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ADDRESSING PROCESS PLANNING AND VERIFICATION ISSUES WITH MTCONNECT

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ABSTRACT

Robust interoperability methods are needed in manufacturing systems to implement computer-aided process planning algorithms and to verify their effectiveness. In this paper we discuss applying MTConnect, an open-source standard for data exchange in manufacturing systems, in addressing two specific issues in process planning and verification. We use data from an MTConnect-compliant machine tool to estimate the cycle time required for machining complex parts in that machine. MTConnect data is also used in verifying the conformance of toolpaths to the required part features by comparing the features created by the actual tool positions to the required part features using CAD tools. We demonstrate the capabilities of MTConnect in easily enabling process planning and verification in an industrial environment.

INTRODUCTION

Automated process planning methods are a critical component in the design and planning of manufacturing processes for complex parts. This is especially the case with high speed machining, as the complex interactions between the tool and the workpiece necessitates careful selection of the process parameters and the toolpath design. However, to improve the effectiveness of these methods, they need to be integrated tightly with machines and systems in industrial environments. To enable this, we need robust interoperability standards for data exchange between the different entities in manufacturing systems.

In this paper, we discuss using MTConnect – an open source standard for data exchange in manufacturing systems – to address issues in process planning and verification in machining. We discuss two examples of using MTConnect for better process planning: in estimating the cycle time for high speed machining, and in verifying the effectiveness of toolpath planning for machining complex features. As MTConnect standardizes the exchange of manufacturing process data, process planning applications can be developed independent of the specific equipment used (Vijayaraghavan, 2008). This allowed us to develop the process planning applications and implement them in an industrial setting with minimal overhead. The experiments discussed in this paper were developed at UC

Berkeley and implemented at Remmele Engineering Inc.

The next section presents a brief introduction to MTConnect, highlighting its applicability in manufacturing process monitoring. We then discuss two applications of MTConnect – in computing cycle time estimates and in verifying toolpath planning effectiveness.

MTCONNECT

MTConnect is an open software standard for data exchange and communication between manufacturing equipment (MTConnect, 2008a). The MTConnect protocol defines a common language and structure for communication in manufacturing equipment, and enables interoperability by allowing access to manufacturing data using standardized interfaces. MTConnect does not define methods for data transmission or use, and is not intended to replace the functionality of existing products and/or data standards. It enhances the data acquisition capabiltiies of devices and applications, moving towards a plug-and-play environment that can reduce the cost of integration. MTConnect is built upon prevalent standards in the manufacturing and software industry, which maximizes the number of tools available for its implementation and provides a high level of interoperability with other standards and tools in these industries.

MTConnect is an XML-based standard and messages are encoded using XML (eXtensible Markup Language), which has been used extensively as a portable way of specifying data interchange formats (W3C, 2008). A machine-readable XML schema defines the format of MTConnect messages and how the data items within those messages are represented. At the time of publication, the latest version of the MTConnect standard defining the schema is 1.0 (MTConnect, 2008b).

The MTConnect protocol includes the following information about a device:

- Identity of a device
- Identity of all the independent components of the device
- Design characteristics of the device
- Data occurring in real or near real-time by the device that can be utilized by other devices or applications. The types of data that can be addressed includes:
    - Physical and actual device design data
    - Measurement or calibration data
    - Near-real time data from the device

Figure 1 shows an example of a data gathering setup using MTConnect. Data is gathered in near-time from a machine tool and from thermal sensors attached to it. The data stored by the MTConnect protocol for this setup is shown in Table 1. Specialized adaptors are used to parse the data from the machine tool and from the sensor devices into a format that can be understood by the MTConnect agent, which in turn organizes the data into the MTConnect XML schema. Software tools can be developed which operate on the XML data from the agent. Since the XML schema is standardized, the software tools can be blind to the specific configuration of the equipment from where the data is gathered.

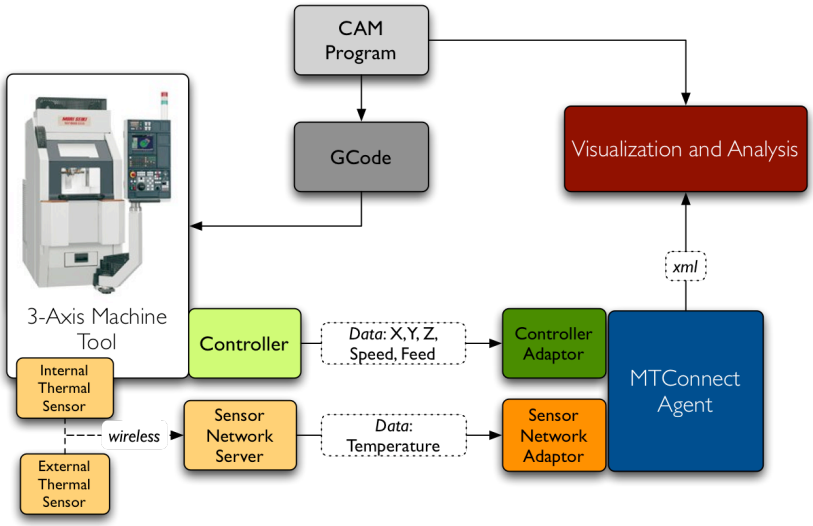

FIGURE 1: MTCONNECT SETUP.

TABLE 1:MTCONNECT PROTOCOL INFORMATION FOR MACHINE TOOL IN FIGURE 1.

Device identity	"3-Axis Milling Machine"
Device components	1 X Axis; 1 Y Axis; 1 Z Axis; 2 Thermal Sensors
Device design characteristics	X Axis Travel: 6" Y Axis Travel: 6" Z Axis Travel: 12" Max Spindle RPM: 24000
Data occurring in device	Tool position: (0,0,0); Spindle RPM: 1000 Alarm Status: OFF Temp Sensor 1: 90ºF Temp Sensor 2: 120ºF

An added benefit of XML is that it is a hierarchical representation, and this is exploited by designing the hierarchy of the MTConnect schema to resemble that of a conventional machine tool. The schema itself functions as a metaphor for the machine tool and makes the parsing and encoding of messages intuitive. Data items are grouped based on their logical organization, and not on their physical organization. For example, Figure 2 shows the XML schema associated with the setup shown in Figure 1. Although the temperature sensors operate independant of the machine tool (with its own adaptor), the data from the sensors are associated with specific components of the machine tool, and hence the temperature data is a member of the hierarchy of the machine tool. The next section discusses applying MTConnect in estimating cycle time in high-speed machining.

ACCURATE CYCLE TIME ESTIMATES

In high speed machining processes there can be discrepancies between the actual feedrates during cutting and the required (or commanded) feedrates. These discrepancies are dependent on the design of the controller used in the machine tool and the toolpath geometry. While there have been innovative controller designs that minimize the feedrate discrepancy (Sencer, 2008), most machine tools used in conventional industrial facilities have commercial off-the-shelf controllers that demonstrate some discrepancies in the feedrates, especially when machining complex geometries at high speeds. There is a need for simple tools to estimate the discrepancy in these machining conditions.

Apart from influencing the surface quality of the machined parts, feedrate variation can lead to inaccurate estimates of the cycle time during machining. Accurate estimates of the cycle time is a critical requirement in planning for complex machining operations in manufacturing facilities. The cycle time is needed for both scheduling the part in a job shop, as well as for costing the part. Inaccurate cycle time estimates (especially when the feed is overestimated) can lead to uncompetitive estimates for the cost of the part and unrealistic estimates for the cycle time.

Related Work

de Souza and Coelho (2007) presented a comprehensive set of experiments to demonstrate feedrate limitations during the machining of freeform surfaces. They identified the causes of feedrate variation as dynamic limitations of the machine, block processing time

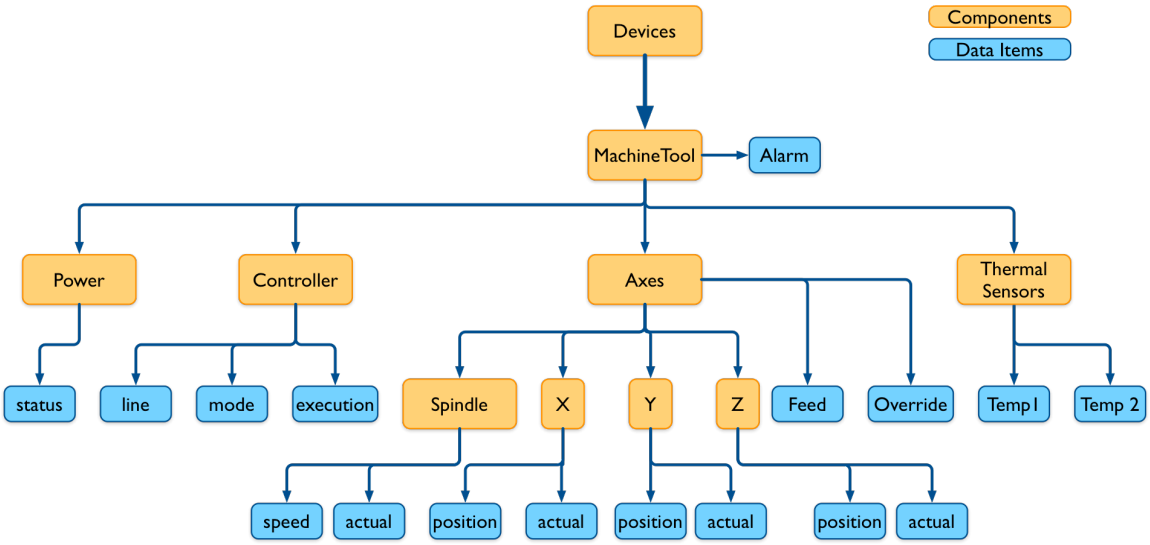

FIGURE 2: MTCONNECT HIERARCHY.

for the CNC, and the feature size in the toolpaths. Significant discrepancies were observed between the actual and commanded feeds when machining with linear interpolation (G01). The authors used a custom monitoring and data logging system to capture the feedrate variation in the CNC controller during machining.

Sencer et al. (2008) presented feed scheduling algorithms to minimize the machining time for 5-axis contour machining of sculptured surfaces. The algorithm optimized the profile of the feedrate for minimum machining time, while observing constrains on the smoothness of the feedrate, acceleration and jerk of the machine tool drives. This follows earlier work in minimizing the machining time in 3-axis milling using similar feed scheduling techniques (Altintas, 2003). While these methods are very effective in improving the cycle time of complex machining operations, they can be difficult to apply in conventional factory environments as they require specialized control systems. The methods we discuss in this paper do not address the optimization of cycle time during machining. Instead, we provide simple tools to estimate the discrepancy in feedrates during machining and use this in estimating the cycle time for arbitrary parts.

Methodology

During G01 linear interpolation the chief determinant of the maximum feedrate achievable is the spacing between adjacent points (G01 step size). We focus on G01 interpolation as this is used extensively when machining simultaneously in 3 or more axes. The cycle time for this machine tool to machine an arbitrary part (using linear interpolation) is estimated based on the maximum feed achievable by the machine tool at a given path spacing. MTConnect is a key enabler in this process as it standardizes both data collection as well as the analysis.

The maximum feedrate achievable is estimated using a standardized test G-code program. This program consists of machining a simple shape with progressively varying G01 path spacings. The program is executed on an MTConnect-compliant machine tool, and the position and feed data from the machine tool is logged in near-real time. The feedrate during cutting at the different spacings is then analyzed, and a machine tool “calibration” curve is developed, which identifies the maximum feedrate possible at a given path spacing.

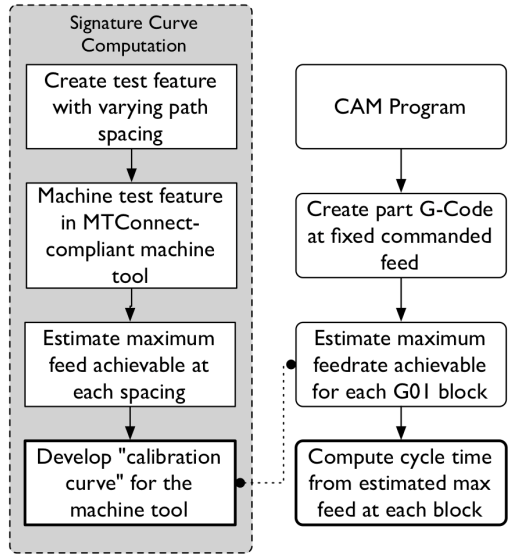

FIGURE 3: METHODOLOGY FOR ESTIMATING CYCLE TIME.

Conventionally, the cycle time for a given toolpath is estimated by summing the time taken for the machine tool to process each block of G-code, which is calculated as the distance travelled in that block divided by the feedrate of the block. For a given arbitrary part G-code to be executed on a machine tool, the cycle time is estimated using the calibration curve as follows. For each G01 block executed in the program, the size of the step is calculated (this is the distance between the points the machine tool is interpolating) and the maximum feedrate possible at this step size is looked up from the calibration curve. If the maximum feedrate is smaller than the commanded feedrate, this line of the G-code is modified to machine at the (lower) actual feedrate, if the maximum feedrate is greater, then the line is left unmodified. This is performed for all G01 lines in the program, and finally, the cycle time of the modified G-code program is estimated the conventional way. This methodology is shown in Figure 3. The next section discusses an example applying this methodology on a machine tool.

Results

We implemented the cycle time estimation method on a 3-axis machine tool with a conventional controller. The calibration curve of this machine tool was computed by machining a simple circular feature at the following linear

spacings: 0.0001”, 0.00025”, 0.0005”, 0.00075”, 0.001”, 0.0025”, 0.005”, 0.0075”, 0.01”. We confirmed that the radius of the circle (that is, the curvature in the toolpath) had no effect on the feedrate achieved by testing with circular features of radius 0.5”, 1.0”, and 2.0”, and observing the same maximum feedrate in all cases. Table 2 shows the maximum achievable feedrate at each path spacing when using a circle of radius 1”. We can see from the table that the maximum feedrate achievable is a linear function of the path spacing. Using a linear fit, the calibration curve for this machine tool can be estimated. Figure 4 plots the calibration curve for this machine tool. The relationship between the feedrate and the path spacing is linear as the block processing time of the machine tool controller is constant at all feedrates. The block processing time determines the maximum federate achievable for a given spacing as it is the time the machine tool takes to interpolate one block of G-code. As the path spacing (or interpolatory distance) linearly increases, the speed at which it can be interpolated also increases linearly. The relationship for the data in Figure 4 is:

*MAX FEED (in/min) = 14847 * SPACING (in)*

TABLE 2: MAXIMUM ACHIEVABLE FEEDRATE AT VARYING PATH SPACING

Spacing	Maximum Feedrate
0.0001”	0.7
0.00025”	3.6
0.0005”	7.2
0.00075”	10.5
0.001”	14.6
0.0025”	35.6
0.005”	71.2
0.0075”	106.7
0.01”	147.68

We also noticed that the maximum feedrate for a given spacing was unaffected by the commanded feedrate, as long as it was lesser than the commanded feedrate. This means that it was adequate to compute the calibration curve by commanding the maximum possible feedrate in the machine tool.

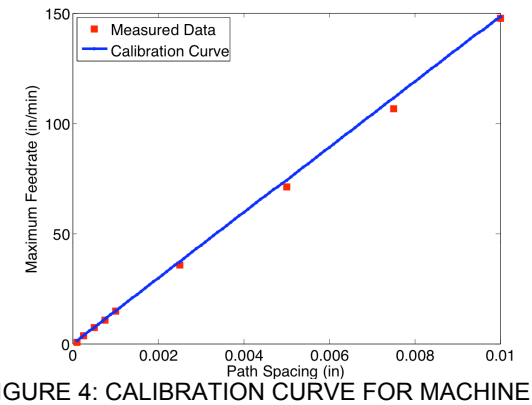

FIGURE 4: CALIBRATION CURVE FOR MACHINE TOOL.

Using this calibration curve, we estimated the cycle time for machining an arbitrary feature in this machine tool. The feature we used was a 3D spiral with a smoothly varying path spacing, which is shown in Figure 5. The spiral path is described exclusively using G01 steps and involves simultaneous 3-axis interpolation. The path spacing of the G-code blocks for the feature is shown in Figure 6.

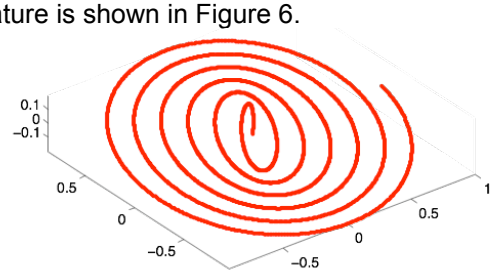

FIGURE 5: 3D SPIRAL FEATURE.

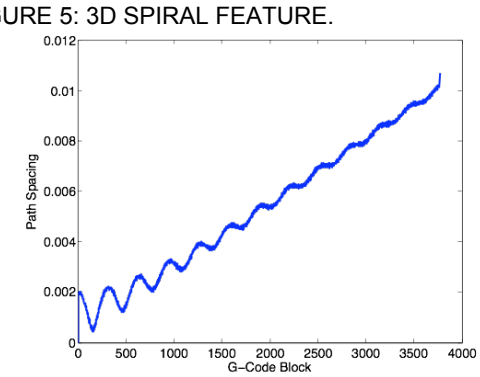

FIGURE 6: PATH SPACING VARIATION WITH G-CODE LINE FOR SPIRAL FEATURE.

Figure 7 shows the predicted feedrate based on the calibration curve for machining the spiral shape at 100 inches/min, compared to the actual feedrate during machining. We can see that the feedrate predicted by the calibration curve matches very closely with the actual feedrate. We can also observe the linear relationship between path spacing and maximum feedrate by

comparing figures 6 and 7.

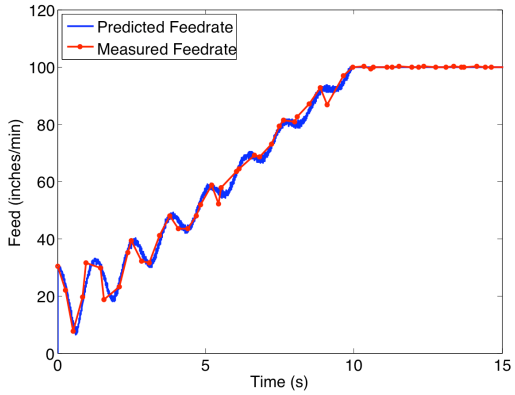

FIGURE 7: PREDICTED FEEDRATE COMPARED TO MEASURED FEEDRATE FOR SPIRAL FEATURE AT 100 IN/MIN.

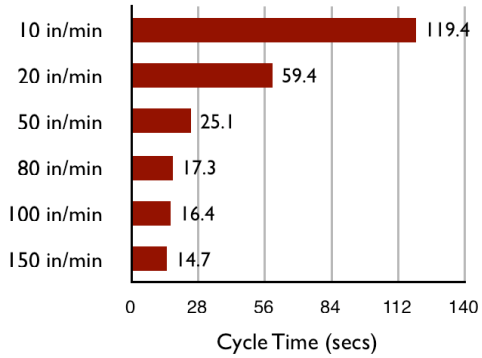

FIGURE 8: ACTUAL CYCLE TIME TO MACHINE SPIRAL FEATURE AT DIFFERENT FEEDRATES.

The cycle time for machining the spiral at different commanded feedrates was also estimated using the calibration curve. Figure 8 shows the actual cycle time taken to machine the spiral feature at different feedrates. Notice here that the trend is non-linear – an increase in feed does not yield a proportional decrease in cycle time – implying that there is some feedrate discrepancy at high feeds. Figure 9 compares the theoretical cycle time to machine at different feedrates to the actual cycle time and the model predicted cycle time. We can see that the model predictions match the cycle times very closely (within 1%). Significant discrepancies are seen between the theoretical cycle time and the actual cycle time when machining at high feed rates. These discrepancies can be explained by the difference between the block processing time for the controller, and the time spent on each block of G-Code during machining. At high feedrates, the time spent at each block is shorter than the block processing time, so the controller slows down the interpolation resulting in a discrepancy in the cycle time.

These results demonstrated the effectiveness of using the calibration curve to estimate feed, and ultimately apply in estimating the cycle time. This method can be extrapolated to multi-axis machining by measuring the feedrate variation for linear interpolation in specific axes. We can also specifically correlate feed in one axis to the path spacing instead of the overall feedrate.

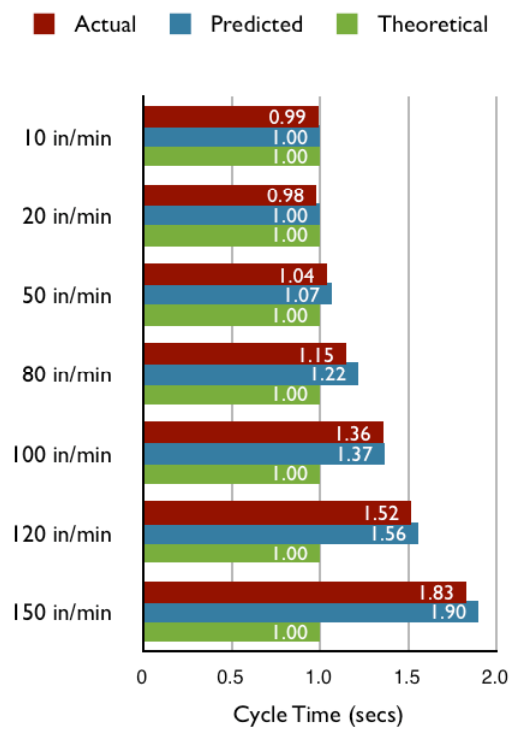

FIGURE 9: ACTUAL OBSERVED CYCLE TIMES AND PREDICTED CYCLE TIMES COMPARED TO THE NORMALIZED THEORETICAL CYCLE TIMES FOR MACHINING SPIRAL FEATURE AT DIFFERENT FEEDRATES.

TOOL POSITION VERIFICATION

MTConnect data can also be used in verifying toolpath planning for the machining of complex parts. Toolpaths for machining complex features are usually designed using specialized CAM algorithms, and traditionally the effectiveness of the toolpaths in creating the required part features are either verified using computer simulations of the toolpath, or by surface metrology of the machined part. The former approach is not very accurate, as the toolpath commanded to the machine tool may not match the actual toolpath travelled during machining. The latter approach, while accurate, tends to be time consuming and expensive, and requires the

analysis and processing of 3D metrology data (which can be complex). Moreover, errors in the features of a machined part are not solely due to toolpath errors, and using metrology data for toolpath verification may obfuscate toolpath errors with process dynamics errors. In a previous work we discussed a simple way to verify toolpath planning by overlaying the actual tool positions against the CAM generated tool positions (Vijayaraghavan, 2008). We now discuss a more intuitive method to verify the effectiveness of machining toolpaths, where data from MTConnect-compliant machine tools is used to create a solid model of the machined features to compare with the desired features.

Related Work

The manufacturing community has focussed extensively on developing process planning algorithms for the machining of complex parts. Elber (1995) in one of the earliest works in the field, discussed algorithms for toolpath generation for 3- and 5-axis machining. Wright et al. (2004) discussed toolpath generation algorithms for the finish machining of freeform surfaces; the algorithms were based on the geometric properties of the surface features. Vijayaraghavan et al. (2009) discussed methods to vary the spacing of raster toolpaths and to optimize the orientation of workpieces in freeform surface machining. The efficiency of these methods were validated primarily by metrology and testing of the machined part.

Methodology

To verify toolpath planning effectiveness, we log the actual cutting tool positions during machining from an MTConnect-compliant machine tool, and use the positions to generate a solid model of the machined part. The discrepancy in features traced by the actual toolpath relative to the required part features can be computed by comparing these two solid models. The solid model of the machined part from the tool positions can be obtained as follows:

- Create a 3D model of the tool
- Create a 3D model of the stock material
- Compute the swept volume of the tool as it traces the tool positions (using logged data)
- Subtract the swept volume of the tool from the stock material
- The remaining volume of material is a solid model of the actual machined part.

The two models can then be compared using 3D boolean difference (or subtraction) operations.

Results

We implemented this verification scheme by logging the cutter positions from an MTConnect-compliant 5-axis machine tool. The procedure to obtain the solid model using the tool positions was implemented in Vericut. The two models were compared using a boolean *diff* operation in Vericut, which identified the regions in the actual machined part that were different from the required solid model. An example applying this method for a feature is shown in Figure 10.

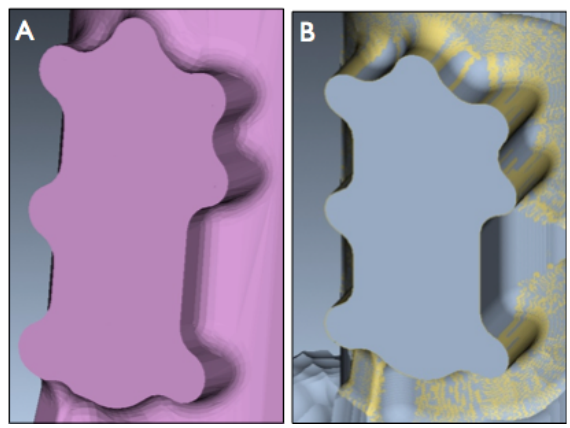

FIGURE 10: A – SOLID MODEL OF REQUIRED PART; B – SOLID MODEL OF PART FROM TOOL POSITIONS SHOWING DISCREPANCIES BETWEEN ACTUAL PART FEATURES AND REQUIRED PART FEATURES. SHADED REGIONS DENOTE ~0.001" DIFFERENCE IN MATERIAL REMOVAL.

DISCUSSION AND CONCLUSIONS

MTConnect makes it very easy to standardize data capture from disparate sources and develop common planning and verification applications. The importance of standardization cannot be overstated here – while it has always been possible to get process data from machine tools, this can be generally cumbersome and time consuming because different machine tools require different methods of accessing data. Data analysis was also challenging to standardize as the data came in different formats and custom subroutines were needed to process and analyze data from different machine tools. With MTConnect the data gathering and analysis process is standardized resulting in significant cost and time savings. This allowed us to develop the verification tools independent of the machine tools they were

applied in. This also allowed us to rapidly deploy these tools in an industrial environment without any overheads (especially from the machine tool sitting idle). The toolpath verification was performed with minimal user intervention on a machine which was being actively used in a factory. The only setup needed was to initially configure the machine tool to output MTConnect-compliant data; since this is a one-time activity, it has an almost negligible impact on the long term utilization of the machine tool.

Successful implementations of data capture and analysis applications over MTConnect requires a robust characterization of the data capture rates and the latency in the streaming information. Current implementations of MTConnect are over ethernet, and a data rate of about 10~100Hz was observed in normal conditions (with no network congestion). While this is adequate for geometric analysis (such as the examples in this paper), it is not adequate for real-time process monitoring applications, such as sensor data logging. More work is needed in developing the MTConnect software libraries so that acceptable data rates and latencies can be achieved.

One of the benefits of MTConnect is that it can act as a bridge between academic research and industrial practice. Researchers can develop tools that operate on standardized data, which are no longer encumbered by specific data formats and requirements. The tools can then be easily applied in industrial settings, as the framework required to implement the tools in a specific machine or system is already in place. Greater use of interoperability standards by the academic community in manufacturing research will lead to faster dissemination of research results and closer collaboration with industry.

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