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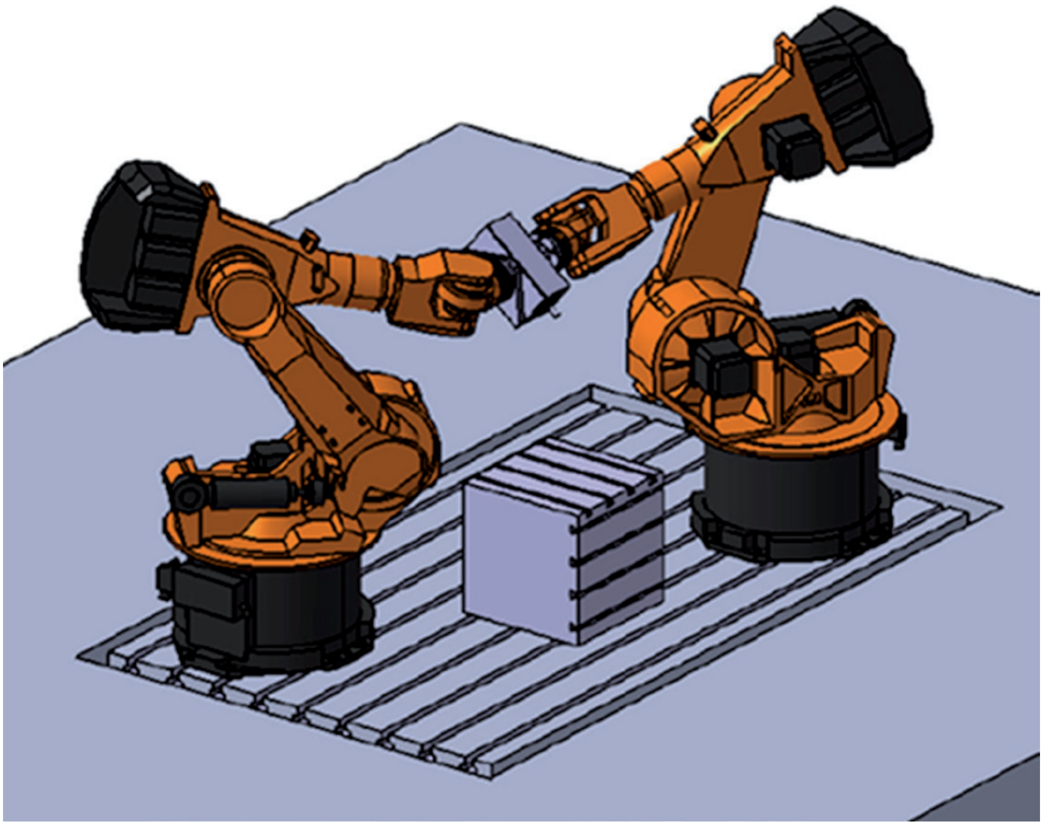

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Editors:

Michael Valášek, Zbyněk Šika, Tomáš Vampola, Michal Hajžman, Pavel Polach, Zdeněk Neusser, Petr Beneš, Jan Zavřel

Contact address:

Czech Technical University in Prague
Faculty of Mechanical Engineering
Technická 4
166 07 Prague
Czech Republic
Phone: +420 22435 5038

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Improved Calibration of Machine Tools by Redundant Measurement

Michael Valášek, Filip Kovář

Faculty of Mechanical Engineering
Czech Technical University in Prague
Technická 4, 16607 Praha 6, Czech Republic
[Michael.Valasek, Filip.Kovar]@fs.cvut.cz

Abstract

The paper deals with the new procedure of calibration of machine tools or robots by redundant measurements. The usage of laser tracker cannot provide sufficient accuracy of calibration within large workspaces. It is based on redundant measurements. The laser tracker measures the position of multiple reflectors firmly attached in the workspace. This enables to increase the accuracy of measurements several times.

Keywords: calibration, improved accuracy, redundant measurement, laser tracker, machine tool

1. Introduction

The main disadvantage of current techniques for accurate measuring of machines is a time of measuring. There is no possibility to guarantee constant conditions during the entire measurement. In this point of view the thermal deformation is the main problem. The proposed solution is based on patent [1] .The solution is based on the laser tracker located near the tool (end-effector). Laser tracker then in each measuring point monitors the position firmly fixed reflectors.

In the proposed solution was chosen configuration with one laser tracker and any number of reflectors in the workspace. The laser tracker was mounted on the slide of the machine. Redundant measurement brings results with high accuracy in the relatively short time.

2. Getting Data – Redundant Measurements

As was mentioned above, the basic diagram is composed of a laser tracker – the follower located on the slide of the machine and a number of reflectors located in the whole workspace. This scheme is shown in figure 1 of patent [1].

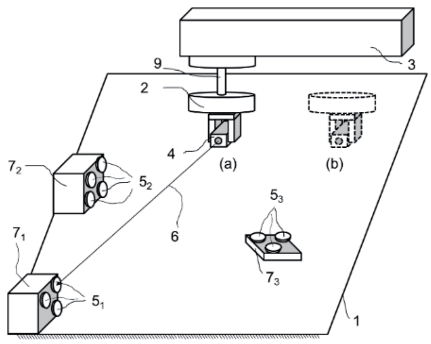

Figure 1: Measurement scheme

Figure 1 shows us a workspace - 1 spindle - 2, headstock - 9, slide – 3, follower - 4, reflectors - 5, the laser beam - 6, the platform holding the reflector - 7.

Measurement starts by moving the end effector (corresponds to the position of follower) to the first position (Figure 1 position (a)). The relative position of the reflectors is measured in this point by tracker. After that, end-effector moves in to the second position (Figure 1 position (b)). In this point the position of reflectors is measured again. This cycle is repeated for a selected number of follower positions. From the measurement of reflectors in one position it is obtained the relative position of all reflectors and one position of the tracker. With each new end point location and subsequent measurement the redundancy is obtained. To determine the amount of redundancy the formula is used

$$E = \frac{v}{b} \tag{1}$$

where v is the number of measurements exceedings the number of DOFs and b is the number of kinematic loops [5].

Figure 2 is a diagram showing the 2D model utilized for basic simulation testing of the proposed method. Blue crosses are reflectors and red circles are tracker positions. As shown, in the planar model each point have two unknown parameters - x and y coordinates. As a coupling conditions can be used distance between the position of the follower and all reflectors (indicated by red arrows) and the distance between any reflectors (indicated by green arrows).

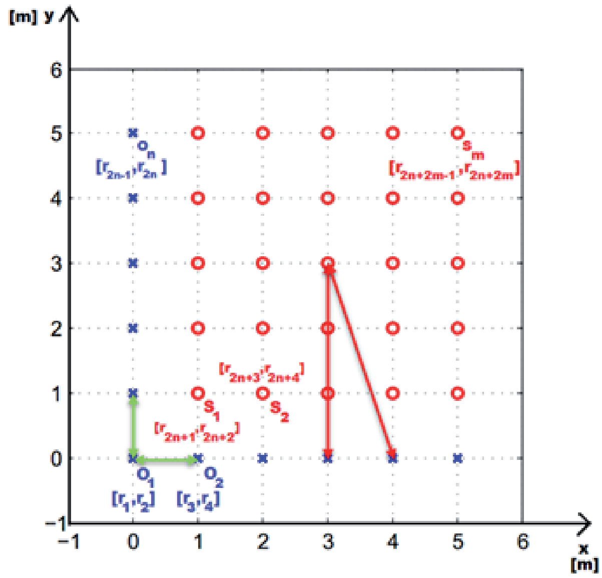

Figure 2: Measurement procedure

For the 3D model the situation is similar, except that each reflector and each position of the follower has 3 calibration parameters.

3. Data Processing

Data processing takes place after the measurement in all positions. As described above, in the planar case each point has two coordinates, which are also calibration parameters r_i.

$$\boldsymbol{R} = [r_1 \quad r_2 \quad r_3 \quad \dots \quad r_{2n+2m}]^T \tag{2}$$

In the expression (2) calibration parameters are entered in vector. Their number depends on the number of reflectors and the number of positions of the follower, as is evident from Figure 2.

For calibration it is needed to suitably choose the coupling conditions. For this method it is used the distance between two selected points as shown in the expression below.

$$f_k = (r_{2i-1} - r_{2j-1})^2 + \left(r_{2i} - r_{2j}\right)^2 - l_{ij}^2 \tag{3}$$

There is the k-th coupling condition for the i-th a j-th point in the expression (3). Expression l_{ij} is the dimension between these two points. Expression (3) expresses the vector of all conditions.

$$\boldsymbol{F} = [\boldsymbol{f}_1^T, \boldsymbol{f}_2^T, \dots, \boldsymbol{f}_a^T]^T \tag{4}$$

For calibration was selected modified Newton method, for which it is needed to draw Jacobian. Jacobian is composed of the partial derivatives of binding conditions according to the calibrated parameters. This creates a matrix:

$$\boldsymbol{J} = \begin{bmatrix} \frac{\partial f_1}{\partial r_1} & \frac{\partial f_1}{\partial r_2} & \cdots & \frac{\partial f_1}{\partial r_{2(m+n)}} \\ \frac{\partial f_2}{\partial r_1} & \ddots & & \frac{\partial f_2}{\partial r_{2(m+n)}} \\ \vdots & & \ddots & \vdots \\ \frac{\partial f_{2nm+2}}{\partial r_{r1}} & \frac{\partial f_{2nm+2}}{\partial r_2} & \cdots & \frac{\partial f_{2nm+2}}{\partial r_{2(m+n)}} \end{bmatrix} \tag{5}$$

The modified Newton method according to [2-4] solves overdetermined system. This is further complemented by a variable step length. For s-th iteration is valid:

$$\boldsymbol{F}_s = \boldsymbol{F}(\boldsymbol{R}_s, \boldsymbol{l}) \tag{6}$$

$$\boldsymbol{J}_s = \boldsymbol{J}(\boldsymbol{R}_s, \boldsymbol{l}) \tag{7}$$

$$\Delta \boldsymbol{R}_s = -\lambda (\boldsymbol{J}_s^T \boldsymbol{J}_s)^{-1} \boldsymbol{J}_s^T \boldsymbol{F}_s \tag{8}$$

$$\boldsymbol{R}_{s+1} = \boldsymbol{R}_s + \Delta \boldsymbol{R}_s \tag{9}$$

The algorithm begins with inaccurate parameters R_0. Iterative calculation is carried out in a loop until $\|F\| > \varepsilon$ or $\lambda \geq \varepsilon$, where ε is sufficiently small number. Variable step length ensures the convergence. In our case it is chosen the bisection method. It means that if there is a divergence in s+1 iteration ($\|\boldsymbol{F}s{+}1\| \geq \|\boldsymbol{F}s\|$), step λ is decreased by half.

4. Simulations

The 2D model (Figure 2) and 3D model with dimensions 3 x 3 x 10 m were selected for basic verification of the proposed method. The position of the tracker and reflectors were distributed in the space equally. The results of the basic testing are shown in Table 1.

Table 1: Simulation results

		Max. coordinate error	
Number of reflectors	*Number of position of laser tracker*	*Original [m]*	*Final [m]*
2D:			
7	9	1,2E-04	4,03E-05
7	25	1,47E-04	2,31E-05
7	81	1,79E-04	1,79E-05
3D:			
5	10	2,32E-04	7,52E-05
8	10	3,82E-04	5,27E-05
12	10	8,65E-04	2,67E-05

In the Table 1 it can be seen that the accuracy achieved is increasing for the increasing number of reflectors and positions of tracker. According to the expression (2), it is obvious that the redundancy depends on the number of positions of the reflectors and the tracker. Obviously, with increasing redundancy, the achieved accuracy of the simulation increases.

5. Testing and Verification

As a follower was selected laser tracker Leica AT901 (Figure 3 left). To results verification was chosen interferometer XM-60 of Renishaw (Figure 3 right). Experimental verification methods was conducted on the machine Grata in the company TOS Varnsdorf (Figure 4). The machine was used only for translation x, y, z.

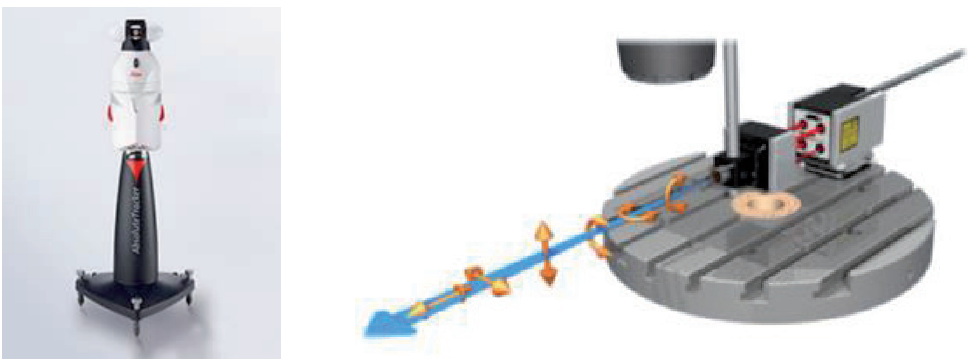

Figure 3: Measuring instruments

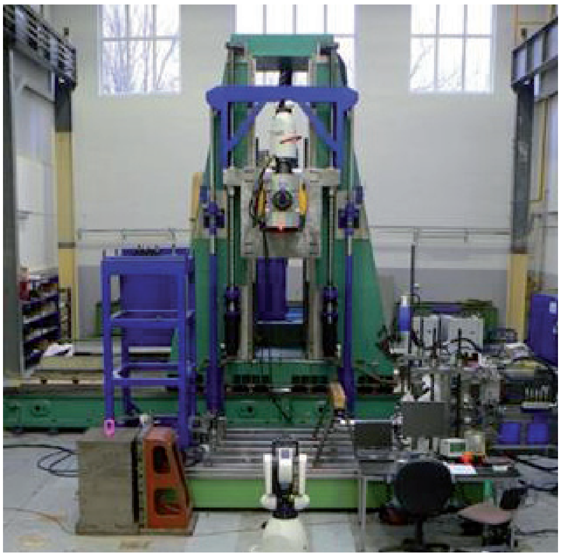

Figure 4: Grata – TOS Varnsdorf

During the experiment were used 17 reflectors and 32 follower positions.

Table 2: Experiment results

Number of reflectors	17
Number of position of laser tracker	32
Max. error of machine-tool	0,027 mm
Max. error of eternal laser trackers	0,069 mm
Max. error of laser tracker before algorithm	0,072 mm
Max. error of laser tracker after algorithm	0,011 mm

Machine tool moved with maximal error 0.027 mm. External laser tracker had maximal error 0.069 mm. External follower was used to compare the results of follower mounted on the slider and the static external follower. Laser tracker located on the slider have maximal error before algorithm 0.079 mm and 0.011 mm after the algorithm.

6. Conclusion

The algorithm for processing data for redundant measuring was managed to compile. Simulations for 2D and 3D model were made. After that experimental verifications were realized. Simulation shows us a dependence between accuracy and the number of reflectors and the number of the positions of laser tracker. The experimental test results (shown in Table 2) indicate more than 6-times improvement. This is considered as a very good result.

In the following steps, the factors will be examined that are influencing the achievable improvement, as spatial arrangement of the followers and reflectors, the impact of changes in the length between the reflectors during testing etc.

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