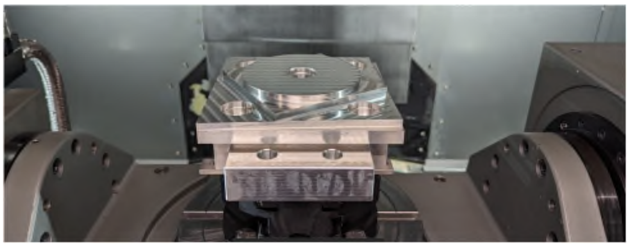


Figure 3. Aluminium test part located on the machine tool.

2.3 *Virtual production*

The machine geometry is usually represented by simplified structures although detailed models can be used if they are available. A Parent/child tree is built as per the machine structure with additional 6DoF added to each joint to allow the axis motion errors to be added to each axis using simple rotational and translational transformations, applied sequentially. Additional non-motion axes can be used to add additional degrees of freedom, for example for squareness between axes or where the centre of rotation does not move with the axis. There is no algorithmic definition of the machine so developing new configurations with any configuration is very easy and accessible for many types of users. This assumes rigid body behaviour which has shown to be effective [1] and is used in most NC systems for compensating geometric errors.

During the simulation, multiple parts can be generated simultaneously in the engine, one nominal and the rest with different sets of errors active. In this case just one extra with geometric errors was used. Figure 9 (left) shoes a uniform mesh, the spatial resolution of which depends on the number of cuts and the simulation resolution. Figure 9 (right) show more variability in the face shapes due to the tool to workpiece errors. The generated meshes can also be saved as STL files for additional post processing such as virtual inspection (section 3.1).

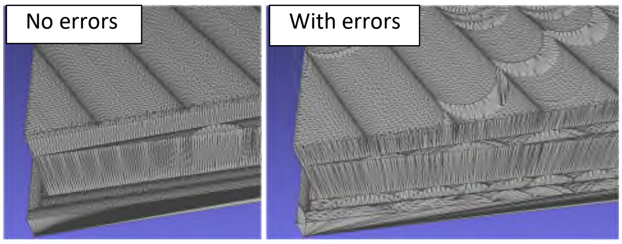


Figure 4. Generated STL surface examples with and without errors

During machining, the tool to workpiece cartesian error and orientation errors are recorded. **Figure 5** shows the errors during the full machining cycle. The number of process steps on the X axis is 1.9 x 10^5. The software has built in colour map analysis to show material on and off compared to set tolerances. Increasing dark red colour indicates more material off and increasingly darker blue indicates material on. The 250mm part is shown in Figure 6.

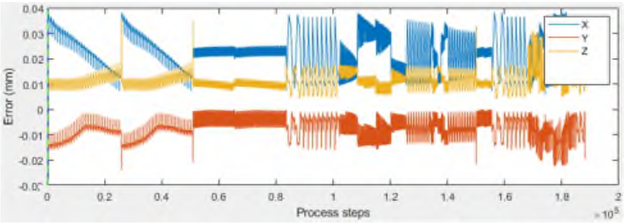


Figure 5. Full machining path tool to workpiece error record.

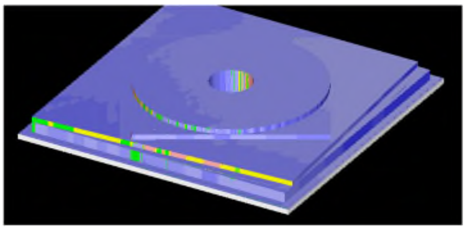


Figure 6. Colour map indicating path errors on virtual part.

3. Part inspection

Part inspection was performed on a Zeiss Prismo Access CMM in a temperature-controlled room. The volumetric accuracy of the CMM is 3 µm. Typical characteristics of size, roundness flatness and straightness were measured on the main features with a selection of these included in this short paper. Figure 7 shows the part on the CMM (inset) and some of the characteristics in the Zeiss Calypso software.

All the features were scanned so that a high number of points were available to the form characteristics. For example, the top circle scan typically includes between 500 to 1000 points depending on the size. Standard filtering and outlier elimination were used which are included in the Calypso software and which conform to the ISO standards. The typical scan speed was just 10mm/s to minimise vibration and the stylus tip was a 4 mm diameter ruby.

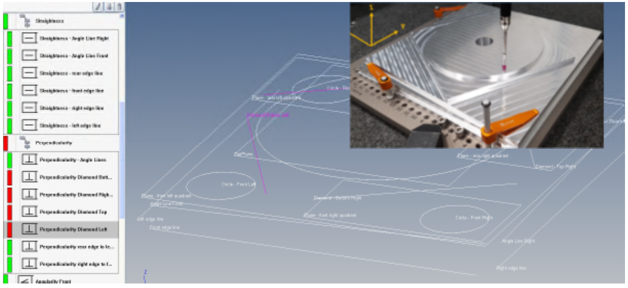


Figure 7. Modular machine and process simulation block

3.1 *Inspection of virtual part*

The STL file faces were selected for each of the features using a search for all contiguous faces based on how similar the normal angles are. **Figure 8** shows two example features (top cylinder and diamond edge), the faces of which are saved to be compared with the CMM probing points. In this example there are more than 2000 faces for the top cylinder but the number varies depending on the spatial resolution of the simulated cuts and the rate of change of the errors.

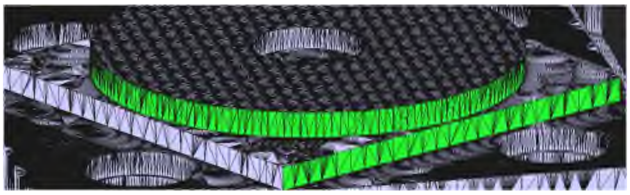


Figure 8. Selection of mesh faces for different part features.

The Zeiss CMM Calypso software stores the probe contact points and these are used to find the closest mesh faces or vertices to calculate virtual parts errors. If the virtual part datum is made the same as the CMM, then no global mesh modification is needed and the next stage is to find all the mesh faces that have a centre location nearest to all the CMM probe locations. Figure 9 shows the CMM probing points as red dots on the green mesh surface for the top circle feature. **Figure 10** shows the differences in the nearest face centre location to all the probe points for a cylinder feature and the cartesian distances are all less than 4mm. There should be negligible change in machine error over such small distances, however the option for weighted triangle centroid is being considered as future work.

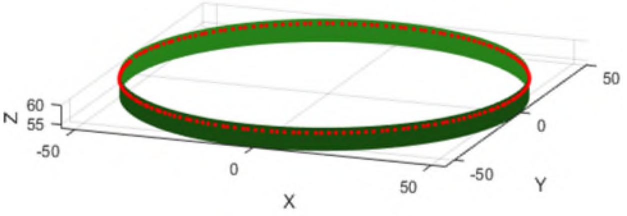


Figure 9. Imported top circle feature surface and CMM probing points.

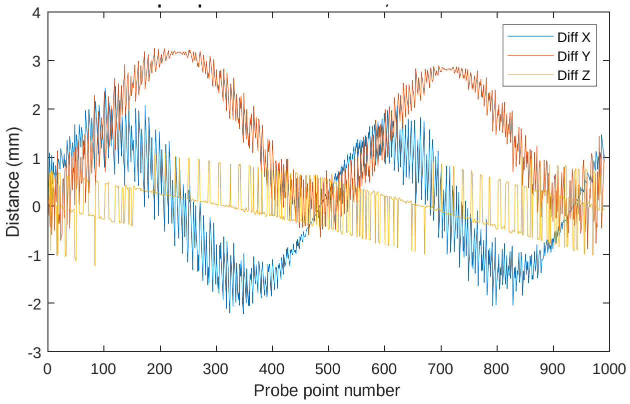


Figure 10. Variation in face centre locations to CMM probe location.

4. Virtual part inspection results

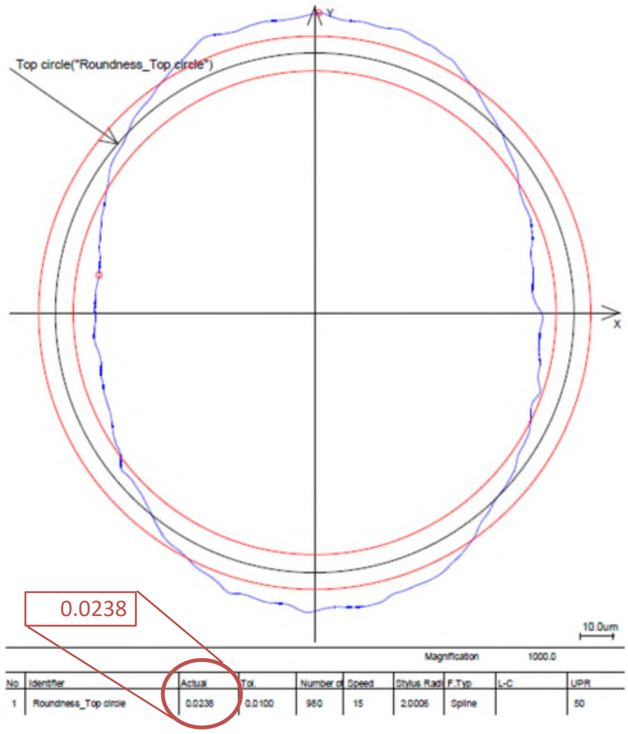
Figure 11 and Figure 12 shows the roundness plots for the same top circle feature of the real (from Zeiss Calypso software) and virtual parts respectively. The shape of the characteristic is very similar, and the roundness values are 0.024 mm for the real part and 0.028 mm for the virtual part. Similar low pass filtering was used for the Matlab calculation of roundness (A UPR of 50 is used in the Zeiss Calypso software but their implementation is not known).

So far in this work, a few characteristics have been compared and these are included in the **table 1**. The percentage correlation uses a comparison between the magnitude of the error measured by the CMM and difference between the simulated error and the CMM measured error. This did result in a relatively low correlation for the bottom roundness because the magnitude of the error is very small. In terms of dimensional differences, they are all within 6 µm.

One of the benefits of the virtual production is the potential for time and cost saving for testing new processes. Using a drawing to create a model and NC program are the same and currently the simulation does not run much faster than real machining. Most of the time saving comes from not needing fixture creation or taking a machine out of production. Another significant benefit is reduced material, tooling, and energy costs.

Table 1 Comparison of simulated inspection results to CMM results

Part	Measurement	Nominal	Sim	CMM	Sim Error	CMM Error	Difference	Correlation %
250	Diameter	160	159.966	159.969	0.034	0.031	-0.003	89
250	Roundness	0	0.028	0.024	-0.028	-0.024	0.004	82
250	Distance	150	150.032	150.027	-0.032	-0.027	0.006	79
150	Diameter	108	107.975	107.973	0.0246	0.027	0.003	90
150	Roundness	0	0.012	0.007	-0.012	-0.007	0.005	31



Magnification 1000.0

No	Identifier	Actual	Tol.	Number of	Speed	Stylus Radi	F.Typ	L-C	UPR
1	Roundness_Top circle	0.0238	0.0100	980	15	2.0006	Spline		50

Figure 11. Roundness plot for test part top circle

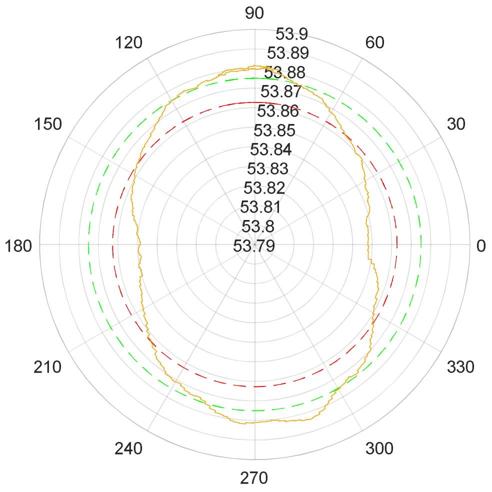


Figure 12. Roundness plot from the virtual part top circle

5. Conclusions

The correlation of the virtual part inspection characteristics with the CMM results is greater than 74% on average with deviations of less than 6 µm. With due consideration of the conformance zone, this software can be used to predict machine and process capability and work toward right first time or reduce the cost of prototyping and setting up new processes. It may also help schedule maintenance and calibration activity on machines. Providing the ability to derisk capital investment in machining platforms by virtually trialling operations prior to procurement and through out machine acceptance processes.

5.1 Future work

A new 5-axis test part has been designed that will be used, in combination with the ISO 230 part 12 (Test code for machine tools. Accuracy of finished test Pieces) fulcrum test, to validate 5-axis machining simulation and characteristics that involve multi axis interpolation.

Incorporating time varying and dynamic error source models is also in development using new and existing models developed in previous research.

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Figure 13. Tool deflection during machining