Improvements in Self Calibration Methodologies for High Precision Machines

S. Petrò[1], R. J. Hocken[2]
[1]*Department of Mechanical Engineering, Politecnico di Milano, Via La Masa 1, 20156, Milan, Italy*
[2]*Center for Precision Metrology, University of North Carolina at Charlotte, 9201 University City Blvd., Charlotte, NC 28223, USA*

stefano.petro@polimi.it

Abstract
Sensors with resolution up to few picometers are currently available. However, this performance cannot be completely exploited in 2D and 3D geometric measurement because of inaccuracy of measuring machines, which generates measurement errors at least three order of magnitude greater. But a relevant part of these errors is systematic: if a systematic error map can be identified, it could be compensated. In this work a methodology for dealing with very small scale systematic errors is introduced, which solves some problems in the application of classical self-calibration techniques.

1 Introduction

Recent years have seen a continuous improvement in the performance of high precision measuring and manufacturing systems. These instruments have achieved resolution levels well under the nanometer level, like the so called “Sub-Atomic Measuring Machine” (SAMM), jointly developed by the center for precision metrology (CPM) of the University of North Carolina at Charlotte and the Massachusetts Institute of Technology (MIT), whose nominal resolution is around 8 pm.

The nominal resolution of the instrument does not correspond however to its actual performance. Even if the adopted sensors (capacitance gauges, laser interferometers, etc.) are able to distinguish very small displacements, most of the components of the machines cannot be manufactured with an accuracy better than about 20-30 nm, which leads to errors due to e.g. non squareness and non linearity of machine axes or interferometers target mirrors. Luckily these errors tend to show systematic behavior. It is then possible to evaluate and numerically compensate them [1]. The evaluation is usually based on the measurement of a calibrated artifact. Unfortunately, calibrated artifacts with the accuracy required for an 8 pm resolution system are not currently available. Therefore, self-calibration methodologies [2], which do not require the artifact to be calibrated, should be adopted.

Self-calibration methodologies involve artifacts usually constituted by evenly spaced grids of subartifacts (e.g. ballplates), which are measured in different locations of the measuring volume. In general these methodologies can have two kinds of outputs: a complete model of the volumetric error [3], or its evaluation on a discrete set of points [4]. Even if for machine compensation a full model is required, a local evaluation of the error is needed for testing the machine itself, with or without a compensation algorithm. This work will deal with local volumetric error evaluation.

In this work, a slight modification of the algorithm proposed by Ye *et al.* [4] will be proposed, which is suitable for dealing with high precision machines. An indication of the acceptable error in artifact placement is given, too.

2 Self calibration methodology

Ye *et al*.'s methodology allows the local evaluation of the volumetric error based on the measurement in three placements (original, rotated and translated) of a plate with a square grid of subartifacts on it. The translated placement requires the plate to be accurately moved by the distance between adjacent subartifacts. The methodology can deal only with the case of a 2D linear moving stage (or analogue 2D configuration).

The plate proposed for self-calibrating the SAMM presents 25x25 1 mm spaced subartifacts. Obtaining a translation equal to 1 mm with the required accuracy (which will be discussed later) is very hard. Therefore, a modification of the algorithm is proposed, in which a plate with an odd number of subartifacts is required, which has to be measured in four placements:

1. the first placement is a reference placement;
2. in the second placement the plate is 90° counterclockwise rotated;
3. in the third it is shifted to the right by twice the distance between adjacent subartifacts;

4. in the last it is shifted to the left by three times the distance between adjacent subartifacts. In this last view only two adjacent subartifacts columns and the central row need to be measured, so the measurement effort is not greatly increased with respect to the original Ye *et al.*'s algorithm.

This way larger shifts are allowable, making the accurate placement of the plate easier. Measurement results are then analyzed in the frequency domain. According to Ye *et al*. Fourier analysis allows a reduction of the influence of random measurement error on the accuracy of the volumetric error evaluation, with respect to a conventional approach. Mathematical details are not reported here due to space constraints.

Figure 1 shows the dependence of the error in the volumetric error evaluation as the random measurement error and the volumetric error vary. As one can see, the error in the evaluation of the volumetric error is slightly less than twice the random error, and is not influenced by the volumetric error. This is coherent with results by Ye *et al*., so the proposed modification should not reduce methodology performance.

2.1 Tolerance in artifact placement

The proposed methodology assumes that rotation and shifts of the plate are exact, i.e. equal to 90° or multiples of the distance between adjacent subartifacts. Of course this is impossible. Therefore, in subsequent placements, subartifacts measurements happen in slightly different measurement volume points, characterized by different volumetric errors. This generates an additional uncertainty in the volumetric error evaluation. The contribution to the overall uncertainty due to misplacement can be approximately evaluated as

$$\sigma_p = \frac{2E_v}{l_v}\delta s \tag{1}$$

where E_v is the expected overall volumetric error, l_v is the measurement volume size, and δs is the misplacement error. In the case of the SAMM, for which E_v is expected to be around 20-30 nm, l_v is equal to 25 mm, and 0.1 nm is considered acceptable for σ_p, δs should not exceed 25 µm, which justifies the need for the proposed modification.

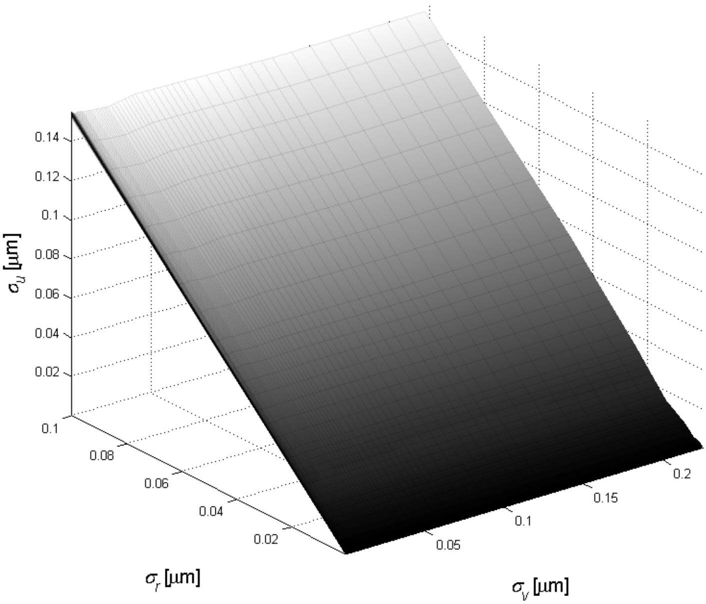

Figure 1: Standard deviation of the error in the evaluation of the volumetric error σ_u as the real volumetric error σ_v and the random measurement error σ_r change. Linear behavior of the dependence from σ_r and independence from σ_v are apparent.

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