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# A practical system for 5-axis volumetric compensation

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## Abstract

Compensation is a recognised technique for correcting the systematic errors inherent to machine tool positioning systems. It offers a cost effective and flexible solution to the problem of enhancing machine accuracy. In spite of this controller manufacturers provide limited facilities for applying compensation, and in many cases linear positioning compensation only is available. The main reason for this is the potential complexity of a comprehensive compensation system able to cope with the variety of axis combinations and configurations available in the modern machine tool market. This problem is compounded by the demand from industry for precision 5 axis machining. This paper describes a practical geometric error compensation system that can be applied to any machine tool that has up to 5 axes. The system can correct for the effects of all the geometric errors associated with a machine's linear axes, together with the geometric errors associated with a fork type servo head. The system applies compensation dynamically and in real time as the machine moves throughout its working volume.

## 1 Introduction

Over recent years international standards[1] have become available to support the measurement and analysis of all machine tool geometric errors. This has led to an increased understanding within the machine tool community of the affect of geometric errors on machine tool performance. It is becoming accepted that a machine's ability to produce accurate components is not just a function of its positioning accuracy down a single straight line, and that if precision machining is required all sources of geometric error must be considered. This is particularly true on large machines where the dominant geometric error components are likely to be angular and squareness errors.

Machine accuracy can obviously be improved by reducing the geometric errors during machine manufacture, but for most machine tools this can only be taken so far. Cost and manufacturing limitations mean that even on high quality, precision machine tools geometric errors can not be eliminated completely. A cost effective and flexible alternative to eliminating geometric errors is software based geometric error compensation.

## 2 Error Compensation

Error compensation is a technique in which the positions of the machine's axes are moved to correct for the effect of the geometric errors. Compensation is relatively cheap and easy to implement, is flexible and can be updated to accommodate changes in the errors, and can correct for errors that cannot easily be eliminated through machine design. To operate compensation systems require stored geometric error data, access to all the axis positions and a mechanism for applying the corrections. If the machine is of a reasonable quality and the errors are repeatable then error compensation can be extremely effective at improving machine tool accuracy[3, 4, 5].

Most modern CNC's have limited error compensation facilities built in. In many cases this is simple linear positioning compensation with maybe a single backlash value. This type of compensation can improve the accuracy of a single axis along a straight line but may not have a significant effect on the machine's positioning accuracy throughout its working volume.

### 2.1 Volumetric Accuracy and Compensation

In practical terms volumetric accuracy can be defined as the positioning capability of the machine tool throughout its working volume. Volumetric accuracy is a function of all the geometric error components and not just linear positioning error. Volumetric accuracy is directly related to a machine tool's production capability. As such, knowledge of a machine's volumetric accuracy would be very useful, and the ability to have some control over its volumetric accuracy would be more useful still.

Volumetric error compensation provides this ability by correcting for the affect of all the geometric error components throughout the volume of the machine. This is usually achieved using a geometric model generated from a kinematic analysis of the machine[2]. A geometric model is a set of equations that relate the individual geometric error components to the axis position errors at any point in the machine volume relative to a reference co-ordinate frame. Over recent years volumetric error compensation has been applied successfully to a number of three axis machine tools[3, 4, 5]. In most cases error compensation has been applied to individual machine tools to overcome specific problems or as a proof of concept, and a universal compensation system has not been produced. The main reason for this is the potential complexity of a comprehensive compensation system able to cope with the variety of axis combinations and configurations available in the modern machine tool market. Recent work carried out at the University of Huddersfield has overcome these problems and resulted in the production of a practical volumetric error compensation system that can be applied to most machine tool configurations with up to 5 axes. This system offers the potential of enhanced machine tool accuracy and improved production performance to a broad range of manufacturing industries.

## 3 The 5 Axis Volumetric Compensation System

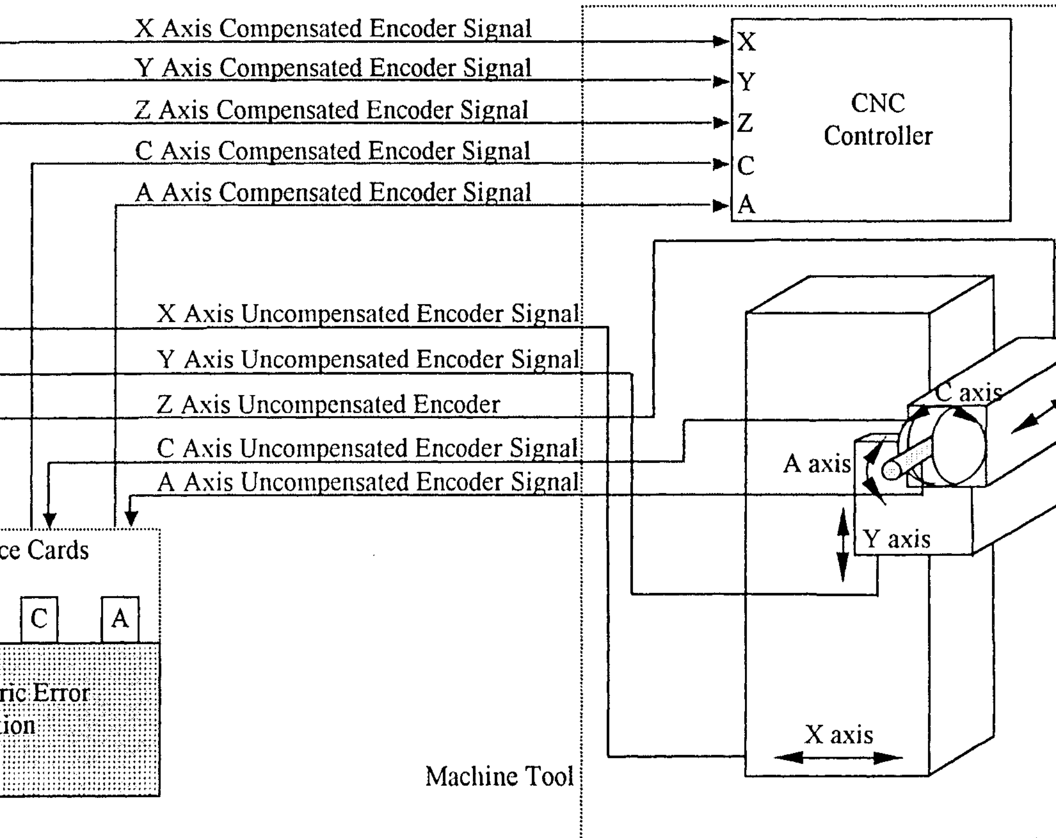
### 3.1 Overview of the System

The 5 axis volumetric error compensation system is a PC based system that can enhance the accuracy of CNC machine tools by correcting for the effects of the small rotations and translations inherent to axis slideways (i.e. the geometric errors). The system applies the correction dynamically in real time. The system is universal in that it can be applied to any basic 2 axis turning machine, or 3 axis machine tool fitted with (or without) a fork type servo head.

The system connects into the position control loops of the machine's axes. The axes position transducer signals are connected directly to the compensation system, and correction is achieved by modifying these feedback signals in real time. The compensated transducer signals are connected directly to the CNC. By modifying the transducer signals the compensation system is effectively invisible to the CNC and does not affect the normal operation of the machine tool in any way. Figure 1 is a schematic showing the connection of the compensation system to a typical 5 axis machine tool.

The compensation system uses a rigid body geometric model to calculate the correction values. This model comprises a set of equations that relate the geometric error components of all the axes, such as straightness, roll, pitch and yaw, to the position errors at any point in the machine volume. The previously measured geometric error components are stored in the memory of the computer system. The geometric model assumes that the machine tool structure is stiff, such that the error components do not change significantly across the volume.

The compensation system determines the current position of all the axes from the transducer signals. Based on the axes positions it selects the appropriate geometric error values from memory, then calculates the correction values to be applied to the machine axes. Finally it applies the correction values to the machine by modifying the axis transducer signals.




1: Schematic of the 5 axis volumetric compensation system integrated to a typical machine tool

### 3.2 Description of the System

The system hardware consists of an industrial PC fitted with an encoder interface card for each machine axis to be compensated. Upon power up the PC automatically runs the volumetric compensation software. The software has three modes of operation, start-up, automatic and manual. In start-up mode the software initialises the control signals, resets and checks the hardware and reports on the system status.

If start-up is completed successfully the system goes into automatic mode. This is the normal operating mode of the system where, once all the axes have been homed, it continuously calculates and applies error correction values and monitors the system for fault conditions.

Manual mode is provided for the integration, set-up and test of the system. It allows the user to set-up parameters and error correction data files and to test the operation of the system. When operating in manual mode the PC has a keyboard and monitor attached to provide a user interface, but during normal automatic operation these can be removed.

#### 3.2.1 Automatic Mode

The system will normally operate in this mode once it has been set-up. In automatic mode the system first checks that error compensation is enabled, then it monitors each of the axis encoder interface cards to determine if the axes servo systems are active. When the axis servo systems become active the system monitors each of the axis encoder interface cards to determine if the axes have been homed. Once all axes have been homed the system can determine the absolute machine position and it enters the compensation loop. In the compensation loop the system continuously checks the positions of the machine's axes, extracts the appropriate error values from the stored compensation tables, calculates error compensation values for each axis, and applies the compensation to the machine's axes.

#### 3.2.2 Manual Mode

In manual mode the user has operational control of the system. The system functions are menu driven, using the menu structure shown in figure 2. In manual mode the user can define the system parameters, process the raw geometric error data to produce compensation tables and monitor and test the operation of the system.

The compensation system is designed for use on most types and configurations of machine tool, and it is the system parameters that allow the user to customise the compensation system for use with a specific machine tool. The parameters define important details, such as:

- **Machine Name** - A unique identifier for the machine.
- **Machine Configuration** - The configuration of the machine's linear axes.

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- **Axis Type** - Axis parameter indicating that the axis is physically present, and defining the type of axis either linear, rotary or rollover.
- **Axis Name** - Axis parameter defining a single letter axis name
- **Error Band Values** - Axis parameters defining the maximum expected compensation values.
- **Slave Axis** - Axis parameter that indicates that a slave axis is physically present.
- **Servo Head Orientation** - Servo head axis parameters defining the linear axes that the rear and front head joints rotate about. These parameters determine the orientation of the servo head with respect to the machine's linear axes.

**Main Menu**
Set-up System → **Set-up System Menu**
- Prepare Comp. Tables → **Prepare Comp. Tables Menu**
  - Process Error Data → **Error Data Menu**
    - Linear Axes Data
    - Servo Head Data
    - To Previous Menu
  - Transfer Data Files
  - Display Data Files
  - To Previous Menu
- Modify Password
- Enter Parameters
- Type of Machine → **Select M/C Type**
  - Machining Centre
  - Turning Centre
- Set M/C Directory
- To Main Menu

Compensation → **Compensation Menu**
- Comp. with Display
- Fast Comp.
- System Inf.
- Diagnostics
- To Main Menu

Log File
Quit to DOS

Figure 2: Manual mode menu tree

With the parameters set the compensation tables used to calculate the axis correction values have to be created from the geometric error data source files. The data source files are stored on the computers hard disc drive prior to this operation. The type of geometric errors associated with the machine's linear axes is different to those associated with the rotary axes of the servo head. Most linear axis errors are position dependant and are presented to the compensation system as Renishaw error data files, whereas most of servo head errors are constant and are presented to the compensation system as single numbers. To accommodate this and avoid confusion the linear and servo head error data is entered through two separate dialog boxes.

When entering the linear axis error data the user is presented a dialog box listing the relevant geometric error components for the selected machine configuration. The error components are named and listed in three columns, one for each of the three axes. There is also a miscellaneous column listing the relevant squareness and parallelism errors and axis offset values associated with the angular error measurements. The user is guided through the process of selecting and loading error data for each of the geometric error components. When the required error data has been entered the user exits from the linear error dialog box. This starts the process of creating and loading the compensation tables. The tables are produced by merging together all the error data, with linear interpolation being used to ensure that the maximum change between adjacent errors is only 1 micrometer. A compensation table is produced for each machine axis and consists of a list of target positions together with corresponding forward and reverse errors for each of the possible sources of error, namely, one linear, two straightness and three angular.

The servo head error data is entered in a similar way to the linear axis error data, with the user being presented with a dialog box listing the servo head geometric error components. The angular positioning errors for the rear and front joint of the head are presented as standard Renishaw angular error files, but all other servo head error values are entered as single values using the keyboard. The effect of some of the servo head errors is tool length dependent and the system allows the user to define up to 4 different tool lengths.

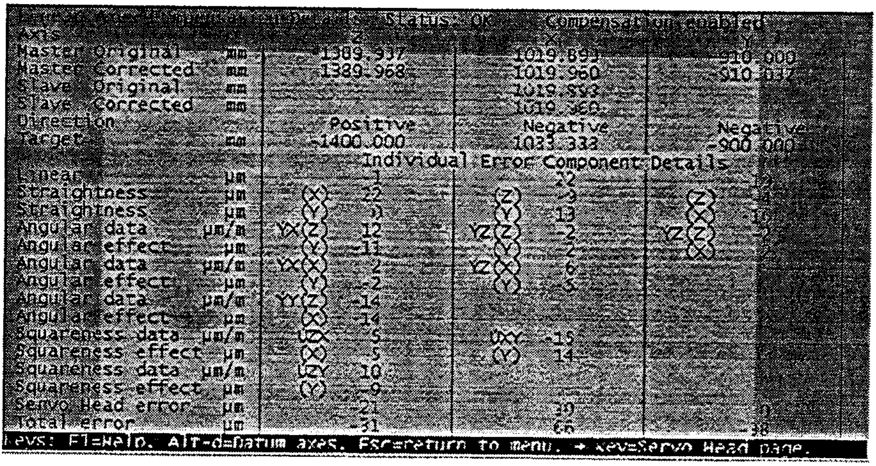


Figure 3: Typical linear axes compensation details

With the machine parameters defined and the compensation tables produced the operation of the compensation system can be tested and analysed using the compensation menu options. Here details of all the geometric error values can be displayed during active compensation, and system status and diagnostic information can be viewed.

When the "compensation with display" option is selected the system applies full volumetric compensation to the machine and provides a complete breakdown of the compensation details on the screen, as shown in figure 3. With the servo head fitted the compensation details are presented on to two screens, the linear axes compensation details screen and the servo head compensation details screen.

The information displayed on these screens includes a list of all the error components, along with the axes positions, targets and status information. This feature allows the user to test and monitor the operation of the compensation system during commissioning.

## 4 Typical Results

The compensation system has been applied to a large 5 axis machine tool. This is a high specification machine tool designed for an application demanding a volumetric accuracy of 72μm over the whole of the machine's volume. The working strokes of the axes are 5m for X, 3m for Y and 2.5m for Z. The machine is located in a temperature controlled environment to minimise thermal errors. The machine is fitted with a fork type servo head with a C axis (rear joint) stroke of 360°, and an A axis (front joint) stroke of ±100°. The manufacturing process requires the machine to perform full 5 axis contouring. Although the machine is of a very high quality, and designed specifically for high precision machining, it would be very difficult for it to meet such a stringent volumetric accuracy specification without the use of compensation. The large size of the machine means that even the smallest angular errors would produce significant positioning errors within the machine's volume.

The compensation system has been fitted to all 5 axes of the machine and compensation applied for all the axes geometric errors (31 in total). The geometric errors were measured using standard machine tool metrology equipment. After each error had been compensated it was remeasured to test the effectiveness of the compensation. For the axis angular errors the effect of the angular errors with and without compensation were measured. These tests provided confidence in the functionality of the compensation system but could not provide a direct indication of the machine's volumetric accuracy. To determine the machine's volumetric accuracy the "Error Simulation Program"[6] produced at the University of Huddersfield was used. This is a Windows based program that calculates the effect of the machine geometric errors at all points in the working volume. The program presents the volumetric accuracy results in terms of the worst case individual axis positioning errors and their location in

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the machine volume, together with the worst case vector sum of the axis positioning errors and its position in the machine volume. The worst case vector sum provides a direct measure of the machine tool's volumetric accuracy. The geometric errors measured on the machine with and without error compensation were both processed by the Error Simulation Program and the results are summarised in tables 1 and 2 below.

Table 1: Machine Volumetric Accuracy Results - Without Compensation

| | | | |
|---|---|---|---|
| X minimum error | = | **-27μm** | at Z-1200, X-2000, Y0 (mm) |
| X maximum error | = | **80μm** | at Z-400, X1600, Y-1690 (mm) |
| X axis error range | = | **107μm** | |
| Y minimum error | = | **-78μm** | at Z-1800, X-600, Y-2600 (mm) |
| Y maximum error | = | **17μm** | at Z-700, X-1600, Y0 (mm) |
| Y axis error range | = | **95μm** | |
| Z minimum error | = | **-88μm** | at Z-2000, X2000, Y-2600 (mm) |
| Z maximum error | = | **70μm** | at Z-2000, X-2000, Y0 (mm) |
| Z axis error range | = | **158μm** | |
| Volumetric Accuracy | = | **109μm** | at Z-2000, X2000, Y-2600 (mm) |

Table 2: Machine Volumetric Accuracy Results - With Compensation

| | | | |
|---|---|---|---|
| X minimum error | = | **-24μm** | at Z0, X600, Y0 (mm) |
| X maximum error | = | **7μm** | at Z-1900, X-200, Y-2210 (mm) |
| X axis error range | = | **31μm** | |
| Y minimum error | = | **-5μm** | at Z-700, X-800, Y-2600 (mm) |
| Y maximum error | = | **18μm** | at Z-300, X-400, Y-520 (mm) |
| Y axis error range | = | **24μm** | |
| Z minimum error | = | **-13μm** | at Z-600, X-1400, Y-520 (mm) |
| Z maximum error | = | **15μm** | at Z-1800, X-1600, Y0 (mm) |
| Z axis error range | = | **28μm** | |
| Volumetric Accuracy | = | **25μm** | at Z0, X600, Y0 (mm) |

The results show a significant improvement in the individual axis positioning accuracy across the machine volume and in machine volumetric accuracy. With compensation the machine tool's volumetric accuracy is well within specification, allowing the machine to produce components to the required tolerance. The compensation system has also provided the user with some control over the machine's accuracy capability and so production performance. Through regular, planned calibration of the machine the compensation can be updated to account for machine wear and settling in order to maintain its accuracy within specification. Following this successful application of the volumetric compensation system it is now being applied to a range of similar machines.

## 5 Conclusions

- Error compensation is a cost effective and versatile technique for improving machine tool accuracy beyond what can be achieved through normal machine tool design.
- The simple linear error compensation facilities in most machine controllers cannot significantly improve the volumetric positioning accuracy of large machine tools.
- A 5 axis volumetric error compensation system has been produced that can be applied to most machine tool types and configurations.
- The system has been applied to a large 5 axis machine tool, producing a significant improvement in its volumetric accuracy.
- Volumetric error compensation can provide the machine user with some control over the production capability of their machine tools.

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