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Development of Methods for Numerical Error Correction of Machine Tools*

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Summary

In November 1989, a research project, funded by BCR*, has been initiated to improve the accuracy of a commercially available five axis machine tool with software error correction. Therefore, the most significant error sources have been investigated: basic geometric errors, thermal behaviour of the machine's structure and finite stiffness effects.

A general model has been developed describing the geometric error structure of an arbitrary five-axis milling machine. With this model it is also possible to model the finite stiffness errors. An empirical and an analytical approach have been investigated to model the thermo-mechanical errors. The calibration of the machine tool has been carried out with both direct and indirect measurement techniques. Therefore, new test-workpieces are developed.

Using the developed methods a real-time error correction has been designed and implemented. This correction has been verified by test-workpieces and holeplate measurements, which showed an improved product accuracy of 80%.

Introduction

One can observe a tendency towards more accurate production machines, driven by the demand for better performance and reliability of products. The classical way to improve the accuracy of a machine is to enhance its hardware. However, these methods are costly and the physical limits will soon be achieved. With the aid of computer technology it is possible to compensate for the positioning errors existing in production machines, instead of avoiding them.

In November 1989, a research project, funded by BCR, has been initiated to improve the accuracy of a commercially available five-axis machine tool with software error correction. The target was to achieve an accuracy improvement by 70% with a software error correction for the most significant error sources.

Method

In order to accomplish a software error correction, the errors in a machine tool have to be modelled first. Based on this model the real-time error correction can estimate the error during normal operation and determine the contribution of this error component to the total error vector. By compensation with the estimated error, the remaining error during normal operation will be minimized.

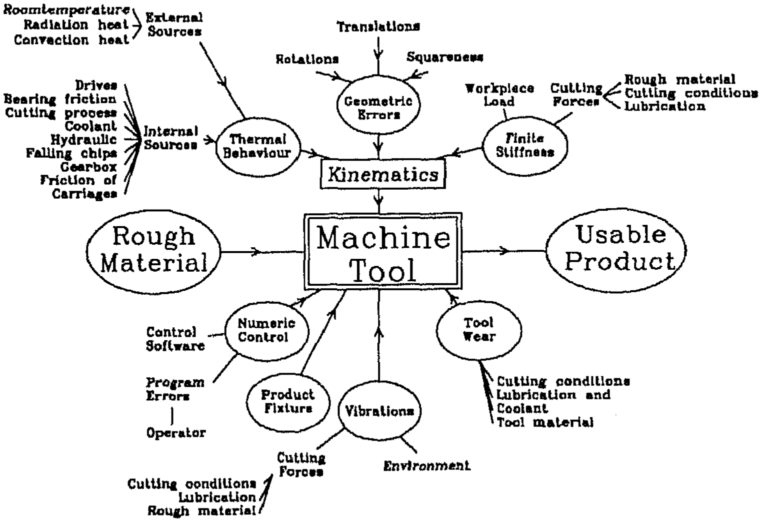

Figure 1: Sources of errors in machine tools

After a careful analysis of the error sources which disturb the final product accuracy (Figure 1), the following three major error sources have been selected:

1 - Geometric errors due to imperfect movements of the carriages;
2 - Geometric errors due to finite stiffness of the machine;
3 - Thermal behaviour of the machine's structure.

Together these errors contribute to more than 70% of the resulting error of a machine tool [1,2].

The research has been carried out on a five-axis milling machine. In order to automate the measurements an external computer is connected to the milling machine and the applied measurement instruments. In figure 2 the experimental setup is depicted.

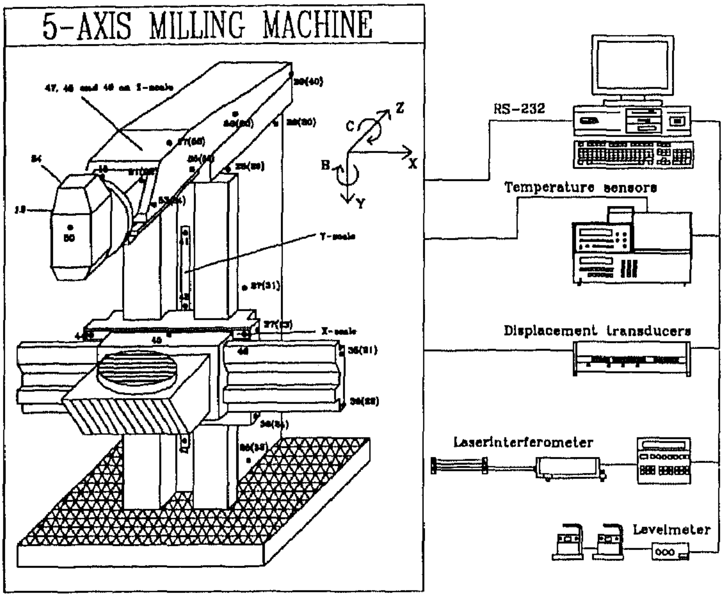

Figure 2 : Experimental setup

A special software package has been developed to interface with these instruments and the milling machine to facilitate all necessary activities, like:

1 - Calibration measurements with laserinterferometer, levelmeters and displacement transducers;
2 - Measurement of the temperature distribution on the machine tool;
3 - Evaluation of the thermo-mechanical models;
4 - Communication with the machine tool controller.

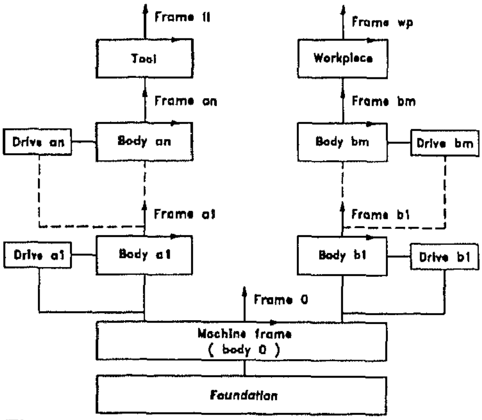

Figure 3: The kinematic modelling system

Geometric error model

A general model has been derived, which can be applied to an arbitrary machine, composed of prismatic and revolute elements (figure 3). It relates errors between the actual and nominal location of the tool, to errors in the location of coordinate frames, attached to successive components of the machine. Such errors describe the difference between the nominal and actual geometry of machine parts enclosed by two frames.

The error vector, which describes the errors of the tool with respect to the workpiece, can be described as similarly denoted errors in the relative location between successive frames:

$$ {}_{wp}E_{tl} = -\sum_{k=1}^{m} ({}_{tl}F_{bk}\ {}_{bk-1}E_{bk}) + \sum_{k=1}^{n} ({}_{tl}F_{ak}\ {}_{ak-1}E_{ak}) + {}_{an}E_{tl} \qquad (1) $$

With: ${}_{wp}E_{tl}$: Error in the location of the tool with respect to the workpiece (result)
${}_{k-1}E_k$: Error in the location of frame k with respect to frame k-1 (estimated with measurement results)
${}_{tl}F_k$: This matrix describes the effect of the errors ${}_{k-1}E_k$ on the resulting error. It is completely defined by the nominal machine geometry.

The model has been applied to describe both the geometric and finite stiffness errors.

Thermo-mechanical error models

Two different models have been developed to describe the thermo-mechanical errors of the machine tool as a functional dependence of its temperature distribution. The aim of modelling is the determination and (on-line) correction of thermally induced displacements between a workpiece and the tool of the five-axis milling machine.

Analytical model

To model thermo-mechanical deformations two basic setups are used. They describe changes of length and bending of a body with stationary temperature field and a homogeneous expansion coefficient. Because of the complexity of a machine tool these both assumptions are complied for limited areas of the machine structure. Therefore, the machine structure is divided into segments (Figure 4) corresponding to the finite element method (FEM). Total deformation is the sum of the deformations of each segment.

Statistical model

In order to determine the relationship between the temperature distribution and the deformation of the machine tool, the displacement of the tool is directly measured. The measurement of the temperature distribution is carried out with 39 Pt-100 temperature sensors. The machine is loaded with different spindle speeds to obtain different thermal situations. To acquire a thermally stationary mode the milling machine is loaded with a constant spindle speed of 6000 rpm. For the transient states, a new spectrum has been defined with a more random behaviour than the known spindle speed sequence according to DIN 8602 [3]. Within 24 hours, the machine is loaded with randomly chosen spindle speeds (between 800 and 6300 rpm) for randomly chosen time intervals (between 5 and 45 min).

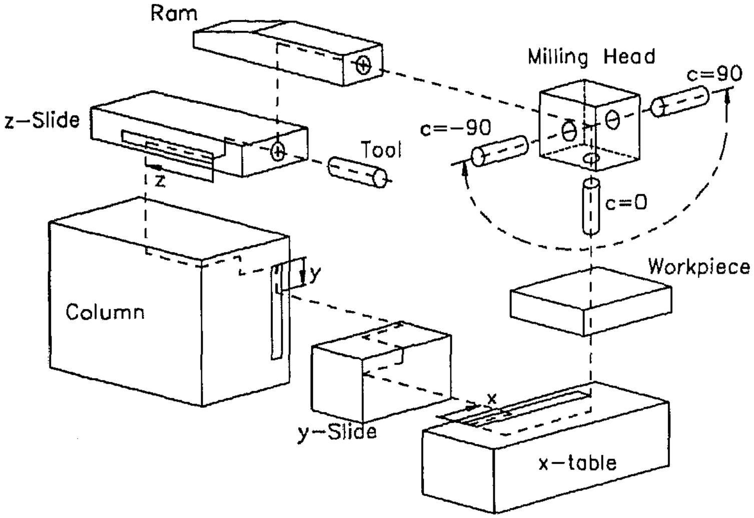

Figure 4 : Path of integration to calculate thermal expansions

The empirical obtained measurement results are analysed by statistical methods. Therefore, the statistical software package SAS [4] has been used.

The goal of this part of the study is to determine the relationship between the temperature distribution on the machine tool and the displacement of the tool holder. The temperature sensors are selected such that the predictive power of the model is optimal. This selection procedure has been carried out for 1 to 10 sensors. For each set of sensors the coefficients of the predictors (senors) are determined [5].

In figure 5 the results are depicted of this analysis for each direction separately. In this figure the effiency of the model is depicted for the zero-point drift, on one position. To judge the results quantitatively the efficiency of the simulation is calculated. The efficiency is the ratio of the simulated error to the measured error. Similar analysis are carried out on other positions within the range of the milling machine.

Based on this analysis the optimal model has been chosen, which has a total of 16 temperature sensors.

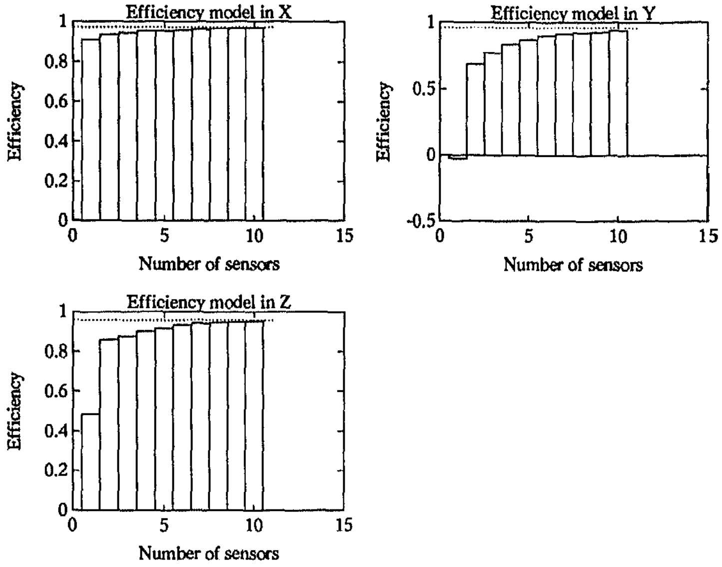

Figure 5 : Efficiency of the model for the calculatin of the zero-point drift in each direction seperately

Calibration methods

In order to determine the errors in the machine tool both direct and indirect measurement procedures have been applied.

Direct measurement methods

In order to complete the individual model, which describes the error structure of an individual machine at a certain time and place, the error components of the machine tool have to be identified. These error components are measured directly, using instruments as laserinterferometer, levelmeters and displacement transducers. With these measurements not only the geometric errors are measured, but also the change in geometric errors due to finite stiffness effects of the investigated milling machine.

Indirect measurement methods

Specially designed test workpieces have been developed to determine the machine tool errors under real operating conditions. With these workpieces it is possible to extract both geometric and thermo-mechanical errors. In figure 6 the top view of this test-workpiece with a total of 1700 machined tracks is depicted. The 28 holes represent a square with which it is possible to extract errors of length, straightness, parallelism and squareness. Each centre point of a hole is defined by 4 tracks. The surfaces (webs) between the holes represent the points of a plane. With these points errors of straightness and flatness are determined. The average position of 28 holes and 28 plane tracks is defined as the zero point (centre point) of the workpiece. The workpieces are designed to determine 12 error situations during an operation time of 3 to 4 hours. The error components and the zero point of the workpiececs are recorded on 12 parallel workpiece planes. To separate all axial error components of the machine tool the test workpieces have to be machined in 3 different orientations of the milling head (vertical spindle with C = 0°, +90°, -90°) and with the horizontal spindle. As shown in figure 7 the workpieces are fixed orthogonally to the machine axes with the zero point in the middle of the machining range (Xm, Ym, Zm). A coordinate frame U, V, W has been attached to each workpiece, with the W-direction always pointing into the workpiece.

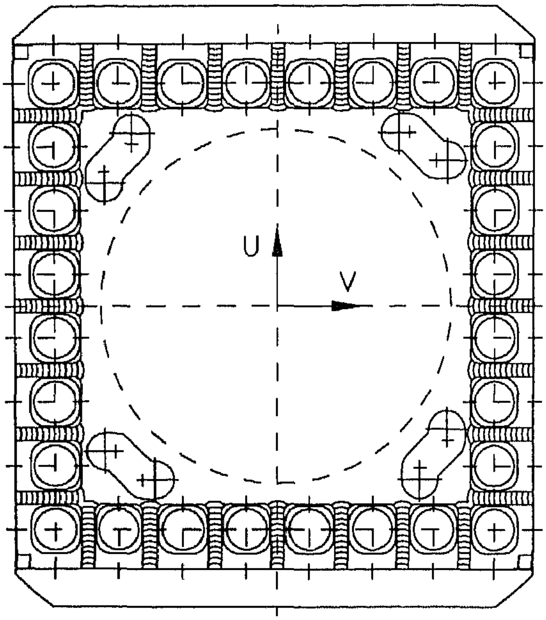

Figure 6: Test-workpiece for the error determination of milling machines

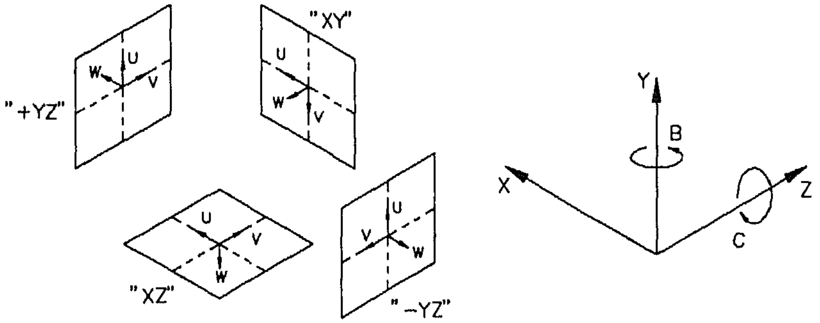

Figure 7 : Test-workpiece orientation with workpiece coordinateframe

The test-workpiece method is very suitable for the calibration of machine tools. Therefore these workpieces are applied for verification of the real-time software error correction.

Real-time error correction

The real-time error correction has been implemented in the controller software of the milling machine. The thermal error compensations are computed by an external PC that continuously monitors the thermal state of the machine tool. The finite stiffness compensations are determined as a function of the current load. Both compensation terms are added to the geometric compensations and sent to the controller.

Results

Finally, the effectiveness of the compensation and thereby the modelling methodology, is verified. The geometric and finite stiffeness error correction has been verified with the holeplate method [6]. A calibrated holeplate, with a rectangular pattern of holes, is measured by the machine tool with and without software error correction. In figure 8 the results of this experiment are depicted.
With the developed test-workpieces the effectiveness of the total error correction has been verified.
The next three figures (figures 9,10 and 11) show the results of the real-time software error correction with both thermo-mechanical models. In these figures the zero-point drift is depicted in three directions for three different conditions.

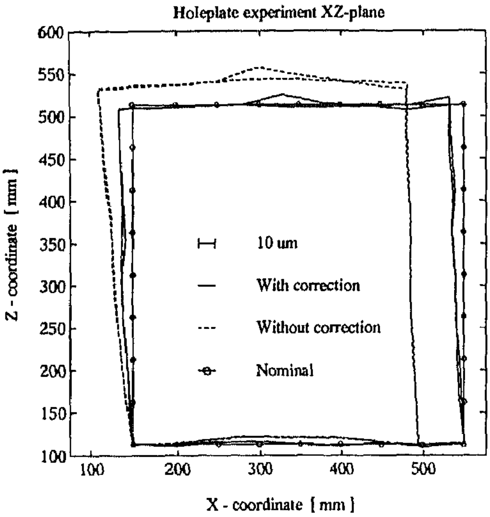

Figure 8 : Holeplate measurement for verification of the geometric error correction

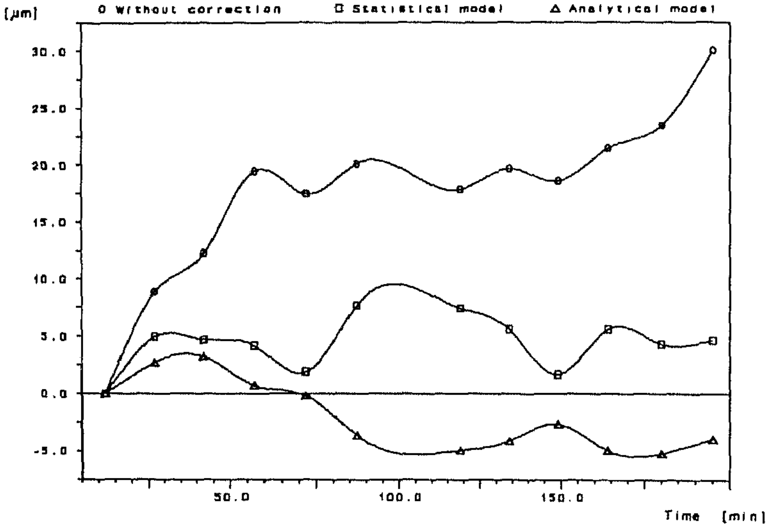

Figure 9 : Zero-point drift in X-direction (NTX) with and without correction

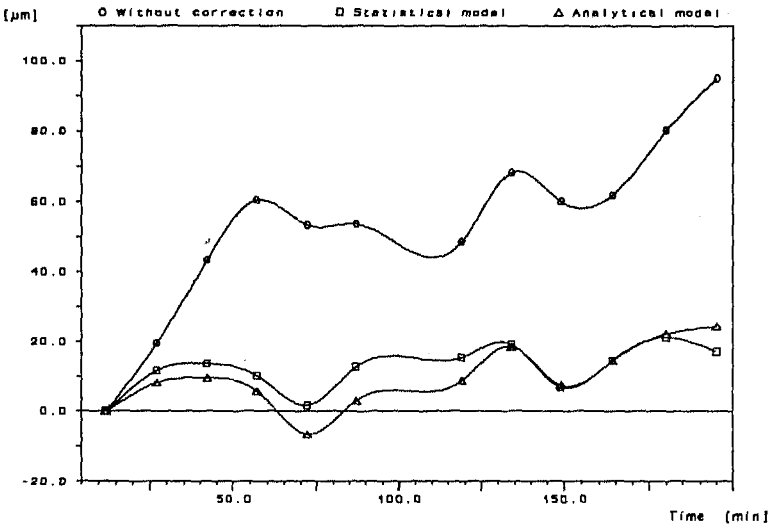

Figure 10 : Zero-point drift in Y-direction (NTY) with and without correction

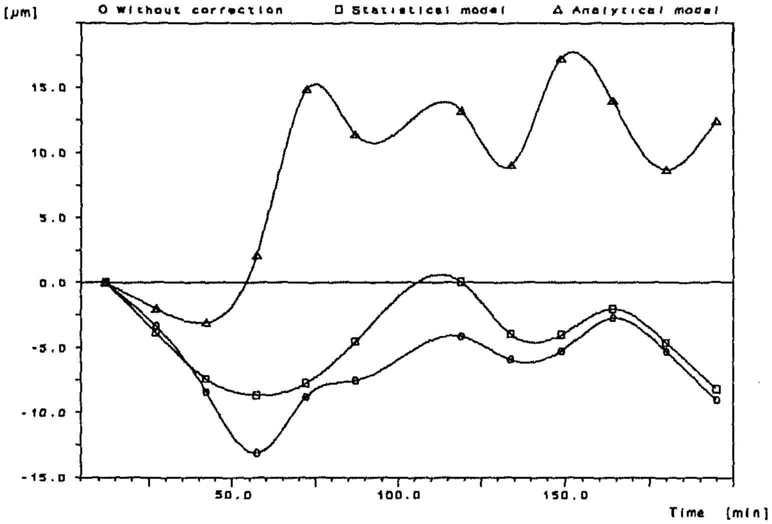

Figure 11 : Zero-point drift in Z-direction (NTZ) with and without correction

The validation of the real-time error correction, with respect to the thermo-mechanical error model, showed an overall product accuracy improvement of 66% for the analytical model and 69% for the statistical model. Considering the results of the real-time error correction depicted in figure 11, the zero-point drift in Z-direction is slightly improved by the statistical model and not improved by the analytical model. The latter would result in a negative effectiveness. However, the absolute value of the zero-point drift error in Z-direction is very small. Therefore, the absolute value of the remaining error should also be considered, in order to obtain a proper impression of the achievements of the real-time error correction. In figure 11, the absolute value does not exceed 17 μm.

The 28 holes of the test-workpiece represent a square. It is possible to extract errors of length with these holes. Figure 12 shows the linearity error in the workpiece extracted from two workpieces milled with and without software error correction.

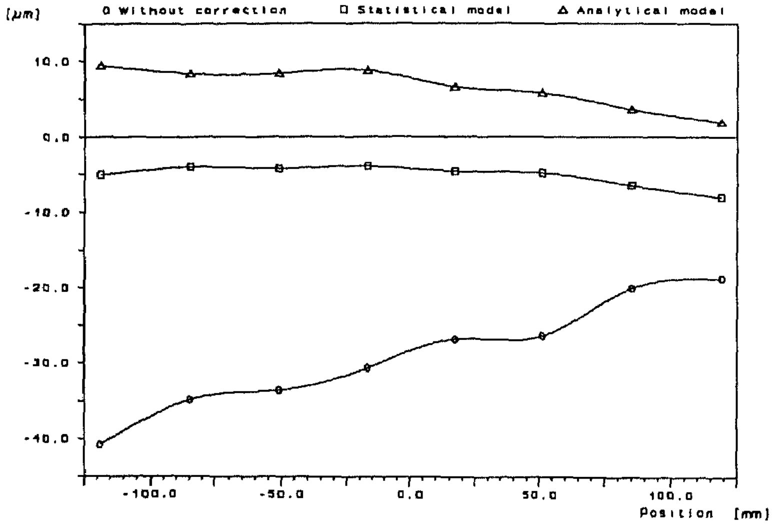

Figure 12 : Linearity error in the workpiece with and without correction

Conclusions

This research project has proven that it is possible to improve product quality considerable by real-time software error correction for geometric, finite stiffness and thermo-mechanical error sources.

For both the geometric and finite stiffness errors a model has been derived, capable of describing the errors of an arbitrary machine, consisting of revolute and prismatic elements. For the description of thermo-mechanical errors two different models have been developed. A statistical model, which relates the thermo-mechanical errors of the machine tool to the temperature distribution in an empirical way. Secondly, an analytical model has been developed, which describes these errors with a simplified 3-dimensional FEM-model.

All these error models have been implemented in the real-time software error correction. With this error correction, the remaining error of the tool with respect to the workpiece can be minimized during normal operation.

In order to verify the developed models and to show the possible accuracy improvement, the developed test-workpieces have been milled on the investigated machine tool. The results show an accuracy improvement of 80% for geometric, finite stiffness and thermal errors. The project goal was to achieve an accuracy improvement by 70%. The developed real-time error correction turns out to be even better.

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