Virtual CNC with Performance Error Modeling

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Abstract: Speed and accuracy are important criterion for evaluating any NC verification system. The speed must be much faster (preferably by orders of magnitude) than physical machining. The accuracy must meet shop floor usage. Extension of an NC verification system to model the impact of very small CNC performance errors (geometric and thermal machine errors) on the workpiece introduces additional and very stringent demands. Typical performance errors can be as small as 10 microns or less. On a 3 axis CNC, the performance errors can lead to effective 5 axis tool moves (e.g. by rotating the spindle from the nominal tool axis). The central issue is whether any virtual CNC can model such small errors over complex tool paths in reasonable computational times. Progress will be reported on a research program designed to meet these requirements.

1. INTRODUCTION

MentorLink, in collaboration with N-See Software, is developing a virtual CNC that models performance errors on a 3 axis CNC. The work is being carried out in collaboration with several industry partners as party of the NIST National Advanced Manufacturing Testbed (NAMT) project [Blomquist, 1996]. This paper will report on progress on that project, which in the first phase is limited to geometric errors.

The focus of the project is on the workpiece. Much earlier work on performance modeling has only considered a general map of the errors at points as generated by applying the CNC error data to a rigid body kinematic model of the CNC or have limited the tool paths and geometries to simple slotting cuts [e.g. Donmez, 1986; Kirendena, 1991; Chen, 1993; Pahk, 1997]. The error map gives some guidance on the scale of the errors, but does not translate directly into errors on the workpiece since the map only provides errors at the tool tip while the tool and the tool sweeps are extended objects.

Our interest is on the signatures left behind by CNC performance errors on the workpiece. The goal can be stated as

> Given the error model for a CNC, the NC part program and the Set Up (stock geometry, position and orientation, fixturing and tooling), determine if the part produced on that CNC will meet specified quality conditions.

An Industry representative in the NIST NAMT project [Covington, 1997] has re-stated this as requiring

> A simple and reliable way for a shop floor person to accept the above information (error data, stock, tool) and to receive a Go/NoGo signal for his particular quality requirements on a particular CNC for a specified part program, prior to physical part production.

2. PROJECT SUMMARY

The first phase of this project is limited to geometric errors on a 3 axis mill. The end product will be attuned to shop floor use, being robust, reliable and semi-automated, so as to meet highly variable skill sets. The project is composed of three parts: A Kinematic Error

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Model, A Virtual CNC capable of handling the required speed and accuracy, and Quality Assurance.

3. KINEMATIC ERROR MODEL

Geometric errors can arise from a variety of sources. Guides may not be straight or the spindle may not be correctly aligned. Each axis can have up to 6 degrees of freedom for its error components. For example, moving the CNC to a nominal X coordinate can lead to errors in the actual X,Y and Z location as well as pitch, yaw and roll (angular) errors. In addition, there may be errors due to a lack of squareness between axes, leading to a total of 3 axes*6 Degrees of Freedom per axis for a total of 21 degrees of freedom or error parameters as described, for example in [Chen, 1993].

The error parameters can be extracted from the raw error data using such devices as ball bars, electronic levels and laser measurements. Guidelines for characterizing the performance errors on a CNC may be found in the ANSI/ASME B 5.54 Standard [ANSI/ASME, 1991]. Sample results for the error parameters are given in [Chen, 1991; Donmez, 1986; Kiridena, 1991; Pahk, 1997]. Normally, they are obtained by a least squares fit to the data, but Tajbakhsh and collaborators [Tajbakhsh, 1997] suggest some modest improvement in the error modeling can be made using a Chebyshev norm (essentially minimizing the maximum deviation, rather than minimizing the sum of squared deviations in the fit.

We will adopt the following notation for these 21 error parameters. R refers to rotational or angular errors, T refers to translation errors and S to squareness errors. The left subscript will indicate the moving slide associated with the error and the right subscript will indicate the error direction. So, for example, xTy refers to the translational error of the X axis along the Y direction. The error parameter is normally considered to be a function of the position of the associated moving slide relative to a reference point.

The kinematic equation relates these 21 error parameters to actual error offsets and angular displacements in the CNC machine coordinate system. The form of the kinematic equations depend on the machine tool configuration – how each slide is stacked on top of the other. The following derivation is for a vertical spindle, traveling gantry machining center as shown in Section 2.2.11 of the ANSI/ASME B5.54 Standard [ANSI/ASME, 1991]. The results reported will be for this class of CNC. We have also derived similar kinematic equations for other classes of CNCs.

The derivation of the kinematic error equations starts with homogeneous transformations for each machine axis. For each slide or axis there is a transformation indicating how a point is referenced in an ideal system (e.g. Hxideal) and how that position is altered due to the geometric performance errors (e.g. Hxerror). For this specific machine tool configuration, the transformation matrices are:

$$\mathrm{Hxideal} := \begin{bmatrix} 1 & 0 & 0 & X \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \mathrm{Hxerror} := \begin{bmatrix} 0 & -(xRz+Sxy) & xRy+Sxz & xTx \\ xRz+Sxy & 0 & -xRx & xTy \\ -(xRy+Sxz) & xRx & 0 & xTz \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathrm{Hyideal} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & Y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \mathrm{Hyerror} := \begin{bmatrix} 0 & -yRz & yRy & yTx \\ yRz & 0 & -(yRx+Syz) & yTy \\ -yRy & yRx+Syz & 0 & yTz \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

$$\mathrm{Hzideal} := \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & Z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad \mathrm{Hzerror} := \begin{bmatrix} 0 & -\mathrm{zRz} & \mathrm{zRy} & \mathrm{zTx} \\ \mathrm{zRz} & 0 & -\mathrm{zRx} & \mathrm{zTy} \\ -\mathrm{zRy} & \mathrm{zRx} & 0 & \mathrm{zTz} \\ 0 & 0 & 0 & 0 \end{bmatrix}$$

The total transformation can be found by a matrix product as:

$$H_{\mathrm{system}} := \mathrm{Hxideal} \cdot \mathrm{Hyideal} \cdot \mathrm{Hzideal} \cdot T + \mathrm{Hxerror} \cdot \mathrm{Hyideal} \cdot \mathrm{Hzideal} \cdot T + \mathrm{Hyerror} \cdot \mathrm{Hzideal} \cdot T + \mathrm{Hzerror} \cdot T$$

This leads to the final equations relating ideal (as-programmed) coordinates to the actual (true) coordinates:

$$X_{\mathrm{true}} := X + \mathrm{Xp} + \mathrm{xTx} + \mathrm{yTx} + \mathrm{zTx} - (\mathrm{xRz} + \mathrm{Sxy}) \cdot (Y + \mathrm{Yp}) + (\mathrm{xRy} + \mathrm{Sxz}) \cdot (Z + \mathrm{Zp}) + \mathrm{yRy} \cdot (Z + \mathrm{Zp}) - \mathrm{yRz} \cdot \mathrm{Yp} + \mathrm{zRy} \cdot \mathrm{Zp} - \mathrm{zRz} \cdot \mathrm{Yp}$$

$$Y_{\mathrm{true}} := Y + \mathrm{Yp} + \mathrm{xTy} + \mathrm{yTy} + \mathrm{zTy} - \mathrm{xRx} \cdot (Z + \mathrm{Zp}) + (\mathrm{xRz} + \mathrm{Sxy}) \cdot \mathrm{Xp} - (\mathrm{yRx} + \mathrm{Syz}) \cdot (Z + \mathrm{Zp}) + \mathrm{yRz} \cdot \mathrm{Xp} - \mathrm{zRx} \cdot \mathrm{Zp} + \mathrm{zRz} \cdot \mathrm{Xp}$$

$$Z_{\mathrm{true}} := Z + \mathrm{Zp} + \mathrm{xTz} + \mathrm{yTz} + \mathrm{zTz} + \mathrm{xRx} \cdot (Y + \mathrm{Yp}) - (\mathrm{xRy} + \mathrm{Sxz}) \cdot \mathrm{Xp} + (\mathrm{yRx} + \mathrm{Syz}) \cdot \mathrm{Yp} - \mathrm{yRy} \cdot \mathrm{Xp} + \mathrm{zRx} \cdot \mathrm{Yp} - \mathrm{zRy} \cdot \mathrm{Xp}$$

In these equations, X, Y and Z refer to the as-programmed tool position in machine coordinates at the "tool gauge point." Xp, Yp and Zp refer to an offset from the tool gauge point and defines where the tool is actually cutting the part leaving a surface feature at X_{true}, Y_{true}, Z_{true}.

4. VIRTUAL CNC

The virtual CNC for this project is based on the N-See 2000™ true solid model verification system. This system is based on a proprietary solid model that is tuned to CAM, as opposed to CAD, applications. The system is designed to replicate actual CNC metal removal, to shop floor accuracy, in times that are orders of magnitude less than physical machining times. The program is available both in a PC version (95, 98 and NT) as well as Unix. N-See 2000 has recently been extended to include support for full 5 axis verification.

The NC verification program is solid model based, so there is no need to re-compute the model or open a new window for each view orientation. The model may be rotated, zoomed (including a very accurate "deep zoom" for unlimited depth of zoom), cross-sectioned, and inspected. Automated comparison is available with a CAD solid model. N-See 2000 also includes a dexel-based module that allows the user to follow the tool as the part is cut.

Dexel-based systems usually have some limitation due to the preferred direction of the dexels. Further, there can be a compromise between speed and accuracy since increased accuracy entails a denser array of dexels which in turn increases computational times. A true solid model is isometric, not anisotropic in accuracy, and can offer much faster computational times while maintaining the required accuracy. Nonetheless, dexel systems are very attractive since they offer a hands-on, direct view of the tool cutting process.

N-See 2000 offers a unique combination of the two techniques. The user can start out in a dexel or animated view and then "fast forward" to a later point in the NC program in the solid model mode. They can then re-start the animation, with the new dexel view derived from the underlying solid model. This also means that users can rotate to any view at any time in the part program to follow tool animation from any perspective.

This flexibility is particularly important for 5 axis machining, where the part programs can be very long to process and views to see, for example, if the programmed 5 axis tool motion causes a collision with the part can be difficult to predict in advance. The users can fast forward to a problematic portion of the part program, rotate to a view of interest and follow the tool animation from that point onwards.

A key question to answer in this research project is whether the N-See 2000 solid model engine will be able to model the effective 5 axis tool moves (a 3 axis CNC with performance errors) in acceptable CPU times. This and other characteristics of the N-See 2000 system follow in the next section.

5. N-SEE 2000 PERFORMANCE

The N-See 2000 solid model engine is able to model full 5 axis tool moves, including tool cuts that involve undercutting (such as a turbine blade) in quite acceptable CPU times. This is significant, since even 3 axis tool moves – when simulating a CNC with performance errors – become effective 5 axis tool moves due to the angular errors introduced into the tool orientation.

The CPU processing times depend on the part program and the tooling. A tool cut that removes a large volume takes longer than a short tool move. So the "CPU time per block of NC code" depends on the length of the tool moves and the size of the tool. That said, for typical sculptured surface parts, N-See 2000 processes between 500 and 4000 blocks of NC code per second in its current "Turbo" mode on a Pentium II 233 MHz PC. Further optimizations are feasible which can substantially increase that processing speed. The Turbo mode is for strictly 3 axis milling with no tool animation displayed. The higher speeds are for true finishing passes where the tool sweeps are relatively short and shallow. The 5 axis variation, which is referred to as the Common Modeling System, runs at about half that speed. Previous commercial systems typically report a slow down of a factor of 4 to 8 when running in the 5 axis mode.

The N-See 2000 Common Modeling System includes both the solid model and a tool animation (dexel) system. The user is able to switch between the two presentation methods. That is, the user can process a part in the solid model mode and then switch at any time to a tool animation from any point of view without reprocessing the entire part program from the start. Currently, this appears to be the only commercial system that offers this expedited switching between animation and solid mode. This is done since the data structure for the animation is created from the accurate solid model (Common Model), placing no constraints on the animation orientation. This is particularly convenient, for example, when the user needs to follow the details of a complex 5 axis tool sweep midway through the part program in a region that is not immediately accessible to view.

6. QUALITY ASSURANCE

The nominal tool path, derived from the part program, must be modified. The equation given above for the error in X for a nominal XYZ, tool length and parametric errors only provides the error coordinate at a point. As the tool sweeps out a path, the entire path must be modified, not just the end points. So, for example a nominal path from **A** to **B** becomes an actual path from **A'** to **B'** in the presence of performance errors. The tool path will be modified in an iterative fashion to maintain a suitably close approximation to the actual path.

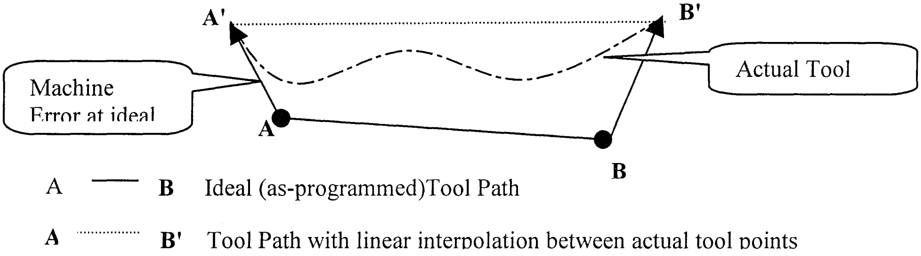

Figure 1. An example of the presence of performance errors

Working from these altered tool paths, this project will introduce a number of quality assurance modules to assist the end user in determining whether the part program, stock, tools and CNC performance errors combine to produce an acceptable or unacceptable workpiece, based on a quality criterion.

The quality assurance modules will include:

- Graphical and Numeric Comparison of perfect (as-programmed) vs. imperfect (performance errors) CNC part
- Comparison of part made on imperfect CNC with as-designed part
- Sensitivity Analysis: Error Signatures associated with certain types of machine errors for a particular class of parts
- CMM point (XYZ, normal and error value) inspection
- Automated reporting of Worst Point(s) – indicate graphically and numerically the location, the error value, tooling and line(s) of G code that may be edited to correct the error
- Sweet Spot Location: Apply 6 degrees of freedom to the stock position and orientation to find optimal fixturing for minimum performance errors on the workpiece.

7. RESULTS

The kinematic error model equations have been used to perturb the tool sweep for various parts being modeled with the N-See 2000 software. Currently the input data is derived by assuming each of the 21 error parameters can be treated as a second degree polynomial in the axis of interest (a reasonable assumption based on most actual CNC error data) with the polynomial coefficients specified in a table. Currently all trial runs have been carried out with synthetic data using selected values for the polynomial coefficients.

The N-See 2000 Software Development Kit (a suite of C and C++ procedures that form the basis for the commercial product) was used as the basis of a program which carries out a preliminary error analysis of a series of parts. Part programs have been run with an ideal (perfect) CNC, the resulting ideal part is then output in solid model (STL) format and then run again with specified CNC performance errors. The ideal part is then compared with the part made with an imperfect CNC via the "STL Compare" feature available in N-See 2000. The latter results in a colored display of the part, with different regions in different colors depending on whether the region is within a given tolerance of the standard (ideal part) model, is undercut (excess material) or overcut (gouged).

The time to process the STL compare is about 10 seconds on a 233 MHz PC for a modest sized (few MB) STL file. The time to re-display the comparison image, with new colored bands for a new tolerance value, is less than 10 seconds, relatively independent of the STL file size.

The colored display from the STL compare has been shown to be a convenient tool in carrying out a sensitivity analysis to determine how specific or combined CNC geometric errors may imprint themselves on a given part.

The accuracy of the STL Compare is a few ten thousands of an inch over a ten inch part. The "Deep Zoom" capability of N-See 2000 allows users to to select a specific part region and re-process the part over that region. This means that the current system can accommodate very small errors over even large parts by successively analyzing discrete regions.

8. FUTURE PLANS AND NEEDS

This is an on-going research project and we are reporting on "work in progress." There is a need to make the error analysis much faster and more convenient. Currently, changing the error parameters and generating a fresh part with shaded error regions is cumbersome and a relatively slow process. The goal is to substantially increase the processing time and, at the same time, allow a convenient real time variation of the error parameters.

Another important need is good CNC performance data along with corresponding part inspection data. There is a dearth of CNC performance data since a complete machine tool characterization can take as long as 40 hours. However, new systems are being developed by various commercial vendors which are reducing that by an order of magnitude and more. To completely validate the simulation process, we also require parts which have been made on well characterized CNCs and which have then been carefully inspected with a CMM. This will provide us with an external check on our simulation program. We would very much welcome partners who are interested in such a collaboration.

9. SUMMARY

Quality – making a part right the first time – is clearly the focus of industry today. Performance characterization of CNC machines is an important first step in that process. But the time and expense in generating that error data can be wasted if there are no tools available for a shop floor person to use that data to determine if his particular part will be made to his particular specifications on this particular CNC. The raw error data can be voluminous and confusing. The compression of this data into parameters for a kinematic error model is helpful to a researcher, but is hardly in an accessible format for a shop floor worker. What is needed by industry, as was stated at a recent NIST/NAMT Conference is a tool that will accept normal shop floor information (stock and tooling setup, part program, machine selected), have available a data base that contains the performance characteristics for a particular machine and a simple Yes/No answer to the question: Will this CNC machine this part program to this required tolerance?

Currently, the only way to answer that question definitively is to cut the part on the machine and inspect the part. There is an important void that needs to be filled. A part programmer has a selection of commercial systems to prove out (verify) his part program on a perfect CNC. But the shop floor person has no such guide concerning errors introduced by the machine performance characteristics.

MentorLink and its partner, N-See Software, stand uniquely positioned to respond to this market need. As stated earlier, the virtual CNC must be capable of very high precision, while maintaining the speed demanded by on-time shop floor delivery. The N-See 2000 solid model engine, now extended to include full 5 axis tool motion, is being customized to meet these very demanding requirements while delivering a shop floor hardened application.

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