

Implementing Geometric Error Compensation Software in a PC-Based Controller

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Introduction

In an effort to modernize its production manufacturing equipment, the Department of Energy's Y-12 Plant in Oak Ridge, TN is investigating replacing the existing proprietary CNC machine tool controllers with new controllers based on personal computer (PC) technologies. It is now possible to buy machine tool controllers that utilize PC hardware with common plug-in motion control cards that offer functionality equivalent to the 1980s-vintage controllers currently being used.

One of the controllers being considered is developed by Manufacturing Data Systems, Inc. (MDSI) of Ann Arbor, Michigan. A characteristic that sets it apart from other PC-based controllers is that it utilizes no motion control cards. It is a software-based controller, which means that the motion control servo loop is closed by the PC's central processing unit. The controller software is called OpenCNC, and it currently runs under two operating systems: Windows NT from Microsoft Corporation and QNX from QNX Software Systems Ltd.

Project Description

An area of particular interest to the Y-12 Plant is OpenCNC's ability to support software compensation of machine tool errors other than the lead-screw compensation currently implemented. A joint project was initiated between Y-12 and MDSI to implement within the OpenCNC controller a software architecture capable of compensating for geometric errors in two- and three-axis machine tools. The software was named the Geometric Error Compensation System (GECS), and the initial implementation was on an Excello 921 two-axis T-base lathe. These lathes were designed and built specifically for Y-12 in the 1960s. A computer model of this lathe is shown in Figure 1.

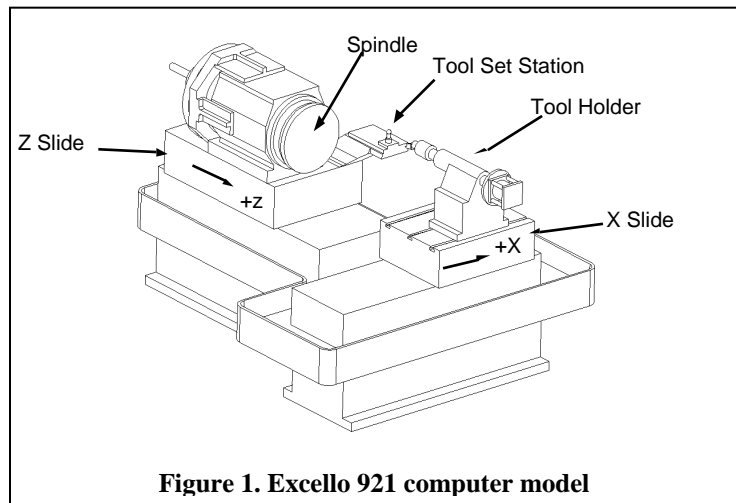


Figure 1. Excello 921 computer model

Based on a literature review of previous work in the area of geometric error compensation, examples of which are given by Hocken [1] and Donmez [2], previous implementations

utilized prototype controllers, or they required the use of external computers to perform the compensation calculations and special hardware to intercept the axis position feedback signals and to interject the compensation signal. This project may be the first in which the compensation system was totally implemented in software.

Geometric Error Model

As detailed by Slocum [3], an element of a machine tool (slide, tool, workpiece, base, turret, etc.) can be represented by a homogeneous transformation matrix (HTM). The HTM gives the position and orientation of that element relative to another element of the machine that has its own HTM assigned. Starting from the HTM of the machine base, one can create a series of HTMs that traverse the elements of the machine tool to either the cutting tool or to

the workpiece. This gives the location of both the workpiece and the tool in the same base reference system, as shown in Figure 2.

In the ideal case the HTM of the workpiece relative to some reference frame R , ${}^R T_{work}$, and the HTM of the tool, ${}^R T_{tool}$, would coincide. However, in the actual cutting case, due to the inaccuracies of the system, the two HTMs are not identical. To make ${}^R T_{tool}$ coincide with ${}^R T_{work}$ one can use another HTM, referred to as E_{rel} , which quantifies the relative error between the tool and workpiece, as shown by the following formula:

$${}^R T_{tool} = {}^R T_{work} E_{rel} \quad (1)$$

The homogeneous transformation matrix E_{rel} , is thus given by

$$E_{rel} = {}^R T_{work}^{-1} {}^R T_{tool} \quad (2)$$

where ${}^R T_{work}^{-1}$ represents the inverse of the homogeneous transformation matrix.

The relative error HTM E_{rel} quantifies the changes in position and orientation required to cause ${}^R T_{tool}$ to coincide with ${}^R T_{work}$. Because the contact between the tool and the workpiece is assumed to be point contact, the orientation of the tool, represented by the rotation matrix in E_{rel} , is of no concern. The position vector \mathbf{P} in E_{rel} represents the translations relative to the tool's coordinate frame that must be made to the tool so that it is properly located on the workpiece.

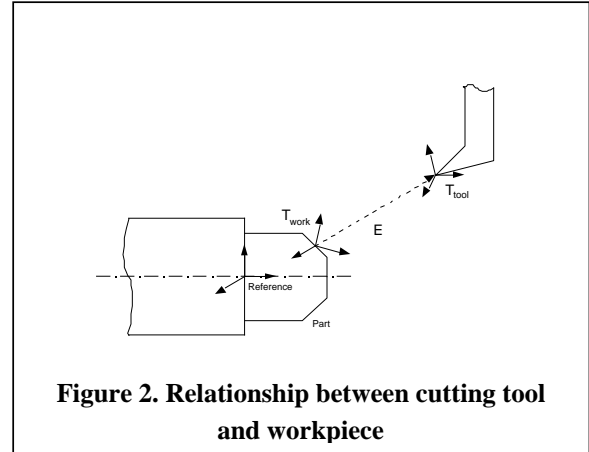


Figure 2. Relationship between cutting tool and workpiece

Excello Error Model

The machine model used in the development of the error equations for the Excello lathe is shown in Figure 3, which depicts a plan view of the lathe. All the coordinate systems (HTMs) shown are at spindle center height. The HTMs are aligned so that the positive direction of the coordinate axes corresponds to positive displacement of the machine slides. The direction of positive rotation is also shown, and will become important for compensation of angular errors. In Figure 3 and in the error equation development, uppercase Roman letters represent constant terms while lowercase Roman letters represent position variables, and Greek letters represent geometric errors.

HTM 0 is the base reference system used in the model, and its location does not change. HTM 1 is attached to the spindle face and moves with the Z-slide. HTM 2 is attached to the table of the X-slide

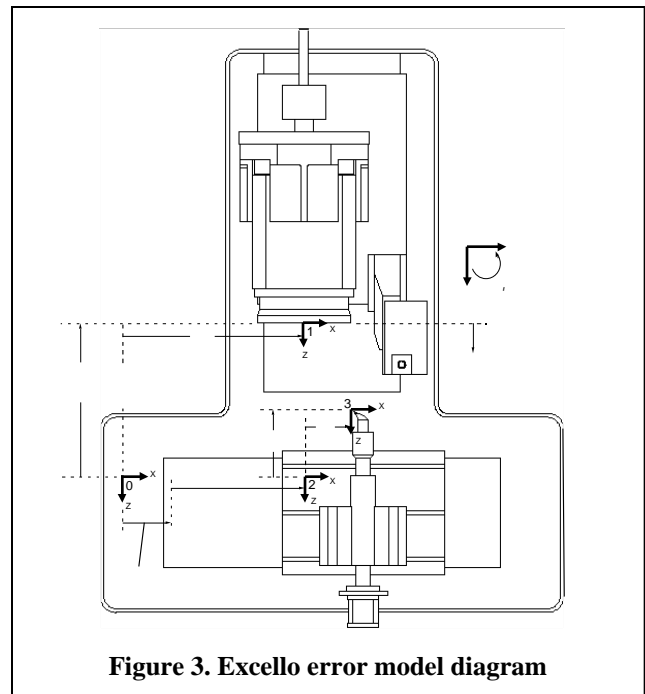


Figure 3. Excello error model diagram

and moves with it. The X-axes of HTM 0 and HTM 2 are aligned, so there is no Z offset between them. HTM 3 is defined at the tip of the cutting tool with constant offsets from HTM 2 of X_t and Z_t .

The error equations for a given machine tool are created using Equation (2). Before applying this equation to the Excello lathe, the HTMs for ${}^R T_{work}$ and ${}^R T_{tool}$ were developed as follows.

$$T = T = \begin{array}{ccc|ccc} 1 & 0 & (z) & X_1 + (z) + z & & \\ 0 & 1 & 0 & 0 & & \\ - (z) & 0 & 1 & Z_1 + z + (z) & & \\ \hline 0 & 0 & 0 & 1 & & \end{array} \quad (3)$$

$$T = T T = \begin{array}{ccc|ccc|ccc} 1 & 0 & (x) & X_2 + x + (x) & 1 & 0 & 0 & & \\ 0 & 1 & 0 & 0 & 0 & 1 & 0 & & 0 \\ - (x) & 0 & 1 & (x) - x & 0 & 0 & 1 & & \\ \hline 0 & 0 & 0 & 1 & 0 & 0 & 0 & & 1 \end{array} \quad (4)$$

Term	Description	Term	Description
x, z	nominal positions of X- and Z-slides	${}_z(x), {}_x(z)$	straightness errors as functions of position
${}_x(x), {}_z(z)$	X- and Z-scale errors		perpendicularity error between X-slide and spindle
${}_y(x), {}_y(z)$	yaw errors as functions of position		parallelism error between Z-slide and spindle
X_1, Z_1, X_2, X_t, Z_t	offset constants		

Performing the mathematical operations given by Equation (2) produced expressions in x and z that described the position of the tool tip relative to the workpiece and included the positioning errors of all moving components between them. The equations were comprised of several terms, but these terms could be grouped as Nominal Positions, Offsets, or P terms. When implementing a software compensation system, the terms of interest are those pertaining to the error motions of the slides, which are the P terms. With this in mind, the error equations used to compute the actual axis compensations are given as

$$= (x) - (z) + (x) + (z + -) (z) - z \quad (5)$$

$$= (z) + (x) - (x) + (x - + +) (z) - x \quad (6)$$

Error Characterization

Y-12 has procured a new laser system called the 5-D Laser Measuring System that significantly reduces the time required for error measurement. Automated Precision, Inc., in Gaithersburg, Maryland produces the system. By combining several sets of optics into one sensor head, the 5-D system allows the acquisition of five error measurements (scale, horizontal straightness, vertical straightness, pitch, and yaw) with a single setup of the laser. An available add-on module allows horizontal roll measurements to be made, creating a 6-D system, but that is currently not part of the Y-12 system. The 5-D laser system was used to provide the axis error data for the lathe as functions of axis position and direction of motion. Three error data files are produced by the 5-D system for each measured axis. Squareness and parallelism errors of the lathe were obtained using an electronic indicator.

System Implementation

In developing the system architecture of the GECS, an effort was made to make the system flexible enough to support machines of different configurations and numbers of axes. Another design goal was to seamlessly interface the software with OpenCNC. To accomplish this, variables and arrays were patterned after those used in the lead-screw error compensation system provided within OpenCNC.

One of the steps involved in implementing the GECS was creating an Error File that contained the measured error data. This file was read at system startup to load the internal error arrays. These arrays contained the error data needed by the error equations developed earlier. Software was written to combine the data from the multiple 5-D laser system files into a single file.

To facilitate the incorporation of the GECS functionality into OpenCNC, MDSI provided a software template for an external compensation system. This general-purpose template will allow any type of compensation system to be implemented within OpenCNC. Compensation of thermal errors and tool-wear are two examples of systems that could be supported with this template in addition to GECS. The template provided the interface code that communicated with OpenCNC. It obtained controller parameters needed by the compensation system and passed compensation values back to the controller. New code developed during the project included functionality to initialize the GECS, read the Error File data, and actually perform the compensation calculations. Given the machine positions of the axes and their directions of motion, the GECS first converted the machine positions into the model space coordinates as depicted in Figure 3. The components of the error equation components were then computed, using data from the appropriate positive or negative data arrays, depending on the slides' directions of motion. Finally, the error terms were combined using Equations (5) and (6) to give the tool's total position errors.

System Evaluation

A Renishaw ballbar was used to evaluate the effects of the compensation system. Shown in Figure 4, the ballbar was used to conduct static positioning tests on the lathe. The ballbar consists of a high accuracy displacement sensor housed inside a telescopic bar. The ends of the bar are held in strong magnetic cups, one held fixed on the spindle faceplate, and one held by the moving tool holder.

Three runs were performed with GECS disabled, and three were performed with it enabled. After the data was collected, the ballbar control software calculated a positioning error it referred to as circularity error. This error was calculated by combining the maximum and minimum deviations from the best-fit arc through the measurement data. For the case in which the GECS was disabled, a typical test resulted in a circularity error of 14 microns, which was considered to be very high for that machine. The uncompensated errors were on the order of the positioning compensations being applied to the axes, which would mask their effects. Tests with the GECS enabled sometimes showed positioning

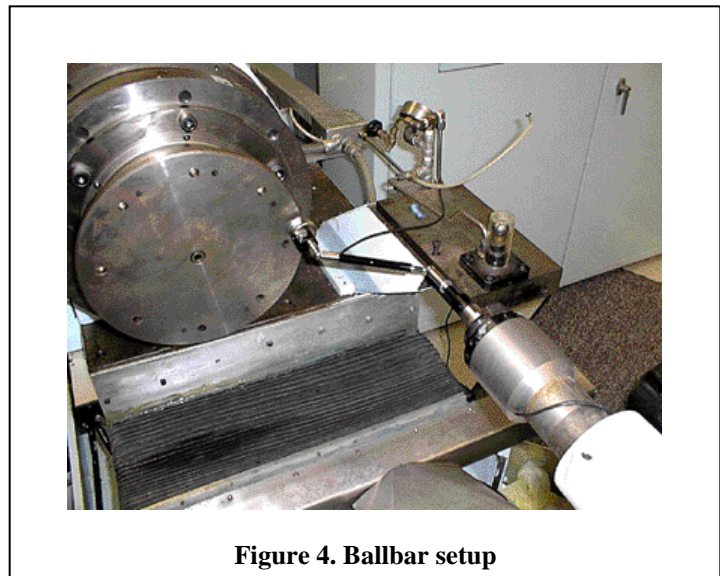


Figure 4. Ballbar setup

accuracy improvements, but not consistently. It was felt that the machine had some mechanical problems that prevented it from providing repeatable measurements, but project resources were not sufficient to allow machine maintenance operations to be performed or for further investigation.

Conclusions

While the desired result of showing definite positioning improvements due to axis compensation was not realized during this project, several other goals were achieved. Knowledge was obtained on application of geometric error compensation techniques, and the experience gained in performing the actual implementation details will be invaluable in future work. OpenCNC may be the first commercially-available machine tool controller to provide a software interface for external compensation processes, and the external compensation template will provide a unique platform for developing other types of compensation systems.

[1] R. Hocken et al, "Three Dimensional Metrology," in *Annals of the CIRP*, Vol. 26/2, pp. 403–408, 1977.

[2] M.A. Donmez, C.R. Liu, M.M. Barash, "A Generalized Mathematical Model for Machine Tool Errors," presented at The Winter Annual Meeting of the American Society of Mechanical Engineers, Anaheim, California, December 7–12, 1986.

[3] A.H. Slocum, *Precision Machine Design*, Society of Manufacturing Engineers, Dearborn, MI, 1992.