Virtual CMM method applied to aspherical lens parameters calibration

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Abstract

Micro coordinate measuring machines (μ-CMMs) are attractive to accurately measure optical components like aspheres. Nevertheless, providing the measurement uncertainty for each parameter of the asphere is not trivial. Therefore, a parametric fitting algorithm coupled with a virtual μ-CMM based on a realistic model of the machine was developed to perform Monte Carlo simulations and provide the asphere parameters uncertainties.

1 Introduction

Tactile ultra-precise coordinate measuring machines such as the METAS μ-CMM (fig. 1) are commonly used for measuring optical components. This instrument exhibits a single point measurement uncertainty in the range of a few nanometres, even in scanning mode [1], which renders it very attractive for measuring optical components having high slopes like aspheres. Nevertheless, the analytic estimation of the measurement uncertainty for each asphere parameter is almost impossible because of the many combined influences from the measurement strategy, the applied fitting procedures and the different sensitivities of each one of the asphere parameters. The application of a Monte Carlo method offers a simple solution to this complex problem.

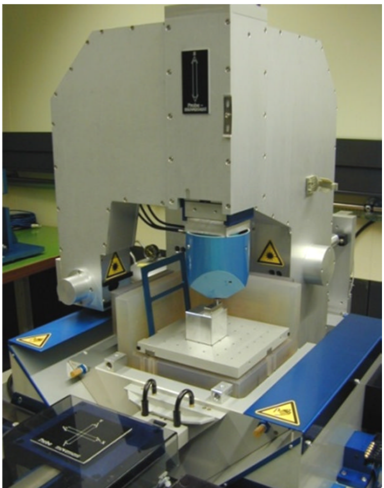

Figure 1: The METAS μ-CMM.

The example described in this paper can be easily used for the calibration of any complex parametric surface other than an asphere.

2 Parametric form fitting

Parametric form fitting in 3D is not that simple since the fitting algorithm must minimise the sum of least square distances between the measured points and the parametric surface by iterating on the surface parameters. Hence, these distances must be computed orthogonally to the parametric surface, which also requires an iterative process in each point. For the parametric form fit we used the Levenberg-Marquardt iterative algorithm. Since this algorithm relies on the local derivative of the parameters to converge to a local minimum, one has to pay attention to the initial guess parameters, the stopping criteria, the relative sensitivity between the parameters and the symmetries of the parametric form.

2.1 Asphere fitting

In our specific case of fitting an asphere, the fitting parameters are *Xc*, *Yc* and *Zc* the coordinates of the asphere centre, αX and αY the rotation angles around the *X*, and *Y* axis (αZ can be eliminated as an asphere has a rotation symmetry along the Z axis), *R* the asphere radius, *K* the asphere conicity and C_2, C_4, C_6 ... the asphere parameters as given by the generic asphere equation:

$$Z = \frac{r^2/R}{1+\sqrt{1-(1+K)r^2/R^2}} + C_2 r^2 + C_4 r^4 + C_6 r^6 + \cdots \qquad \text{where: } r = \sqrt{X^2+Y^2}$$

Since the C_2, C_4, C_6... coefficients are multiplying r^2, r^4, r^6..., they do not have the same relative weight. In order to re-equilibrate their weight, parameters C_2, C_4, C_6... were replaced by $C'_2\ 10^{-2}$, $C'_4\ 10^{-4}$, $C'_6\ 10^{-6}$,.... so the incremental step in the fitting algorithm is thus more or less equally weighted for each parameter, and guaranties the stability of the fit convergence to a local minimum solution.

For a robust fitting, the initial guess parameters where computed by fitting a sphere to the measured points, whereas all other remaining initial guess parameters can be chosen to be zero. The stopping condition was set to the least significant digit of the computer in order to insure a good fitting even for the highest order C_x parameter.

2.2 Implementation

The fitting algorithm was implemented in Labview, as an iterative algorithm. The Quindos software forwards the coordinates of the measured points and the initial guess parameters for the asphere to the Labview executable by means of a file. The

Labview executable replies back to Quindos by sending the coefficients of the fitted asphere (fig. 2).

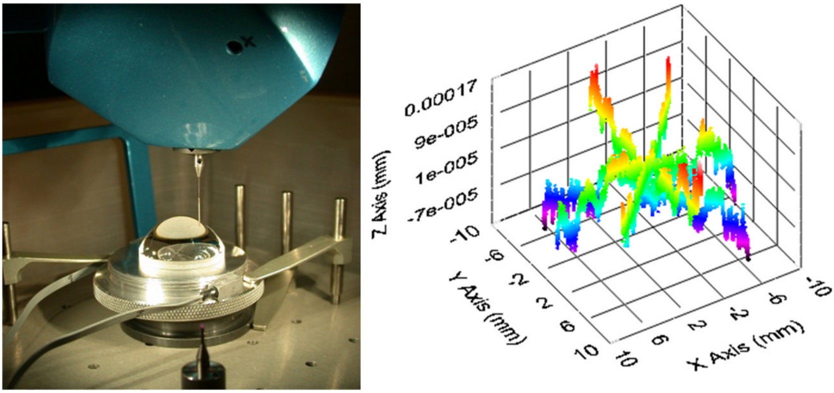

Figure 2: Asphere artefact under measurement and residual form deviation after fitting of less than ±50 nm.

3 Monte Carlo simulation to provide measurement uncertainty

The fitting algorithm of the 3D parametric surface provides information about the quality of the fitting through the covariance matrix. Nevertheless, in order to provide a measurement uncertainty for each parameter of the asphere, one has to include the uncertainty of the measuring machine, the measurement strategy and measurement conditions. Therefore a numerical model of the µCMM measurement process was developed in which the error contributions were previously determined by measurements. The model includes six basic types of contributions:

- Single point repeatability
- Residual axis orthogonalities
- Probing sphere residual shape error
- Linear length variation
- Machine axis straightness
- Thermal drifts

This model can then be used to perform Monte Carlo simulations of a specific measurement task [2].

3.1 Determining the asphere measurement uncertainty

First, a real measurement is performed on the aspheric artefact. Then, to each data point from the asphere measurement, a simulated measurement variation is added using the realistic numerical model of the µ-CMM. An asphere is then again fitted to all these newly simulated points using the algorithm described in paragraph 2, and

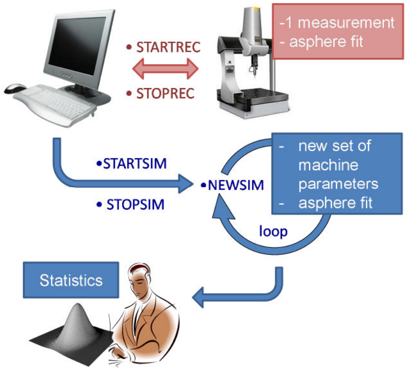

Figure 3: The virtual µ-CMM process

the asphere parameters as well as the covariance matrix are stored. This virtual measurement is then repeated many hundred times to finally deliver statistical data for each asphere parameter (fig. 3).

3.2 Results

The many results of the virtual measurements are processed with a separate software. The statistical evaluation in the table here below reveals an uncertainty which includes the measurement strategy, the machine geometry errors, temperature drifts, etc.

Parameter	αX (°)	αY (°)	Xc (mm)	Yc (mm)	Zc (mm)	R (mm)	K	C_2 (mm^{-1})	C_4 (mm^{-3})	C_6 (mm^{-5})	C_8 (mm^{-7})	C_{10} (mm^{-9})
value	0.0187	0.012	0.00272	0.00486	0.00038	9.849	-0.459	0.158	0.213	0.353	-0.3839	0.320
uncertainty	0.0006	0.007	0.00013	0.00012	0.00004	0.014	0.008	0.007	0.008	0.008	0.0049	0.007

In addition, the cross-correlations between the asphere parameters can be analysed, for instance the strong correlation between the asphere radius R and the quadratic parameter C_2 in the asphere equation. This explains the large uncertainty of 14 µm on R, even though the variations induced by the virtual CMM are smaller than 25 nm! Fixing one of these two parameters ($C_2 = 0$) is usually more meaningful.

4 Conclusion

Any parametric surface such as an asphere can be calibrated. Thanks to the realistic model of our µCMM, measurement uncertainties for each parameter can be delivered. Additionally, the eventual cross-correlation between parameters can be analysed.

Acknowledgement:

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References:

[1] Proc. of the 7th euspen Int. Conf. – Bremen - May 2007, Vol. 1, 230-233

[2] Proc. of the 10th euspen Int. Conf. – Delft - June 2010, Vol. 1, 91-94