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OUT OF MACHINE CALIBRATION TECHNIQUE FOR ANALOG PROBES

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Abstract: A technique for the out of machine calibration of analog probes for CMM is presented in this paper. The process and the results obtained in different tests carried out on two different probes are shown. This calibration procedure allows to find out the measuring errors of these systems in a quick and reliable way.

Keywords: analog probe, calibration, coordinate measuring machine.

1. INTRODUCTION

A conventional CMM uses a probe head that records a single data point with each deflection of the probe tip. These are the touch-trigger probes. Although they are very effective for inspection purposes to compare real part dimensions to design dimensions, they are not suitable for measuring complex shapes, such as gears, cams, turbine blades, free form surfaces in general…

Analog probes usually operate as small and accurate three-axis measuring machines whose readings complement those of the CMM [1]. In the scanning process, the probe stylus has to be in constant contact with the part surface, and the measuring machine control system ensures that a consistent probing force is maintained by detecting any deviations and regulating them immediately.

Currently two kinds of contact analog probes exist: the active ones and the passive ones. The active probes generate forces inside the probe in order to maintain constant the probing force. This make these probes be larger, but more accurate. On the other hand, the passive probe does not generate internal forces, so the probing force is not constant. This make its size be smaller, but more non-corrected influences appear that usually make them be less accurate.

The use and the number of analog probes commercially available have increased during the last years and new manufacturers different from the traditional CMM producers have appeared. Most of these probes share some features such as measuring ranges lower than 1.5 mm, restriction of the rotational freedom degrees, or measurement accuracies around 1 µm. Nevertheless, they usually get the best performance while working with low deflections. So, either for high range CMMs or for high speed applications, the requirements on the control systems are very tight.

Probes are usually characterized on CMM, so the results are a combination of the probe errors and the errors of the coordinate measuring machine, even more in passive probes. This is supposedly due to the impracticality of isolating the performance of the probing system from that of the CMM. Although the determination of the error probe may improve its performance, most of the out of machine calibration systems developed [2, 3] are very expensive because of the use of several laser interferometers.

2. PURPOSE

The aim of this paper is to describe the development of an out of machine calibration system [4, 5] for passive analog probes which we have tested on a self-developed probe and on a commercial one. The results obtained during the calibrations carried out are shown. They allow to find some interesting characteristics of the probes that can be used to improve their performance by a parameters optimization process or by correcting some of the not usually corrected errors of the passive probes.

3. METHODS

The calibration principle used in this technique is based on comparing the calibrated positions of a standard artefact with the measuring results in every cartesian axis obtained by the probe when measuring those positions.

3.1. Calibration cube

The standard artefact developed for this application is a kind of miniature ball cube with spheres fixed to its surfaces (Fig. 1 left). Several sets of locating elements (6 pairs of 5 mm spheres) are located in every face in order to precisely position the device on a reference base plate (resting on 3 cylinders by a kinematic coupling) (Fig. 1 left). The calibrated positions of the artefact to be measured by the probe are formed by a three-spheres nest in every face. When calibrating, the spherical tip of the probe is placed in a very repeatable way in each of the nests. The locating elements and the spheres to be probed have different relative positions and orientations in each face. So by placing the cube on the base engaging different locating elements, the calibrated positions cover a range from ±0.2 mm to ±3 mm in X, Y and Z. This lets a precise characterisation of the probes (with ranges up to ±3mm) inside all their measuring range. In Fig. 1 right the distribution over the XY plane of the positions achieved by the cube is shown.

The material used for the spheres is tungsten-carbide in order to maintain their diameter invariable along the time. On the other hand, the contact between the cube and the reference base is maintained thanks to some magnets fixed on the base.

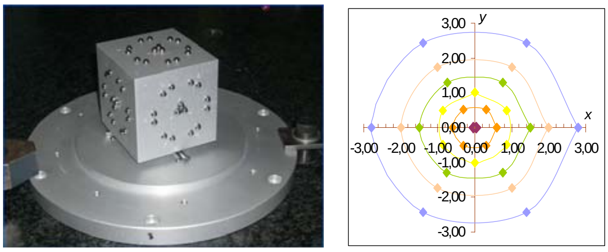

Fig. 1. Calibration cube on the reference base (left) and positions achieved by the cube over the XY plane (right)

Another important point is that the calibration cube was designed to be used for probes with tips from 1 mm to 8 mm of diameter (R_1 in Fig. 2). This requirement was essential to chose the diameter (R_2 in Fig. 2) and the relative positions of the three spheres of every of the six nests (one in every face).

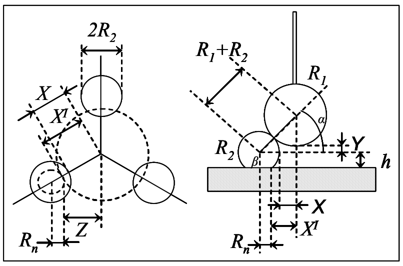

Fig. 2. Scheme of the parameters to dimension the nests of the cube

On the other hand, with this system the possibility of orientating in a different way while maintaining the contact between the tip and the spheres-nest also exists. In that case, the coordinates measured by the probe should remain the same in spite of its different orientation because the position of the stylus tip centre has not changed at all.

A very important matter related to the reliability of the calibration cube is its own calibration in order to know the real positions of the spheres of every nest referenced to the base plate. The calibration of the cube was carried out by measuring it with a high-precision CMM (Fig. 3).

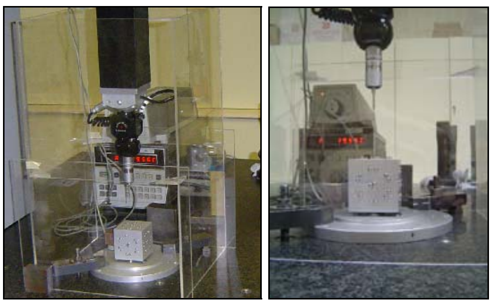

Fig. 3. Calibration of the calibration cube

Due to the fact that the measuring of the cube is a very important process, some precautions were taken into account in order to minimise the influence of the temperature changes. Thus, the measuring area was isolated. In spite of these precautions, some influences of the temperature were observed when analysing the results. In order to analyse this influence, a reference position of the cube was measured several times (13 times) during the process. In Fig. 4 the relation between the Z coordinate of this position (red line, which is the tendency line of the squares pink line) and the temperature (blue line, which is the tendency line of the rhombus blue line) is shown.

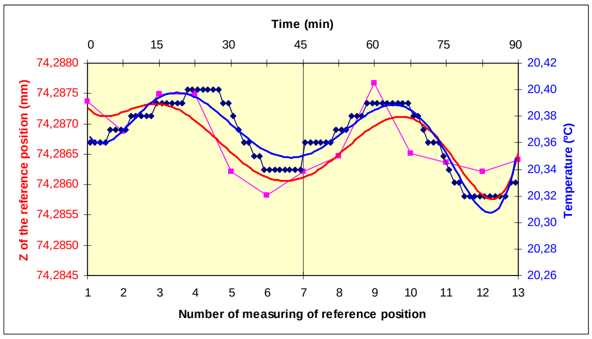

Fig. 4. Influence of the temperature in the calibration of the cube

The reference position was used not only to analyse the influence of the temperature, but also to correct this influence.

3.2. Calibration set-up

Apart from the standard artefact (calibration cube), a device (test set-up) to place the probe in relation to the calibration cube was developed. The probe is mounted in a moving part that moves up and down thanks to a motion system (Fig. 5). When the probe is up, the position of the cube can be changed. When the probe is down it rests on a very repeatable (±0.1 µm) positioning system based on the contact between three cylinders and three pairs of spheres (kinematic coupling) where the measuring is made. During the tests, the temperature was controlled and latterly corrected. A transformation matrix between the reference systems of the probe and the cube had to be calculated in order to compare the calculated coordinates to the calibrated ones.

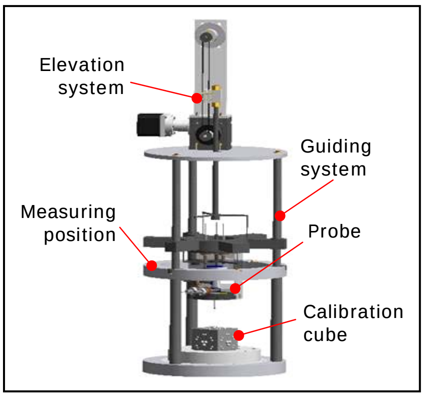

Fig. 5. Calibration set-up

The excellent repeatability of this system is necessary to test the repeatability and the accuracy of the probes themselves. Therefore, the tests of the probe carried out with the combination of the calibration cube and the calibration set-up gives information about its geometrical errors along its measuring range.

Moreover, the calculation of the transformation matrix between the reference systems of the probe and the cube gives information about the orthogonality and orthonormality of the axes of the probes. The process is the following: generally, the reference system-changing matrix has the form shown in (1)

$$\bar{\bar{T}}(\bar{t})=\begin{bmatrix} & \bar{\bar{R}} & & \bar{O} \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

where O denotes a 3 x 1 translation vector between the origins of the different coordinate systems and R represents a 3 x 3 rotation matrix. Therefore, it is possible to formulate the transformation between the two reference systems as:

$$\overline{X}_{CUBE} = \overline{\overline{T}}^{CUBE}_{PROBE} \cdot \overline{X}_{PROBE} \quad (2)$$

That is to say:

$$(X_k)_{PROBE} = R_{11}\cdot(X_k)_{CUBE} + R_{12}\cdot(Y_k)_{CUBE} + R_{13}\cdot(Z_k)_{CUBE} + t_x \quad (3)$$

$$(Y_k)_{PROBE} = R_{21}\cdot(X_k)_{CUBE} + R_{22}\cdot(Y_k)_{CUBE} + R_{23}\cdot(Z_k)_{CUBE} + t_x \quad (4)$$

$$(Z_k)_{PROBE} = R_{31}\cdot(X_k)_{CUBE} + R_{32}\cdot(Y_k)_{CUBE} + R_{33}\cdot(Z_k)_{CUBE} + t_x \quad (5)$$

The axes of the probe satisfy the orthogonality condition when the expressions (6), (7) and (8) are fulfilled:

$$R_{11} \cdot R_{21} + R_{12} \cdot R_{22} + R_{13} \cdot R_{23} = 0 \quad (6)$$

$$R_{11} \cdot R_{31} + R_{12} \cdot R_{32} + R_{13} \cdot R_{33} = 0 \quad (7)$$

$$R_{21} \cdot R_{31} + R_{22} \cdot R_{32} + R_{23} \cdot R_{33} = 0 \quad (8)$$

and the orthonormality condition is satisfied when the expressions (9) is fulfilled (i = 1,2,3):

$$\sqrt{R_{i1}^2 + R_{i2}^2 + R_{i3}^2} = 1 \quad (9)$$

3.3. Self-developed probe

Previously to the work presented here a six-degrees-of-freedom analog probe was designed and manufactured in our University. The main feature of this probe is its high measuring range (±3mm). The alternative used to get this range was the design of the probe with 6 degrees of freedom (Fig. 6). Hence, the probe has an intern body that moves when touching the part to be measured. This body is suspended of an immobile frame by two rings of an elastomeric material. In order to know the position of the body in relation to the frame, 6 sensors were used: 3 for determining a plane in the body, 2 for a line and 1 more for a point. The sensors used were LVDTs, which were previously tested in order to find out their suitability to the requirements of the probe.

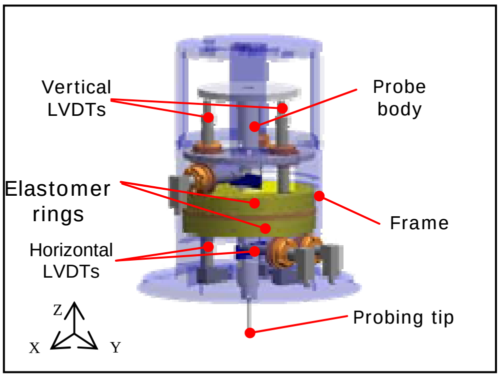

Fig. 6. Self-developed passive analog probe

The design process of this probe included some simulations in order to find out the best positions where the probes should be placed, the accuracy necessary for this probes in order to achieve the requirements of the probe, the rigidity of the elastomer rings and so on. Alternatively to the design, the geometrical model was also developed, bearing in mind the parameters necessary to correct the possible manufacturing deviations. Once manufactured, the geometrical parameters of the probe were determined by measuring them with a CMM.

The main advantage of a self-developed probe is that all these geometrical parameters and the geometrical model are known. Hence, every improvement considered as necessary after the analysis of the results of the calibration of the probe could be applied to it.

A passive analog probe with such a wide measuring range is very suitable for high-range CMMs, mainly arm CMMs, whose errors due to elastic deformations are bigger than in a conventional CMM. Moreover, the high measuring range of the probe allow to work with no so tight requirements on the control systems of the machine, what make easier its adaptation to any commercial controls, and even to Machine-Tools.

Apart from the LVDTs, the probe also mounted a non-contact measuring device: three LEDs, three mirrors and three 2D PSDs. The aim of this is to test both measuring technologies and to compare them. In this way, in a future development, the probe will be improved by decreasing its size by applying only non-contact measuring devices.

The self-developed analog probe was calibrated using the calibration cube and calibration set-up previously presented. As for the influence of the temperature, the calibration system was again isolated. From this calibration, results regarding the geometrical repeatability and accuracy of the probe along its measuring range were obtained, as it is shown in point number 4.

3.3. Commercial probe

Apart from this self-developed probe, a commercially available probe was also calibrated with the described system. This probe is based on the traditional structure, with only three degrees of freedom (the translational ones), so the probe is like a miniature CMM with a range of ±1mm in each axis. This probe was also evaluated according to the ISO 10360-4 standard.

4. RESULTS

4.1. Self-developed probe

The first tests carried out using the calibration system showed the results indicated in Table 1. Several series were carried out in order to find the repeatability and the accuracy of the probe in each of its axes.

Table 1. Results of the self-developed probe before the optimization.

Axis	X	Y	Z
Repeatability (µm)	0.7	0.8	0.7
Error limits (accuracy) (µm)	±7.6	±8.6	±9.4

The repeatability covered perfectly the initial requirements of the probe, but there were some accuracy problems. At this stage, the main source of errors seemed to be the determination of the geometrical parameters of the probe in the CMM, because of the measuring errors during the process. In order to correct these errors an optimization process was developed and applied. This process consists of introducing small variations in the values of the parameters (inside a range), applying the geometrical model and checking if the error is lower or higher than the previous one. If it is lower, the new parameters are taken as good ones. The process continues until the error satisfies a stop criterion.

This optimisation process is essential in order to complete the usability of the calibration system, due to the fact that, if the geometrical parameters and the errors of the probe are known, the optimisation can correct a big part of these errors and make the probe measure more accurate.

The results obtained after the optimization process are shown in Table 2.

Table 2. Results of the self-developed probe after the optimization.

Axis	X	Y	Z
Repeatability (µm)	0.7	0.8	0.7
Error limits (accuracy) (µm)	±2.9	±2.7	±2.2

As can be seen comparing Table 1 and Table 2, the repeatability is maintained but the accuracy has been sensibly improved by the optimization process. The graphics showing the errors in every position of the cube are shown in Figs. 7 to 9.

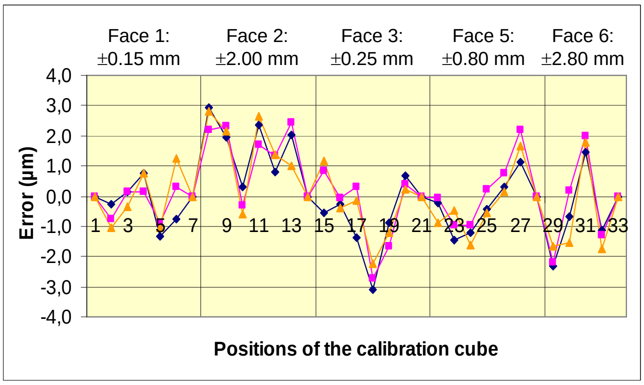

Fig. 7. Error in X of the self-developed probe after optimization

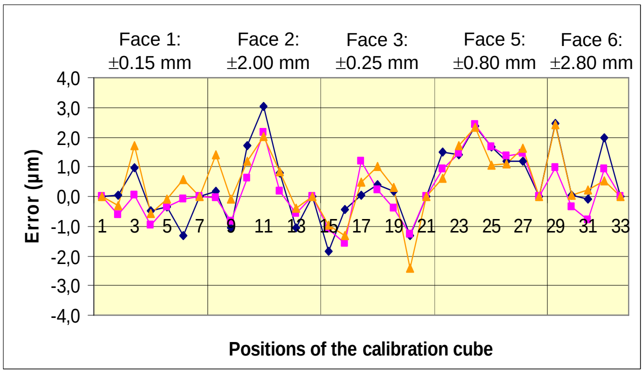

Fig. 8. Error in Y of the self-developed probe after optimization

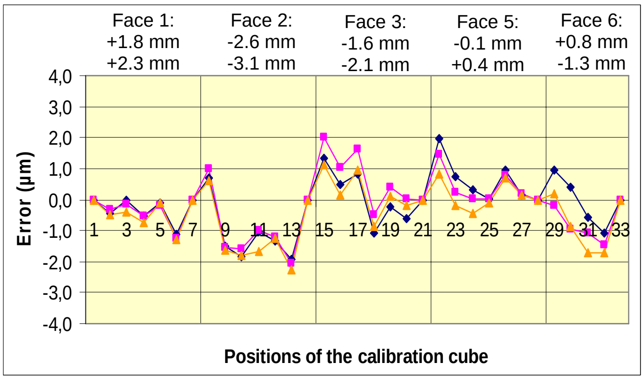

Fig. 9. Error in Z of the self-developed probe after optimization

In these results the influence of the temperature was corrected by using the reference position (measured once after every face of the cube). In Figs. 7 to 9 the reference position is indicated by numbers 7, 14, 21, 28 and 33. Moreover, the optimization and the calculation of the transformation matrix were carried out forcing the probe to maintain their axes orthogonal and orthonormal, in order to avoid non-real adaptations of the probe reference system to the cube one.

As can be observed in the previous figures, the errors in small ranges of measuring (near to the nominal / rest position of the probe, e.g. in Face 1) are usually lower than in higher ranges (e.g. Face 2). This may be due to several reasons but in this case it probably happens because the error of the sensors is higher when they approximate to their non-linear measuring range.

4.2. Commercial probe

First of all, the probe was evaluated according to the 10360-4 ISO standard [6]. This test consists of measuring a sphere with four scan planes while stylus shaft has a 45º orientation angle (this makes the scan paths more complex for the CMM control unit). Moreover, no additional filtering or other optimisation process should be used. Before the measuring operation, the maximum, minimum and average deflection value can be configured, so any scan point out of this interval is discarded by the software. Nevertheless, the sphere has also been evaluated with another least squares algorithm using all the points. Fig. 10 shows the influence of the scanning speed in the process. However, these substantial errors are not due to the probe itself but to the CMM control, because, with low deflections the contact between probe and sphere is lost every 90º (as it is shown in Fig. 11), while there is enough margin to absorb these oscillations for the larger deflection values.

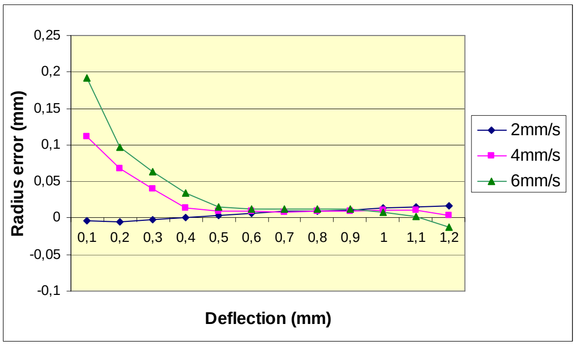

Fig. 10. Radius error for different scanning speeds and deflection values

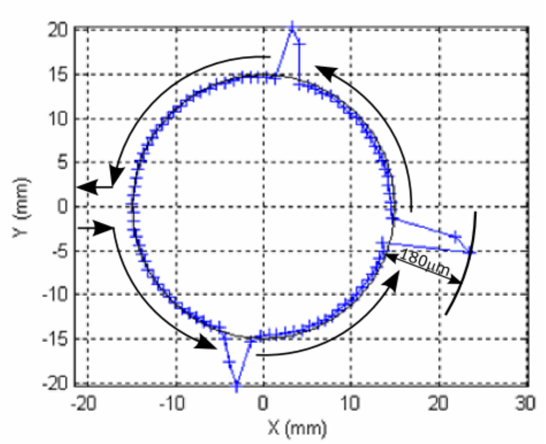

Fig. 11. Magnified error for the measured equatorial circle in the sphere and probe path

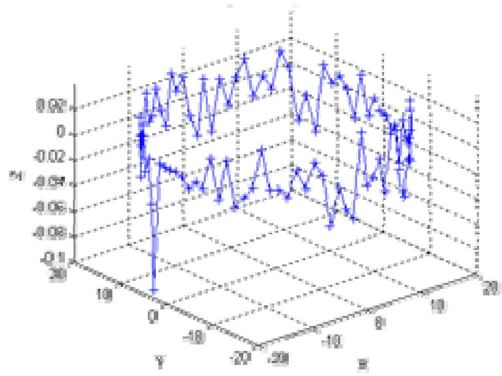

Fig. 12. Error for the measured equatorial circle in the sphere

These tests clearly show the influence of the CMM control features in the results.

In order to analyze the accuracy of the probe independently of the CMM, the developed calibration system was used. Moreover, it was necessary a special 16 bits A/D PC-card from the probe manufacturer to get the 3 analog axis signals. Nevertheless, the digital values provided by the card (0~65536) lack from dimensional units. So a simple test in the CMM to learn the relationship between the digital numbers and one millimetre was carried out; while the probe tip was in contact with a surface, the CMM was moved with increments of 0.1 mm in the axis perpendicular to that surface, and the probe outputs and the CMM position was simultaneously captured. This test was carried out in the three cartesian axes with displacements (deflections) of the probe from -1.5 mm to +1.5 mm, that is its maximum movement range. Thereby, the output variation equivalent to one millimetre was calculated. However, as can be seen in Fig. 13, to calculate the searched relation, it must be borne in mind that this value depends on the probe deflection.

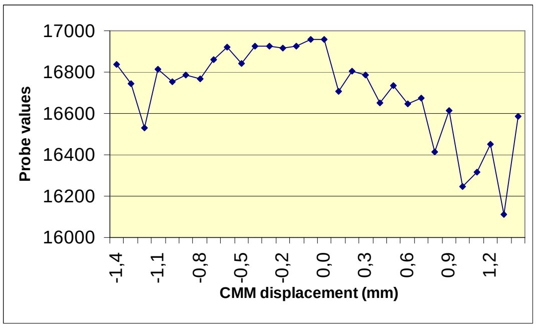

Fig. 13. Relationship between output in the X axis of the probe and the CMM displacement

This test also showed the lack of orthonormality in the three probe axis. This means that the lower the deflection used to measure, the lower the final error.

Finally, after these previous tests, the calibration system was used to calibrate the commercial probe. However, not all the positions of the cube could be measured, because some of them were out of the range of the probe. The results are shown in the Figs. 14 to 16.

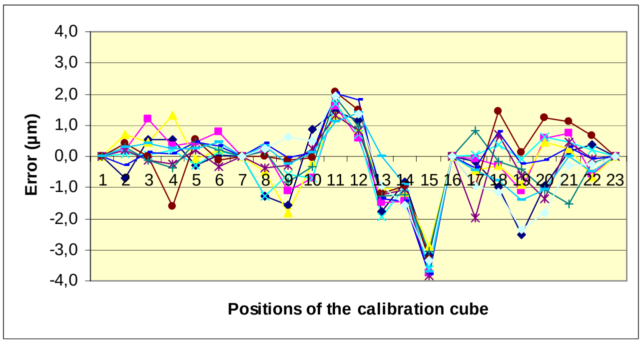

Fig. 14. Error in X of the commercial probe

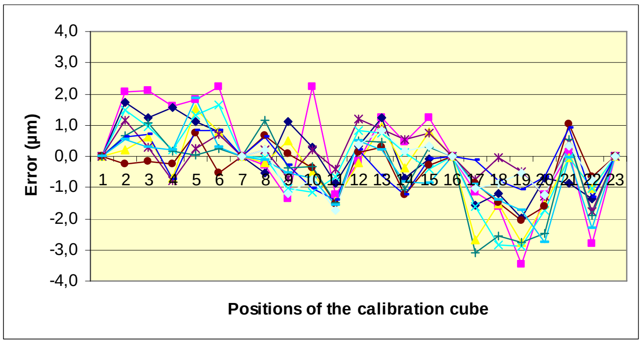

Fig. 15. Error in Y of the commercial probe

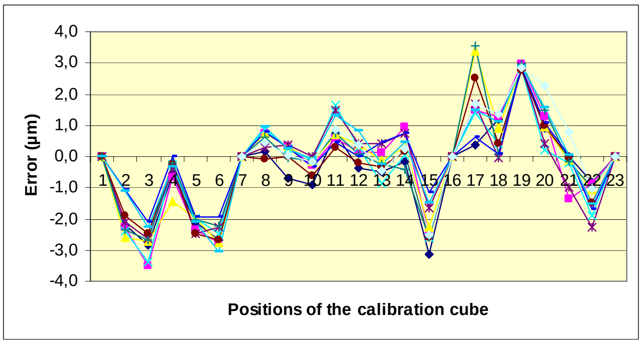

Fig. 16. Error in Z of the commercial probe

As can be seen in these figures the repeatability of this probe is about ±1.5 µm. The points with the lowest errors correspond to the short measuring range of the probe, very close to its usual working range (deflection = 0.1 mm). In the higher range the errors are larger. Alternatively, the calculation of the transformation matrix shows again problems of orthogonality and orthonormality in the axes of the probe.

5. DISCUSSION

These first tests that we carried out appear to show errors of our self-developed probe about ±3µm in each axis while its repeatability is inside a range of ±0.8µm.

On the other hand, the results obtained with the commercial probe seems to show a worse repeatability, lower errors in its short measuring range (< ±0.5 mm), but larger errors in the rest of its measuring range. These errors seem to be acceptable inside its usual working range (0.1 mm), but not in a larger one. Moreover, problems related to the orthogonality and orthonormality of their axes have been found.

With these results our self-developed probe (with a measuring range of ±3mm) would make easier its electronic control and the scanning process of parts with abrupt changes at its surface. This is especially important for high range CMMs, which have larger errors, and for high speed applications.

6. CONCLUSIONS

The presented calibration system allows to know the errors of passive analog probes in the three cartesian axes at representative points along all their measuring range. The first results obtained show that the system could be used to find the errors of the probes themselves (out of machine) and, with the consequent optimization process, to improve their performance. So, this should stimulate probes manufactures to standardize the output signals of their probes for easing the out of machine calibrations. Moreover, this may simplify the development of a new ISO standard for analog probes calibration using this system.

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