Accuracy Improvement of Multi-Axis Systems Based on Laser Correction of Volumetric Geometric Errors

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Abstract. The article describes a volumetric geometric errors correction method for CNC-controlled multi-axis systems (machine-tools, CMMs etc.). The Kalman’s concept of “Control and Observation” is used. A versatile multi-function laser interferometer is used as Observer in order to measure machine’s error functions. A systematic error map of machine’s workspace is produced based on error functions measurements. The error map results into error correction strategy. The article proposes a new method of error correction strategy forming. The method is based on error distribution within machine’s workspace and a CNC-program postprocessor. The postprocessor provides minimal error values within maximal workspace zone. The results are confirmed by error correction of precision CNC machine-tools.

1. Introduction

CNC-controlled multi-axis systems are widespread in contemporary industry. Both machine-tools and measuring systems (i.e. CMM’s), used to produce and measure complex parts, include numerical controlled moving components [1-2].

There are several up-to-date trends in modern industry:

- Integration of measuring and machining operations;
- Constantly increasing accuracy requirements;
- Usage of complex shaped parts.

Thus, the requirements increase not only for positioning accuracy of machine’s parts, but also for volumetric accuracy of the whole machine – it’s ability to precisely reproduce complex surfaces.

2. Statement of the problem

Volumetric accuracy is characterised by volumetric error – vector between desired and actual position of cutting edge or measuring probe ending in any workspace point. The “Volumetric accuracy” term was first introduced in [3] and is actively studied in recent papers [4-6].

Volumetric accuracy depends primarily on technology of machine’s parts production and assembly. There are limited opportunities to increase volumetric accuracy by means of technology, making accuracy increase quite expensive or impossible [5]. Thus a new method is being developed, one based on error measurement and automated compensation [6-7].

The two especially strong trends benefit this method. First, CNC-control system evolve greatly, for both machining and measuring applications. Second, there is certain progress in the field of error measurement. Instead of microscopes, standards and strings, versatile laser interferometers are used,
allowing measurement of not only linear, but also angular and straightness errors for wide range of machine dimensions and with high precision. Moreover, recent advances in laser measurements allow simultaneous measurement of several error components. These trends, one in the field of control, and the other in the field of observation, provide new opportunities to increase volumetric accuracy. By means of software error correction. These opportunities are based on Kalman’s concept of “observation-control” duality [7]. This concept is used in MSTU “Stankin” in the field of multi-axis systems accuracy [5-7]. The concept unites processes of observation and control.

As mentioned in [5-7], the information stream consists of control – system’s adjustments - and observation – creation of system’s state model based on measurements of spatial error functions listed in [7]. [7] states that in order to map volumetric errors a number of error functions should be measured, i.e. 21 function for 3-axis machine, and more than 30 for 5-axis one. It is possible to collect a number such amount of data quite rapidly using a versatile laser interferometer.

Thus an increased volume of observation provides more informative state model and more effective error correction strategy. The error map can be not only created once, but, using a rapid measuring interferometer, can also be regularly updated and corrected.

3. Theory

Any machine-tool or CMM consists of several CNC-controlled moving parts. The parts provide linear movement and rotation of workpiece along or around coordinate axes. Errors of these movements and axes misplacement make up volumetric error of the machine.

Parts are machined and measured within the three-dimensional machine’s workspace. Machining and measurement errors are caused by linear and angular errors that distort the workspace. Thus the task is to determine the part’s distortion by means of measuring spatial error functions.

The versatile interferometer is used as an observer in order to create the machine’s state model. This kind of models are frequently described in papers. Many methods are used for this purpose, i.e. Denavit-Hartenberg method [8], rigid body kinematics method [9], multiple-body kinematics method [10], matrix simulation method [11]. Some papers consider not only systematic errors, but random errors as well.

Volumetric geometric error can be calculated as follows:

\[
XYZ = R^T \left( R^{-T} T + Z - Y \right) - X
\]

where X, Y, Z are the linear error vectors; \( R^T \), \( R \), \( R_z \) are the rotation errors matrices; \( T \) is the tool offset vector.

Hence, the equations for the axes errors are:

For X axis:

\[
\Delta X = \delta_{xx} (X) + \delta_{xz} (Z) + \delta_{yz} (Y) + \gamma [e_{zy} (Y) + e_{xz} (X)] + \gamma a_{xz} - Z [e_{xy} (Y) + e_{yx} (X)] - \\
-X a_{yx} + Y [e_{yx} (X) + e_{zy} (Y)] - Z [e_{yz} (Z) + e_{yx} (Y) + e_{yx} (X)];
\]

For Y axis:

\[
\Delta Y = \delta_{yx} (Y) + \delta_{xy} (X) + \delta_{yz} (Z) - X e_{yz} (X) - Z [e_{yx} (Y) + e_{yx} (X)] - Z a_{yz} + \\
+X [e_{zx} (X) + e_{zy} (Z)] + Y - Z T [e_{yx} (Y) + e_{yx} (X) + e_{xy} (Z)];
\]

For Z axis:

\[
\Delta Z = \delta_{zx} (Z) + \delta_{xz} (X) + \delta_{zz} (Y) - X e_{xz} (X) - Z [e_{zx} (Y) + e_{zz} (X)] + \\
+X T [e_{zx} (X) + e_{xy} (Z)] + e_{zz} (Y)] + Y T [e_{zx} (Y) + e_{xx} (Z) + e_{xx} (X)] + Z T,
\]

Where X, Y, Z are the current workspace point coordinates; \( X_T, Y_T, Z_T \) are the vector T components;
Others are the error functions from part II. The absolute value of volumetric error vector can be calculated as:

\[ \Delta = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2} \]  \hspace{1cm} (5)

High volume of observation is required in order to obtain information on volumetric error, i.e. 21 error function must be measured for a 3-axis machine, and more than 30 for 5-axis machine. Thus, the accuracy control can only be realized by means of versatile contactless and rapid interferometers.

4. Experiments

A HAAS “VF3” machine was used as the observation object. It has a commonly used alignment of parts, with horizontal X-table and vertical spindle.

![Figure 1](image1.png)

**Figure 1.** View and scheme of HAAS VF3 alignment.

Rigid body kinematics method was used in order to map errors of this machine. Renishaw XL-80 interferometer was used as observer. Following workspace points were used to collect data:

- X axis: 50 mm – 950 mm. step 100 mm – 10 points.
- Y axis: 25 mm – 475 mm. step 50 mm – 10 points.
- Z axis: 25 mm – 520 mm. step 55 mm – 10 points.

Special CNC programs were made in order to move machine’s elements to preset points. Figure 2 presents the resulting error map.

![Figure 2](image2.png)

**Figure 2.** Volumetric error distribution within machine’s workspace. Color scale in mm. There are about 20% points with volumetric error less than 5 micron.

Contemporary industry is based on interaction between CAD/CAM systems and CNC systems in order to transform a drawing into CNC program and then into cutting edge path. Thus a method of error control was used, based on changing coordinates of path’s points within CNC program. Figure 3 describes the method.
Figure 3. Error correction vector. Black – errors for each workspace point, grey – workspace point A errors, subtracted from all the other points.

For any workspace point A numbered \((l,m,p)\) and point \(B\) numbered \((r,s,t)\) error vectors are determined as \(\Delta x_{(l,j,k)}\), \(\Delta y_{(l,j,k)}\), \(\Delta z_{(l,j,k)}\) and \(\Delta x_{(r,s,t)}\), \(\Delta y_{(r,s,t)}\), \(\Delta z_{(r,s,t)}\). If errors for point A are subtracted from all workspace points (i.e., by means of coordinates origin shifting), then compensated errors for point A will be zero \((\Delta x_{(l,j,k)} = 0, \Delta y_{(l,j,k)} = 0, \Delta z_{(l,j,k)} = 0)\), and compensated errors for other points will be calculated as:

\[
\begin{align*}
\Delta x_{(r,s,t)}^{ck} &= \Delta x_{(r,s,t)} - \Delta x_{(l,j,k)} \\
\Delta y_{(r,s,t)}^{ck} &= \Delta y_{(r,s,t)} - \Delta y_{(l,j,k)} \\
\Delta z_{(r,s,t)}^{ck} &= \Delta z_{(r,s,t)} - \Delta z_{(l,j,k)}
\end{align*}
\]

Thus, absolute value of volumetric error vector for point A is zero:

\[
\Delta A = 0
\]

Absolute value of volumetric error vector for point B:

\[
\Delta B = \sqrt{\left(\Delta x_{(r,s,t)}^{ck}\right)^2 + \left(\Delta y_{(r,s,t)}^{ck}\right)^2 + \left(\Delta z_{(r,s,t)}^{ck}\right)^2}
\]

By picking all points within the workspace and subtraction their errors from all the other points, a point can be found so that sum of corrected errors will be minimal:

\[
\sum_i \Delta F_i \rightarrow \min
\]

Where \(i = 1, \ldots, N\); \(N\) is the number of workspace points; \(F\) is the random point in machine’s workspace.

These changes can be introduced: 1) during CNC-program creation via CAM system; 2) via CNC system after the program is loaded; 3) after program creation but before loading it into the machine. The last method was chosen because it is not uncommon that access to CNC system is limited or restricted. In order to introduce changes into CNC program a special software postprocessor was developed.

The postprocessor is integrated into technological system as shown on figure 4.
Figure 4. Technological streams interaction

Figure 5 presents result of error correction by means of a postprocessor. First, an optimal origin point was found. Then corrections were introduced into CNC system. Finally, all error functions were measured again. As result, error zone with smaller errors (less than 5 micron) make up to 80% of machine’s workspace (compared to 20% before correction).

The postprocessor works as follows:
1. Error measurements results are loaded into postprocessor;
2. Error vectors is being calculated according to (2)-(5) for all workspace points;
3. Coordinates origin shifts by calculated error value for a certain workspace point in order to correct measured errors;
4. Error vector for the given point is subtracted from all other points so that errors in other points decrease (or increase);
5. Steps 3-4 repeat for each workspace point so that an optimal point is found.
6. Condition (6) provides minimal errors within largest workspace area.
7. A CNC program created by Cam system is loaded into postprocessor;
8. The postprocessor analyses G-code lines and adjusts coordinates according to the correction values;
9. The corrected program is loaded into machine’s CNC system.

5. Discussion
Error map gives opportunities to:
- visualize error distribution within the machine’s workspace;
- determine workspace areas with required error value;
- determine workpiece’s distortion due to machining errors;
- calculate corrections to load into CNC system in order to minimize errors.
6. Conclusion

1. The article presents an algorithm and software developed for rapid error mapping.
2. A strategy of “optimal origin” selection is produced based on error mapping in order to provide minimal errors within largest workspace area.
3. A rapid origin search method is proposed.

The proposed method of error correction is based on finding “optimal origin point” considering volumetric errors of a machine and providing minimal errors within largest workspace area.

Usage of interferometer provides this method with an important reference point – point of beam splitting within interferometer’s optics. This point is machine-independent and can be used as a basis of machine’s origin point search.

The method’s effectiveness was tested by correcting real machine errors.

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