On the problem of laser error correction of multi-axis influence of loading on laser accuracy correction of multi-axis systems

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Abstract. The paper considers a method of error correction for numeric-controlled multi-axis systems (such as machine-tools or CMMs). The paper adds influence of static load research to previous author’s papers. The paper features loaded and unloaded machine’s error correction results. The migration of “zero point” described in previous papers is considered.

1. Introduction
The paper continues previous research on multi-axis systems error correction [1]. Numeric-controlled multi-axis systems are the essential part of modern industry [2-4]. Such systems, both technological (machine tools based on various physical principles) and measuring (coordinate-measuring machines and devices). Precision requirements increase constantly for both machine’s parts movement and for volumetric accuracy [5-7] – ability of a machine to accurately reproduce complex three-dimensional surfaces with cutting edge or measuring point.

The method of volumetric error of multi-axis machines measurement was described in [8-11]

2. Research task
The previous papers by authors considered error measurements without load applied to the machine. Current paper considers influence of static load applied to the multi-axis machines on error measurements result.

A machine-tool TOMILL-160 by CMT was selected as research object.

Figure 1. Exterior (a) and layout (b) of TOMILL-160 machine-tool by CMT

The machine’s characteristics are following:
- X axis movement range: 0 - 300 mm;
- Y axis movement range: 0 - 160 mm;
- Z axis movement range: 0 – 250 mm.
- Positioning accuracy ±0.01 mm.

The authors utilize rigid-body kinematics method in order to map the machine’s errors [11]. Renishaw XL-80 measuring system was used for data collection.

The error values were measured within following coordinates of machine-tool’s axes:
- X axis: 30 mm-270 mm, step 30 mm – 9 points total;
- Y axis: 5 mm-140 mm, step 30 mm – 9 points total;
- Z axis: 5 mm-245 mm, step 30 mm – 9 points total.

Corresponding CNC programs were loaded into the machine-tool’s CNC system in order to perform the required movements.

A static load was imitated by means of a load weighing 4 kg placed onto the machine-tool’s table. 21 spatial error functions [11] were measured using appropriate combinations of XL-80 optical components according to methods described in [6]. Figures 2-4 present measuring layouts and system’s view during the experiment.

![Image](attachment:image1.png)

**Figure 2.** Layout (a) and unloaded (b) and loaded (c) machine’s view during position error measurements.

![Image](attachment:image2.png)

**Figure 3.** Layout (a) and unloaded (b) and loaded (c) machine’s view during angular error measurements.

![Image](attachment:image3.png)

**Figure 4.** Layout (a) and unloaded (b) and loaded (c) machine’s view during straightness error measurements.

### 3. Theory

The volumetric accuracy of three-coordinate machine-tools is calculated by means of matrix equation solving:

\[
X\check{Y}\check{Z} = R_X \cdot \left[ R_Y \cdot \left( R_Z^{-1} \cdot \check{T} + \check{Z} - \check{Y} \right) - \check{X} \right]
\]

Where \( R_X, R_Y, R_Z \) are rotation matrices containing information on angular error;
\( \check{Z}, \check{Y}, \check{X} \) are displacement vectors containing information on linear errors (position and straightness errors);
\( \vec{T} \) is tool size correction vector.

The solution of this equation produces following results for X, Y and Z axes error components.

X axis error:

\[
\Delta X = \delta_{xx}(x) + \delta_{xz}(x) + \delta_{yx}(y) + \delta_{zy}(y) + \delta_{yx}(y) + \delta_{zy}(y) + \delta_{xy}(x) + \delta_{xz}(x) + \delta_{z}(x)
\]

Y axis error:

\[
\Delta Y = \delta_{yy}(y) + \delta_{yx}(x) + \delta_{zy}(y) + \delta_{yz}(z) + \delta_{xy}(x) + \delta_{xz}(x) + \delta_{z}(x)
\]

Z axis error:

\[
\Delta Z = \delta_{zz}(z) + \delta_{zx}(x) + \delta_{zy}(y) + \delta_{yy}(y) + \delta_{xy}(x) + \delta_{xz}(x) + \delta_{z}(x)
\]

Where \( \delta_{RR} \) are the measured linear errors;
\( \varepsilon_{RR} \) are the measured angular errors;
\( \alpha_{RR} \) are the axes squareness error.

The absolute value of volumetric error is calculated as:

\[
\Delta = \sqrt{\Delta_x^2 + \Delta_y^2 + \Delta_z^2}
\]

4. Experimental results

The maximal absolute value of the machine-tool’s volumetric error was calculated as 130 micron (loaded) and 60 micron (loaded). Figure 5 presents the error maps.

**Figure 5.** Unloaded (a) and unloaded error maps. Color scale in microns.

The “less than 5 micron error” zone comprises 20% of unloaded machine-tool’s workspace and 30% of loaded machine-tool’s workspace.

In order to correct errors a method was chosen that changes coordinates within CNC-program in order to move the cutting edge to correct position. The method was described in [10].

After introducing error correction the spatial error functions were measured again. Figure 6 presents the results of measurement.

**Figure 6.** Unloaded (a) and unloaded error maps after introduction of error correction. Color scale in microns.
The measured errors are no more than 3% greater than expected after preliminary simulation. The “less than 5 micron error” zone now comprises 80% of unloaded machine-tool’s workspace (compared to 20% before error correction) and 90% of loaded machine-tool’s workspace (compared to 20% before error correction).

5. Discussion
The software developed to process experimental data takes only 40-50 seconds to find a so-called “zero point” within the machine’s workspace. The “zero-point” makes errors within all other workspace points minimal relative to it. The previous papers by the authors [7-8] propose a computational method allowing to find the “zero point’s” coordinates of a machine-tool. A software was created to perform these calculations. Introduction of error correction by values of errors calculated for the “zero point” allows to reach minimal error values for maximal machine-tool’s workspace zone. A CNC-programs postprocessor was developed in order to introduce the error correction [7]. The developed postprocessor edits the CNC-program and “binds” the machined part’s datum to the calculated “zero point”.

During the experiments the “zero point’s” coordinates were calculated for both unloaded and loaded machine-tool. It was stated, that “zero point” migrates influenced by load, moving down the Z axis or shifting along X or Y axes depending on the load’s position.

6. Conclusions
The experiment has shown that an unloaded machine-tool’s volumetric accuracy can be considerably different from a loaded one’s. The reasons for this are gaps between machine-tools’ parts and other factors, disappearing whenever load is applied. Thus, error measurement should be performed with load applied to the measured machine, making its status closer to working conditions. The “zero point” migration allows effective dynamic correction of machine-tool’s errors.

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