euspen's 16th International Conference & Exhibition, Nottingham, UK, May 2016

www.euspen.eu

Calibration and correction of a 6 degree of freedom piezo driven stage

Alain Küng, Anaïs Nicolet and Felix Meli

Federal Institute of Metrology (METAS), Switzerland

Alain.Kueng@metas.ch

Abstract

This paper presents a smart calibration method for 6 degrees of freedom actuators with large rotation angles of several degrees and translations of several millimetres. As demonstrator, a piezo motor driven system small enough to fit into the measuring volume of the METAS µCMM was used. The positions of the hexapod output stage are calibrated by measuring the position of three spheres attached to it. Experimental calibration results obtained from µCMM measurements are given before and after the application of an error correction model.

6 degrees of freedom stage, calibration, parallel cinematics, nano-positioning, multi-axis correction model

1. Introduction

With the advent and the affordability of small piezo actuators, hexapods and other multi-axis actuators are more and more commonly used in scientific and industrial applications. Such 6 degrees of freedom (6DoF) systems are for example applied in focussed ion beam (FIB) nanofabrication processes, for sample positioning in particle accelerator beam lines and micro assembly lines. These systems include line scales on all drive axes and often claim nanometre resolution. Nevertheless, their accuracy is often not even mentioned since their geometry is complex and is often based on parallel cinematics. It is thus very difficult to link the motion errors of each axis to the motion error of the output stage. The calibration of such systems is thus not straightforward.

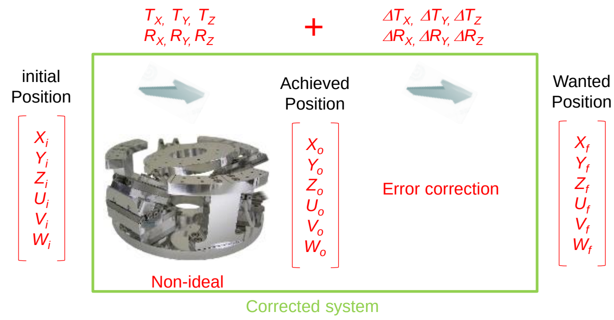
In addition, for a complete calibration, one would like to map the whole actuator working volume. But with 6 degrees of freedom, the number of calibration positions to be measured increases with the power of 6. With for example only 10 calibration positions per axis, mapping the complete volume with such a grid would require measuring 1 million positions! This obviously requires too much time and more efficient calibration methods are required.

2. Calibration procedure

The calibration procedure for a 6DoF positioning system needs to be smart enough to be independent from the actuators geometry and efficient enough to rely on a small number of measured positions since a complete mapping of the working volume is obviously too time consuming.

2.1. Mathematical model

The general mathematical model proposed here is given in figure 1. It is a polynomial correction applied to a 6 components vector equation [1]. The number of correction parameters increases with the power of the polynomial order if all cross-parameters are considered. For a 2nd order correction this represents already 156 parameters. A complete 3rd order correction would require 912 parameters. In general, not all parameters are required so one can hope to obtain a good correction using only a few selected correction parameters.



where the 6 terms of the error correction are given by:

$$\overset{6}{\boxed{\Delta_i}} = \overset{6}{\boxed{C_i}} + \overset{24}{\boxed{\sum_j C_{ij}\, j}} + \overset{126}{\boxed{\sum_{jk} C_{ijk}\, jk}} + \overset{756}{\boxed{\sum_{jkl} C_{ijkl}\, jkl}} + \cdots$$

$$with \quad i, j, k, l, \ldots = T_x, T_y, T_z, R_x, R_y, R_z$$

Figure 1. Mathematical model for the error correction. The model is similar to a polynomial correction but applied to a 6 component vectorial equation. The number of parameters increases with the power of the polynomial order used.

2.2. Measurement strategy

Choosing the optimal positions to measure within the working volume was done according to the following thoughts.

1) Measuring positions along each main axis of the 6DoF Cartesian coordinate system, leaving the other axis centred, should already give a good hint about the correction. Cross terms should be less important. In addition, for 6DoF systems like hexapods, the travel range along the main axes is usually longer than with combined axes motion. Therefore a rather high position density along the main Cartesian axes was chosen.

2) Mapping all positions on a grid in the 6D volume quickly generates a lot of positions, thus a lower position density was chosen which covers the largest range of reachable positions within the working volume. In addition, one may want to keep some symmetry for applying error separation techniques. A volume mapping over a minimum 3x3x3x3x3x3 grid for a 2nd

order correction already represents a total of 729 positions to measure.

3. Demonstration of a 6DoF piezo stage calibration

The calibration procedure has been applied to the 6 DoF system shown in figure 2. The system has a full range of ±10 mm in *X* and *Y*, ±5 mm in *Z*, ±10 ° in *Rx* and *Ry* and ±17 ° in *Rz*, but its reach is limited to about 1/3 of the range for combined axes motions. This 6DoF positioning system is small enough to be placed on the METAS µ-CMM [1]. The system can thus be accurately calibrated by probing at each position 3 of the spheres attached on its output stage.

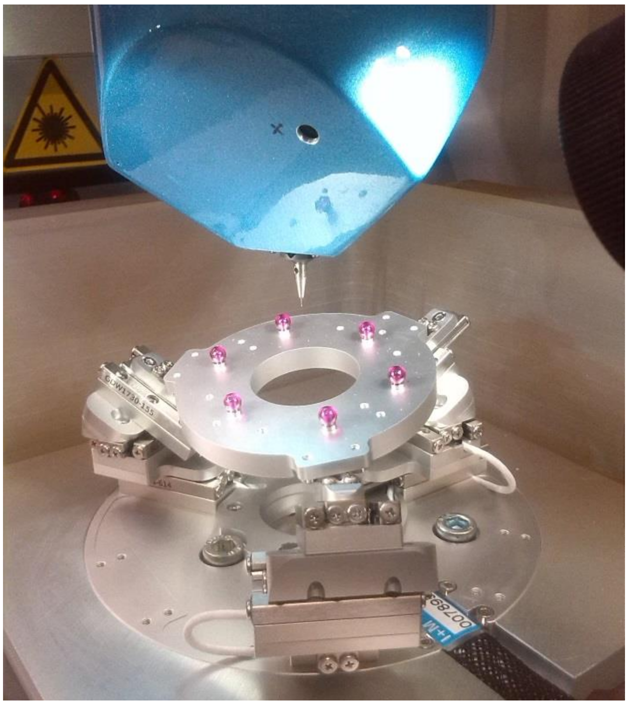


Figure 2. 6 DoF stage under calibration mounted onto the METAS µ-CMM. The exact position of the output stage is determined by measuring 3 of the spheres attached to it.

Following the previously mentioned strategy, positions every millimetre and respectively ever degree along the main axes and positions at 1/3 of the axis ranges on a 3x3x3x3x3x3 grid in the volume were measured. It took almost 2 days to measure all the 867 actuator positions.

The positioning errors of the 6DoF system are given in figure 3, plotted vs the position number. The first positions were measured along the main axes followed by the systematic mapping of its working volume at a 3x3x3x3x3x3 grid. One can observe that the positioning errors shown on the figure 3 follow a certain systematic pattern. This pattern was used to identify which correction terms are strongly needed and which can be neglected. For instance, the errors along the main axes are mainly corrected with the linear and some of the quadratic components. The cubic terms can be neglected. A simple solver was used to find the optimum values of the correction parameters using the least square of the 3D position errors given by the equation in figure 1. Figure 4 shows the positioning errors after optimizing all offset, linear and 18 quadratic correction terms. Finally figure 5 shows that even smaller deviations can be reached by adding only 4 more specific cubic correction terms to the correction model. Corrected positions deviations remain mostly below 2 µm and 0.005 ° which is a good result knowing that the positioning repeatability of the hexapod is about ±0.3 µm and ±0.15 °.

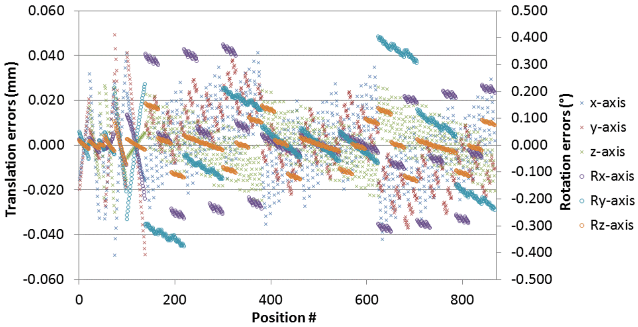


Figure 3. The positioning errors without any correction go up to ±50 µm and ±0.4 °.

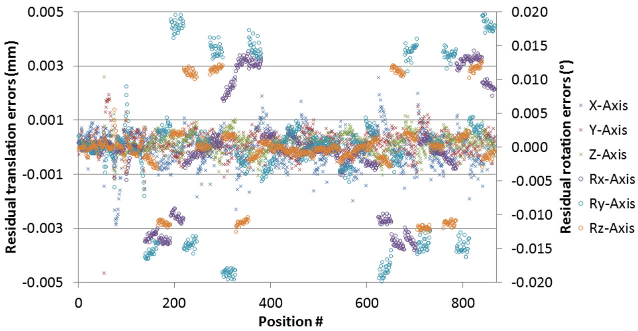


Figure 4. The positioning errors after optimizing all offset, all linear and 18 quadratic correction terms. Errors are corrected down to ±5 µm and ±0.02 °, but the introduction of some cubic correction terms is needed.

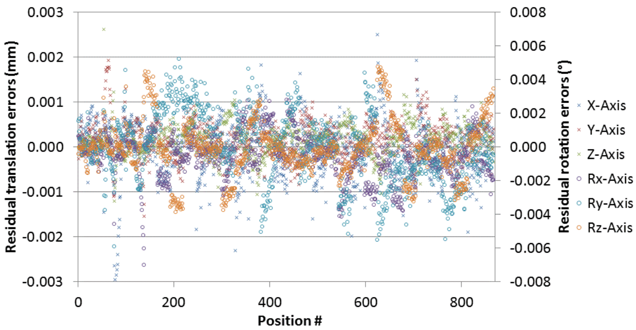


Figure 5. The positioning errors after optimizing all offset, all linear, 18 quadratic correction terms and 4 cubic terms. Errors are now corrected down to ±3 µm and ±0.007 °.

4. Conclusion

A procedure for calibrating 6DoF systems is proposed. No pre-knowledge of the actuator geometry is required and the procedure is general enough to be applied to any actuator geometry. As demonstrator, a piezo motor driven 6 DoF actuator small enough to fit into the measuring volume of the METAS µ-CMM was used. The implemented correction shows an improvement of the positioning of 20x in translation and 50x in rotation.

References

[1] N. R. Fazenda Carrico, calibration of high-precision flexure parallel robots, Ph.D. Thesis Nr 3712, Ecole Polytechnique Fédérale de Lausanne, December 2006

[2] A. Küng, F. Meli and R. Thalmann, Meas. Sci. and Tech., Vol.18 , pp. 319-327, January 2007