Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

Volumetric compensation through the machine controller

S. Fletcher, S.R. Postlethwaite & D.G. Ford
Precision Engineering Centre, University of Huddersfield, England

Abstract

Compensation is a cost effective method of correcting for machine tool systematic errors. Although controller manufacturers are providing increasingly more sophisticated compensation, they do not include for all geometric sources of error for the variety of 3- and 5-axis configurations that exist today. A small number of comprehensive PC-based compensation systems exist, requiring hardware modifications and interface electronics to interact with the position control loop, which can be expensive and difficult to implement.

This paper describes a general purpose error compensation system that is located and runs inside the machine controller. The system has been designed to run on a modern open architecture Computer Numerical Controller, namely an Osai UK series 10 controller. One of the facilities within this controller is a DOS Real Time Interface, which allows a user to develop custom applications that can run and communicate with various parts of the NC system in real time. Compensation software, based on a 5-axis geometric error compensation system produced at the University of Huddersfield, has been developed to run in the DOS real time environment.

The system has been applied to three machine tools and the volumetric accuracy significantly improved. Requiring only a simple software installation, the system is also shown to be inexpensive, simple and fast to implement.

1 Introduction

Pre-calibrated compensation for rigid body errors, using a geometric model of the machine and data obtained by calibrating individual error components is a proven method of improving machine tool geometric accuracy [1-6]. Current systems use a separate computer to carry out the necessary calculations and alter

Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

the position control loop appropriately. A 5-axis geometric error compensation system, based on the above philosophy, has been developed at the University of Huddersfield [6]. This system provides the basis for applying compensation through the controller.

This 5-axis geometric compensation system is a DOS based program. It is designed to run on an industrial grade PC interfaced to a machine tool. This requires interface electronics to read the quadrature feedback signal from the axis encoder devices and supply a modified signal to the controller. Figure 1 shows a schematic of the compensation system.

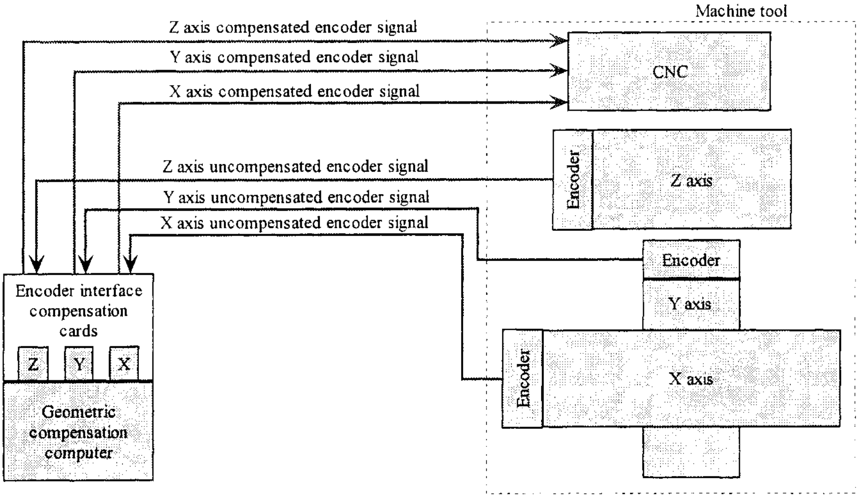


Figure 1: Schematic of PC based Geometric Compensation System Integrated to CNC Machine

This PC based method has significant cost and time resources associated with it, including:

- Cost of the computer
- Cost of interface electronics
- Hardware alterations
- Machine downtime during alterations
- Complicated software to manage the interface

A solution to these problems would be a system incorporated inside the machine controller. This has been investigated and a new system developed based on a modern CNC controller.

2 Open architecture controller

In most modern controllers that employ windows-based operating systems, the Numerical Control system runs separately in real-time. The Windows operating system does not operate in real-time and the programs that run in this environment also do not operate in real-time. A compensation program would

Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

require access to information such as current axis position in real-time making windows unsuitable. The Osai series 10 controller utilises a simpler DOS operating environment that does run and communicate with the NC system in real-time.

2.1 DOS Real Time Interface (DOS rti)

One of the facilities within the series 10 controller is a DOS rti, which allows a user to develop custom applications that communicate with various parts of the NC system in real time. The applications must be developed and compiled in Microsoft C v5.11 for compatibility with the DOS rti environment. The NC system has a library of interface functions that can be used in the program code enabling communication with the NC system in real time. Before applications can be executed, the DOS rti environment has to be configured using a configuration file. This file defines certain requirements in terms of memory management and details about the various tasks or applications to run and executes when the controller is booted up and the DOS rti option is installed and turned on.

3 Software development

The controller was initially interfaced to a gantry robot to test the compensation system. Three orthogonal axes, all moving the tool, are controlled through a closed loop system employing rotary encoders on the ends of the motors and axis drive cards designed at the University of Huddersfield.

Initially, basic programs were written in Microsoft ‘C’ to individually test some library commands that would be required later in the compensation software. The ability of the DOS rti to write a file to the floppy disc drive was tested and is required to load calibration data into the compensation software while the CNC is operating.

In order to move the axes and effectively apply compensation, a 'zeroshift' library function was tested which applies an absolute offset to individual axes. The tests proved that the axes could be controlled and that normal operations of the NC system i.e. in-position bands, were not effected.

3.1 Compensation software

Initially the existing PC based programs that were compiled in Borland C, including the compensation program, were tested in the DOS rti environment. The system failed, confirming the requirement for the executables to be created using Microsoft ‘C’ v5.1. Many of the problems associated with transferring the existing compensation software to the DOS rti were associated with the graphics. The graphical routines developed for the PC had to be re-written in accordance with the DOS Graphic Interface. The DOS Graphic Interface is another software environment available within the series 10 controller, allowing customisation of the graphic user interface using special functions similar to the DOS rti. These functions were used in the code of the compensation software where necessary.

Once the new program ran without errors, programming of the relevant DOS rti commands commenced to allow communication with the NC system.

The compensation system retrieves axis information from the NC system regarding the axis names, whether slave axes are present, and whether the axes are linear or non-linear. If non-linear axes are present, then detail about the type of non-linear axes i.e. rollover or rotary are also retrieved from the NC system. This type of communication simplifies the set-up process and improves the robustness of the system. An overview of the system and interface is shown in Figure 2.

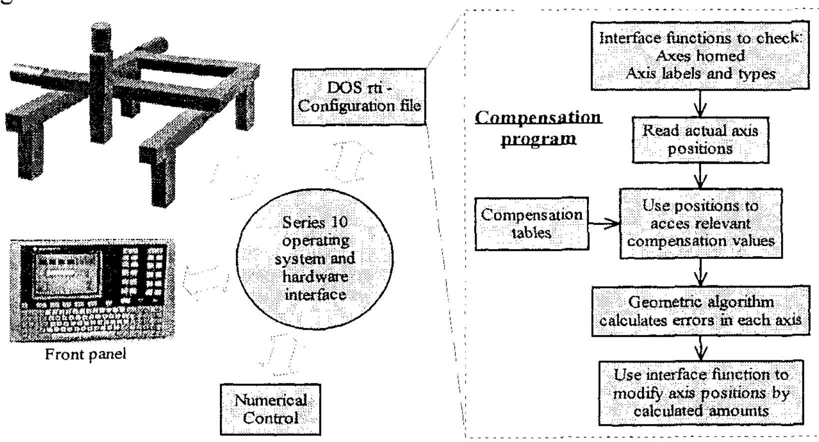


Figure 2: Compensation system overview

The DOS rti display screen is accessed by simply scrolling through the active NC screens. Figure 3 shows the compensation auto mode screen. The format of the interface is identical to the University of Huddersfield PC based system.

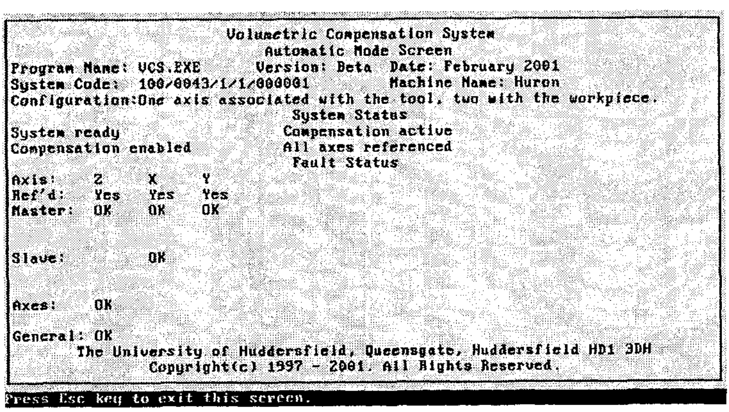
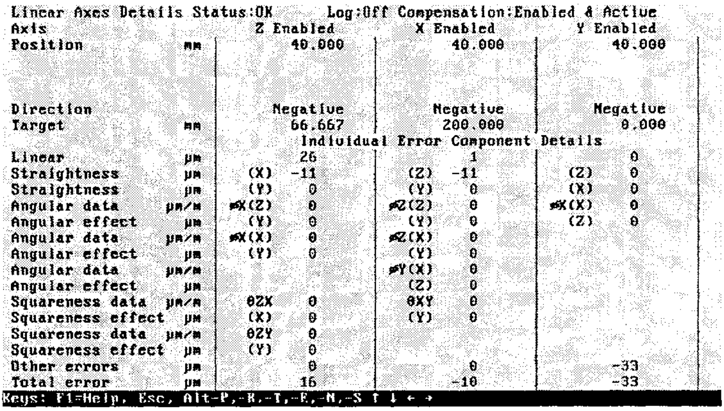


Figure 3: Screen shot of compensation system showing compensation system auto mode

Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

Figure 4 shows the 'compensation with display' screen which allows visualisation of the individual error components, their effect and the compensation values being applied.



Linear Axes Details Status:OK Log:Off Compensation:Enabled & Active

Axis		Z Enabled	X Enabled	Y Enabled
Position	mm	40.000	40.000	40.000
Direction		Negative	Negative	Negative
Target	mm	66.667	200.000	0.000
		Individual Error Component Details		
Linear	µm	26	1	0
Straightness	µm	(X) -11	(Z) -11	(Z) 0
Straightness	µm	(Y) 0	(Y) 0	(X) 0
Angular data	µm/m	øX(Z) 0	øZ(Z) 0	øX(X) 0
Angular effect	µm	(Y) 0	(Y) 0	(Z) 0
Angular data	µm/m	øX(X) 0	øZ(X) 0	
Angular effect	µm	(Y) 0	(Y) 0	
Angular data	µm/m		øY(X) 0	
Angular effect	µm		(Z) 0	
Squareness data	µm/m	θZX 0	θXY 0	
Squareness effect	µm	(X) 0	(Y) 0	
Squareness data	µm/m	θZY 0		
Squareness effect	µm	(Y) 0		
Other errors	µm	0	0	-33
Total error	µm	16	-10	-33

Keys: F1=Help, Esc, Alt-P,-R,-T,-E,-N,-S ↑ ↓ ← →

Figure 4: Screen shot of compensation system showing compensation with display

3.2 Benefits of CNC based compensation

There are many advantages of a system integrated into the controller over using external devices such as PC based compensation:

- The most obvious benefit is the reduced cost. There are no additional hardware requirements and there are no interface requirements other than the DOS rti environment being enabled. Additionally, the compensation system can be installed very easily and quickly on the controller, reducing the amount of downtime on the machine.
- The removal of additional hardware and complicated interface electronics significantly reduces the number of potential areas for faults to occur, improving the robustness and reliability of the system. Any errors that do occur within the compensation system can be communicated directly to the NC system and the appropriate built-in shut down procedures used, providing a safe system.
- Built in safety checks can be applied to the compensation values as well as the initial drive signal.
- Many of the settings within the compensation system can be set automatically by retrieving details about the axes and axis servos status directly from the NC system, again increasing the robustness of the system, in addition to simplifying the set up process.
- Different encoder feedback systems and the way in which position is determined at power up e.g. homing or by use of an absolute system, can create significant difficulties for the interface electronics used by PC based compensation systems. The majority of existing compensation systems work only with digital quadrature feedback from the encoders and homing via an

Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

index signal from the encoder in conjunction with a homing switch. The feedback device is irrelevant with this system because it simply interrogates the Numerical Control system.

- Additional information can also be accessed by the compensation system enabling further developments to improve the system functionality. For example, tool length could be used to include tool offset in the calculation of compensation values. Currently, an average tool length is used which will produce small compensation errors with varying lengths of tool [7].

4 Compensation test results

Three machines have been tested to verify the ability of the compensation system to correct for volumetric geometric errors. Initial test data was obtained from the gantry robot and validation data from a machine provided by a collaborating company and a grinding machine at a machine tool builder company.

4.1 Gantry machine test results

The compensation program was tested using the standard Renishaw [8] data files collected from geometric calibration tests. The data was copied to the controller's hard disk and the files selected in the compensation program. Initially, only linear positioning data was used, which gave encouraging results as shown in Figure 5.

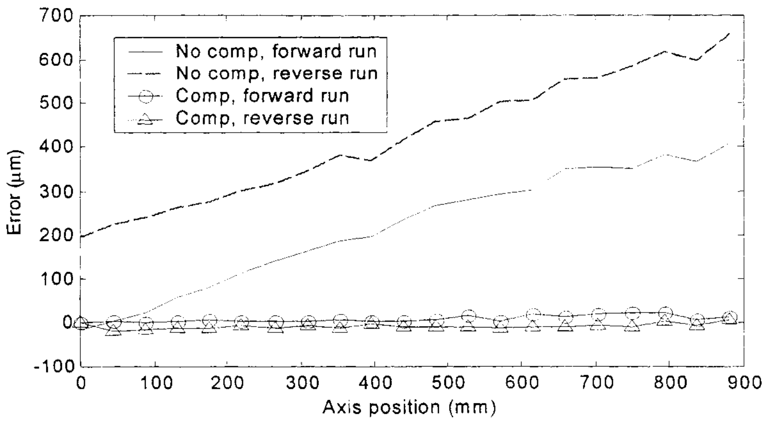


Figure 5: X axis linear positioning with and without compensation

Further sources of error were included in the compensation program to test dynamic performance using multiple axes. A Heidenhain grid plate was used to measure error during circular interpolation. Figure 6 shows the results of the test with and without compensation active. A major limiting factors on the positioning improvement is the poor repeatability of the test machine.

Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

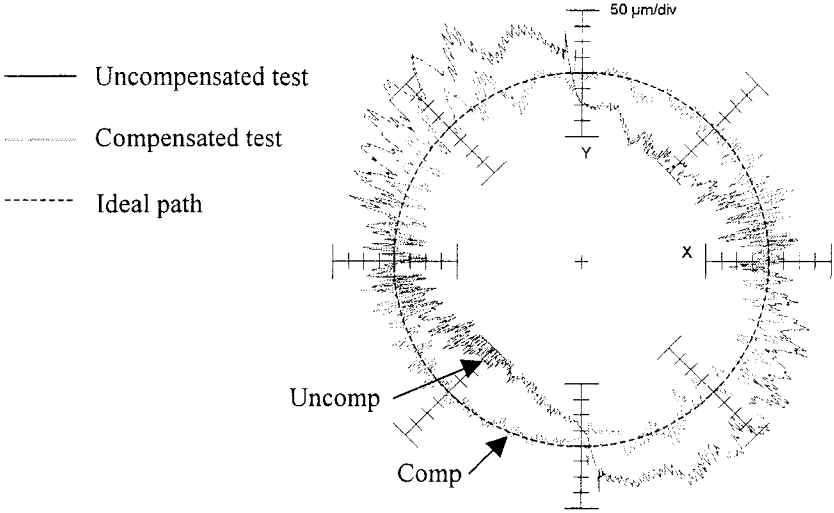


Figure 6: Grid plate data of compensated/uncompensated circular test

4.2 Validation on a machine tool

The series 10 controller has since been interfaced to a Knee type Huron machine tool at the University of Huddersfield and compensation applied through the controller. On this machine, the X-axis is supported by the Z-axis. Figure 7 shows an error of 30µm remaining after linear compensation is applied when the Z-axis is moved to the other end of its travel. By measuring linear positioning error at this Z-axis position, the effect of angular error 'X about Y' can be calculated and compensation applied. The error in X is significantly reduced for any position of the Z-axis.

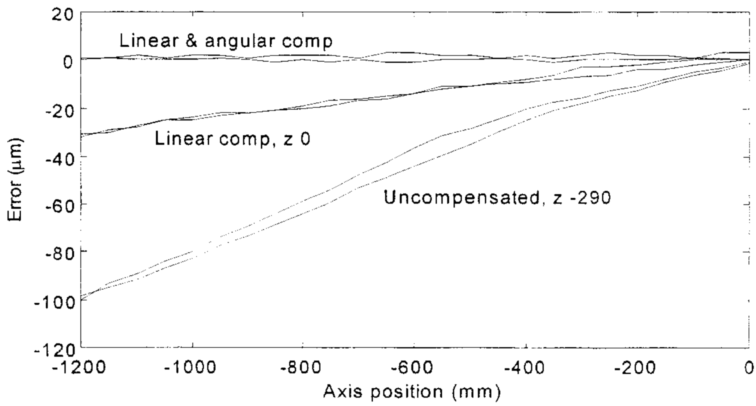


Figure 7: X axis linear and angular compensation

The next validation phase required application of the compensation strategy to an industrial machine that uses a series 10 controller.

4.3 Validation on an industrial machine tool

The compensation system has been shown to work in principle, but validation is required on an industrial machine tool. The purpose is not only to prove the capability of the system to compensate for geometric error, but also to illustrate the efficient nature in which the system can be applied to a machine using this type of controller on site. The grinding machine used did not exhibit significant geometric error, however, the principle remains and the errors that did exist were reduced. The configuration of the machine was that one axis was associated with movement of the tool and one axis associated with movement of the workpiece, as shown by the diagram in Figure 8. The geometric algorithm designed for a machine with two axes associated with movement of the tool and one with the workpiece is used in conjunction with a special 'zero' file to simulate an imaginary middle (*M*) axis.

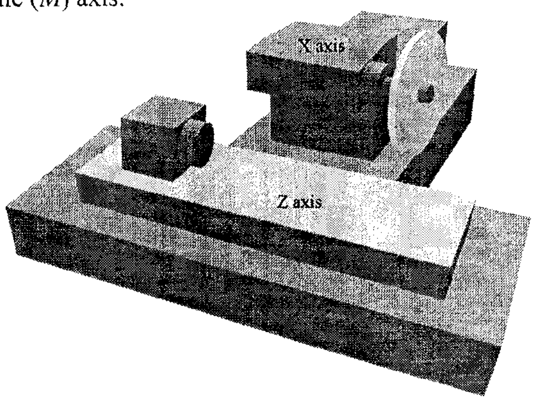


Figure 8: Grinding machine fitted with Osai series 10 controller

Geometric error data was taken using a laser interferometer and precision square, the measurements required are based on the errors affecting the volumetric accuracy of the machine, which are defined in the modified geometric algorithm in equation (1). The Y-axis is an imaginary axis perpendicular to the X and Z axes.

$$
\begin{aligned}
Z_{error} &= Z_{lin} + X_{strt(Z)} + \left(\phi_{Y(X)} \cdot X\right) + \left(XZ_{sqr} \cdot X\right) \\
Y_{error} &= Y_{lin} \\
X_{error} &= X_{lin} + Z_{strt(X)}
\end{aligned}
\qquad (1)
$$

Where:

$Axis_{error}$ = Resulting error on the axes
$Axis_{lin}$ = Linear positioning error
$Axis1_{str(axis2)}$ = *Axis1* straightness in the direction of *Axis2*
$\phi_{axis1(axis2)}$ = Rotation of *Axis2* about *Axis1*
BM_{sqr} = Squareness between B and M axes.

Transactions on Engineering Sciences vol 34, © 2001 WIT Press, www.witpress.com, ISSN 1743-3533

Figures 9 and 10 show two examples of the compensation being applied to correct for straightness error. The remaining errors are within ±2μm, which will not be much greater than the repeatability of the axis, which is the limitation of compensation.

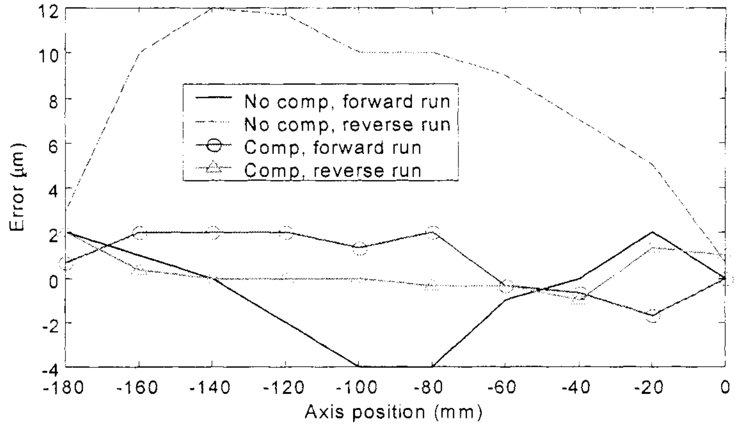


Figure 9. X axis straightness in Z compensation result

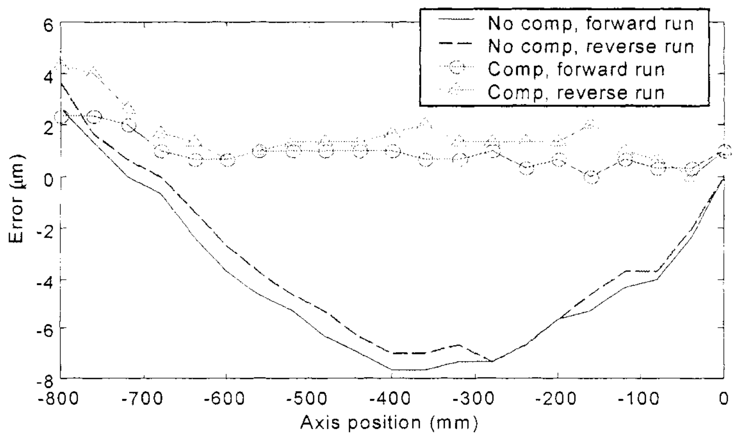


Figure 10. Z axis straightness in X, compensation result

Some dynamic tests were also completed using a Heidenhain grid plate to carry out circularity tests. Many of the geometric errors on the machine were small to begin with and many of the ISO 230-4 analysis results provided by the Heidenhain grid-plate software are dominated by reversal spikes. The most noticeable difference is in the rectangularity value which reduces from -168μm/m to just 21μm/m. This value represents the orthogonality (squareness) of the two axes. The 21μm/m of error still remaining may be attributable to measurement uncertainty associated with using the precision square and dial test indicator, and/or servo mismatch which would also affect rectangularity.

5 Conclusions

This is the first time a commercial CNC based compensation system has been produced for correcting the major sources of machine tool error. The system has been applied to three machine tools for validation and has been shown to significantly improve geometric accuracy. The installation of the system to an industrial machine tool highlighted the speed and simplicity of installation and potential reduction in cost of applying compensation.

Further developments are already in progress and thermal compensation has been included and tested. Upon validation, thermal compensation will be an important addition toward compensating for all major sources of machine tool errors through the machine controller.

6 References

1. Postlethwaite, S.R. "Electronic based accuracy enhancement of CNC machine tools". PhD thesis, 1992.
2. Mou, J., Liu, C.R., "A robust error correction method for multi-axis machines". Dynamic Systems and Control, V2, P1011-1018, 1994.
3. Ferreira, P.M., Liu, C.R., "A method for estimating and compensating quasistatic errors of machine tools". Journal of Engineering for Industry, V115, P149-159, 1993.
4. Chen, J.S., "Computer-aided accuracy enhancement for multi-axis CNC machine tool". International Journal of Machine Tools & Manufacturing, V35, N4, pp593-605, 1995.
5. Fowler, D., "Drilled for accuracy", *The Engineer*, 24 July 1998.
6. Postlethwaite, S.R., Ford, D.G., "A practical system for 5-axis volumetric compensation", *Laser Metrology and Machine Performance III*, pp379-388, 1999.
7. Longstaff, A.P., Postlethwaite, S.R., Ford, D.G., "Assessment of the volumetric accuracy of a machine with geometric compensation", Submitted for Publication in *Laser Metrology and Machine Performance V*, 2001.
8. Renishaw is an abbreviated name for Renishaw plc., Transducer Systems Division, Wooton-under-Edge, Gloucestershire.