Self calibration method for 3D roundness of spheres using an ultraprecision coordinate measuring machine.

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Introduction

With the ongoing miniaturisation in the mechanical and optical production there is an increasing demand for highly accurate 3D geometrical measurements on small parts. Today's coordinate measuring machines (CMM) proudly achieve a precision of a few nanometres [1] [2], but at this level, spheres used as touch probes, or as reference for the probe calibration are far from perfect. Thus calibration of those ultra-precise CMMs impose new challenges.

Knowing that it is impossible to manufacture perfect geometrical references, one has to deal with the mapping of their imperfections. In this paper, we propose a method for the calibration of the diameter and the mapping of the 3D roundness of three calibration spheres. The method requires the three spheres to be measured against each other in various configurations. In this way the absolute diameters can be obtained without any external reference standard.

The absolute calibration method

When measuring an object with a contact probe one has to know the size and imperfection of the probe itself in order to subtract it from the measurement, and to obtain the dimension of the measured object. If one does not know the dimension of the probe, the measurement is thus an equation with two unknowns:

$$Ma = R1\alpha + R2\alpha$$

Where Ma is the measured distance between the two sphere centres, and $R1\alpha$ and $R2\alpha$ are the two unknown radii of the object sphere and the probe sphere at point α respectively. In order to solve the problem, one has to include a third object, here a third sphere of radius $R3$, and measure it against the two others in order to obtain three equations with three unknowns:

$$Ma = R1\alpha + R2\alpha$$
$$Mb = R1\alpha + R3\alpha$$
$$Mc = R2\alpha + R3\alpha$$

Thus the system can be solved, for instance for $R1\alpha$:

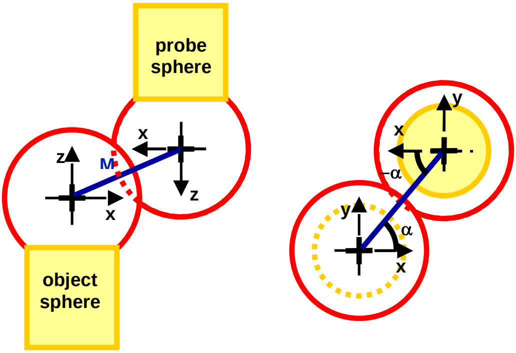
$$Ma+Mb-Mc= 2^* R1\alpha$$

In the same way, the entire surface of each sphere can then be mapped without the need of any external reference.

Figure 1 : The ultra-precise coordinate measuring machine (µCMM) at METAS

Solutions in 3D space

The method requires that each sphere is used as an object and as a probing sphere by turning it 180° around the y-axis. The problem is that one cannot bring two spheres in contact at the same point mapped on their surface without rotating one of the spheres in between each measured point. As shown in figure 2, the contact point on the probe sphere is at an angle of $-\alpha$ and the contact point on the object sphere is at an angle $+\alpha$ to the symmetry plane.



Side view

Top view

Figure 2 : Schematic lateral view and top view of 2 spheres in contact

Figure 3 : picture of two of the sapphire spheres being measured against each other

In this situation, solving the equation system is not possible and includes a symmetry differential error term from another sphere:

$$Ma+Mb-Mc = 2 * R1(\alpha) + (R2(\alpha) - R2(-\alpha))$$

To further minimize this residual term, additional symmetry configurations have to be used. So we rotated each object sphere by 120° and 240°, and measured all points again, giving the following set of nine equations:

$Ma = R1(-\alpha) + R2(\alpha)$ $\quad Ma120 = R1(-\alpha) + R2(\alpha+120)$ $\quad Ma240 = R1(-\alpha) + R2(\alpha+240)$

$Mb = R1(-\alpha) + R3(\alpha)$ $\quad Mb120 = R1(-\alpha) + R3(\alpha+120)$ $\quad Mb240 = R1(-\alpha) + R3(\alpha+240)$

$Mc = R2(-\alpha) + R3(\alpha)$ $\quad Mc120 = R2(-\alpha) + R3(\alpha+120)$ $\quad Mc240 = R2(-\alpha) + R3(\alpha+240)$

Solving the system now includes two times nine differential error terms, showing that the error term is averaged out. This means that only roundness components of the spheres having a multiple of a third order symmetry, like a triangular shape, cannot be separated. Of course one can perform more measurements with a finer rotation than 120° to push back the limit to higher symmetry orders.

Results

Using this method, the absolute diameter and the roundness of three 1 mm sapphire spheres were mapped over their entire usable surface using our µCMM [2]. Such a precision is hardly achieved with the classical two steps using a comparator for measuring the diameter, and a roundness measuring machines for measuring the roundness.

The measurement of their equators, shown in figure 4, was mapped with a resolution of 1°. The spheres exhibit roundness at the equator ranging from 98 nm to 48 nm. One can clearly observe the excellent repeatability of our µCMM, the standard deviation at one given point being usually less than 4 nm.

Equator of sphere 1	**Equator of sphere 2**	**Equator of sphere 3**
Diameter: 1.000827 mm	Diameter: 1.000852 mm	Diameter: 1.000796 mm
Roundness: 49 nm	Roundness: 21 nm	Roundness: 32 nm

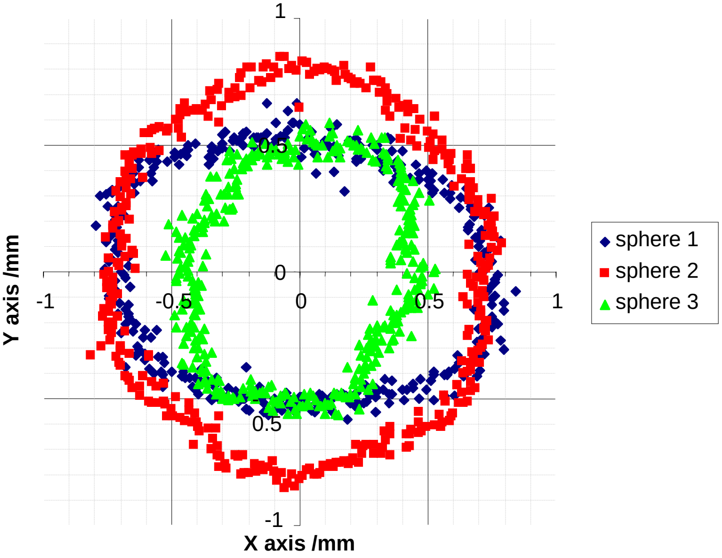


Figure 4 : Equator plots of the 3 measured spheres with an error magnification of 10'000 to the nominal diameter of 1.0008 mm

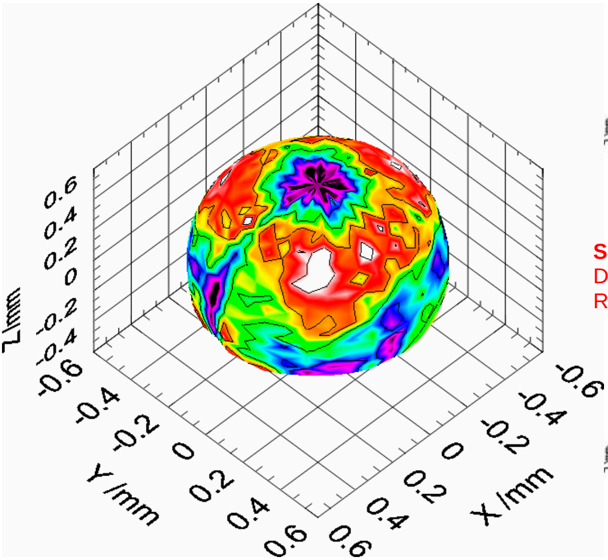
The measurement was then extended to the whole surface of the three spheres. The 3D plots in figure 5 to 7 show the results obtained by scanning the surface with a 10° resolution in longitude and a 5° resolution in latitude. Diameters and roundness over the whole sphere are in excellent agreement with the results obtained over the equator only.

The spheres tend to exhibit a cubic error shape that seems to be correlated with their crystal orientation. This would indicate that the manufacturing process reached a physical boundary and that it may be difficult to produce even rounder sapphire spheres.

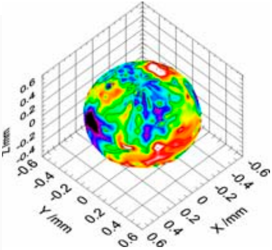
Discussion

The absolute diameter of the spheres finally relies only on the direct traceability of the µCMM interferometer.

Sphere 2
Diameter: 1.000859 mm
Roundness: 37 nm



Sphere 1
Diameter: 1.000824 mm
Roundness: 53 nm



Sphere 3
Diameter: 1.000804 mm
Roundness: 39 nm

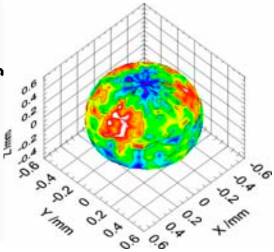


Figure 5 to 7 : 3D plots of the 3 measured spheres

The method of course includes the errors from the µCMM and special care has been taken to minimize them: To avoid anisotropy, the orthogonallity of the µCMM axis was set using a roundness measurement over a 44 mm sphere. The machine drift was compensated by measuring only a few points at a time allowing a frequent re-centering of the sphere. This way, only the drift during the measurement time of a few points is not compensated.

Conclusion

We have reported a method to determine the absolute diameter and completely map the roundness errors of three spheres by measuring them against each other, without the need of an external reference. Such an error separation technique is important to precisely map errors of calibration references, which then serve to map the probe spheres. Thereby one can overcome the precision limit in manufacturing those references.

Acknowledgments

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References

[1] T. Ruijl, J. Franse, J. van Eijk, "Ultra precision CMM aiming for the ultimate concept", *Proc. of 2nd euspen Int. Conf.*, Turin, Italy, (2001), 234-237,.
[2] F. Meli, and A. Küng, "Performance of a low force 3D touch probe on an ultraprecision CMM for small parts", *proc. of 4th euspen Int. Conf*., Glasgow, UK, (2004), 270-271.