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THE MOST RECENT WAYS OF CMM CALIBRATION

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Abstract: The aim of modern calibration methods is to determine the total position uncertainty of a coordinate measuring machine (CMM) in the whole working range, but also to identify all 21 partial errors. These errors can be entered as correction factors in modern CMMs, thus reducing the total position uncertainty of the machine. New calibration artefacts are being developed and suitable positions are being looked for with the aim, among others, to shorten the calibration time.
Keywords: CMM calibration, partial errors, CMM with horizontal arm

1 INTRODUCTION

Some years ago, the Czech Meteorological Institute (CMI) faced the task to find how to calibrate coordinate measuring machines (CMMs) as precisely and quickly as possible. There are approximately 380 CMMs in the Czech Republic. Annually, several tens of CMMs are calibrated in Škoda Auto and other companies using flat artefacts such as ballplates or holeplates [4]. These calibrations are often completed with laser interferometer measurements. In many cases, due to an excessively high uncertainty, a CMM had to be put out of intended operation after the calibration has been carried out and the calibration report has been issued. In that case, the CMM user has to call the appropriate maintenance service. The effort of the CMI is to find a methodology that would both determine the total uncertainty and calculate all 21 partial components of geometrical uncertainties that can be quite easily entered into the control system of modern CMMs.

At present, the CMI is involved in a EU project whose purpose is to find new artefacts, a new calibration methodology for large CMMs with a horizontal arm. Moreover, the algorithm for the computation of all partial geometrical uncertainty components is looked for. Partial elastic errors have been included in the project for the first time.

2 CALIBRATION

Using a ballplate or holeplate, the CMM can be easily calibrated whose measuring space is comparable with the size of the calibration artefact used. The artefact is put in three basic positions

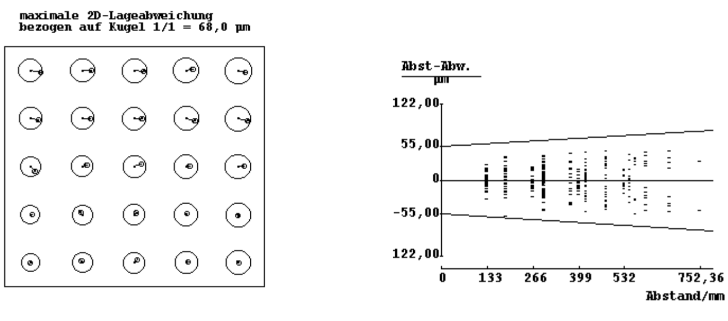


Figure 1.

one horizontal and two vertical, mutually perpendicular, ones. The calibration yields information on perpendicularity deviations of the coordinate axes and the waveform of the resultant uncertainty. A test of the touch probe system based on measurements of the ball and cylinder is added to the calibration. A very quick method including evaluation software verified in PTB (Physikalish Technische Bundesanstalt), Germany, is offered by ITI, Germany [2]. For the result refer to Fig. 1. CMI has used this calibration methodology for several hundreds of CMMs in recent years.

3 TOTAL UNCERTAINTY – SUM OF PARTIAL ERRORS

To determine the total uncertainty as the sum of partial errors, an appropriate kinematic and mathematical model has to be created. The resulting movement of the CMM is divided into partial translation and rotation movements. Three small translation deviations and three angle changes superimpose to the single partial translation movement. All these six components of the variation to the ideal movement induce real bonds. The partial rotation movement would be described likewise.

This principle of determining the total uncertainty as the sum of partial errors was projected and developed in PTB. Four years ago, the CMI faced the question whether to adopt this methodology in the Czech Republic. Because the PTB offered the software as a black box, only with resulting matrix relations and without a detailed derivation, the CMI and CVUT Faculty of Mechanical Engineering, Department of Mechanics, created their own calculation model.

4 THEORETICAL APPROACH TO THE TASK

From the mechanical point of view it is possible to regard the CMM as a spatial mechanical device used to transform movements. It consists of a system of linked bodies, one of which is stationary and serves as a frame. The bodies are combined in pairs which can be connected into open or closed chains. Vector or matrix methods are often used for mathematical description. Transformation of the coordinate system is used to describe position of a point or a body, or to describe concurrent movements of bodies.

This chapter presents a calculation model used for determining the final position uncertainty of such type of CMM, which consists of three mutually perpendicular translation movements. This is common with CMM5 SIP, for example.

For the kinematic diagram of the machine in question see Fig. 2.

We will distinguish three large movements determined by values *x, y, z* and 21 small movements (errors). We will isolate 3 constants (perpendicularity errors of axes *x, y, z*) and 18 variables, 6 for each axis.

Since there are a lot of variables employed in the problem, they have to be designated properly. We will use the symbols that seem to be logical and clear. For example, in Äö$_x$ (y)

Ä is a symbol for small movement (error),

ö$_x$ is the relevant coordinate, here rotation around axis *x*,

y in brackets says that the assumed error is a function of variable *y*.

The same applies to the other cases.

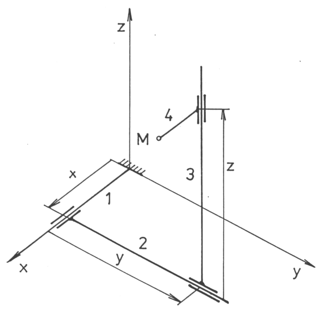


Figure 2.

Let's return to the problem of position precision of point *M* now.

4.1 Basic Matrices

Let us suppose that the sets of bodies *a* and *b* coincided with each other at the beginning. Suppose that body *b* moves in relation to body *a* in such a manner that one axis designated identically for both systems remains the same. Such types of motion are called **basic movements.** There are evidently 6 basic movements, namely 3 translations (shifts) in the direction of axes *x*, *y*, *z* (let us call them basic movements *Z1*, *Z2*, *Z3*) and 3 rotations around axes *x*, *y*, *z* (let us call them *Z4*, *Z5*, *Z6*). In these cases, the afore mentioned transformation matrices have extremely simple forms. We will list them without comment below. For details refer to [5,6,8].

1**. Basic movement:** shift on axes $o \equiv x_a \equiv x_b$, $o \equiv y_a \equiv y_b$, $o \equiv z_a \equiv z_b$ by length *x, y, z:*

$$\mathbf{T}_{Z1} = \begin{bmatrix} 1 & 0 & 0 & x \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{T}_{Z2} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & y \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \mathbf{T}_{Z3} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & z \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad (1, 2, 3)$$

2. **Basic movement**: rotation around axis $o \equiv x_a \equiv x_b$, $o \equiv y_a \equiv y_b$, $o \equiv z_a \equiv z_b$ by angle j_x, j_y, j_z:

$$\mathbf{T}_{Z4}=\begin{bmatrix}1&0&0&0\\0&\cos j_x&-\sin j_x&0\\0&\sin j_x&\cos j_x&0\\0&0&0&1\end{bmatrix},\mathbf{T}_{Z5}=\begin{bmatrix}\cos j_y&0&\sin j_y&0\\0&1&0&0\\-\sin j_y&0&\cos j_y&0\\0&0&0&1\end{bmatrix},\mathbf{T}_{Z6}=\begin{bmatrix}\cos j_z&-\sin j_z&0&0\\\sin j_z&\cos j_z&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\qquad(4, 5, 6)$$

Matrices (1) to (6) are called **basic matrices**.

4.2 Small Movements

We have supposed so far that we work with „large“ values of basic matrix arguments corresponding to „large“ movements of bodies. In the theory of kinematic precision of position of mechanisms, however, we meet with „small“ arguments corresponding to errors („small“ movements). „Large“ and „small“, however, are relative terms. For the purpose hereof, „large“ will include measured values of the order of [mm] or [rad], and "small" will mean errors of these values expressed in [ìm] or [ìrad], i.e. two to three orders lower. Small quantities will be designated as Ä*s,* where s is the coordinate whose small value (error) is in question.

Small movements do not bring any changes to basic shift matrices, so that

$$\mathbf{T}_{Z1}(\Delta x)=\begin{bmatrix}1&0&0&\Delta x\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\qquad(7)$$

and similarly in matrices $\mathbf{T}_{Z2}$ and $\mathbf{T}_{Z3}$. However, such basic rotation matrices which contain sine and cosine functions will change. If we use approximations by first members of the McLaurin series only for small arguments of these functions, i.e.

$$\sin\Delta j \doteq \Delta j\,,\quad \cos\Delta j \doteq 1$$

the form of basic rotation matrices will change as follows:

$$\mathbf{T}_{Z4}(\Delta j_x)=\begin{bmatrix}1&0&0&0\\0&1&-\Delta j_x&0\\0&\Delta j_x&1&0\\0&0&0&1\end{bmatrix},\mathbf{T}_{Z5}(\Delta j_y)=\begin{bmatrix}1&0&\Delta j_y&0\\0&1&0&0\\-\Delta j_y&0&1&0\\0&0&0&1\end{bmatrix},\mathbf{T}_{Z6}(\Delta j_z)=\begin{bmatrix}1&-\Delta j_z&0&0\\\Delta j_z&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\qquad(8, 9, 10)$$

Neglecting products of two and more small quantities of higher order in resultant matrix elements, we get the same matrix in all the above mentioned cases. Therefore, we can claim that

- **All basic small movement matrices are commutative in the product. The product of all six basic small movement matrices in any sequence always gives the same result,** namely

$$\Delta\mathbf{T}=\begin{bmatrix}1&-\Delta j_z&\Delta j_y&\Delta x\\\Delta j_z&1&-\Delta j_x&\Delta y\\-\Delta j_y&\Delta j_x&1&\Delta z\\0&0&0&1\end{bmatrix}\qquad(11)$$

Note that these (very convenient in practical computation) conclusions are applicable within the linear theory only.
The resultant transformation matrix $\mathbf{T}_{\bar{14}}$ of the real movement of the body 4 with respect to the body 1 is obtained in the following form:

$$\mathbf{T}_{\bar{14}}=\mathbf{T}_{14}\,\Delta\mathbf{T}\text{ó}=\begin{bmatrix}1&-\sum\Delta j_z&\sum\Delta j_y&x+\sum\Delta x\\\sum\Delta j_z&1&-\sum\Delta j_x&y+\sum\Delta y\\-\sum\Delta j_y&\sum\Delta j_x&1&z+\sum\Delta z\\0&0&0&1\end{bmatrix}.\qquad(12)$$

Hence, we have arrived at the following conclusion: if the measuring machine gives values *x, y, z* for the ideal position of point *M* determined by radiusvector $\mathbf{r}_{1M}$, the real position $\overline{M}$ of point *M* is determined by radiusvector

$$\mathbf{r}_{1\overline{M}} = \mathbf{T}_{1\bar{4}}\mathbf{r}_{4M} \qquad (13)$$

The last-mentioned equation includes the effect of all 18 partial errors. For details see [6].
Note: the above mentioned result evidently complies with the PTB methodology. The PTB formulation of the error in the form

$$\mathbf{E} = \mathbf{P} + \mathbf{A}_p\mathbf{X}_p,$$

where

$$\mathbf{A}_p = \begin{bmatrix} 0 & -xrz - yrz - zrz & xry + yry + zry \\ xrz + yrz + zrz & 0 & -xrx - yrx - zrx \\ -xry - yry - zry & xrz + yrx + zrx & 0 \end{bmatrix}, \mathbf{X}_p = \begin{bmatrix} x_p \\ y_p \\ z_p \end{bmatrix}, \mathbf{P} = \begin{bmatrix} xtx + ytx + ztx \\ yty + xty + zty \\ ztz + xtz + ytz \end{bmatrix} \qquad (14)$$

expresses the same as (13) using other symbols.
The afore mentioned symbols are different from those used by the PTB [2]. Let us give the following table for comparison (examples given for the x-axis):

X axis	our symbol	Äx(x)	Äx(y)	Äx(z)	Äö$_x$(x)	Äö$_x$(y)	Äö$_x$(z)
	PTB symbol	x t x	y t x	z t x	x r x	y r x	z r x

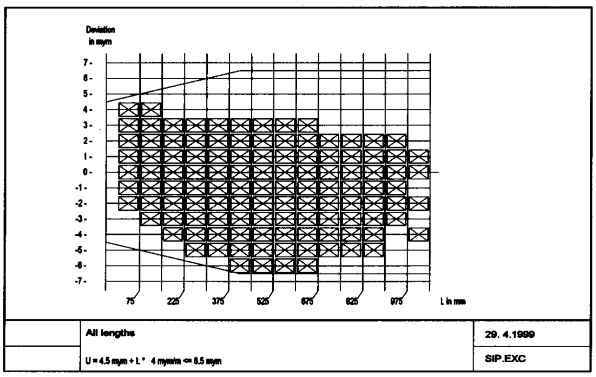


Figure 3. U = 4.5 ìm + L * 4 ìm/m ≤ 6.5 ìm

5 APPLICATION OF THE PTB CALIBRATION METHOD IN THE CZECH REPUBLIC

Working together, the CMI and ÈVUT (Technical University), Prague, derived the computation algorithm for the total uncertainty considering all 21 geometrical uncertainty components. The resultant matrix formula is the same as represented in the PTB software in the so-called virtual coordinate measuring machine. The PTB software is the only software so far to compute both the total CMM position uncertainty (Fig. 3) and all 21 partial geometrical errors. It helps simulate measurements of various shapes and compute the uncertainty of such measurements. Therefore, the CMI purchased this software in 1998 (Kalkom, Megakal, and other programs). Unlike the calibration procedure mentioned in Chapter 1, the artefact is placed in 4 basic positions in the PTB method. The body in vertical positions is measured from both sides (Fig. 5). CMM5 SIP in the CMI Prague was the first machine calibrated using this methodology (1996). Dr. Trapet from PTB made the calibration using a Zerodur holeplate (Fig. 5). The calibration yielded the waveform of the total uncertainty and all 21 partial geometrical uncertainty components. Three years later, the CMI staff made the CMM5 SIP calibration themselves, having borrowed the same artefact from PTB. The waveforms of the partial components did not change practically (see the small figures as examples – Fig. 4). This shows a very good stability of this CMM. A significant deviation was measured in one geometrical error only: You can see a change of the YTY waveform (length deviation ÄY in dependence on axis Y – Fig. 4) between 1996 and 1999 measurements. This deviation was corrected immediately by the CMI in the correction factor map.

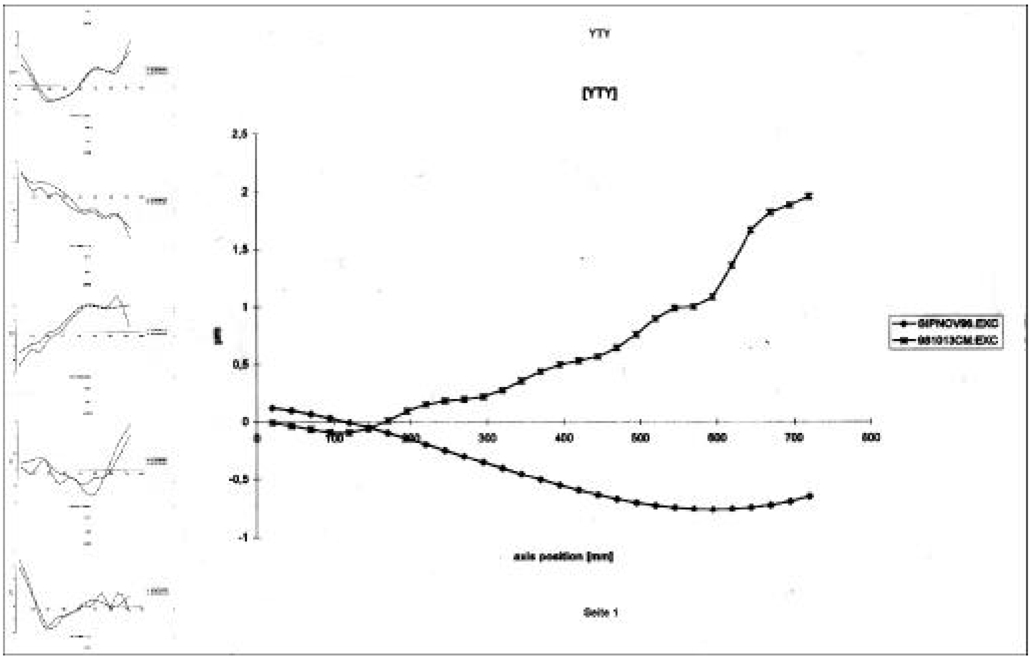


Figure 4.

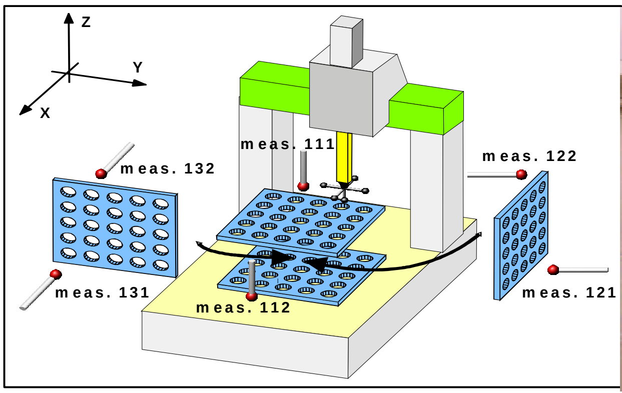
In 1999, the CMI performed several calibrations of highly precise CMMs using the PTB methodology [3]: CMMs in Škoda Auto (UPMC 850 Zeiss Carat, e.g.), but also in OMH, Budapest (SIP CMM5).

The waveforms of measured partial components are approximated by a polynomial curve. In many cases, these curves can be called correction curves and polynom coefficient in the sequence of square powers can be entered into the CMM. Some CMMs require the entering of discrete values with the particular step for the input.

6 CALIBRATION OF LARGE CMMS WITH HORIZONTAL ARM

In 1998, the CMI was integrated in the three-year EU project Mestral, which will be completed in this year, i.e. in the year 2000. The aim of the project is to provide a two-dimensional and one-dimensional disassemblable artefact and calibration methodology. The core of the artefact is a long cylinder made of a wound carbon fibre. A low temperature extensibility coefficient and low weight are the main advantages of the material. Balls are placed on the body (Fig. 6).

One artefact was designed as a flat L-shaped body, the other as a one-dimensional body. One-dimensional bodies are calibrated as three-dimensional bodies too. The purpose of the project is also to find a number of positions of the artefacts in the CMM space sufficient for the computation of all the above mentioned 21 geometrical uncertainties (Fig. 7). In an experiment, the CMM with the horizontal arm showed an S-shaped deformation of the post caused by elasticity effects. These effects were first applied in the software of the Mestral project.



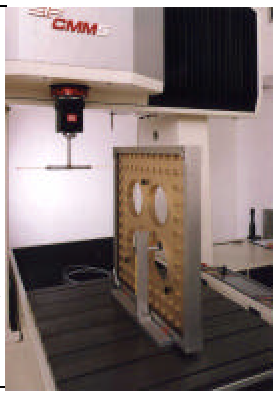


Figure 5.

Figure 6.

For first results of the project, the body and the positions refer to [1]. Within the project, the CMI will calibrate Škoda Auto CMMs using the new artefacts and method in mid 2000.

7 CONCLUSION

It is the intention of the CMI to find CMM calibration methods in co-operation with foreign partners. These methods should help both make calibration and compute partial geometrical uncertainties that can be entered as correction factors. The main goal is to find the optimum status of the CMM, i.e. the lowest possible total uncertainty of measurements in the whole working space in as short time as possible.

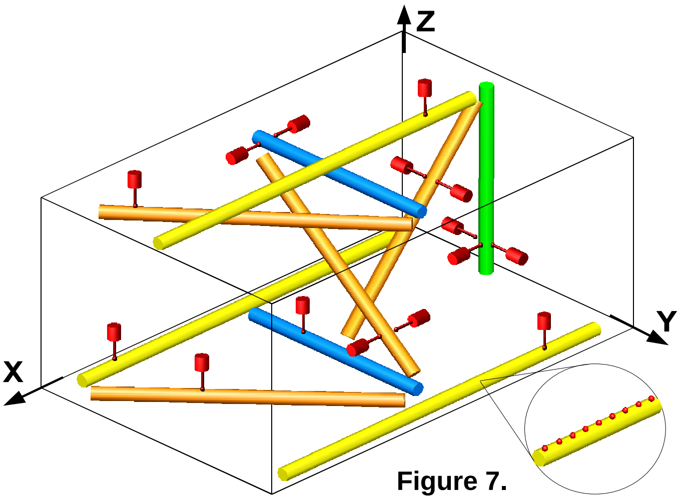


Figure 7.

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