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# Characterization of micro spheres through AFM surface scans 

Erik Oertel \& Eberhard Manske<br>${ }^{1}$ Institut of Process Measurement and Sensor Technology, Technische Universität Ilmenau, Ilmenau 98694, Germany<br>erik.oertel@tu-ilmenau.de


#### Abstract

The precise characterization of micro spheres is essential in improving the performance of micro and nano coordinate measuring machines (CMMs) with both tactile and optical surface sensors. The lack of suitable measurement strategies for spheres with radii in the sub-millimetre range has, therefore, led to research into novel methods. One promising approach is based on a set of atomic force microscope (AFM) surface scans in conjunction with a stitching algorithm. It has been implemented on a nano measuring machine (NMM-1) by extending its capabilities of three translational movements with an additional rotation stage. Initial experiments focused on the radius and roundness measurement of one great circle (equator) and have been conducted on commercially available spheres which are attached to a stylus and have mean radii of $60 \mu \mathrm{~m}, 100 \mu \mathrm{~m}$ and $150 \mu \mathrm{~m}$ Based on these results, the strategy was extended to the characterization of a full sphere. The experimental set-up on a NMM-1 was modified by another rotation stage, which, thus, enables 5D measurements ( 3 translations, 2 rotations). The sphere is sampled through a series of circle scans in each rotational position. The sampling positions on the sphere are chosen, to cover the full sphere by a set of overlapping surface scans. In this contribution, this measurement strategy is demonstrated and discussed on a commercially available ruby sphere with a nominal radius of $60 \mu \mathrm{~m}$. That includes the design of the experimental set-up, the sampling strategy, and initial experimental data.


Keywords: micro CMM, nano CMM, micro spheres, radius, roundness, sphericity, AFM

## 1. Introduction

The precise characterization of micro spheres is essential in improving the performance of micro and nano coordinate measuring machines (CMMs) with both tactile and optical surface sensors [1,2]. However, established instruments and strategies have mainly been developed for the characterization of spheres in the millimetre range or above. The mechanical design and algorithmic approximations for some of these instruments, like roundness measurement machines [3], become less favourable as the size of the sphere is scaled down. Others, like the three-sphere test [4], mainly suffer from a high experimental complexity. Alternative approaches which are based on stitching algorithms in conjunction with optical interferometers (e.g. [5]) have been proven to be precise on special silicon spheres with a mean radius of 46.5 mm . Although stitching approaches can generally be applied on smaller spheres, it is less clear how optical surface sensors (e.g. interferometers [5], white-light-interferometers [6] or confocal sensors [7]) are affected.
The influence of Atomic Force Microscopes (AFMs) on the imaged surface, on the other hand, can be modelled and corrected sufficiently well by morphological filters [8]. In addition, traceability routes based on the secondary realisation of the metre $[9,10]$ are emerging, in case the shape of the AFM's tip is considered to be the dominating influence.
Therefore, and because AFMs can achieve the required spatial resolution, we have recently focused our research efforts towards a novel strategy which is based on a set of AFM surface scans in conjunction with a stitching algorithm [11, 12, 13]. In this contribution, this measurement strategy is demonstrated and discussed on a commercially available $60 \mu \mathrm{~m}$ ruby sphere. That includes the design of the experimental set-up, the sampling strategy and initial experimental data.

## 2. Radius and roundness measurement

Initially the measurement task had been reduced to the measurement of one great circle (equator) of the sphere, in order to reduce the experimental complexity. The sphere is sampled by two line scans along the $x$ - and $z$-axis (equator and meridian scan, figure 1). Each line scan covers an arc of 60 to 100 degrees depending on the aspect ratio of the cantilever and mean radius of the sphere. The sphere is rotated around the zaxis between the surface scans until the equator is fully covered. Figure 1 illustrates this sampling strategy on a simulated sphere with a mean radius of $60 \mu \mathrm{~m}$. In this case the covered arc of each line scan is set to 80 degrees and the sphere is rotated 40 degrees between the surface scans. Thus, at each position two independent line scans overlap and nine scans are required to cover the equator.


Figure 1. Simulated sampling of a sphere with a radius of $60 \mu \mathrm{~m}$ along the equator by two line scans in each rotational position of the sphere.

The meridian scans are only required for the sampling process to centre the line scans on the sphere and are not considered for the evaluation strategy. The equator scans are transformed from the AFM's coordinate system into one which is attached to the micro sphere. An initial coarse transformation is followed by a global stitching algorithm. The stitching algorithm refines the initial transformation and compresses the measurement data to a few constants. For this purpose, the equator $r(\varphi)$ is modelled by a constant $r_{0}$ (mean radius) and a fourier series (roundness deviations).

$$
\begin{equation*}
r(\varphi)=r_{0}+\sum_{k=2}^{k_{\max }}\left(a_{k} \cos (\varphi k)+b_{k} \sin (\varphi k)\right) \tag{1}
\end{equation*}
$$

The constants $r_{0}, a_{k}$ and $b_{k}$ are being determined by the stitching algorithm and are sufficient to compute the local radius $r(\varphi)$ at any position $\varphi$ along the equator (equation 1). Figure 2 illustrates the stitching result of equator scans which have been conducted on a commercially available ruby sphere. It was sampled with the same parameters as the simulated one in figure 1.


Figure 2. Nine surface scans sampled on a ruby sphere with a nominal radius of $60 \mu \mathrm{~m}$ after the stitching algorithm had been applied.

A detailed experimental realisation of the measurement strategy and the stitching algorithm has been published in [11]. The results led to further experiments based on simulations to investigate the influence of the measurement object [12] and real experiments to investigate the influence of the AFM tip [13].

The experiments thus far are promising as they indicate a good repeatability of up to 4 nm [11]. In addition, experiments published in [13] could demonstrate a reproducibility of up to 7 nm with regard to different AFM tips. An uncertainty statement is not yet possible. However, we have begun to model the strategy [12] and intent to extend this model with currently neglegted influences in the future.

The approach is limited to the equator and 60 to 100 degrees of the meridians. As most applications require information about the full sphere, an additional rotation has to be introduced of either the sphere or the AFM tip which is the subject of the next section.

## 3. Radius and sphericity measurement

The extension of our set-up is focused on an additional rotation of the sphere, as it is generally easier to implement than a rotation of the AFM's tip (figure 3). The coordinate system of the AFM is described by the coordinates $x, y$ and $z$ (global coordinate system). The rotation of the sphere consists of two rotation stages which are mounted sequentially. A coordinate system which is attached to the sphere is defined by the coordinates $x^{\prime}, y^{\prime}$ and $z^{\prime}$ (local coordinate system). A rotation around the $z^{\prime}$-axis $\left(\varphi_{s}\right)$ of the sphere is similar to the already implemented equator measurement. It is extended by a rotation
around the $\mathrm{x}^{\prime}$-axis $\left(\theta_{S}\right)$. Thus it is possible to cover the accessible part of the sphere through a set of AFM surface scans. The accessability is limited to the areas which are not covered by the stylus, since we currently limit ourselves to spheres which are permanently attached to one.


Figure 3. Kinematic arrangement of our set-up which consists of two rotation stages and the definition of the local and global coordinate systems. They are linked by two rotations ( $\varphi_{s}$ and $\theta_{s}$ ) and one translation $\left(\overrightarrow{x_{c}}\right)$.

### 3.1. Experimental set-up

The set-up has been realized on a nano measuring machine (NMM-1, SIOS GmbH). It consists of a corner mirror on which the measurement object is placed. The movement of the corner mirror is measured by three interferometers and two autocollimators which define the machine coordinate system $\left(x_{N M M}, y_{N M M}\right.$ and $\left.z_{N M M}\right)$ and are attached to a metrology frame. The interferometer beams and the surface sensor intersect in one point in order to minimize errors of the first order. The surface sensor is also attached to the metrology frame. The general arrangement of our set-up is illustrated in figure 4.

We currently employ self sensing cantilevers with a diamond tip (PRSA-L400-F30-SCD-PCB from SCL-Sensortech. Fabrication $\mathrm{GmbH})$, because of space constraints. The rotations are realized by two rotation stages (SR-2013-S and SR 3610s-50 from SmarAct GmbH ), each containing an angle sensor to measure the angles $\varphi_{s}$ and $\theta_{s}$ respectively. The rotation stages are mounted onto the corner mirror. Because of their orientation, the machine coordinate system of the NMM-1 differs from the coordinate system defined in figure 3.


Figure 4. General arrangement of the set-up used during the experimental investigations.

Figure 5 illustrates the real set-up, which includes an area for a sample to characterize the tip. This area is within the measurement volume of the NMM-1 and, thus, allows for a fully automated measurement process which consists of a tip characterisation before and after the sampling of the sphere. That is necessary due to possible wear or contamination of the tip. This measurement process has been implemented, however, the characterization of the tip and the full measurement process are not subject of this contribution. Initial investigations concerning this influence have been published in [13] for radius and roundness measurements.


Figure 5. The set-up used during the experimental investigations.

### 3.2. Sampling strategy

Conventional AFM-scans are typically based on the raster scan strategy which images the surface on a rectangular field. For the sampling of a sphere, other strategies seem to be more benefical. Among those, a spiral scan strategy (e.g. in [14]) is assumed to be the first choice. It allows the sampling of the sphere to be conducted in a continuous motion. If properly centered, this strategy follows the nominal shape of the sphere with only minimal height changes during each full circle. A control loop, therefore, has to compensate mainly form deviations and the surface roughness.

Despite its benefits, such a scan strategy could not yet be implemented on the experimental set-up. As a compromise, we used a set of circle scans to cover each part of the sphere (figure 3). The outer circle scan was conducted at a surface slope of 40 degrees. Each surface was covered by eight circle scans. The surface scans have been separated by the surface slope in equidistant steps (i.e. a circle scan was conducted in five degree steps).

The number of circle scans are a compromise between the time it requires to cover the surface and sampling density. The scan speed at our set-up is currently limited to $1 \mu \mathrm{~m} / \mathrm{s}$, which leads to a sampling time of roughly 19 minutes in each position given the scan strategy and nominal radius of the sphere. However, the dynamic of our set-up is mainly limited due to the heavy measuring table of the NMM-1. Faster set-ups, including those using an NMM-1, are well known and established (e.g. [15, 16]). Optimizing the scan speed has not been a focus up to this point, since we currently concentrate on exploring and validating the concept. Eight surface scans are, however, not considered to be sufficient for most applications, unless a priori information about the surface roughness is available or the application requires only information about form deviations of a lower frequency.

To cover the accessible part of the sphere, the sphere has been sampled in eleven positions which is illustrated based on a simulated measurement in figure 6. The part which is not covered on the simulated sphere is covered on the real sphere by the stylus. Before the circle scans are conducted, the sphere is centred by two line scans along the $x$ - and $z$-axis which is the same strategy used for the radius and roundness measurement of the sphere. The positions and number of surface scans have been chosen manually to fully cover the accessible parts of the sphere and to allow for a partial overlap. The influence of the overlap and optimum number of sampling positions as well as their distribution have not yet been explored.


Figure 6. Simulated sampling of a sphere with a mean radius of $60 \mu \mathrm{~m}$ covering the accessible area which is not covered by the stylus.

### 3.3. Evaluation strategy

The surface scans are performed in the global coordinate system ( $x, y$ and $z$ ) and have to be transformed into the local coordinate system ( $x^{\prime}, y^{\prime}$ and $z^{\prime}$ ). Both coordinate systems are related by a translation $\overrightarrow{x_{c}}$ and two rotations $\left(\varphi_{s}\right.$ and $\theta_{s}$, figure $3)$. The evaluation strategy is based on the same approach as the one used for the radius and roundness measurement. That is, an initial coarse transformation is followed by a global stitching algorithm.

The translation $\overrightarrow{x_{c}}$ needs to be estimated for each position independently, due to run-out errors of the rotation mechanism. An initial estimate is based on sphere fits [17], which contains systematic errors because of form deviations and because only a part of the sphere's surface is known [12]. The rotational relationship between both coordinate systems ( $\varphi_{s}$ and $\theta_{s}$ ) is measured and expressed through rotation matrices ( $R_{x}$ for rotations around the x-axis and $R_{z}$ for rotations around the zaxis). An in the global coordinate system measured point $\vec{x}_{i}$ is, thus, transformed into the local coordinate system $\vec{x}_{i}^{\prime}$ by equation 2.

$$
\begin{equation*}
\vec{x}_{i}^{\prime}=R_{x}\left(\theta_{s}\right) R_{z}\left(\varphi_{s}\right)\left(\vec{x}_{i}-\vec{x}_{c}\right) \tag{2}
\end{equation*}
$$

Since this transformation uses a biased estimate for the centre of the sphere $\overrightarrow{x_{c}}$, it is labelled as a coarse transformation. Figure 7 illustrates the result of such a transformation on real measurement data.
The necessary refinement of the initial coarse transformation by a global stitching algorithm has not been implemented at the time of writing. We are currently investigating algorithms based on spherical harmonics (e.g. [18]) or on the search for the closest point (e.g. [19]). Using a set of spherical harmonics for the stitching algorithm and to describe the form of the sphere would enable a reduction of the measuremed points to a few constants [18]. Thus, it would be an obvious extension to our current radius and roundness measurement strategy and is, therefore,
our preference. However, the inability of sampling the complete sphere due to the stylus seems to adversely affect the algorithm published in [18] which requires further investigations.


Figure 7. Real measurement data obtained on a ruby sphere with a nominal radius of $60 \mu \mathrm{~m}$ after the coarse transformation has been applied.

## 5. Conclusion and outlook

The lack of suitable measurement strategies for the radius and form measurement of micro spheres led us to propose and investigate a novel strategy based on a set of AFM surface scans in conjunction with a stitching algorithm. In contrast to optical surface sensors, AFMs enable a high spatial resolution and can be modelled sufficiently well with traceability routes beginning to emerge. The measurement time and further unfavourable characteristics, like the wear of the tip, mainly depend on the size of the sphere's surface and, thus, the nominal radius. Compared to the state of the art, like roundness measurement machines, the three sphere test or interferometric stitching methods, this strategy, therefore, seems to become particular beneficial as the radius of the measurement object is scaled down.
Given promising results for radius and roundness measurements on spheres with nominal radii of $60 \mu \mathrm{~m}, 100 \mu \mathrm{~m}$ and $150 \mu \mathrm{~m}$, the sampling process of the sphere has been extended to allow for radius and form measurements. Thus far, this sampling process could be demonstrated on a commercially available ruby sphere with a nominal radius of $60 \mu \mathrm{~m}$. The characterization of a micro spheres still lacks a suitable stitching algorithm, which requires further work.

Besides general optimizations like an increase of the scan speeds, future research efforts need to focus on an uncertainty estimation and comparisons with independent strategies for verification purposes. The latter proves difficult as it requires an independent measurement process with a similar precision and uncertainty. Regarding an uncertainty statement, we have begun to model the measurement process for radius and roundness measurements and intent to extend it in the future with currently neglected influences. This model is generally suitable for the application on radius and sphericity measurements. However, the computation time and ressources become more of an issue. Given the already achieved repeatability and reproducibility for radius and roundness measurements, we generally aim for an uncertainty at or below 10 nm .

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