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# A general purpose thermal error compensation system for CNC machine tools

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## Abstract

Thermal effects cause the majority of machining errors on many types of machine tool, with linear expansion and distortion of the structural elements causing unwanted movement between the tool and workpiece. Heat inputs that cause temperature elevation and gradients come from many sources internal and external to the machine tool and make thermal errors difficult to control without some form of compensation. Many thermal error modelling and compensation systems have been proposed which use neural networks, multi-regression analysis, heat modelling or probing techniques. However, each method suffers from one or more major drawbacks that limits its effectiveness when used in a practical machining environment. One feature of all the thermal error compensation techniques is their lack of flexibility that makes them difficult to apply to more than one machine type in a timely and cost-effective way.

This paper describes a combined thermal and geometric error compensation system with a flexible structure that is general purpose in its application to any machine tool. The system can accept input from any number of temperature sensors. Information from the temperature sensors is acted upon by a novel programming language based model that estimates thermal movement and directs error components to a number of outputs for compensation by axis position modification. The entire compensation system can be applied either in a stand-alone computer that accepts a wide range of feedback signal types, or integrated into an open architecture machine controller. The system allows the management of temporary or permanent input failures and displays every thermal error component as an aid to fault diagnosis. Both position independent and position dependent thermal errors can be reduced through compensation. The system has been applied to several machine tools.

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# 1 Introduction

Thermal error modelling and compensation systems proposed to date have been found to suffer from a number of drawbacks that makes their application in practical machining environments problematic. Neural networks (Chen [1]) may take a long time to train and cannot provide a guarantee of correct output for a wide range of input values and conditions. Multi-regression analysis (Wang [2]) also requires a long training time and has been shown to be sensitive to the positioning of sensors. Heat modelling (Fraser [3]) requires the thermal parameters of the system to be identifiable and repeatable. Probing techniques (Jan [4]) require an artefact that can take up a significant amount of space within the working volume of the machine and which slows down the machining process.

Research by Allen et al. [5] and White et al. [6] has found that thermal errors on CNC machine tools can be estimated well by breaking the machine tool into its constituent elements and modelling only those parts exhibiting the greatest thermal movement. They also demonstrated that machine tool structural elements can be modelled as rectangular based prisms with a good degree of accuracy. White [7] showed that it was necessary to have a knowledge of both the magnitude and position of temperature gradients in order to successfully model the two dimensional distortion of a machine tool structural element over a wide range of machine usage conditions. In order for this to be achieved, White developed a temperature sensor system that was capable of being cheaply and quickly applied to a machine tool structural element, and which required only a single, quick, heating and cooling test for calibration. In order for this temperature measurement system to be able to compensate for the thermal errors, a method has to be devised which can integrate the information supplied by the temperature sensors into a model that can then apply correction to the machine tool axes.

# 2 The requirements of a thermal model definition system

In order for a thermal error modelling system to be truly general purpose, it must be able to perform any calculation on the information supplied by the inputs, and apply this as output(s). The temperature model definition system thus has to perform the following operations:

- Name the temperature sensors and identify their positions.
- Perform calculations on the values associated with these names.
- Generate intermediate calculation results.
- Pass the calculated compensation value to an output.

For this task a programming language based approach is concise, flexible, easy to understand and straightforward to modify. A text file based model will facilitate quick changes by any standard text editor with this file being read by the compensation system software and the model interpreted. This arrangement means that the thermal compensation system software is identical for every machine and that a unique model can be entered into each machine according to the level and type of thermal error compensation required.

## 3 Declaration of the variable spaces to be used

The thermal error compensation system has to have the following variable spaces defined to achieve the functionality required of it.

- Temperature sensor names. This links the names used in the model and actual values read from physical devices that are referenced by a configuration file unique to each machine.
- Axis positions. Thermal errors that change with axis position can be calculated using the appropriate axis position.
- Compensation axes. This allows the compensation values calculated by the model to modify the machine position.
- Constants. These allow constants to be inserted into the model calculations, making them more readable and providing the ability to make global changes to the model without having to replace all the occurrences of a particular value.

Variables. These are the intermediate results to which the results of calculations can be assigned. These allow the model to be broken down into a number of self-contained stages that are easy to check for errors. The intermediate results are combined to produce the final compensation value. Figure 1 shows the portion of a model definition file used to declare constants and variables, which can be up to 20 characters long.

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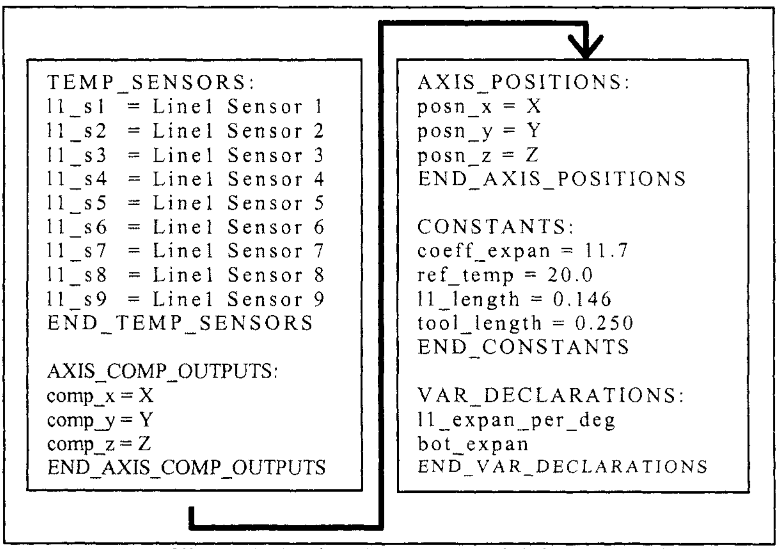


Figure 1: Declarations in a model definition file.

## 4 Setting the sampling rate of the temperature sensors

Some areas of a machine tool gain and lose heat faster than others according to the position and power of heat sources, and the rate of heat loss via conduction, convection and radiation. In order to achieve the fastest possible response to the areas that change temperature quickly, sensors in these areas need to be sampled as quickly as possible whilst sensors positioned in areas of slow temperature change can be sampled at a slower rate. Thus the facility exists in the thermal error compensation system for each sensor to be assigned a different sampling rate. Figure 2 shows the assignment of two groups of temperature sensors to different sampling rates, sensors 1 to 9 with 45 seconds between samples, and sensors 10 to 13 with 15 seconds between samples. Any number of assignments can be made. A default sampling period of 30 seconds is used when no temperature sensor assignment is made.

```
SAMPLE_PERIODS:
temp_sensor_1 – temp_sensor_9 = 45
temp_sensor_10 – temp_sensor_13 = 15
END_SAMPLE_PERIODS
```

Figure 2 – Setting the sampling rate of the inputs

## 5 Description of the calculations to be performed

The simplest and most flexible method of modelling is to use freeform calculations similar to a programming language. An unlimited number of lines can be programmed with normal operator precedence being applied. Thus the model can take any data from the temperature sensors and transform it to output(s) which apply compensation to the machine, as shown in Figure 3.

```
MODEL:
calculation_1 = value_1+value_2/value_3*value_4 – value_5
calculation_2 = value_6/calculation_1 + value_7
END_MODEL
```

Figure 3 – Model programming

## 6 Specialised functions

Whilst many operations can be performed using the basic arithmetical operators, it is more efficient to be able to perform certain operations using in-built functions. In addition, it is important to be able to identify and manage incorrect inputs caused by sensor failures when certain sequences of calculations are being performed on them. For this reason, the following specialised functions are available.

- Average. Calculation of the average temperature of a range of sensors that are position independent.
- Varaverage. Calculation of the average temperature of a range of sensors that are position dependent.

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- Power. Raise a value or identifier to a power.
- Bend. Calculate the effect of transverse bending that will result from a temperature gradient identified by two lines of sensors, with a position independent or position dependent mode.

An example of the use of specialised functions is shown in Figure 4.

```
MODEL:
coefficient_1 = POWER(y_axis_motor_sensor, 1.05)
column_expn = AVERAGE(line_3_sensor_1, line_3_sensor_11, percent_fail_limit)
z_ballscrw_avg_temp = VARAVERAGE(l4_s1, l4_s40, Posn_Z, percent_fail_limit)
z_ballscrew_expn = z_ballscrw_avg_temp*coeff_expan*Posn_Z
head_bending = BEND(l1_s1, l2_s1,15,coeff_expan, head_length, head_depth, transverse)
comp_z = z_ballscrew_expn + head_bending – column_expn*coefficient_1
END_MODEL
```

Figure 4 – The use of specialised functions

## 7 Handling of warnings and errors in the model definition

The flexibility of the modelling scheme means that warnings and errors can occur, both on compilation and at run time. Warnings generated by the system may include variables that have been defined but not used in the model, or temperature sensors that cannot be read. Warnings do not affect the operation of the compensation system. Errors generated during compilation (such as the failure to define a variable) or whilst a model is running (such as division by zero) stop the compensation system from compensating. Warnings and errors are time and date stamped and recorded in a log file.

## 8 Detection and accommodation of input errors

Input values will occasionally contain errors and temperature sensors may fail altogether. Any failures to read a temperature sensor are logged into a master log file, giving a brief diagnosis along with the date and the time to allow problems to be quickly and easily identified. Two systems were designed to prevent anomalies from affecting the compensation values applied to the machine tool. The first checks for large changes in an input value between samples and prevents any erroneous value being passed to the model. The second system detects the lack of response of a particular sensor and after a predetermined number of failed reads, denotes the sensor as having failed. The failure of a single sensor can have a large or small effect on the compensation output, according to calculations performed by the model on that sensor. In addition, several sensor failures can occur that together may cause the compensation value to be inaccurate. It is thus essential that the model designer can identify at what point the compensation system should cease to function. A function **"test(first_sensor, last_sensor, percent_fail_limit)"** is thus available. Using this function, a range of critical sensors can be specified. The percentage failure limit can be set to allow a maximum of sensor failures to occur before compensation is stopped. Any number of test functions can be used in a model.

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# 9 Viewing the operation of the model on-line

The current values of the intermediate results and the compensation output are displayed as the values are calculated. Each line of the model is shown and directly below it the current values being used in that line. In this way, a user can view any part of the model and quickly identify the origin of the proportions of error that make up the total compensated error. The displayed precision of the model values can be changed on-line to accommodate situations where these values are changing very slowly or very fast. Figure 5 shows a display of the model with the intermediate model values highlighted.

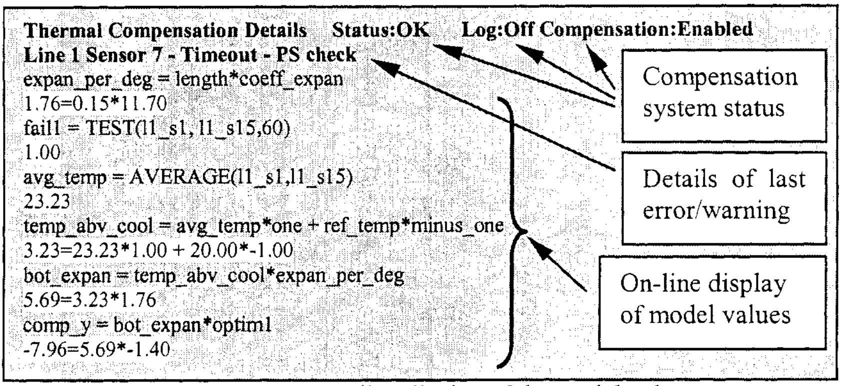


Figure 5 – On-line display of the model values

# 10 Recording model values during compensation

A useful feature of the compensation system is that of being able to record aspects of the operation of the compensation model whilst the machine tool is being used. Values selected by name can be recorded to a disk file at a frequency set by the fastest rate of change of the values selected (except axis positions). In this way, values that do not affect the aspect of the model being investigated can be omitted and the file of recorded values is of a manageable size. The file is in a text format allowing it to be read into any text editor and analysis packages such as MATLAB or EXCEL. When coupled with appropriate measurement of the thermal error components, this can be used to develop improved models. Figure 6 shows how the values to be recorded are selected.

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```
THERMAL_LOG_LIST:
temp_sensor_1 – temp_sensor_9
line1_average
comp_y
END_THERMAL_LOG_LIST
```

Figure 6 – The selection of values to be recorded

## 11 Expansion of the model definition system

An important feature of the thermal model definition system is that it can be easily expanded to meet the requirement of any future thermal error compensation strategy. Future requirements may include:

- Additional sensor types such as displacement or load sensing transducers.
- Additional variable types, allowing the definition of memory arrays.
- Additional specialised functions.
- New programming structures such as conditional operators.
- Tables allowing linearisation and conditioning of input sensor readings for very high accuracy over a wide span.
- Word inputs and outputs allowing the transfer of data to and from external systems.

Any new features can be defined as new keywords and added into the model definition file. The compiler is then modified to recognise these new key words and perform the appropriate action.

## 12 An integrated geometric and thermal error compensation system

The thermal error compensation system has been integrated into the geometric error compensation system developed at the University of Huddersfield, written in 'C'. The geometric error compensation system uses a pre-calibrated technique to correct for geometric errors anywhere within the machine volume. In order to do this the system needs to know the position of each axis and to be able to apply an offset to that axis position. This is achieved using plug-in scaler cards, which modify the incremental position feedback system by adding or subtracting pulses. The machine controller has no knowledge of the correction and thus continues to position the machine as normal. Figure 7 shows a schematic of the physical wiring. The geometric error position correction must be applied within the servo update time of the machine controller in order to ensure it remains valid. Thus the geometric error correction software has to perform a calculation loop within one millisecond. On the other hand, if the thermal errors requiring compensation are position independent, the temperature sensors only need to be read every few seconds (according to the sampling time(s) selected for the sensor(s) related to that error) and perform a calculation when the temperature data changes. For position dependent thermal errors, the temperature sensors only need to be updated at the normal sampling rates whilst the thermal error estimation has to be calculated within the servo update time to ensure thermal errors that change fast with axis position are corrected with precision.

The integrated geometric and thermal error compensation system has to ensure that both systems work within the timings specified. The offset corrections calculated by the geometric and thermal error compensation systems are added together for each axis to produce to overall compensation value that is applied to the machine.

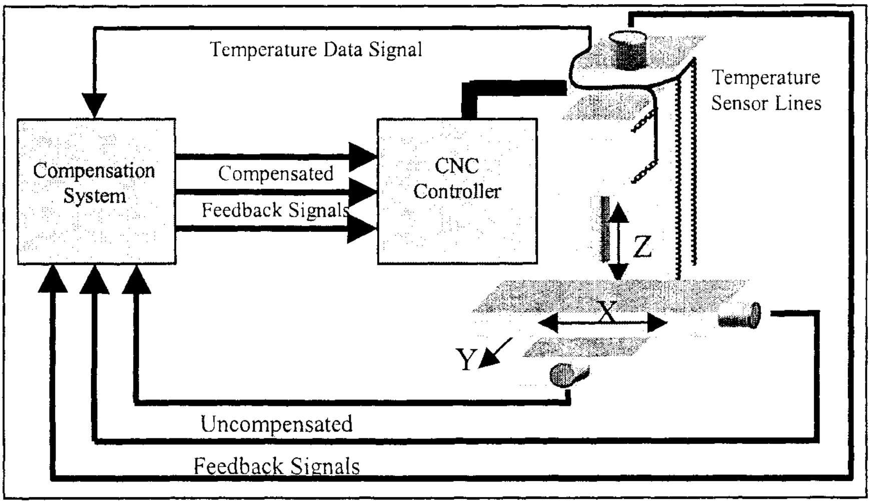


Figure 7 – Error compensation on a CNC machine tool

The general-purpose compensation system can be applied to any machine tool that has incremental rotary or linear feed back transducers and can reduce geometric and thermal errors on machines with 2, 3, 4 and 5 axes, with both primary and slave drive systems. The thermal error compensation system can apply compensation to any of these axes when necessary.

The system can accept TTL (5V) and sinusoidal analogue voltage signals (1Vp-p) incremental signals, with or without distance coded referencing, from the feedback devices. At present the system cannot accept input from absolute encoders.

## 13 Integration of a compensation system within a CNC controller

Compensation can be integrated into the controller. This has many advantages in that no additional wiring is required and that application of the compensation system only requires a software change within the controller. There are cost and reliability benefits over a compensation system applied externally, as close coupling of the compensation system to the machine controller can be achieved through better data interchange, so improving the diagnostic capabilities and functionality of the compensation system.

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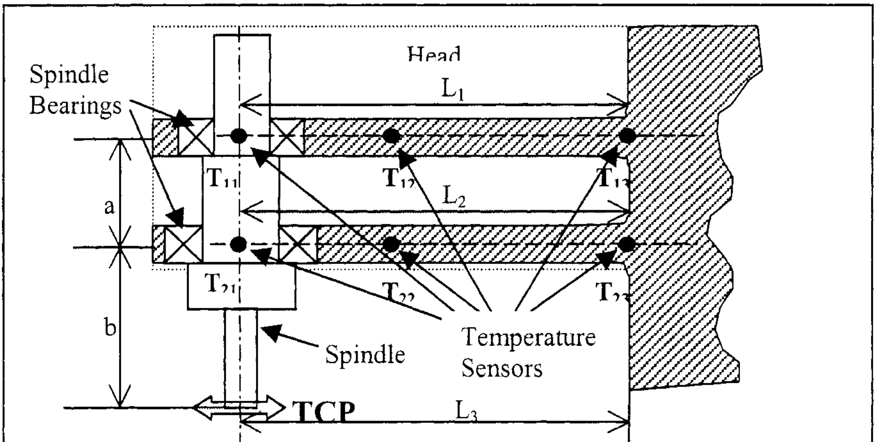
An OSAI series 10 controller was chosen to test the principle of applying compensation to an open architecture controller. The geometric and thermal error compensation system was modified slightly, allowing it to be integrated into the 'real time dos' section of the controller.

## 14 Application of the compensation system to a vertical machining centre

The compensation system has been applied to several machine tools including a system external to the machine controller on a vertical machining centre. Significant thermal growth was identified in the Y axis direction due to heating of the head. The distortion model shown in Figure 8 was programmed into the compensation system. The model is shown in Figure 9, and the results in Figure 10.




$$\Delta L_3 = (\Delta L_2 - \Delta L_1)\frac{b}{a} + \Delta L_2$$

Figure 8 – The distortion model applied to a head

```
bot_line_avg_temp = AVERAGE(line_1_sensor_1,line_1_sensor_17)
top_line_avg_temp = AVERAGE(line_2_sensor_1,line_2_sensor_17)
coolant_temp = temp_sensor_35
bot_temp_abv_coolnt = bot_line_avg_temp - coolant_temp
top_temp_abv_coolnt = top_line_avg_temp - coolant_temp
bot_line_expan = bot_temp_abv_coolnt*bot_line_length*coeff_expansion*bot_optimisation
top_line_expan = top_temp_abv_coolnt*top_line_length*coeff_expansion*top_optimisation
result_1 = bot_line_expan - top_line_expan
y_expan = result_1*tool_length/line_separation + bot_line_expan
comp_y = y_expan*minus_one
```

Figure 9- Programming the distortion model

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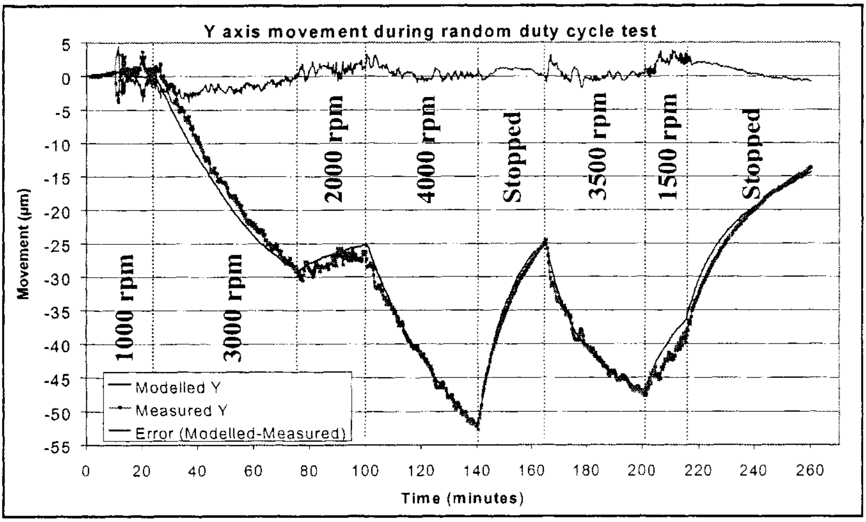


Figure 10 – Modelling of Y axis thermal movement

## 15 Conclusions

The compensation system has been found to be flexible, quick and simple to program, and has been used to reduce thermal movements between the tool and the workpiece by over 6 times using a quick heating and cooling test for calibration. The error and warning messages have been found to quickly identify modelling errors, and the system has shown itself to be tolerant of sensor failures.

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