Proceedings of IDETC/CIE
ASME International 25th Computers and Information in Engineering Conference
September 24–28, 2005, Long Beach, CA, USA

DETC2005-84870

VALIDATING PORTABILITY OF STEP-NC TOOL CENTER PROGRAMMING

S. Venkatesh and D. Odendahl
Boeing Company
Seattle, Washington

X. Xu
University of Auckland
Auckland, New Zealand

J. Michaloski, F. Proctor, and T. Kramer
National Institute of Standards
and Technology
Gaithersburg, Maryland

ABSTRACT

A joint effort between Boeing and the National Institute of Standards and Technology (NIST) was undertaken for validating and evaluating STEP AP238 (STEP-NC) Conformance Class 1 (CC1) for 5-axis machining. STEP-NC is a new manufacturing standard to support "design anywhere, build anywhere, and support anywhere." The joint Boeing/NIST validation intended to prove that five-Axis AP-238 programs with tool center programming (TCP), as opposed to that of axis movement data, are portable. Current RS274 "G code" part programs that use axis movement data are bound to a single CNC, are ineffective on different machine tools, and cannot be used for the exchange of information between process planning, work preparation, tooling, and other production processes. All of these obstacles add considerable time and cost to the production life cycle of a machine part. This paper discusses the joint Boeing/NIST STEP-NC TCP validation work. The major findings were that STEP-NC TCP geometrical data is portable across different 5-axis configuration CNCs. This came with a caveat, that although CNC programs can be "data-neutral", they are not necessarily "process-neutral".

Keywords

Tool Center Programming, STEP, AP238, machine tool, milling, Computerized Numerical Control, open–architecture

Nomenclature

AIM	Application Interpreted Model
AP	Application Protocol
ARM	Application Requirement Model
CAD	Computer Aided Design
CAM	Computer Aided Manufacturing
CL	Cutter Location
CNC	Computer Numerical Control
MCD	Machine Control Data
NAS	National Aeronautics Standard
OEM	Original Equipment Manufacturers
STEP	Standard for the Exchange of Product Model Data
STEP-NC	STEP for Numerical Control
TCP	Tool Center Programming

INTRODUCTION

In the continuing quest for lower costs, manufacturing has seen a shift of large original equipment manufacturers (OEMs) as manufacturers – to large OEMs as assemblers and managers of the supply base. Boeing established a virtual co-operation with several suppliers in order to produce the Boeing 777 airplane. Boeing designs, assembles and markets the aircraft, while an international network of suppliers produces the components. In this scenario, the OEM specifies the product definition that is transferred to a supplier, who eventually machines the part. With OEMs and suppliers processing the part information in different ways, inadequate data exchange hampers productivity and can impair part quality. Ideally, a complete, unambiguous and standardized data exchange representation is required to make the shift in the manufacturing paradigm truly effective.

The prevalent international data exchange standard is the

ISO 10303, Standard for the Exchange of Product Model Data, or STEP. The parts of STEP implemented in software systems are called Application Protocols (APs). STEP AP238 is the "Application interpreted model for computerized numerical controllers" [1]. AP238, or more commonly "STEP-NC", is a new standard for the exchange of comprehensive manufacturing data. STEP-NC offers accurate and complete product definition data from product design all the way to the machine tool. In addition to data exchange, STEP-NC offers a number of potential manufacturing advantages, including:

Vertical Integration – Streamlined data communication between CAD/CAM and CNC without extra data translation or post processing.

Horizontal Integration – Substitution or addition of any STEP-NC compliant system from a different provider with reduced cost and time.

Comprehensive Process Model Complete process and machining data is made available all the way to the CNC/machine tool.

Flexible Deployment – Full support for both off-line and on-line programming, plus any hybrid configuration, in the same process.

Feature Based Precision Machining – Precision machining based on part features not just lines, arcs or canned cycles internal to the CNC.

Unified Part Description – The future of manufacturing is integration of CAD/CAM, so that development, and definition of both part product and part process can be machined or maintained anywhere in the virtual enterprise.

Distributed Machining – Small machine shops across the country and around the world could possess the capability to accept STEP-NC product definition files via the Internet, plan processing operations, and produce part programs.

Adaptive machining – With a complete product model available at CNC, real-time feedback can be had utilized for adaptive control.

Although the potential benefits from using STEP-NC could be enormous, a complete change in manufacturing practices without significant and quantifiable benefits now, and not as a promise at some future point in time, is considered too risky for most in the manufacturing industry to undertake. Understanding this problem, Boeing/NIST took a more benefits-directed approach. The Boeing/NIST AP-238 work first concentrated on the leaner manufacturing benefits related to using AP238 toolpaths. It was hoped that if Tool Center Programming (TCP) cutter movement data could be shown to be portable across 5-axis CNCs, STEP-NC would gain its initial momentum in industry adoption.

Presently, most five-axis CNC machines receive ISO 6983/RS274 [2, 3] data defining each axes movement required in order to manufacture a part. This geometric data is referred to as machine control data (or MCD). MCD provides a very low level of instruction: tool, axes positions, feed, and speed. This direct programming model means that the orientation axes are traversed as synchronized axes, and are tied to specific tool geometry.

The problem with MCD programs is that they are not portable or adaptable. Portability is a problem since unique axes position data must be generated for each machine control combination (part, tool, and machine configuration) on which the part is to be run. Adaptability is a problem because no information is provided to the machine to help it adapt to real-time changes in machining dynamics (feed and speeds) or machine tool alignment (tool and wear offsets).

By comparison, tool center programming defines program geometry as cutter movement data, instead of axes movement data. Tool center programming is similar to robotic 6D pose representation. Motion is defined as a 3D tool-tip position (X,Y,Z) and a 3D tool axis orientation (I,J,K). For each TCP (X,Y,Z,I,J,K), the CNC controls the two rotation axes so that the tool is positioned and oriented as specified. In addition, the CNC controller performs tool offset compensation along the tool axis according to the position of the tool tip in the proper position and orientation.

STEP-NC allows tool center programming to define program geometry as cutter movement data, instead of axes movement data. STEP-NC also provides rich, high level information about the part features, materials, cutters, and dimensional tolerances. In the aerospace industry, tighter and tighter part tolerances are the expected norm so that the need for STEP-NC is pronounced. TCP can provide some direct accuracy improvements since each CNC will determine its tool tip position, as opposed to a CAM system generating static toolpaths as a series of axes positions. Since machine geometries can vary slightly even between identical machines, expected accuracy improvement should be significant.

This paper will look at the portability of STEP-NC for defining 5-axis machining toolpaths. We will discuss what was involved in making TCP programs to be machine neutral for different five-axis configurations. The next section will give an overview of the validation steps in making this happen. It will include the importance of machine-dependent workingsteps as a means to ensure portability of the STEP-NC part programs. Following will be a discussion on the challenges encountered on the way to a portable TCP milled part.

VALIDATION SCENARIO

The Boeing/NIST validation goal was to prove that AP238 Tool Center Programming motion data is "machine neutral" and may be used directly by machines with different five-axis configurations. For the initial testing, the part selected was a half-scale National Aeronautics Standard (NAS) 979 5-Dimensional

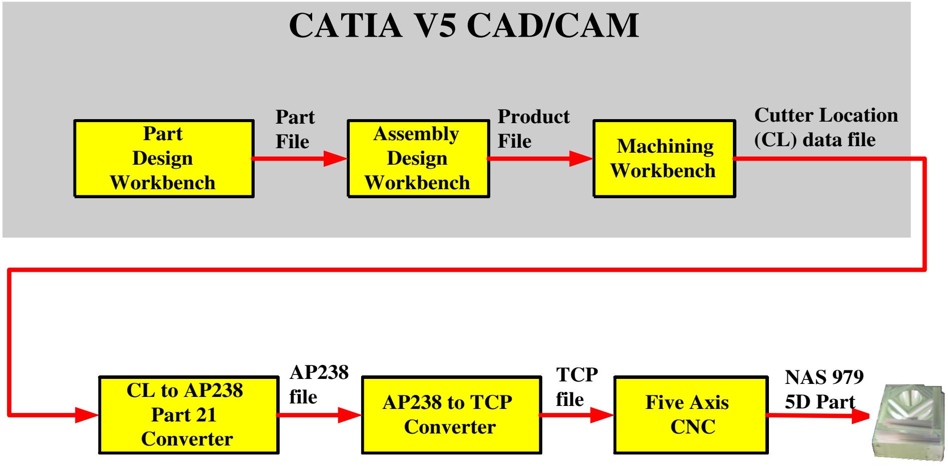

Figure 1. AP238 Tool Center Programming Validation

```
PROC WSTOOL(INT AP238_TOOL)
N70 D0                      ;Tool length compensation off
N80G 500                    ;Workpiece offsets off
N90 TRAFOOF                 ;5-axis transformations off
N120 T=AP238_TOOL           ;Get the new tool number
N130 M6                     ;Change the tool
N150 TRAORI(1)              ;Activate 5-axis transformations
N160 ORIWKS                 ;We're in "part space"
N170 G55                    ;Activate workpiece offset
N180 G90                    ;Absolute programming
N190 D1                     ;Activate tool length compensation
N230 G1                     ;No more rapids
RET
```

(a) NIST Tool Change

```
PROC WSTOOL(INT AP238_TOOL)
DEF REAL OLD_X, OLD_Y, OLD_Z,
    OLD_A, OLD_C
;Save the original position
N10 OLD_X= $AA_IW[X]                 ; x tool base coordinates
N20 OLD_Y= $AA_IW[Y]                 ; y tool base coordinates
N30 OLD_Z= $AA_IW[Z]                 ; z tool base coordinates
N40 OLD_B= $AA_IW[B]                 ; a tool base coordinates
N50 OLD_C= $AA_IW[C]                 ; b tool base coordinates
N60 M11                              ;Smog Hog off
N70 D0                               ;Tool length compensation off
N80 G500                             ;Workpiece offsets off
N90 TRAFOOF                          ;5-axis transformations off
N100 G0Z=$AA_SOFTENDP[Z]-0.5A0       ;Retract to maximum Z
N110 G74C0.0                         ;Resynch table
N120 T=AP238_TOOL                    ;Get the new tool number
N130 M6                              ;Change the tool
N150 TRAORI(1)                       ;Activate 5-axis transformations
N160 ORIWKS                          ;We're in "part space"
N170 G55                             ;Activate workpiece offset
N180 G90                             ;Absolute programming
N190 D1                              ;Activate tool length compensation
N200 G0 C=OLD_C                      ;Restore C position
N210 B=OLD_B                         ;Restore B position
N210 X=OLD_X Y=OLD_Y                 ;Restore X and Y position
N220 Z=OLD_Z                         ;Restore Z position
N230 G1                              ;No more rapids
N230 TOL_5( .0012 )                  ;Toolpath accuracy/speed
RET
```

(b) Boeing Tool Change

Figure 2. Tool change Workingsteps

part (commonly known as the Circle Diamond Square or CDS) designed for runoff tests of new machine tools [4]. Since STEP-NC is a nascent technology with minimal vendor support, it took a bootstrapping operation in order to utilize AP238 and produce TCP part programs. Figure 1 shows the validation process in which a manufacturing part is sequenced through CAD/CAM and ultimately onto a CNC.

Boeing modeled the NAS 979 part in CATIA workbench. Using CATIA Version 5, Boeing then generated a part program into legacy Cutter Location (CL) format [5]. CL can represent angular cutter motions in a CNC configuration-independent I,J,K way, with the assumption that the underlying machine tool controller will translate the I,J,K into machine specific 5 axes angular configuration.

Boeing wrote a program to translate the CL file into AP238 Part 21 [6] file based on the AP238 toolpaths technology. STEP Part 21 specifies the data exchange format for product data based on schemas defined in the EXPRESS language (ISO 10303-11) [7]. In our case the Part 21 file encodes machine workingsteps as TCP toolpaths based on the AP 238 Express schema, which is then suitable for the transfer between manufacturing systems. Boeing wrote another program, which translated the AP238 Part 21 into a controller-specific TCP programs. Boeing successfully demonstrated the ability to produce and run identical TCP programs on different brands and configurations of five-axis CNCs at Boeing/Tulsa. This demonstration alone is significant in that it reduces costs due to post processing to machine-specific RS274 part programs. If CNC vendor participation increases, the translation from AP238 Part 21 toolpath translation would done transparently on the CNC.

With the goal of validating the TCP technology on a CNC in a different setting, Boeing asked NIST to also machine the NAS 979 part using the same TCP program. Upon receiving the Boeing TCP program, it quickly became apparent that there is more to part program portability than just geometries. An initial dry run test of the TCP program proved this out as the NIST CNC expected coordinate transformations to be explicitly turned off during a tool change, which all Boeing controllers implicitly do, so that the NIST CNC ended up crashing into the tool magazine.

CNCs provide auxiliary support for tooling, coolant, feeds and speeds, and the approach to these aspects can vary greatly from machine to machine. Further, Boeing CNCs have more optional machine capabilities than the controllers for NIST machine tools, for example the capability to specify motion tolerancing. To allow portable TCP programs, it was determined that each machine should be required to host a set of standard STEP-NC infrastructure workingsteps (IWs), that are callable CNC subprograms from the STEP-NC downloaded part program, thus promoting portability by pushing machine dependent operation onto the machine.

With machine-dependent infrastructure workingsteps embedded in the CNC, TCP part programs can be machine neutral and made compatible for machines within a given class such as milling or turning. Figure 2 shows the code for a tool change infrastructure workingstep for a NIST and a Boeing machine tool. The `WSTOOL` subprogram was written for the NIST CNC, and must be resident on the CNC controller in order for the Boeing TCP program to be portable.

After establishing an agreed upon set of workingsteps, the 1/2 scale NAS 979 5D part was simulated at NIST on a Deckel Maho Gildemeister (DMG) DMU 70 eVolution running a Siemens 840D controller. NIST wrote customized workingsteps for the DMG and the NAS 979 5D TCP program "worked great in simulation". However, before actual machining, NIST machinists reviewed the NAS 979 5D setup, and said the 1/2 scale part was not really suitable for the DMG. The machinists said the DMG did not have any 1" diameter tools or any 1" cutter holders for the DMG, and that the specified 3.25" length cutters would have too much overhang and be prone to chatter or break. The NIST machinists further pointed out the supplied TCP feeds and speeds were not appropriate for the high-speed machining DMG, but could be used. After the realization of the process divergence, the NAS 979 5D part and tooling were scaled down to 1/4 size at NIST, the Boeing TCP program was successfully used to produce the NAS 979 part on the NIST five-axis DMG.

DISCUSSION

The collaboration between Boeing and NIST proved useful in exposing potential areas of non-portability of AP238 TCP programs. The difference in NIST and Boeing machining cultures dramatically highlighted a machining axiom, that although CNC programs can be "data-neutral", they are not necessarily "process-neutral". The machining cultures between NIST and Boeing vary greatly. NIST is a small batch job shop, where machinists work with engineers to design and then produce CNC programs exclusively using MasterCAM and then post and run the CNC programs themselves. Boeing and its subcontractors operate large production plants with 24/7 manufacturing, with extensive staff for CAD/CAM/CNC programming, post-processing and machine operation. The disparity of manufacturing practice was illustrated by the differing machining process approaches: English versus metric; ways of fixturing; material hogging versus high-speed machining; and typical part sizes. Fortunately, the definition of a suite of standard STEP-NC infrastructure workingsteps (IWs) appeared to resolve all of the portability issues by localizing machine inconsistencies.

Another finding was that even if TCP part programs are indeed portable, they are not necessarily optimal. The use of the most limited process parameters for feeds and speeds in the TCP program may not be practical for machining the same part on a 20-year-old Cincinnati gantry and then on a 1-year-old, high-speed DMG. In spite of these issues related to portability, there is indeed a huge benefit to be gained by a large production facility with many machines of comparable capability, such as Boeing, to exploit TCP program portability and quickly move part production between machines of a similar chip-removal capability on a shop floor. With portability basically solved, further validation needs to be done in the matching of part programs to machine capabilities with the outcome either a "go/no go" and eventually

```
#180=MACHINING_TECHNOLOGY_RELATIONSHIP('WS 1 TP 1','feed and speed',#160,#190);
#190=MACHINING_TECHNOLOGY('WS 1 TP 1','milling','','');
#200=ACTION_PROPERTY('feedrate','WS 1 TP 1',#190);
#210=ACTION_PROPERTY_REPRESENTATION('feedrate','WS 1 TP 1',#200,#220);
#220=MACHINING_FEED_SPEED_REPRESENTATION('feed speed', (#230),$);
#230=MEASURE_REPRESENTATION_ITEM('feed speed', NUMERIC_MEASURE(400.0), #12);
```

(a) AIM Schema

```
#180=MACHINING_FEED_SPEED('feedrate', NUMERIC_MEASURE(400.0),#160);
```

(b) ARM Schema

Figure 3. AIM verus ARM Complexity

as an on-machine adaptive tuning of feeds/speeds based on part features and tolerances.

Within the validation the issue of complexity of the AP238 Express schema and potentially excessive sizes of AP238 Part 21 files was debated. In general, STEP performs a reinterpretation of an Application Reference Model (ARM) (ISO 14649 [8, 9]) schema into a fully-integrated Application Integrated Model (AIM) schema. The basic concept is that the ARM describes the application in the domain terminology, while the AIM makes sure the data is integrated into all STEP product models. As an AIM model, AP238 was mapped from the ARM models into the pre-existing Express data structures using a set of base elements called the Integrated Resources – similar in concept to LISP atoms and properties. The actual relationship between the ARM and AIM is described by AIM mapping tables. Without going into major detail, Figure 3 shows the dramatic textual increase between an ARM and AIM Part 21 file to represent the same feedrate information. In spite of the data inflation, the use of AP238 AIM was still considered acceptable for part sizes comparable to NAS979 and other Boeing test parts. We are attempting more parts size assessment, especially with die and mold test parts, as these parts can become extremely large. However, for a die/mold, there can be a significant reduction of Part 21 file sizes, as die/molds are modeled in a CAM system with splines, but this information is lost in the translation into web of points for the CNC.

The joint Boeing/NIST AP-238 work on proving TCP portability was just a first step toward leaner manufacturing on the journey from legacy RS274 systems to STEP-NC systems. But, the impact of STEP-NC technology on large OEMs, such as Boeing, as well as their suppliers can be even more significant. Boeing and NIST are cooperating on additional validation work in order to evaluate and publicize STEP-NC benefits and increase vendor participation. One validation area relates to the potential benefit from the consolidation of static knowledge and consumable manufacturing data within a single data format representation thus reducing the cost of product changes. Another potential benefit from a consolidated data representation would be improved global supplier collaboration due to the easier exchange of data with a reduction in part defects and costs related to translation errors. Another validation area for STEP-NC is to incorporate in-process inspection under a single data format representation which would lead to more efficient part quality inspection process, and the realization of "first time correct" scenario.

SUMMARY

This paper describes the joint Boeing/NIST AP-238 work to validate portable TCP programs. The Boeing/NIST work attested to the need for standardizing STEP-NC workingstep infrastructure as a way to allow TCP program portability and handle the CNC machine dependent variations and options. Using AP238 toolpaths and a common working infrastructure, TCP cutter movement data was shown to be portable across different 5-axis configuration CNCs as well as across manufacturing cultures with different machining practices.

DISCLAIMER

Commercial equipment and software, many of which are either registered or trademarked, are identified in order to adequately specify certain procedures. In no case does such identification imply recommendation or endorsement by the National Institute of Standards and Technology or Boeing Aerospace, nor does it imply that the materials or equipment identified are necessarily the best available for the purpose.

REFERENCES

[1] ISO TC 184/SC4/WG3 N1089, 2004. *ISO/DIS 10303-238: Industrial automation systems and integration Product data representation and exchange Part 238: Application Protocols: Application interpreted model for computerized numerical controllers.* Geneva, Switzerland.

[2] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1982. *ISO 6983/1 – Numerical Control of machines – Program format and definition of address words – Part 1:*

Data format for positioning, line and contouring control systems. Geneva, Switzerland.

[3] ENGINEERING INDUSTRIES ASSOCIATION, RS274D, 1979. *EIA Standard - EIA-274-D, Interchangeable Variable, Block Data Format for Positioning, Contouring, and Contouring/Positioning Numerically Controlled Machines*. Washington, D.C.

[4] NATIONAL AEROSPACE STANDARD, 1969. *Uniform Cutting Tests - NAS Series: Metal Cutting Equipment Specifications*. Washington, D.C.

[5] ELECTRONIC INDUSTRIES ASSOCIATION, 1992. *ANSI/EIA-494-B-1992, 32 Bit Binary CL (BCL) and 7 Bit ASCII CL (ACL) Exchange Input Format for Numerically Controlled Machines*. Washington, D.C.

[6] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1996. *ISO 10303-21: 1996, Industrial automation systems and integration – Product data representation and exchange – Part 21: Implementation methods: Clear text encoding of the exchange structure*. Geneva, Switzerland.

[7] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 1994. *ISO 10303-11: 1994, Industrial automation systems and integration Product data representation and exchange Part 11: Description methods: The EXPRESS language reference manual*. Geneva, Switzerland.

[8] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2004. *ISO 14649: Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 10: General process data*. Geneva, Switzerland.

[9] INTERNATIONAL ORGANIZATION FOR STANDARDIZATION, 2000. *ISO 14649: Industrial automation systems and integration – Physical device control – Data model for computerized numerical controllers – Part 11: Process data for milling*. Geneva, Switzerland.