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# Calibration and use of an optical 5-axis micro coordinate metrology machine

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**Abstract**
Due to the ongoing miniaturization and the increasing complexity of small engineering parts, new 3D measurement techniques are required to check if specified geometric tolerances are met. Traditional tactile coordinate measurement machines are either not fast enough or are not able to measure complex surface details, whereas most existing optical surface measurement techniques are only able to measure an object from one direction and therefore cannot measure form parameters where a 360° 3D measurement is required. Here we describe a 5-axis micro coordinate metrology machine based on the focus variation technology, which is equipped with a motorized xyz-stage and a highly accurate motorized rotation and tilt unit. We focus on the description of the fully automatic adjustment and calibration of this 5-axis coordinate machine which is realized using a proprietary calibration artefact. The paper will show the capabilities of the calibration artefact and procedure. The performance of the system is demonstrated on geometry measurements of micro gear wheels showing the ability to measure geometric dimensioning and tolerancing parameters.

Focus variation, 5-axis micro coordinate metrology machine, optical 3D surface measurement, micro gear wheel

## 1. Introduction

In order to measure complex micro-scale geometries, often very specific measurement strategies are required. These include the acquisition of dense data points and the measurement of a part from multiple directions which are then merged to a dataset with a common coordinate system. Although this strategy is widely used for large-scale geometries [1], metrology solutions in the micro scale are very rare [2]. These are either limited to few measurement points as in tactile CMMs or the movement of only 3, or sometimes 4 axes which is not sufficient to reach all measurement directions. Recently XCT systems have become increasingly popular since they are able to measure complex parts, their resolution however is still not sufficient for various tasks [3].

Here we present a novel calibration procedure on an established 5-axis measurement device equipped with an automatic rotation and tilt unit to enable measurements of a part with high precision from arbitrary directions to generate a 360° 3D dataset. We start with a description of the system and the calibration tool used to establish the orientation and position of the rotation and tilt unit with respect to the xyz-axis. Then we show the results of the calibration procedure and an example measurement on micro gear wheels. Due to their small size and complex geometry, such parts have already been in the focus of measurement devices previously, see e.g. [6].

## 2. System description

### *2.1. Measurement device with rotation and tilt unit*

The optical measurement device (Figure 1, left) used here, is based on the focus variation technique [4, 5]. Exploiting the small depth of focus of an optical system and vertical scanning the system is able to provide topographical and color information with a vertical resolution down to 10nm.

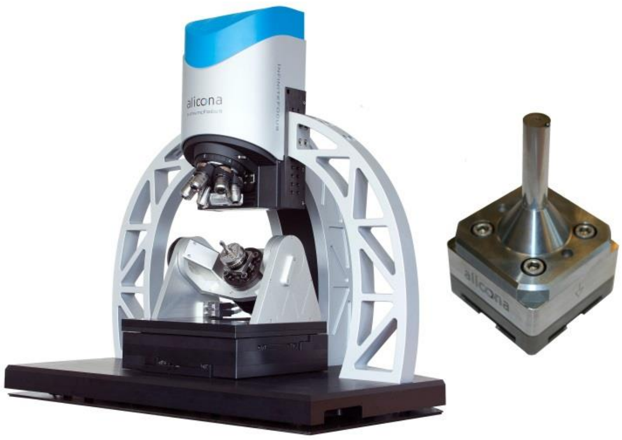


**Figure 1.** InfiniteFocus G5 with an automatic rotation and tilt unit (left). Calibration pin used for calibration procedure (right, for details see text).

A white light source inserts light into the optical path of the system which is focused by the objective onto the specimen. The small depth of field of the optics leads to only small sharply imaged regions of the object. During vertical movement along the optical axis of the precision optics, surface data is continuously captured, resulting in each region of the object being sharply focused. Algorithms which analyze the variation of focus along the vertical axis convert the acquired sensor data into a true color 3D dataset. The working distance of the objective defines the vertical scan range (between 3.2 and 22mm). Focus variation can be used with different illumination sources allowing measurements of slope angles exceeding 80°.

The system can be equipped with a motorized rotation and tilt unit which can rotate freely around 360° and tilt between –15° and +90° degree. The accuracy of the tilt axis is ±0.0055°, those of the rotation is ±0.00275°. The axes can be equipped with 3R, 3-jaw chuck and EROWA clamping systems in order to allow repeatable part change.

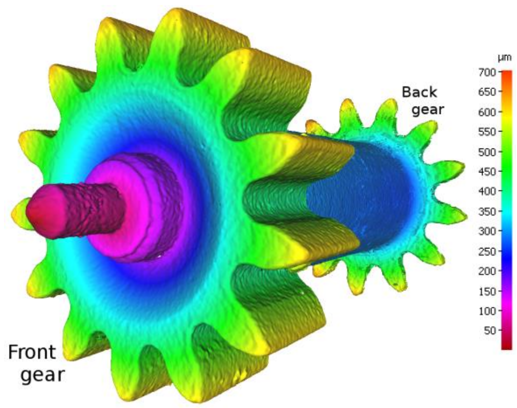


**Figure 2.** Resulting 3D dataset of the measurement of a micro gear system. Pseudocolours represent distance to the rotation axis.

In order to measure the complete geometry of a part it is measured from multiple directions with different rotation and tilt angles. Then the single datasets are automatically merged to one 3D dataset, thus allowing to measure miniaturized workpieces around 360°. This merging algorithm however requires the knowledge how to rotate the different datasets in order to bring them into a common workpiece coordinate system, as described below.

### *2.2. Calibration pin*

The calibration pin (Figure 1, right) is used for adjusting and calibrating the position of the rotation and tilt axis in respect to the x-, y- and z- axis of the system. The pin consists of a cylindrical element, planar elements and a sphere with a diameter of 1mm attached at the front side of the cylinder. Different elements of the calibration pin are calibrated by a DakkS laboratory, providing e.g. the sphere position with respect to the mounting plate with an uncertainty of 1.5µm and the sphere radius with an uncertainty of 0.5µm.

## 3. Calibration Procedure

The fully automated calibration procedure is used to establish the transformations, necessary to transform all 3D measurements at arbitrary rotation and tilt angles from the machine coordinate system (MCS) to one common part coordinate system (PCS).

The procedure starts by measuring the cylindrical part at an angle of 0° and various rotation angles and lateral positions. Then the planar element of the cylinder's mounting plate as well as thirty measurements of the spherical element divided in three different rotation angles (at 0°, 90° and 270°) and ten different tilt angles (equally distributed between 0° and 90°) are measured. Afterwards a nonlinear optimization technique is used in order to calculate the position of the rotation and tilt axis in machine coordinates that gives the best correspondence between the known position of the cylinder and sphere position from the calibration pin certificate and the measured datasets at different rotation and tilt angles.

## 4. Results

### *4.1. Results of the Calibration Procedure*

A result of the calibration procedure described above is the deviation between the nominal sphere position at a certain rotation and tilt angle, based on the calibration pin certificate and the measured sphere position. Measurements were performed at rotation angle values of 0°, 90° and 270° and tilt angles between 0° and 90°. The mean deviation in all measurements was below 4µm.

It should be noted that the accuracy of 3D measurements around 360° is not only dependent on the accuracy of the hardware components since small misalignments between the different measurements can be compensated by software means.

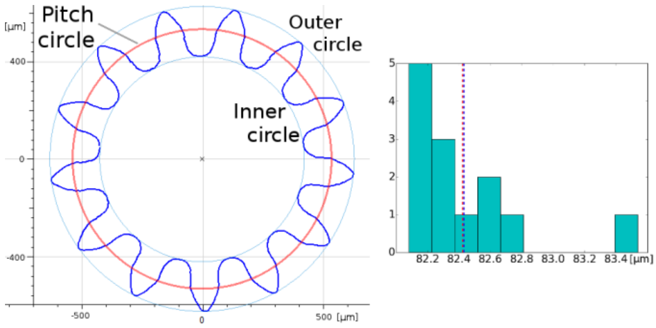


**Figure 3.** Analysis of the 3D dataset. Results of the front gear (left). A comparison between its module sizes (right).

### *4.2. Measurements of micro gears*

A micro gear system consisting of a front gear and a back gear as a tool with complex geometry (see Figure 2, for the resulting dataset) was used as an applicability test of the system. The front gear's outer diameter was measured with 1261.0µm and the pitch diameter was measured with 1.071µm (see Figure 3, left). With 13 teeth the nominal value for the module of the front gear is 82.42µm. The mean of the measured modules is 82.43µm, the standard deviation is 0.37µm. A histogram to compare the modules of the 13 teeth is shown in Figure 3, right. The nominal value is inserted as dashed, red line. The mean is inserted as dashed, blue line, both being only 0.01µm apart.

A difference analysis between the two gears of the gear system retrieved a larger outer diameter of the back gear by 3.2µm. Setting the cylinder as reference z-axis, the coaxiality between the two gears in x-direction is 3.27µm and in y-direction it is 11.32µm.

## 5. Conclusions and Discussions

In this paper we presented a novel calibration procedure and tool for an optical 5-axis micro coordinate metrology machine. This procedure is the basis for high precision 3D measurements which e.g. allow retrieving complex geometry parameters of micro gear wheels as shown in this paper. The provided calibration tool and method may give an additional input to current standards such as ISO 10360 [7] and VDI 2617 which do not provide methods and calibration tools that are useful in all cases for this rather novel class of optical micro coordinate machines [8].

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