Available online at www.sciencedirect.com

ScienceDirect

Procedia CIRP 52 (2016) 108 – 111

www.elsevier.com/locate/procedia

Changeable, Agile, Reconfigurable & Virtual Production

Roadmap for deploying semantic GD&T in manufacturing

Dr. Martin Hardwick *

RPI & STEP Tools, Inc., 14 First Street, Troy NY 12180, USA

* Corresponding author. Tel.: +1-518-687-2848 x306; *E-mail address:* hardwick@cs.rpi.edu

Abstract

A five phase roadmap is proposed for deploying semantic GD&T in manufacturing. In the first phase real manufacturing is connected to virtual manufacturing using protocols such as MTConnect. In the second phase the virtual manufacturing results are connected to virtual and real CMM's. In the third phase new services optimize the models to make them more efficient while still meeting their design requirements. In the fourth phase closed loop machining systems evaluate proposed changes in real time. In the fifth phase the usage of cloud based models in virtual twin factories becomes ubiquitous. We describe how the virtual twin factories are built in Node.js, and how a new suite of protocols called the SWIM is used to track the relationships between normalized STEP models and the easy to use JSON objects of the virtual factory.

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016

Keywords: Semantic Geometric Dimensions and Tolerances; Virtual Factories; Virtual Measurement; MTConnect; STEP; Node.js

1. Introduction

Today's shop floor is a place where skilled operators convert drawings into machined parts. The methods used to interpret the drawings, generate the machine codes and inspect the results are largely unknown to the rest of the enterprise. This paper proposes using standards to expose them to others so that they can be made more efficient. The key standard is AP242 because it allows the manufacturing requirements to be shared as semantic dimensions and tolerances [1]. With this standard it becomes possible to measure the shop floor solutions against how well they are meeting their design requirements. The other standards are MTConnect for reporting the run time machining results [2], QIF for evaluating the measurements [3] and STEP-NC for sharing the manufacturing solutions [4]. Figure 1 illustrates how they are being assembled into a system for transparent, inspected machining.

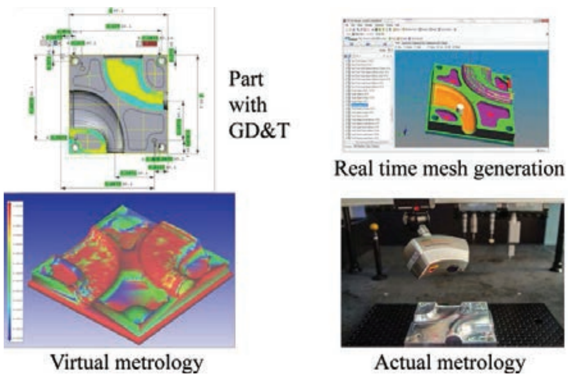

Fig.1. Components of a transparent manufacturing system: (a) Design requirements as semantic GD&T (AP242); (b) real time mesh generation from MTConnect data; (c) virtual metrology of the virtual mesh to make QIF; and (d) real metrology of the machined part.

Peer-review under responsibility of the scientific committee of the Changeable, Agile, Reconfigurable & Virtual Production Conference 2016
doi:10.1016/j.procir.2016.07.052

2. Roadmap

Figure 2 is a roadmap for deploying the technology. The first phase is to enable remote monitoring of machining on smart phones and tablets. A demonstration is being developed to show this capability at the Future of Flight Museum in Mukilteo, Washington on October 5th 2016. A preview is available at: http://www.steptools.com/demos/mtc/. For this stage the current state of a machined part is shown in real time. First, the latest coordinates of the machine tool are transmitted using MTConnect. Second, a simulator applies them to STEP models of the manufacturing product and process. Third, the updated models are sent to the phone along with information about how the machining can be made more efficient by reducing tool wear or increasing the feeds.

The online demonstrations also show some aspects of the second phase. The full second phase is to enable virtual measurement of the virtual models. The enabling standard (AP242) is being deployed by the CAD and CMM vendors. The risk for this phase is that the new systems will not be able to produce a virtual model that is sufficiently accurate for worthwhile measurement. Factors that may impact the virtual modelling include (i) being able to reliably measure the setup coordinates and tooling dimensions, (ii) being able to estimate errors due to tool bending and CNC inaccuracies, and (iii) being able to model the result with sufficient fidelity while keeping the data volume manageable.

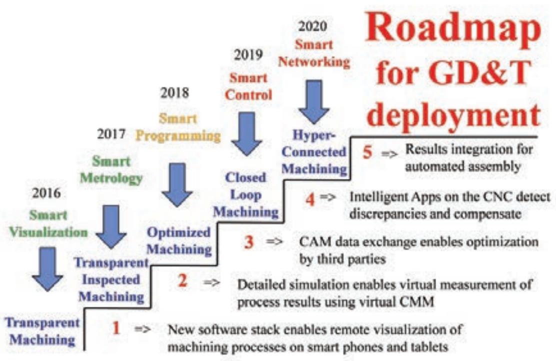

Fig.2. Roadmap for GD&T deployment

3. Pathway to Implementation

Paper calculations backed up by experiments show that the error in a path approximated from MTConnect measurements decreases proportionally to the square of the sampling rate. For example, an approximation error of 0.4mm for a 1 second sampling rate is reduced to 0.1mm if the sampling rate is doubled. We are finding that a sampling rate of 100ms is not sufficient to capture rapid moves accurately, but 10ms is sufficient, and many CNC machines may soon be able to report their position at 1ms rates.

If the setup and tool dimensions are measured accurately and the sampling rate is good, then the remaining errors are due to the machining forces and their impact on the tools and the CNC. A simulator connected to the machining can calculate the speed and profile of the cut. A database of previous job / material / force combinations connected to a machine learning system can predict results for the next cut. Figure 3 shows some of the data paths being established.

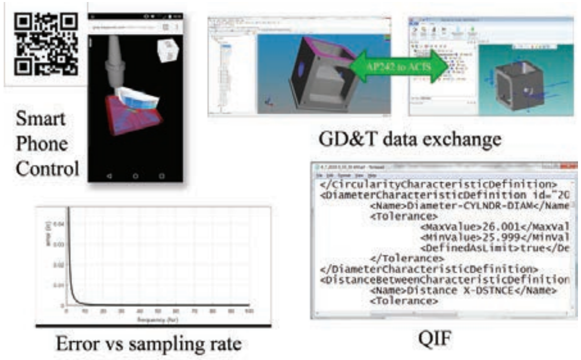

Fig.3. Early results for the October demonstration (a) smart phone display; (b) the test part with semantic GD&T; (c) graph showing relationship between sampling frequency and measurement accuracy; (d) first QIF metrology results for the test part.

The third phase of the roadmap uses the results of the first two phases to enable third party optimizations. In this phase remote systems have the ability to monitor machining programs, and measure their results using virtual and real coordinate measurement machines (CMMs). Therefore, third parties will be able to optimize manufacturing solutions by making suggestions for process improvements. For example in an experiment at IMTS 2104, two cutter vendors made a model based machining program 15% better by substituting better tooling [4]. In 2018 the roadmap anticipates that this optimization will start to take place at industrial sites using a mixture of CAD/CAM data exchange and new cloud services.

In order to enable third party optimization there must be accurate monitoring of results. Therefore, experiments are being organized in which streams from multiple data sources are compared to validate processes. Sound is simple though it may be better to measure the spindle force directly. If there is no sound when the coordinates show the tool should be cutting metal then the setup is wrong. If an increase or decrease in volume does not correspond to a change in the depth of the engagement then something else is wrong. Predictions that prevent damage will be highly valued.

The fourth phase requires two innovations. The first is full modelling of the machine tool including both the CNC and PLC components. This modelling is necessary so that a complete simulation of the machining can be optimized by third party apps. The second innovation is the connection of the QIF output of Figure 3 to the STEP inputs. Today an operator understands the machine and is able to watch for discrepancies. The goal of the fourth phase is to enable intelligent apps that do the same thing.

The risk for the third phase is implementation of the necessary CAM translators. The risk for the fourth phase is being able to model the internal logic of each machine in a language like JavaScript. The risk for the fifth phase is reaching consensus on the standards necessary for all of the models. This consensus is necessary so that the models can be made at reasonable cost by a multitude of systems. Figure 4 shows the standards pathway. Those for the product and process are technically complete. The standard for the product (nominal geometry) is fully deployed. The standard for the process data input (GD&T requirements) is going into place. The standard for the resource data is nearing completion, but has not yet been shown to meet all of the requirements of the whole CAD/CAM community. A second edition is underway to complete these requirements.

Product	Process	Resource
• STEP 1.0 B-reps	• STEP 2.0 GD&T	• STEP 3.0 Assets
– 1984 IGES	– 1998 AP214/224	– 2001 ISO 14649
– 1989 IPIM	– 2006 AP203 e2	– 2007 AP238
– 1995 AP203	– 2015 AP242	– 2020? AP238 e2

Fig.4. Standards necessary to complete the roadmap – product: why you need to make it; process: what you are going to do; resource: how you will do it.

4. Enabling software

A risk for all the phases is that writing apps on today's CAD/CAM systems is hard because they are large and monolithic. Therefore, a new software programming stack is proposed to make the programming easier. The stack consists of a STEP backbone, the Web gateway, the Interpretation environment and the Manufacturing app (SWIM). In Figure 5 the STEP backbone and the Web gateway are part of a new component called STEP Node that communicates STEP data to a system that is very popular for network programming called Node.js [5].

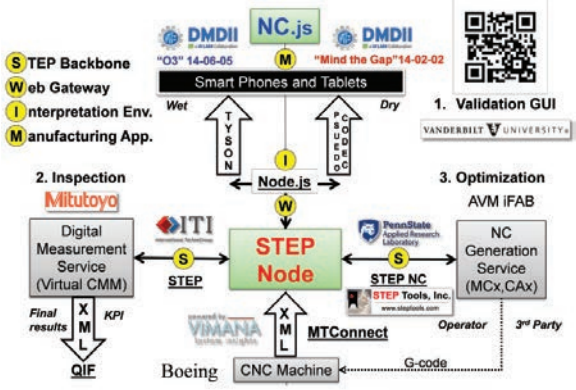

Fig.5. New services for cloud based machining

The STEP backbone can be implemented by any system that reads and writes STEP data. The web gateway can be any system with manufacturing machine simulation capability that also meets the protocols of Part 21 Edition 3. The interpretation environment can be any system that supports the REST protocols. Node.js is the most important example because it makes building web servers for manufacturing services easy. The first manufacturing app is NC.js. It has been built by RPI students over the summer of 2016 using a lightweight extension to Three.js made by Vanderbilt University called CAD.js. NC.js shows how to balance tool wear and the production schedule by making the machining faster or slower.

The SWIM stack relies on the Part 21 Edition 3 protocol (ISO 10303-21:2016). This standard has several new features. For the first phase we are using UUID's to track the connection between JSON Web objects, and normalized STEP objects. This is making machining simulation on the web possible. For 2017 we predict digital signatures will be used determine the provenance (origin) of the operation that produced a result when it is measured as out of tolerance by a CMM. In 2018 anchors and references will be used to link products and processes so that requirements and solutions can be shared across the supply chain. In 2019 JavaScript will be used to communicate PLC logic between machines and remote systems. In 2020 modular data sharing will enable hyper-connection of engineering web services.

In 2016 the stack is enabling the development of the three new engineering services shown in Figure 5. Other services are being contemplated for asset management, load balancing and production scheduling. GD&T makes the definition of all the services possible because upper and lower limits can be computed for optimizations. Figure 6 summarizes the stack with references to the source documentation and explanations of the risks and benefits of each stage.

Year	Requirement	P21 E3 Enabler	Risk
2016	Model sharing	Universally Unique Identifiers (UUID)	Cannot model machining on the web
2017	Tolerance sharing	Digital signatures for provenance	Insufficient detail for measurement
2018	Process sharing	Anchors and references for connectivity	CAM translators not yet available
2019	Machine sharing	JavaScript for machine specific ops	Standard not reached consensus
2020	Results sharing	Hyper-connection across the web	P21 E3 protocols unable to scale

- (S) STEP Backbone (Information Models)
  - http://www.steptools.com/support/stdev_docs/stpman/html/index.html
- (W) Web Gateway (P21 Edition 3)
  - http://www.steptools.com/support/stepnc_docs/stepncdll/
- (I) Interpretation Environment (appropriate schema definitions)
  - http://www.iso.org/iso/home/store/catalogue_ics/catalogue_detail_ics.htm?csnumber=63141
- (M) Manufacturing Apps (open source)
  - https://github.com/ghemingway/cad.js/tree/master

Fig.6. SWIM stack as enabled by Part 21 Edition 3

5. Conclusion

The goal of all this work is to reduce costs by delivering new efficiencies. The first efficiency is a reduction in the cost of tooling by automating optimization during machining. The second efficiency is a reduction in scrappage because of continuous monitoring of results using virtual metrology. The third efficiency is a reduction in time to market because design requirements and manufacturing results are immediately shared across the supply chain. The fourth efficiency is making machine tools as easy to use as 3D printing. The fifth efficiency is a substantial reduction in software costs using almost free cloud services. Complete implementation of the roadmap at the schedule shown is unlikely because of interruptions to evaluate results.

References

[1] Bernard-Feeney A, Hedberg T. Standard for the exchange of product data. MBE 2014, http://www.nist.gov/el/msid/upload/16_aBarnardFeeney.pdf.

[2] Vijaraghavan A, Sobel W, Fox A, Dornfield D, Warndorf P. Improving Machine Tool Interoperability using Standarized Interface Protocols: MTConnect. Proceeding of 2008 Symposium on Flexible Automation 2008, http://escholarship.org/uc/item/4zs976kx.

[3] Brown C. QIF 2.0: A New Digital Interoperability Standard for Manufacturing Quality Data. Dimensional Metrology Standards Consortium. 2014, http://www.nist.gov/el/msid/upload/17_cBrown.pdf.
[4] Hardwick M, Zhao Y, Proctor F, Nassehi A, Xu A, Venkatesh S, Odendahl D, Xu L, Hedlind M, Lundgren M, et al.. A roadmap for STEP-NC-enabled interoperable manufacturing. The International Journal of Advanced Manufacturing Technology, Volume 66, Nos. 1-4, Springer Verlag, March 2013, http://link.springer.com/article/10.1007%2Fs00170-013-4894-0.
[5] Tilkov S, Vinoski S. Using JavaScript to Build High-Performance Network Programs. IEEE Internet Computing, 2010, http://steve.vinoski.net/pdf/IC-Node.js.pdf.

Acknowledgements

This work was supported by the DMDII under programs 14-02-02 and 14-06-05, the US Army and the DARPA AVM program.