Software correction of geometric errors for multi-axis systems

V Teleshevskii 1 and V Sokolov 1

1 MSTU «STANKIN», 1, Vadkovsky per., Moscow, 127994, Russia

E-mail: Vasokolov-stankin@yandex.ru

Abstract. Accuracy control for software-controlled multi-axis systems (i.e. machining centers and CMMs) is an important problem for contemporary industry. The paper concerns a method of systematic geometric errors correction for such systems. Practically this method increases machining and measuring accuracy without mechanical adjustments of the machine. The goal of accuracy improvement was achieved by means of completing the following tasks: measuring components of volumetric error by means of multi-function laser interferometer; visualizing volumetric error distribution within the machine’s workspace (error mapping); developing of error correction strategy based on the mapping; developing of postprocessor for CNC programs in order to get minimal errors within the machine’s workspace. The paper includes results of volumetric errors correction for three-axis CNC-controlled precision machine-tools. The results prove adequacy of models and efficiency of the method.

1. Introduction (Heading 1)

Software-controlled multi-axis systems, both technological (various machine-tools and robotic systems) and measuring (coordinate-measuring machines and devices) are the basis of modern industry [1,2]. Present-day systems of this kind may be comprised of as many as 5 or 6 axes and even more.

Parts with complex three-dimensional surfaces are widely used in modern industry. This requires not only high positioning accuracy for machine’s axes, but also high volumetric accuracy - ability of a machine to precisely create a complex three-dimensional shapes by means of a cutting edge or gaging tip. The problem of volumetric accuracy improvement is often considered in recent papers [1-3].

2. Problem Description

The volumetric accuracy is defined by volumetric error (similarly to measurement error as difference between measure and datum value) – a vector from nominal (program defined) and actual position of a cutting edge or gaging tip within a certain point of machine’s workspace. Volumetric error for CNC-controlled multi-axis systems is defined as follows [3]. A real Cartesian coordinate system of a machine is concerned with three axes X_M, Y_M, Z_M, with a movement of ΔX, ΔY, ΔZ from point A to point B (Figure 1 a). This movement in an ideal coordinate system X_I, Y_I, Z_I moves not from point A to point B_I with coordinates ΔX_I, ΔY_I, ΔZ_I, but from point A to point B_M. This difference is presented by error vector B_M - B_I with components EX, EY, EZ.

This error is caused by the following. The moving part of a machine, e.g. table, not only moves linearly in the desired axis direction. It also has a number of unwanted degrees of freedom: two linear traversal degrees and three rotary degrees of freedom that can’t be completely excluded. Furthermore, the three axes of a machine have squareness errors. Thus 3 axes with 6 degrees of freedom each and 3
straightness errors make up 21 volumetric error components. These components form volumetric errors vector field within the machine’s workspace (Figure 1.b). The components are listed below. The angular errors are marked with Greek letter ε, linear errors are marked with Greek letter δ, and squareness errors are marked with Greek letter - α [3].

![Figure 1. Volumetric accuracy of machines (a); Errors field (b).](image)

| Component | Equation |
|-----------|----------|
| X positioning (scale) error | \( \delta_{xx}(X) \) |
| Y straightness of X | \( \delta_{yx}(X) \) |
| Z straightness of X | \( \delta_{zx}(X) \) |
| Roll of X | \( \varepsilon_{xx}(X) \) |
| Pitch of X | \( \varepsilon_{yx}(X) \) |
| Yaw of X | \( \varepsilon_{zx}(X) \) |
| Y positioning (scale) error | \( \delta_{yy}(Y) \) |
| X straightness of Y | \( \delta_{xy}(Y) \) |
| Z straightness of Y | \( \delta_{zy}(Y) \) |
| Roll of Y | \( \varepsilon_{yy}(Y) \) |
| Pitch of Y | \( \varepsilon_{xy}(Y) \) |
| Yaw of Y | \( \varepsilon_{zy}(Y) \) |
| Z positioning (scale) error | \( \delta_{zz}(Z) \) |
| X straightness of Z | \( \delta_{xz}(Z) \) |
| Y straightness of Z | \( \delta_{yz}(Z) \) |
| Roll of Z | \( \varepsilon_{zz}(Z) \) |
| Pitch of Z | \( \varepsilon_{xz}(Z) \) |
| Yaw of Z | \( \varepsilon_{yz}(Z) \) |
| X,Y squareness | \( \alpha_{xy} \) |
| Y,Z squareness | \( \alpha_{yz} \) |
| X,Z squareness | \( \alpha_{xz} \) |

In order to effectively correct the volumetric errors an error map – error distribution within the machine’s workspace – is required. Next, a correction strategy will be developed based on the error mapping [4]. Thus, the problem of the paper is to develop a method of measurement and correction of errors.

### 3. Theory

A modern machine-tool or CMM comprises of a software-controlled linear or rotary axes. Movement errors and axes displacement sum up into volumetric errors field [4]. The three-dimensional workspace of a machine is the machining or measurement space. This space is being deformed due to the linear and angular motion errors, thus the workpiece is being processed or
measured with errors. The problem arises to determine the errors of a part (e.g. after machining) or part’s image (e.g. 3d-model after measuring) based on axes errors measurement results. The axes errors should be measured and volumetric error map should be visualized in order to solve this problem.

The authors use Rigid body kinematics method and Denavit-Hartenberg notation in order to describe motion of machine’s parts [3].

The volumetric geometric error in machine’s workspace points is calculated by means of solving a matrix equation (1):

\[
XYZ = R_X \left[ R_Y \left( R_Z \left( T + Z - Y \right) - Y \right) \right] - X
\]  

(1)

where \(X, Y, Z\) – linear and squareness error vectors; \(R_X, R_Y, R_Z\) – rotation matrices; \(T\) – tool size correction vector.

Equation (1) expands into equations for error vector components for any workspace point:

X axis error component:

\[
\Delta X = \delta_{yx} (X) + \delta_{xz} (Z) + \delta_{xy} (Y) + Y [\varepsilon_{yz} (Y) + \varepsilon_{zx} (X)] + Y \alpha_{yx} - Z [\varepsilon_{yz} (Y) + \varepsilon_{zx} (X)] - Z \alpha_{xz} + X_T - Y_T [\varepsilon_{xz} (X) + \varepsilon_{xy} (Y)] - Z_T [\varepsilon_{yz} (Z) + \varepsilon_{yx} (Y) + \varepsilon_{zx} (X)]
\]

(2)

Y axis error component:

\[
\Delta Y = \delta_{yy} (Y) + \delta_{yx} (X) + \delta_{yz} (Z) \cdot X [\varepsilon_{xy} (Y) - \varepsilon_{yx} (X)] - \varepsilon_{xy} (X) - Z \alpha_{yy} + X_T [\varepsilon_{yy} (Y) + \varepsilon_{yx} (X)] + Y_T - Z_T [\varepsilon_{yx} (Y) + \varepsilon_{xy} (X) + \varepsilon_{xz} (Z)]
\]

(3)

Z axis error component:

\[
\Delta Z = \delta_{zz} (Z) + \delta_{zx} (X) + \delta_{zy} (Y) - X [\varepsilon_{xy} (Y) + \varepsilon_{yx} (X)] + X_T [\varepsilon_{yx} (X) + \varepsilon_{zy} (Z) + \varepsilon_{yz} (Y)] + Y_T [\varepsilon_{yx} (Y) + \varepsilon_{zy} (Z) + \varepsilon_{yz} (Y)] + Z_T - \varepsilon_{zx} (X)
\]

(4)

Where \(X, Y, Z\) – coordinates of a workspace point;

\(X_T, Y_T, Z_T\) – vector T components;

Other values were described in part 2.

The absolute value of geometric error vector for a workspace point is calculated as (5).

\[
\Delta = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}
\]

(5)

Thus a large volume of observation is required in order to obtain information on volumetric geometric errors. 21 error components should be measured for a 3-axes system, and over 30 components are required for a 5-axes system. Thus the volumetric accuracy control task can only be solved by means of high-performance multi-functional noncontact measuring systems.

Using laser interferometers makes solution of this kind of task possible [4]. Large volume of observation and computer-based information processing gives new quality to cnc-controlled systems. It is now possible to develop an error correction strategy based on laser measurements and automatically correct the errors by means of CNC system. Next, a post-processor can be introduced between a CAM system and CNC system. The postprocessor is based on error distribution information and introduces corrections into CNC program. This provides a possibility to correct volumetric errors by means of software without mechanical adjustments of the machine [1].

The authors have developed a software for error distribution visualization. The software functions as follows:

1) The software calculates absolute value of volumetric error vectors based on interference measurements results according to (1-5) for a number of workspace points;

2) Each absolute value is associated with a color according to color scale, i.e. minimal to maximal error green to red or black to white;
3) The workspace is output on a screen with its points colored according to the color scale (Figure 2).

![a) Error distribution visualization software depicting errors before (a) and after (b) correction. Colorscale in μm.](image)

The authors have developed a CNC program postprocessor introducing the error correction. Its sequence of operation is as follows:

The volumetric error components and absolute values are calculated for all the considered workspace points according to (1-4):

1) The zero of machine’s coordinate system is displaced by value of each axes error components for a k workspace point. Thus the error within the k point is completely compensated and equals zero.

2) The error components within all other points are changed by same displacement value, thus the error can either increase or decrease for different workspace points.

3) The steps 2-3 are being repeated for each i point of workspace. As a result of this search a workspace point called «zero point» is found, so that the sum of absolute values for all the workspace points is minimal (6):

$$\sum_i \Delta_i \to \text{min}$$

Condition (6) provides minimal volumetric error within maximal workspace zone.

4. Results of experiments

The measuring system required for solving the considered problem should be capable of data storing and transmitting and compatible with data processing software and error mapping visualization software.

A Renishaw XL-80 was used for data collection, being capable of performing noncontact measurements within wide range, with high precision and on high speed of moving parts.

A Kondia A-10 was used as error correction object (Figure 3 a). The type of the machine is a widespread kind including stacked horizontal slides and vertical spindle (Figure 3 b).
The authors have measured the 21 error components of the object. Fig. 4–6 represent schematics, pictures and results of measurements of selected error components. The experiment has determined that a point “A” with coordinates X=440, Y=230, Z=180 complies with (6). The Figure 2 b represents volumetric error distribution after correction using this point. The “green” area of low error (under 20 μm) at Fig. 2b is much larger compared to the Figure 2a shown. Before correction this area included 8% of workspace points; after the correction the “green” area included more than 50% of workspace points.

After computer simulation of correction the machining center’s CNC system was corrected according to the simulation results. Next, the 21 error components were measured again according to part IV in order to validate the simulation results. The actual error values differed from simulation results by no more than 3%.

5. Discussion

The volumetric error mapping makes the following possible:

- Visualization of volumetric geometric machining or measurement errors within the machine’s workspace;
- Determination of workspace areas with minimal or required error values;
- Determination of machined or measured surfaces deformation;
- Calculation of correcting software adjustments of CNC system providing minimal errors within the workspace.

![Figure 3. Kondia A-10 exterior (a) and schematic (b).](image)

![Figure 4. Schematics (a), picture (b) and results (μm) (c) of Y axis positioning errors measurements.](image)
Figure 5. Schematics (a), picture (b) and results (μm) (c) of Y axis straightness errors measurements.

Figure 6. Schematics (a), picture (b) and results (μm/mm) (c) of Y axis angular errors measurements.

6. Conclusion

- Advances in measuring systems and CNC-controlled machinery provides new opportunities for volumetric geometric errors improvement.
- Modern laser measuring devices, being noncontact, multifunctional and efficient, make it possible to acquire large array of measurement data on the tested machine by means of fast and precise measurement of multiple error functions. All sizes and quality classes of machining and measuring equipment can be rapidly tested. Thus previously unsolvable problem of volumetric error correction can now be solved.
- The algorithm and software used for this paper provide high speed of calculations (i.e. it processes 12000 points in 40 seconds).
- The “zero point” error correction strategy is introduced, providing minimal errors within maximal workspace zone.
- The authors described variational search algorithm. The algorithm finds the “zero point” by means of processing the deformed workspace in several dozens of seconds.
- Using CAM and CNC systems with a postprocessor corrects errors of considered machine based on calculated geometric error distribution.

The article describes a method of significant improvement of multi-axis machines volumetric accuracy by means of only software procedures and without mechanical adjustments of the machine.

The method’s effectiveness is confirmed by real measurements within physical workspace of a multi-axis machine.

7. Acknowledgment

The paper was sponsored by The ministry of Science and Education of Russian Federation, research program № 1883.
References

[1] V Teleshevskii, V Sokolov 2012 Laser correction of geometric errors of multi-axis programmed-controlled systems Measurement Techniques vol. 55 5 pp 535-41

[2] S Kononogov, V Lysenko and S Zolotarevsky 2008 Concept of geometric surface parameters measurements traceability Pribory 3 pp 1-13

[3] H Schwenke et al. 2008 Geometric error management and compensation of machines – an update Ann. CIRP vol. 57 pp 660–75

[4] V Sokolov, K Basalaev 2014 Laser measurements based for volumetric accuracy improvement of multi-axis systems Physics Procedia vol. 56 pp 1297-1304