Micro coordinate measuring machine using voice coil actuators with interferometric position feedback control

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Abstract

Quantitative determination of structure properties like length, diameter, height, etc. is essential in research, development and in production process control. Coordinate measuring machines (CMMs) are widely used to measure these parameters. The properties of the two key components of a CMM - the probing system and the positioning stage - define directly the achievable precision of the CMM.

Commercial positioning stages for the micro- and nanoscale usually employ capacitive or inductive position sensors. Both technologies offer a resolution in the nanometre range, but the achievable scanning range is restricted. In addition, they require a (periodical) calibration. To overcome this restriction, we integrated a newly developed positioning system in our µCMM: a voice coil-based actuator with a built-in interferometric encoder. The scanning range of the introduced solution covers about 15 mm with a sub-nanometre resolution. To achieve this, we apply a new interferometer system based on a modified homodyne Twyman-Green interferometer concept [1].

The deployed probing system uses a ruby ball stylus probe and was developed at PTB in the recent years [7]. This probe is manufactured using micro technical production methods. It is a measuring probe, thus it provides a signal corresponding to the deflection of the probe for all three spatial directions. These probes provide nanometre resolution.

1 Introduction

The Physikalisch-Technische Bundesanstalt (PTB) is currently working on a technology transfer project in cooperation with its project partner MPro GmbH.

The aim is to realize a compact desktop coordinate measuring machine with nanometer resolution. This measuring instrument can carry out measurement tasks which go beyond the measurement range of a scanning probe microscope [2] and detect structures which are too fine to be measured with conventional coordinate measuring machines. Typical applications for this system include the measurement of very small holes or of miniature gears with high aspect ratio. The targeted measurement uncertainties are in the two-digit nanometer range.

For this purpose, the following subsystems were developed: a measuring micro probe, a multiaxial positioning unit using voice coil drives and an interferometric position feedback system. These units are merged together into a compact modular tactile coordinate measuring machine.

2 The probing system

The micro probe was developed at PTB within the scope of several projects. As a measuring probe it provides an electrical signal proportional to the applied displacement of the probing sphere in all three directions. The resolution of the values measured is in the one-digit nanometer range. To characterize the probe regarding its repeatability we performed a measurement sequence on a reference sphere according to the ISO 10360 norm. The standard deviation of the measured radii we achieved was 6.1 nm (with a peak to peak value of 21 nm) based on 17 repetitions.

The micro probe is composed of a sensing element (a membrane with integrated piezo resistors) and a stylus with a probing sphere. (see Figure 1).

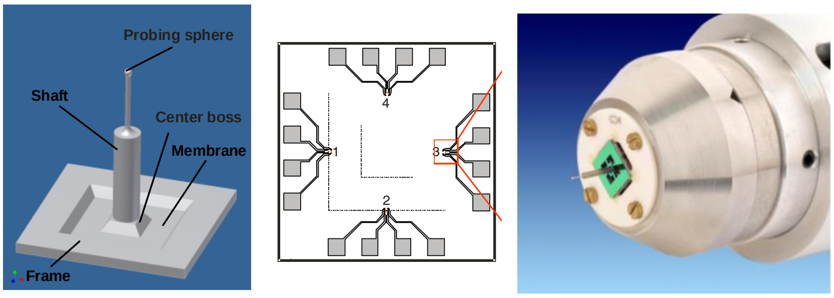

Figure 1. (left) schematic view of the initial microprobe design; (middle) layout of the piezo resistors and the metallization on the backside of the membrane; (right) silicon sense die attached to a ceramic carrier and mounted to the probe head

During measurement process the probing sphere gets into contact with the surface resulting in a deflection of the stylus as well as a deformation of the supporting membrane. This deformation and states of mechanical stresses are shown in Figure 2 for a vertically (z- direction) and a laterally (x-,y- direction) applied deflection.

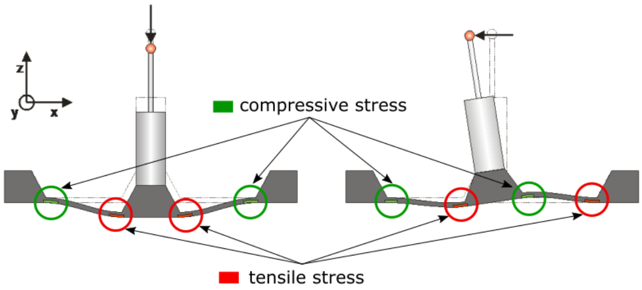

Figure 2. The Working principle of the micro probe; deformation of the boss membrane and resulting states of stress induced on the backside of the membrane by a deflection of the probing sphere in z-direction (left) and x-direction (right)

For an ideal probe with no crosstalk the signals a_i of the four piezo resistor bridges can be transformed in three values a_x, a_y, a_z, which are proportional to the deflection in x-, y- and z- direction using the following equations:

$$a_x = a_2 - a_4 \tag{1}$$
$$a_y = a_1 - a_3 \tag{2}$$
$$a_z = a_1 + a_2 + a_3 + a_4 \tag{3}$$

$a_{x,y,z}$: transformed signal
a_i : signal of bridge i

A variety of sensor designs was developed at PTB in recent years each one optimized (stiffness, sensitivity, isotropy etc.) for a certain purpose [7].

3 Interferometer concept

At PTB an interferometer concept for simultaneous length and angle measurements has been developed over the recent years [1]. The basis of the measurement procedure is a spatial evaluation of the obtained interferogram which enables a sub-Ångström resolution with a bandwidth of several kHz. The measurement concept is based on the working principle of a Twyman-Green interferometer (see Figure 3 left).

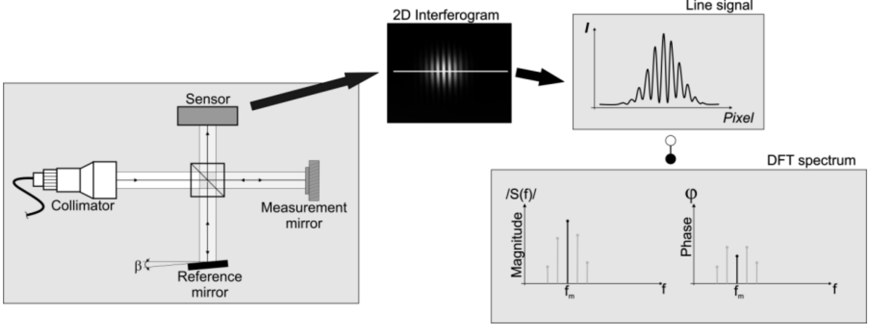

Figure 3. Schematic diagram of the setup and the evaluated signals

The interferometer has a minimum configuration: consisting of a collimator, a non-polarizing beam splitter (NPBS) plate, a tilted reference mirror and a CMOS sensor. The reference mirror and the measurement mirror are adjusted in a way that a fringe pattern is projected onto the sensor. The generated interferogram shows a spatial sinusoidal signal whose frequency per unit length depends on the tilt between the reference mirror and the measurement mirror as well as the wavelength of the light source used (see Figure 3). The small number of optical and mechanical components enables the realization of a compact measurement system. While also adjustment effort and manufacturing costs can be minimized in this way.

The measurement system uses a novel signal acquisition and processing approach: The interference pattern is recorded by means of a 2D image sensor (CMOS) (see Figure 4). Due to the optical components, the generated fringe pattern is imaged on the sensor in such a way that the interference fringes run vertically and several periods are imaged. These fringes are scanned simultaneously by the linewise-arranged sensor elements so that a spatially extended interferogram is achieved (see Figure 3).

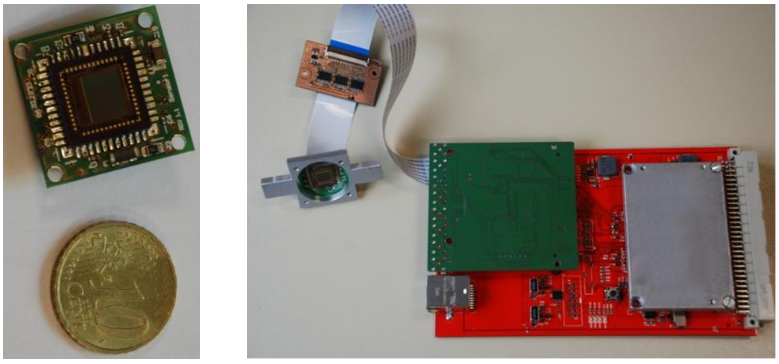

Figure 4. The proprietary image sensor board based on a *e2v EV76C560* chip (left) and the developed signal processing unit based on a *sbRIO-9651 SoM* module (right)

The recorded interferograms are interpreted in a Field Programmable Gate Array (FPGA) as a periodic pattern. The signals detected in this way are transformed into their spectral representation (frequency and phase) by means of a discrete Fourier transformation (DFT) [4-6]. Here, the phase information is directly correlated to the displacement of the positioning unit (see Figure 5).

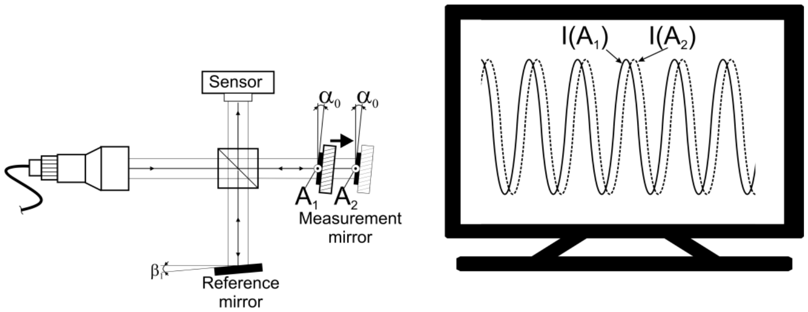

Figure 5. Signal behaviour by moving of the measurement mirror.

Furthermore, a possible stage tilt during the stage's motion causes a shift of the peak magnitude in the frequency spectrum (see Figure 6). This additional information can be used to measure and compensate the guidance errors responsible for the unwanted stage tilts [3].

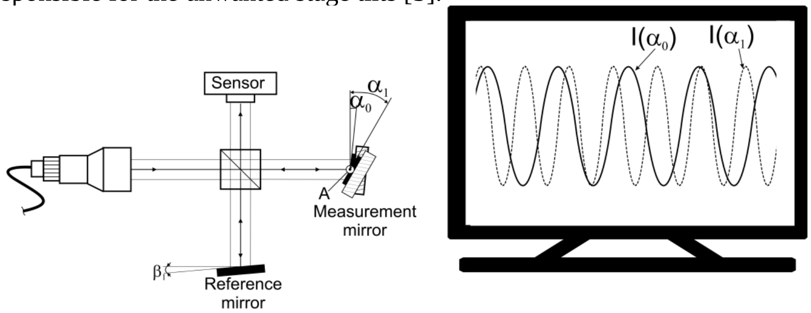

Figure 6. Signal behaviour by tilting of the measurement mirror along the axis "A". (The figure shows only a simplified 2D case to demonstrate the working principle. In reality the system is able to detect the yaw and the pitch movement simultaneously)

To characterize the new interferometer setup, we compared it to a high precision reference interferometer. The reference interferometer – a fully differential plane-mirror interferometer developed at PTB – follows the heterodyne principle. Due to the use of two separated input beams and the prevention of ghost reflections by tilting the optical components, periodic nonlinearities were suppressed at the heterodyne interferometer. They were determined by a comparison with an x-ray interferometer to be smaller than ±10 pm without any quadrature fringe correction [8]. The movement of a double-sided mirror was measured with the two different interferometers aligned complying Abbe's principle. Due to the different wavelengths of the two interferometers, their nonlinearities could be separated. Thereby the periodic nonlinearities of a novel compact Twyman-Green interferometer were determined to be smaller than ±0.2 nm (see Figure 7). Because of the desired relatively short measuring range (about 15 mm in all 3 directions as mentioned above) and because of the ability to continuously detect guidance errors (and thereby compensate the Abbe error) the measurement uncertainty of the positioning system is estimated to be below 10 nm.

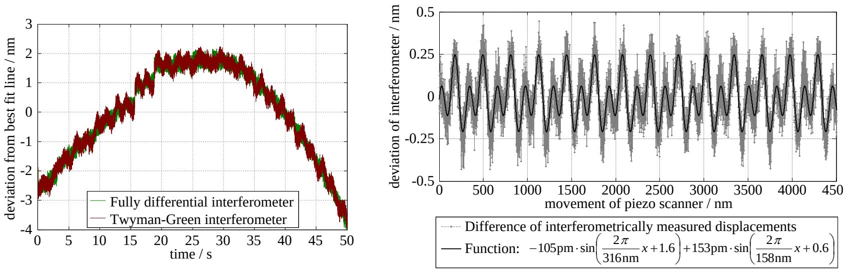

Figure 7. Deviations from a best-fit line of the difference between both interferometers

4 The scanning unit

The scanning unit follows a stacked Cartesian design driven by 3 commercial voice coil actuators (see Figure 8). To operate the system, custom-made current source adapted to the applied hardware components were used. As part of the Cartesian stack of stages 3 *Newport UMR Series* double-row ball bearing linear stages were integrated in the system.

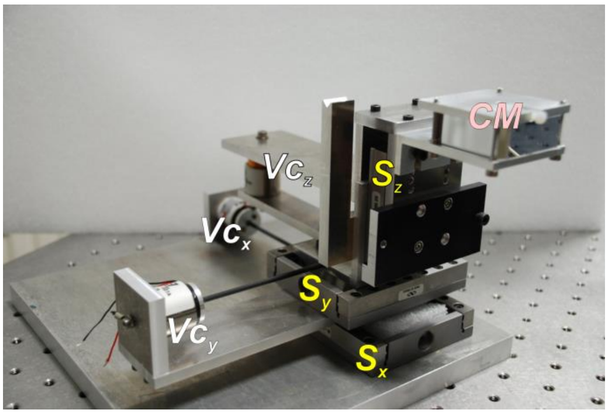

Figure 8. The Cartesian x-y-z actuators (Vc_i: Voice coil actuators; S_i: Newport UMR stages; *CM*: Corner mirror)

5 The measurement system

The measurement system (see Figure 9) follows a modular concept and it consists of the three above described parts: the probing unit (see Figure 1) the scanning unit (see Figure 8) and the position measurement unit (see Figure 9).

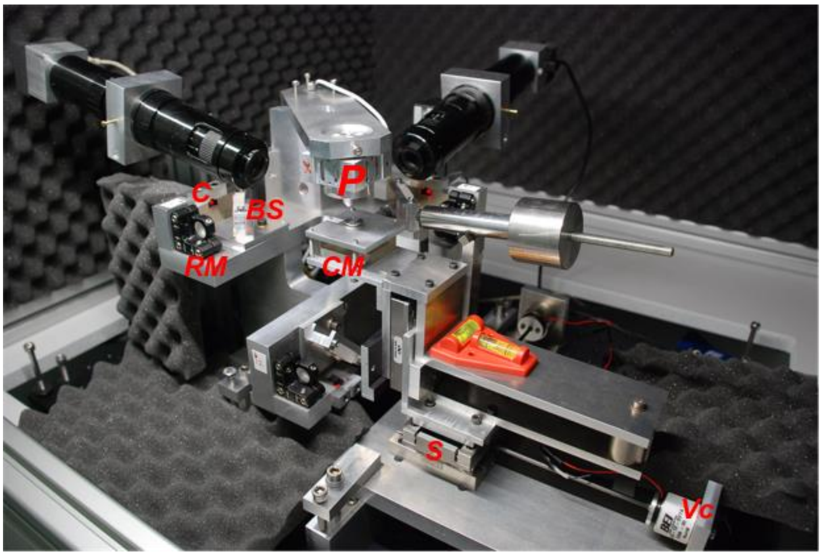

Figure 9. The realized µCMM system (*P*: *Probe*; *CM*: Corner mirror; *C*: Camera; *BS*: Beam splitter; *RM*: Reference mirror; *Vc*: Voice coil actuator; *S*: Newport UMR stage)

Similar to the actuator design, a Cartesian 3 axis interferometric measurement system was set up (see Figure 10). The system is a combination of a length and angle interferometer based on the interferometer principle described above. The unique property of the device, the detection of the tilt of the measurement mirror during the scan makes possible to compensate the guidance errors of the applied linear stages.

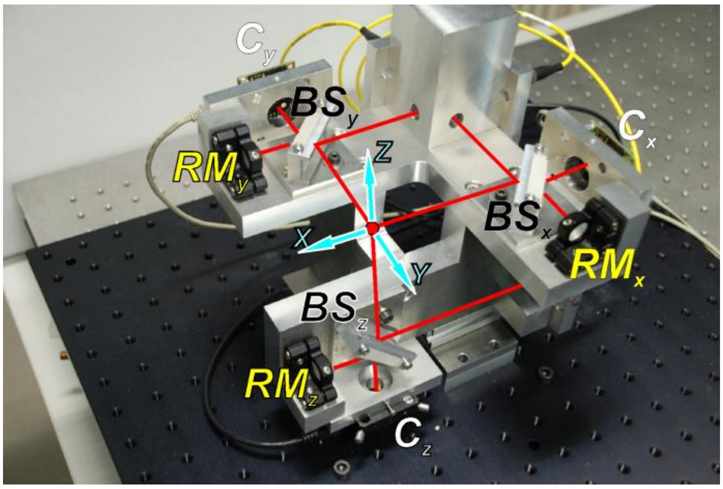

Figure 10. The Cartesian fiber based 3-axis interferometer unit (C_i: Cameras; BS_i: Beam splitters; RM_i: Reference mirrors)

A *LabView* based software was developed for the system control and to configure the FPGA module: it includes a camera configuration module, a signal acquisition part, a signal processing unit and a motion control tool.

6 Summary

Recent developments of a high-precision three axes positioning stage are presented. To realize a motion control during the scan an interferometric position sensing system was adopted to the scanning unit. The introduced custom-made device is a compact Cartesian actuator system with the ability for simultaneous detection of all six degrees of freedom. Therefore, the system allows an Abbe error corrected scanning and positioning. Based on this system feature we estimate the measurement uncertainty of the whole system to be in the range of 40-50 nm.

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