



Title:

**A Modular CAD Based GD&T Workflow for CNC Machining and Inspection**

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Introduction:

Tolerance specification, machining, inspection, and analysis are naturally related workflows, but their practical and seamless integration with CAD/CAM and machining operations remains, for the most part, unattained. The recent STEP AP242 and Industry 4.0 initiatives identify such requirements, particularly with respect to information collection, analysis, and process control. This paper describes development of a CAD/CAM based workflow for integrated tolerance specification, custom CNC based machining and inspection path generation, simulated probe data point generation, and analysis. The workflow begins with Product and Manufacturing Information (PMI) based addition of the necessary Geometric Dimensioning & Tolerancing (GDT) specifications to the geometric part model. The manufacturing setup template then references this PMI data to generate the machining operations. Parametric custom machine tool touch trigger probe paths are then created, with an option to generate simulated data results. These results are then imported for display and analysis within the same CAD/CAM system user interface.

Current Technology Review:

An essential goal of discrete part manufacturing is to produce items that comply with geometric tolerances, as described by the ISO 1011 [1] and related standards. Recent commercial CAD/CAM software releases include support for neutral data exchange using STEP AP242 [2] compatible GDT PMI (Fig. 1). Coordinate Measuring Machine (CMM) motion controllers and related software have developed significant mathematical capability to generate and execute inspection paths, and to analyze resulting data. Sensors have expanded from touch trigger probes to high density analog touch and non-contact scanners. Although information technology integration, from CAD model through machining, inspection, and analysis, is a central theme of the Industry 4.0 [3] trend, realization of this capability within the CNC machine tool and related CAD/CAM software remains very much unattained. Inspection path planning has only recently begun to appear in machining software, and controllers continue to lack the mathematics required for online data processing. Even though the required analysis algorithms are well known, they are not integrated within software CAM modules. Achieving such integration will reduce scrap at the source of production, shifting the inspection step from a dreaded out of tolerance reporter to a pro-active in-process control step. Practical progress towards this goal is reported in the remainder of this paper.

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<sup>1</sup>Contact Author. This project was carried out as private consulting administered by Longterm Technology Services, Inc., London, Ontario, Canada.

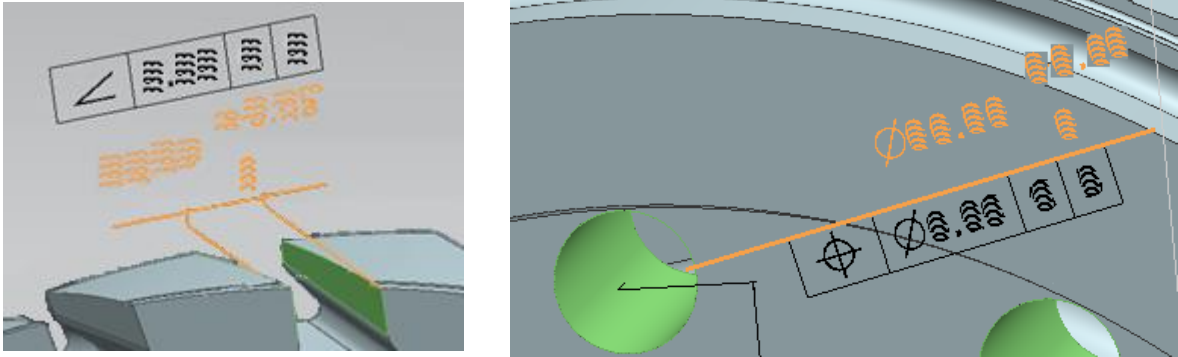


Fig. 1: STEP AP242 [2] compatible Geometric Dimensioning & Tolerancing (GDT) created using Product and Manufacturing Information (PMI). Actual values are obscured for proprietary reasons.

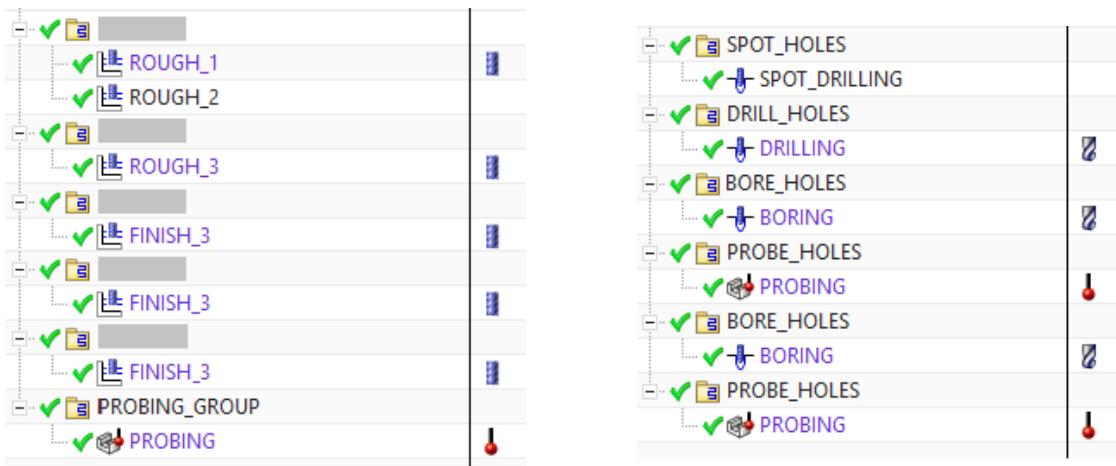


Fig. 2: Manufacturing template setup operation list including custom machine tool probing operations. Both dovetail throat and bolt hole boring examples are shown.

### Implementation:

The implemented system is based on the Siemens NX10 [4] CAD/CAM software. The part is a rotor disk from a land-based turbine containing dovetail blade grooves and bolt hole patterns that must be machined to close tolerances. From both time and financial aspects, scrapping such a large part is very expensive. The PMI GDT is first added to the CAD design model. A manufacturing setup template is pre-configured with manufacturing engineer defined machining operations including use of spot drills, regular drills, boring bars, milling cutters, and custom machine tool probing inspection extensions (Fig. 2). The GDT from the CAD design model is accessible for reference during manufacturing and probing operation specification.

Machine tool probing is most commonly implemented using Renishaw® [5] or equivalent equipment and associated macros. There is a desire to probe the dovetail throat wall angle/position and width, but this unique geometry is not directly supported by a corresponding Renishaw probing macro, or by Siemens NX. Consequently, a special Visual Basic .NET DLL algorithm was developed. The algorithm begins with a dialog box that prompts the user to select the PMI width and position/angle tolerances (Fig. 3(a)). Based on a rectangular grid aligned with the spindle +Z axis and the normal vector of the planar wall, the individual probing path points on the surfaces are then generated. Grid points outside of the wall boundary are discarded (Fig. 3(b)). To assist in offline development, the dialog box provides an option to generate simulated probing data. The simulation data, or, when

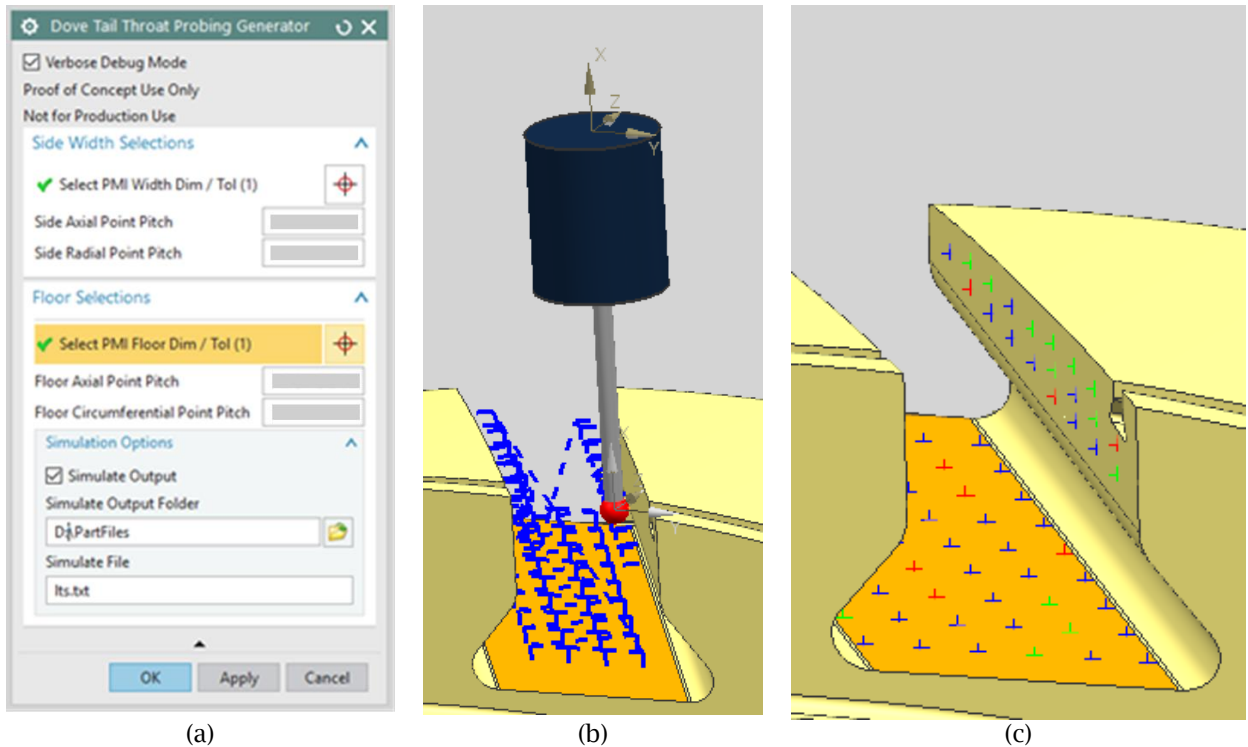


Fig. 3: Dovetail throat geometry probing and analysis: (a) dialog box, (b) generated probing path, (c) simulation data display.

available, actual data, can then be imported into the same CAD manufacturing environment for display and analysis (Fig. 3(c)). The manufacturing engineer is presented with valuable information by simply displaying the actual points using the color code **red=narrow**, **green=wide**, **blue=within tolerance**.

Because the PMI variable data is not automatically carried through to the CNC post processor, completion of the workflow requires additional customization. Within NX, the additional variables are created by adding a User Defined Event (UDE) and associated dialog boxes (Fig. 4) to the manufacturing template. The Visual Basic DLL reads the CAD design model PMI and populates the UDE variables. For example, assuming that the deviation of each throat wall surface point is within bounds, final Renishaw L9810/L9822 macro calls are used to compare with the PMI tolerance. The L9810 coordinates of the point midway between the walls, and the L9822 wall normal vector as well as the width/angle tolerances, are all communicated by the Visual Basic DLL using UDE variables. The customized post processor reads the UDE variables and formats appropriate CNC output (Fig. 5(a)). For this macro  $R1$  represents the wall angle,  $R7$  represents the width,  $R11$  is the bilateral width tolerance, and  $R13$  is the angle (position) tolerance. During execution of the macros, out of tolerance conditions will lead to an alarm and program halt. Otherwise, cutter radius offset variables can be adjusted for a second cut. In all cases data is “printed” to a results file for graphical analysis.

The customized post processor is also programmed to convert the PMI tolerances to conform with the expressions expected by the Renishaw macro. For example, in the case of the bolt hole pattern, the PMI bore hole size tolerance is expressed unilaterally as  $\approx \rightarrow \triangleright \text{---}$   $\rightarrow \triangleright \text{---}$ , but the Renishaw L9814 bore probing macro expects a bilateral tolerance. Accordingly, post processor Tcl/Tk [6] statements (Fig. 5(b)) are used to convert the tolerance to  $\approx \rightarrow \triangleright \text{---} \ll \leftarrow \triangleright \text{---}$ . This is accomplished by reading the PMI extracted UDE variables `pcd_diameter`, `pcd_dia_up_tol`, and `pcd_dia_lo_tol`. The midzone value  $\rightarrow \triangleright \text{---}$  is calculated as assigned to the variable `nominal_diameter`, and output as

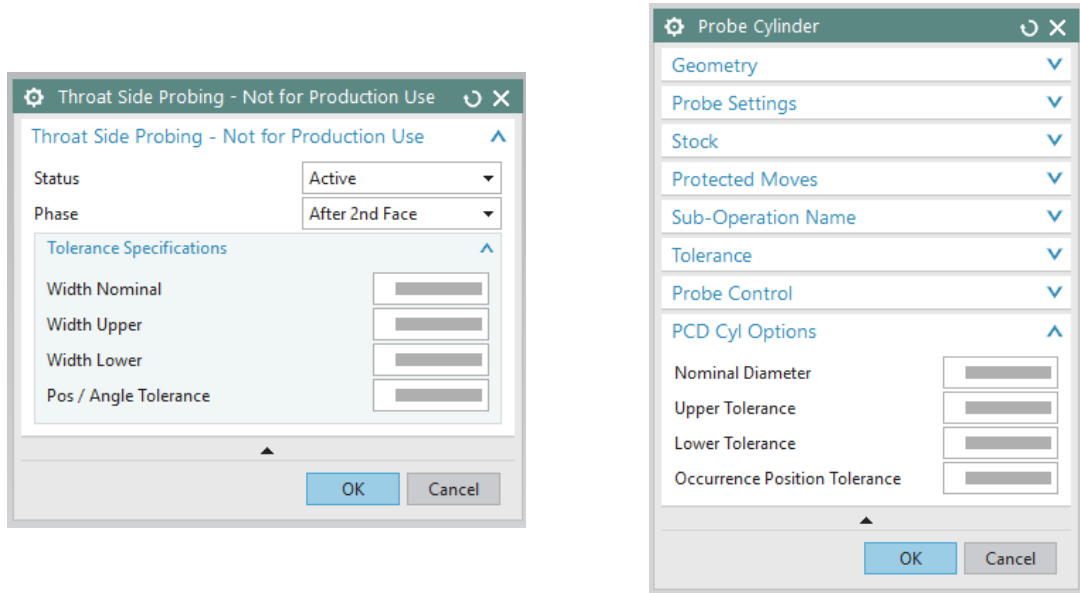


Fig. 4: User Defined Event (UDE) variables added and displayed on probing operation dialog boxes.

Siemens Sinumerik CNC controller [7] parameter register R7. The bilateral tolerance is calculated as  $\frac{1}{2} \Delta$ , and assigned to variable `probe_nominal_tolerance`, and output as parameter register R11. The cylindrical position tolerance zone is represented by UDE variable `pcd_tp_tol` and output as parameter register R13.

#### Discussion:

As can be seen from the above, actual implementation of an integrated PMI/GDT inspection workflow for CNC machining processes remains a tedious task. With the STEP AP242 standard now being implemented within the most recent commercial CAD system releases, significant progress has been achieved at the design specification level. Implementation within manufacturing is impeded by a lack of consistent probing macro support within the CAD/CAM software. Siemens NX provides a rich customization ability that, for specific circumstances, enables developers skilled in Visual Basic or equivalent DLL programming to achieve a working solution. Less skill is required to customize the post processor and it is envisioned that, with appropriate documentation, end user CAD managers could maintain that component of the workflow. A desired next step is for CAD system developers to take note of this and similar DLL customizations, and implement within future releases.

Inclusion of on CNC control inspection and tolerance mathematics is becoming possible with modern controls such as the Sinumerik used herein. To be trusted, actual implementations must be checked against verified standards. Otherwise the conservative mindset of the industry will impede progress.

#### Conclusions:

This paper has presented a modular framework for integration of CAD/CAM with machining inspection and analysis. It includes access to PMI representation of geometric tolerances, simulation and graphical results display. Implementation required Visual Basic DLL programming, as well as post processor customization. Continuing research will focus on adding CNC control capability to support the necessary feature fitting and related tolerancing mathematics, with the aim of achieving closed loop response in the spirit of the Industry 4.0 initiative.

### Acknowledgements:

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```
MSG(" CUSTOM THROAT SIDE PROBING PHASE ANGLED POCKET CYCLE ")
MSG(" L9822 POINT COORDINATES X   xxx.xxx Y   xxx.xxx Z   xxx.xxx ")
MSG(" L9822 POINT VECTOR I   x.xxx J   x.xxx K   x.xxx ")
MSG(" L9822 WIDTH NOMINAL   xxx.xxx UPPER   x.xxx LOWER   x.xxx ")
MSG(" L9822 POS ANGLE TOLERANCE   xx.xxxx ")
MSG(" R9=feedrate R24=x R25=y R26=z ")
N2935 R9=xxxx.xxx R24=xxx.xxx R25=xxx.xxx R26=xxx.xxx
N2940 L9810
MSG(" R1=a R7=d R9=feedrate R11=h R13=m R20=toolno R23=w ")
N2945 R1=xx.xxx R7=xxx.xxx R9=xxxx.xxx R11=xx.xxx R13=xx.xxx R20=xx R24=xxx.xxx
R25=xxx.xxx R26=xxx.xxx
N2950 L9822
```

(a)

```
# set the cylindrical position tolerance
set probe_cylindrical_tolerance $pcd_tp_tol

# set the nominal hole diameter and bi-directional tolerance zone size
set tol_zone_half_width [expr {$pcd_dia_up_tol - $pcd_dia_lo_tol}]
set tol_zone_half_width [expr {$tol_zone_half_width * 0.5}]
set tol_zone_bias [expr {$pcd_dia_lo_tol + $pcd_dia_up_tol}]
set tol_zone_bias [expr {$tol_zone_bias * 0.5}]
set nominal_diameter [expr {$pcd_diameter + $tol_zone_bias}]
set probing_diameter $nominal_diameter
set probe_nominal_tolerance $tol_zone_half_width
```

(b)

```
MSG("L9814 BORE CIRCUMFERENCE POSITION TOLERANCE x.xxx")
MSG("L9814 BORE TOLERANCE DIAMETER xx.xxx, UP TOL x.xxx, LO TOL x.xxx")
MSG("L9814 BORE NOMINAL DIAMETER R7=d, R9=feedrate, BILATERAL HALF TOL R11=h,
POSITION TOLERANCE R13=m, R23=w")
N2390 R7=xx.xxx R11=x.xxx R13=x.xxx R18=x.xxx R20=00 R23=1
N2395 L9814
```

(c)

Fig. 5: Post processing of UDE variables for probing macro parameters: (a) throat side wall CNC output code (b) Tcl/Tk bore probing post processor customization, (c) post processor bore probing with PMI parameters

### References:

- [1] International Organization for Standardization, Geometrical product specifications (GPS) - Geometrical tolerancing - Tolerances of form, orientation, location and run-out, ISO 1101:2012, Geneva, Switzerland.
- [2] International Organization for Standardization, Industrial automation systems and integration - Product data representation and exchange - Part 242: Application protocol: Managed model-based 3D engineering, ISO 10303-242:2014, Geneva, Switzerland.
- [3] Secretariat of the Platform Industrie 4.0, Recommendations for implementing the strategic initiative INDUSTRIE 4.0, 2013, Frankfurt, Germany
- [4] Siemens PLM Software, NX10, Plano, TX, USA
- [5] Renishaw plc, New Mills, Wotton-under-Edge, Gloucestershire, UK
- [6] Tcl Developer Exchange, Tool Command Language / Graphical User Interface Toolkit (Tcl/Tk), [www.tcl.tk](http://www.tcl.tk)
- [7] Siemens AG Digital Factory, Sinumerik CNC systems, Erlangen, Germany.