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# DETERMINING ERRORS OF A ROTARY TABLE USING A SELF-CENTERING HEAD (as one of EU MTCHECK project outputs)

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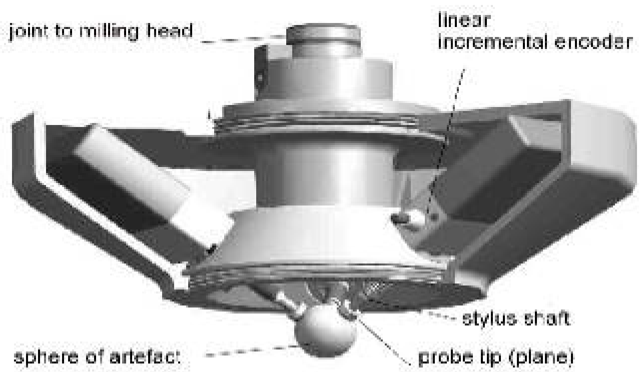
**Abstract** – To determine partial geometric errors of coordinate measuring machines (CMM), laser interferometers are used, but more and more also calibration-fit objects – artifacts. Most of all, objects with balls – ball-plate, ball-bar are used. The EU MTCHECK project intends, as one of its goals, to use these artifacts not only for calibration of coordinate measuring machines,

**Picture 1**

but also for calibration of computer numeric control (CNC) machine tools. Partners in the project were the following companies, institutes and universities: UNIMETRIK, Spain (coordinator), CMI, Czech Republic, IBS, Netherlands, UNIZAR, Spain, MECANER, Spain and FIDIA, Italy. As more and more CMM and CNC machines are equipped by the so-called fourth axis, another partial output was determining errors of this rotary axis.

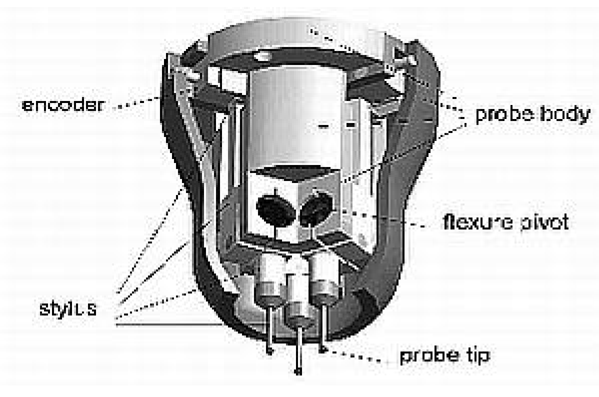
**Keywords** coordinate measuring machines, error assessment using self-centering head, rotary table

As not all CNC machines have a touch measuring system, it was necessary to create a self-centering probe within the project. The probe is fixed in the CNC's spindle or in the head of the CMM. With the head touching the ball on the artifact only once, the position of this ball's center is determined. Several proposals were created, out of which two heads proceeded in the real output. The construction of one successful head (see Picture 2) is assembled of a holder and an annulus with three sensors attached to it.




**Picture 2**

These sensors retract when the ball is touched. The center of the desired ball is calculated from retractions of the sensors. The second head construction also has three sensors, but for space reasons retracting was replaced by swaying of three touch arms (see Picture 3). When the ball is touched, the arms turn. The measured changes produce the ball center again. Both heads were designed in cooperation between the Spanish company UNIMETRIK and the University of Zaragoza. Other partners took part mainly in developing a model of mathematical description and the evaluation software.




**Picture 3**

One of the goals of the project was determining partial geometric errors of a so-called fourth axis of the CNC machine, which may be the rotary table. The position of the table is influenced by six errors. The table may be, in view of its ideal position, shifted generally in three directions and its axis is rotated around two transversal axes. The last error is the error of the rotation of the table itself around the axis of the table. All these errors are a function of the rotation of the table. It is not the subject of our observation whether this space movement is induced by bearings or other eccentricities. The article introduces a method, algorithm and software for determining these six errors using only one ball placed on the rotary table.

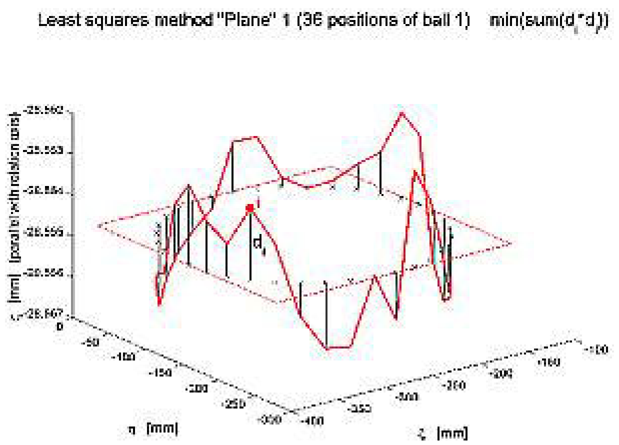
The algorithm determining all six errors (three translatory and three rotary ones) may be described in the following points.

Let's introduce the procedure with a real ball-plate first.

The body consisting – for example – of four balls is fixed to the rotary table. All balls are measured by the self-centering touch probe and the positions of their centers are determined. The board with four balls is then rotated – for example – in 10-degree steps, 360 degrees in total. Most of all, it is necessary to find the real rotation axis of the rotary table, and to assign a real position of the four-ball ball-plate in each position, in dependence on the angle of the table rotation.

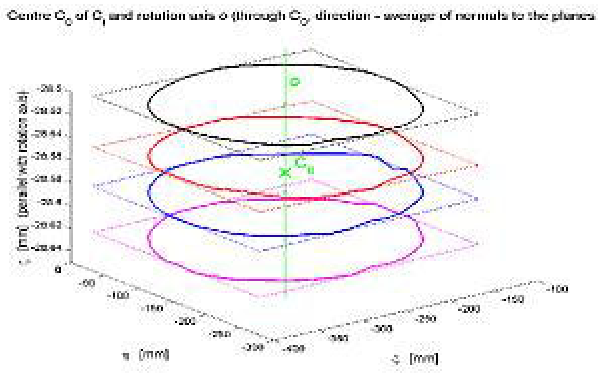
Creating the algorithm is based on the following steps:

1) The track of the center of each ball is traced.
2) The created track may be assigned to a certain plane using the least-square method, as shown in Picture 4.




**Picture 4**

3) In this plane, using the least-square method again, a circle may be assigned to the track and its radius and rotation center determined.
4) As we have an object with four balls, we get four planes and four centers.




**Picture 5**

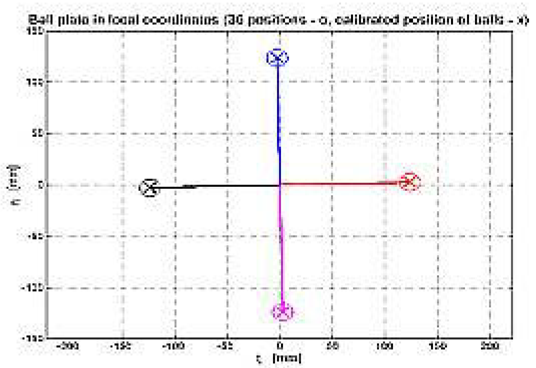
5) As an "average" axis of the table rotation, a line is considered, which has the direction of the vector obtained as the average of normal vectors of planes, and intersects the point $C_0$ (average of all ball centers).
6) This way a rotation axis was obtained, with the one center being the origin of the global Cartesian coordinate system (see Picture 5).

So far, we have worked with a real four-ball ball-plate. Now, this ball-plate will be created as a virtual artifact made of one ball only.

Ball No. 1 is placed in the initial position and its rotation has begun in 10-degree steps. The track is a circle, 36 positions of the ball center are the result.

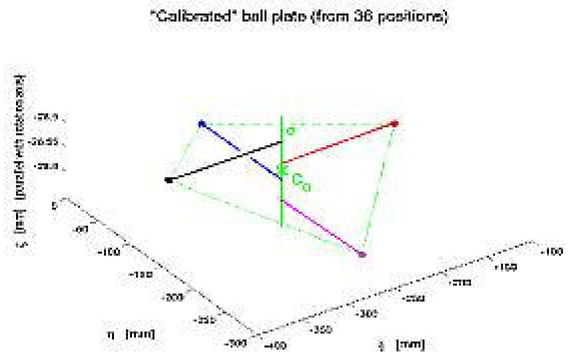
The second ball of the virtual artifact has been created by releasing the ball from Position 1 and fixing it on the board at approximately the same diameter, but turned by 90 degrees. In real, neither the right angle nor the same diameter have been kept. The ball will thus rotate around the same axis, but at a different diameter. Balls 3 and 4 on the virtual artifact are created the same way (see Picture 8).

Now a calibration of the virtual ball-plate will follow. All positions will be rotated back to their initial positions – Position 1. That is, the balls will rotate by 10 degrees back from Position 2. This way, a space cross is created, where each ball has 36 centers with a certain variance, as shown in Picture 6.




**Picture 6**

A single center position, called the calibrated value, is created of the 36 positions. This is how a calibrated four-ball ball-plate is created (see Picture 7).




**Picture 7**

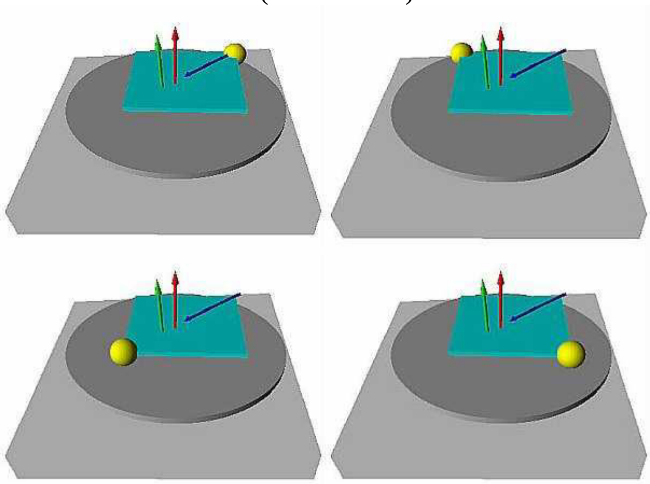
Now the position of the calibrated ball-plate, rotated around the averaged axis by exact angles, is now compared gradually in all 36 positions with the real measured positions. The deviation between the ideal and real positions may be expressed as a general spatial movement described by the transformation matrix (1):

$$T = T_x(x_{C0})T_y(y_{C0})T_z(z_{C0})T_{\varphi y}(pitch)T_{\varphi x}(roll)T_{\varphi z}(C_j). \quad (1)$$

xC0, yC0 a zC0 are translatory errors; pitch and roll are rotary errors around diagonal axes; Cj is the error of the rotation itself.

Because these error movements are small (the argument is small), the order of matrix multiplication makes no difference.

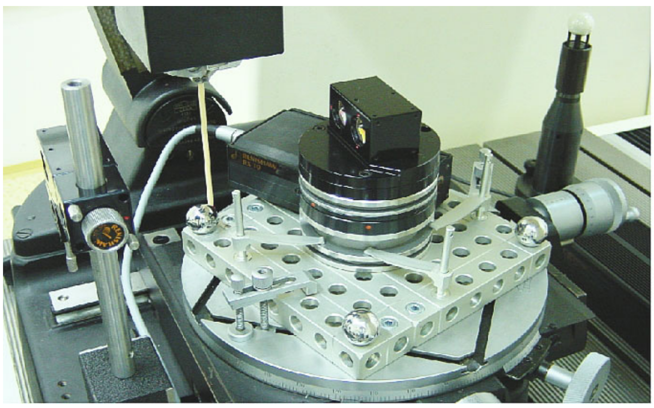
As an input in the computing algorithm, a file with ball centers measured in a pre-set sequence is used. This sequence always begins with measuring the ball in the initial position of the rotary table, then the measuring in agreed increment is carried out (see Picture 8).



**Picture 8**

This serves for a later computation of correction factors. To monitor the systematical errors of the rotary table, usually the increment of 5 or 10 angular degrees is enough. For a rough view of how large the errors will be, increment of 30 or 45 angular degrees may be used. As the calculation simulates measuring of a imaginary real object with evenly spread balls, it is necessary to repeat this procedure with changed initial position of the ball. For example, with a four-ball object, the initial position is to be altered by 90 degrees and with a eight-ball one by 45 degrees. The output of the calculation program is in the form of tables of values divided in given increments for all 6 geometrical errors of the rotary table. These values will be entered as correction factors in the new-generation control systems by FIDIA, which participated in this project.

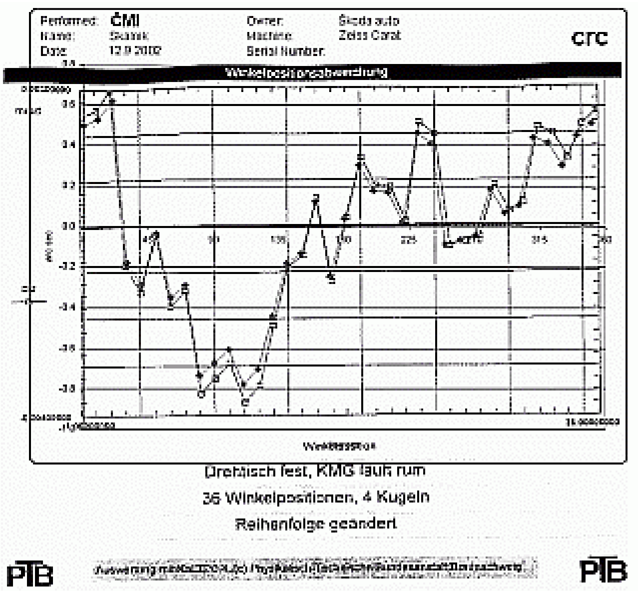
Development of the mathematical calculation model was realized in the MATLAB application, for practical use it was eventually rewritten in Visual Basic in MS Excel. This program is now being fine-tuned for practical use. Verification of used algorithms was done by carrying out many measurements and experiments. Several rotary tables were measured, and the output of the most important error of the table's rotation itself with a conventional measuring device by Renishaw, a so-called rotary axis. This device uses a laser interferometer and a special extension with its own rotary table, motoric movement and two-corner optical reflector. This device was placed on the measured rotary table in the Swiss-made CMM5 SIP three-coordinate measuring machine's space together with the ball-plate (see Picture 9). The measuring sequence was chosen so that the track of the coordinate machine's measuring probe would not cross the laser interferometer's track. Accuracy of orientation of the rotary table was measured using both methods.



**Picture 9**

Similarity of both results oscillated on the level of the declared measurement accuracy of the Renishaw rotary axis, which is a very good result. This is how the functionality of used algorithm for calculating only one geometrical error (although the key one for the rotary table) was verified. To verify the other errors, a series of tests was carried out in cooperation with PTB Braunschweig.

The following chart shows the results obtained in PTB (works with real calibration artifacts) along with those calculated in CMI (virtual calibration artifacts using one ball) as results of the project. The other charts don't show any differences, either.




**Picture 10**

The tests concerned recalculation of the data files by both institutes. PTB developed a software based on a similar idea and it was possible to process data files in the same format as in the CMI's software. Correspondence of both outputs is excellent in all measured errors and all tested cases (different number of balls, different orientation angles). The PTB software itself is said to have been tested by real error measuring on tables using special devices. This information implies that the algorithm developed in CMI is really usable for compensations of systematic errors of rotary tables (compare PTB's and CMI's charts).

## CONCLUSION

A partial output of the EU MT-CHECK project, run in 2000-2002, was creating a self-centering head, which is fixed in the CNC's or CMM's spindle. With the ball being touched by three length (or three angular) sensors only once, the position of this ball's center is determined on the artifact made of carbon and equipped by balls. Artifacts with balls are placed in the machine's workspace. The head measures positions of the center. The values measured by the machine are compared with those of the calibrated artifact. This way translatory and rotary errors of the CNC machine may be used. One of the project partners, FIDIA, Italy, worked on entering these errors as corrections in the control software.

As more and more CMM and CNC machines are equipped by the so-called fourth axis, another partial output was determining errors of this rotary axis. This additional fourth axis is mostly a rotary table. During the rotation of the table, six partial geometrical errors may be found. An algorithm was created and the procedure of obtaining these errors using one ball was experimentally verified. This ball is gradually placed in more different positions on the table. The software was verified by many experiments in CMI Prague using the SIP CMM and Renishaw and Agilent laser interferometers. It was also verified in PTB Braunschweig, Germany.

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