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DYNAMIC ALIGNMENTS AND CALIBARATION OF LINEAR AXIS

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ABSTRACT

Linear positioning axes are used as basic assemblies in a wide range of applications in manufacturing, and measurement technology, such as in machine tools and coordinate measuring machines.

If linear axes are installed in machines and devices, the accuracy of the complete system is limited by the rotational and translatory deviations of the individual axes from the ideal linear path of motion. The highly accurate, dynamic detection of the guiding properties during mounting and alignment of these system components is consequently the key to achieving minimal positioning deviations of the assembled system.

The presented devices for the alignment and calibration of linear axes are based on laser interferometric measuring methods. They enable highly accurate simultaneous measurements of linear position, pitch and yaw angles as well as a straightness component in one measurement run.

Index Terms – 5-DOF laser interferometer, calibration of linear axis

1. INTRODUCTION

Linear positioning axes are used as basic subassemblies in a wide range of applications in the fields of production, measurement and instrumentation, machine tools and coordinate measuring devices. The broad range of applications (machine tools, positioning systems, coordinate measuring machines, etc.) lead to the wide range of positioning and accuracy requirements for the measurement equipment.

All the rotational and translatory deviations of the linear axes from the ideal linear path of motion affect the accuracy of the overall system (see Figure 1). Therefore the correct measurement of the motion path of a linear guided machine part is one of the most important tasks in the acceptance of machines and devices with linear positioning axes.

An exact knowledge of the deviations allows both a characterization of the total positioning uncertainty as well as the definition of correction fields for the compensation of systematic deviations of the motion sequences. Interferometric methods are established in machine calibration and enable highly accurate position and angle measurements in different assemblies, whereby the individual motion components are typically measured one after the other. In addition to the high measurement resolution and linearity of the interferometric measurement, the main advantage is the traceability of the results to the meter definition.

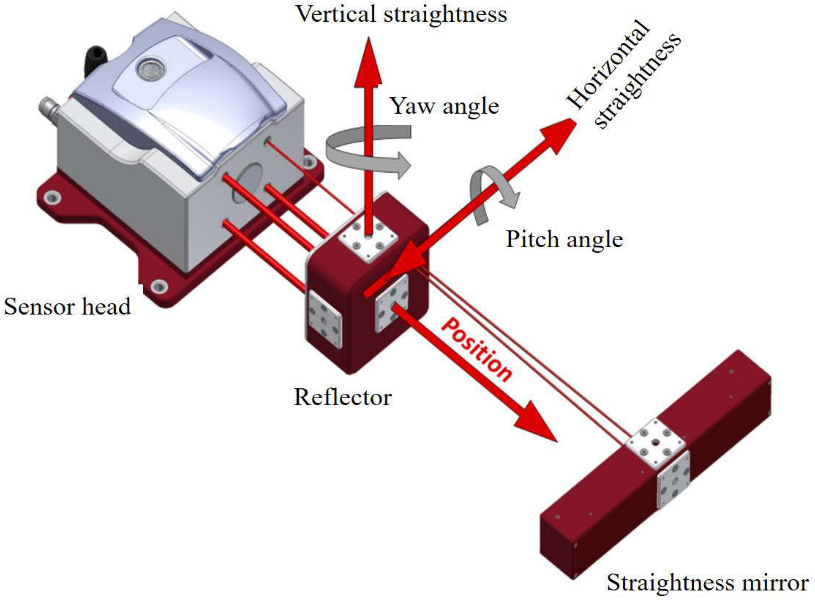

Figure 1. Measured values of the calibration interferometer

The novel calibration interferometers provide highly precise measurement of the linear position, the pitch and yaw angle as well as the straightness components, whereby four moving components are measured simultaneously.

2. DESIGN AND CHARACTERISTICS OF THE CALIBRATION INTERFEROMETERS

The principle of the length and angle measurement by the calibration interferometer is based on the homodyne Michelson interferometer [1,2]. The straightness components of the motion are measured using a straightness interferometer, based on Wollaston prism and angle mirror [6]. The functional groups of the interferometer are shown in Figure 2.

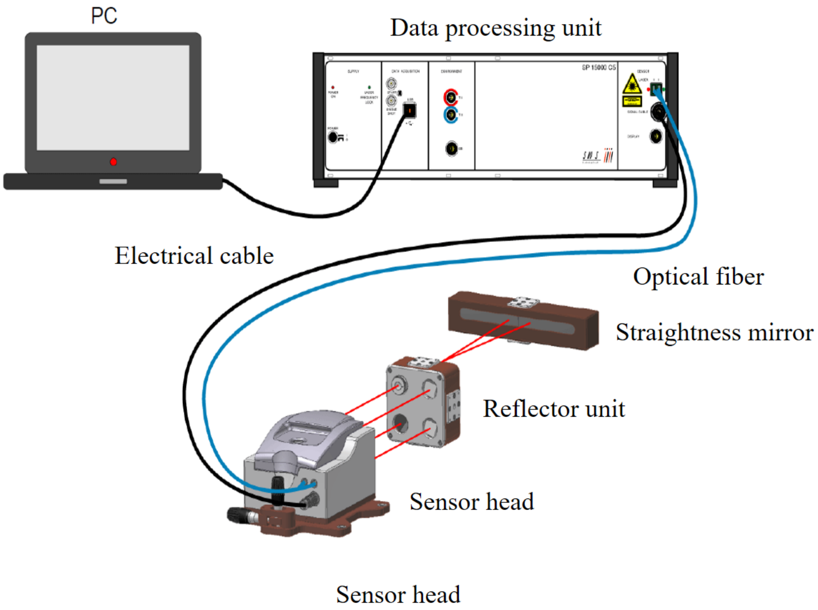

Figure 2. Function groups of the calibration interferometer

The design of the system with fiber-coupled sensor head, reflector unit and spatially separate supply and evaluation unit ensures simple handling and system alignment. The sensor head of the calibration interferometer consist of the interferometer optics for three independent length measuring channels for measuring of the linear position, the pitch and yaw angle as well as another interferometer channel for detecting the horizontal and vertical straightness of the motion. The sensor head is connected to the supply and evaluation unit via an optical fiber and a signal cable. The three channels for length and angle measurement are all supplied by the same stabilized He-Ne laser with a frequency stability better than $2 \cdot 10^{-8}$. The measurement resolution of the interferometric length measurement is 20 pm. The measuring range of the straightness measurement is ± 4 mm. Due to the fiber optic coupling, a thermal influence of the measuring object or of the measuring environment by the laser source can be neglected.

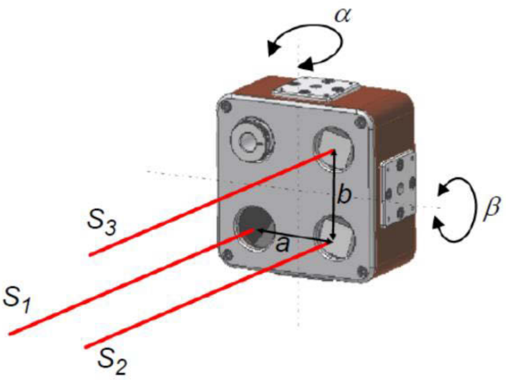

Figure 3. Basic distances in the measuring reflector

The reflector unit (see Figure 3) is a combination of three retroreflectors for length and angle measurement and a Wollaston prism for straightness measurement. The tilt-invariant design of the retroreflectors allows an increase maximum tilting angle of the reflectors for the angle measurement to ± 5 ° [3]. The back-reflected measuring beam of each channel follows the entire beam path and do not have geometrical shift. The three retroreflectors are arranged at a distance of 50 mm. With these base distances and the interferometric measurement resolution, an angle measurement resolution of 0.0004 angular seconds (0.002 µrad) can be achieved.

$$\alpha = \arcsin \frac{s_2 - s_1}{a} \tag{1}$$

A Wollaston prism splits a laser beam at an angle 2γ in a v-shape into two measuring beams and has a function of a straightness optics. The measuring beams are reflected on the straightness mirror.

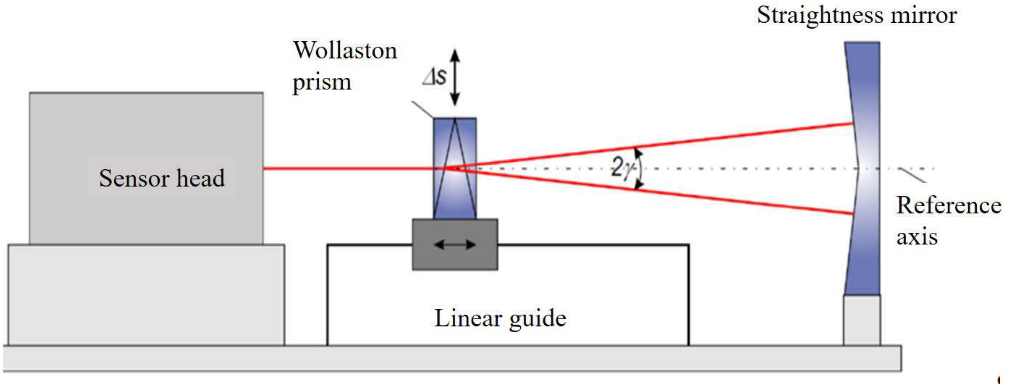

Figure 4. Interferometric straightness measurement

The mirror surfaces of the straightness mirror are inclined according to the splitting angle of the Wollaston prism used. Relative shifts Δs of the Wollaston prism and straightness mirrors cause proportional changes in the optical path lengths of the two partial beams. The Wollaston prism realizes a splitting angle of the measuring beams for the straightness measurement of approximately 1.5 °, whereby a measurement resolution of 0.01 µm is achieved. The symmetry axis of the straightness mirror represents the reference straight line to which the straightness is detected in the vertical direction. In order to avoid measurement deviations caused by angular movements of the straightness mirror, the measurement is carried out mostly with a steady straightness mirror and a moving Wollaston prism.

The possible axial travel range is determined by the length of the partial mirror surfaces, which are perpendicular to the straightness measuring beams, of the straightness mirror. The distance between the measuring reflector and the straightness mirror must be between 0.1 m and 6.5 m and is freely selectable in the linear measuring range.

The angle adjustment of the measuring reflector relates to the interferometric angle measurement, in which relative measurement deviations occur as a result of a reflector which is not perpendicular to the measuring beams in the initial position (s. Figure 5). Although the uncertainty is only in the range of 0.5% at starting angles of 3 °, deviations relevant to applications with high accuracy requirements in connection with the large angular measuring range can occur.

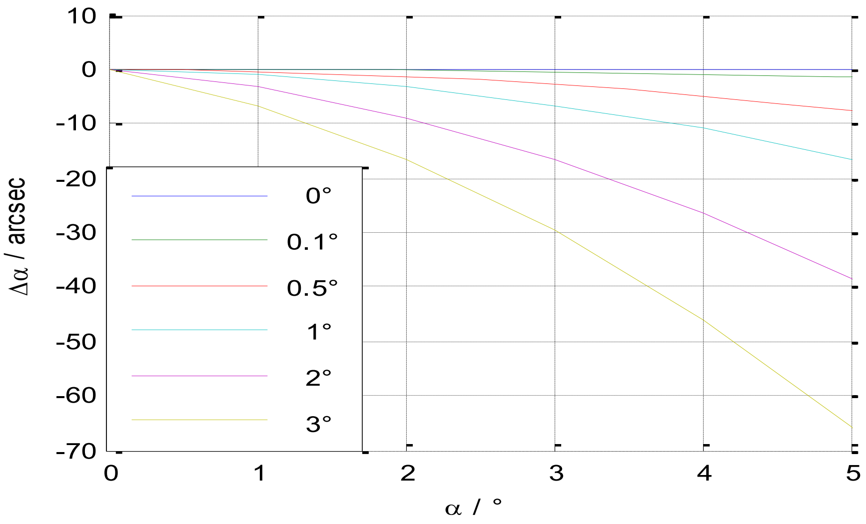

Figure 5. Angle measurement deviations as a function of the measured value for different starting angles

An optoelectronic detector (PSD) integrated in the sensor head detects the lateral position of the back-reflected measuring beam. This allows measurement of the displacement of the measuring reflector transversely with respect to the axis of the measuring beams. Furthermore, the orthogonal angular position of the reflector relative to the beam axis can be detected absolutely in combination with an adjusting mirror which is used in the measuring reflector.

Due this alignment of the measuring system by the PSD, starting angles below 0.1 ° can be realized even for short travel ranges (<10 mm), as a result of which the resulting deviations are negligible.

The PSD-based detection of the lateral displacement allows precise alignment of the traverse axis and the measurement axis of the interferometer to avoid measurement deviations of the form $\Delta L_{cos} = L \cdot (1 - \cos\alpha)$ (Figure 6). For large linear guides, visual alignment is less than $\Delta s < 1$ mm, , while for short guide lengths exact alignment is absolutely necessary. Thus, the measurement deviation $\Delta L_{relative} = 200$ nm/m at $\Delta s = 1$ mm with a guide length of 50 mm, while this proportion drops to 0.02 µm /m when aligned with PSD to $\Delta s < 10$ µm.

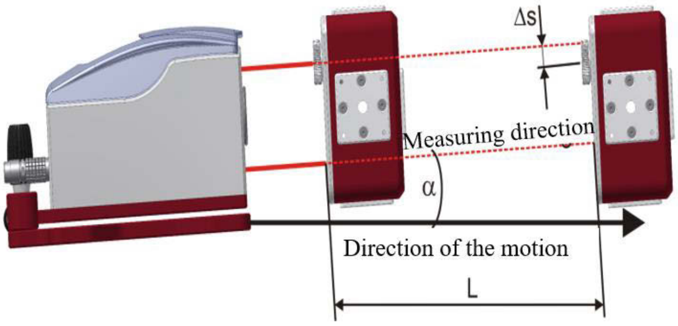

Figure 6. Measurement deviations by alignment of the measuring axis

3. MEASURING UNCERTAINTY

The most important influences to the measurement uncertainty for the calibration interferometer are presented in Table 1. The expected uncertainties are given for the respective measured variables.

Table 1. Environmental measurement data acquisition

Parameter	Measuring range	Uncertainty
Temperature	+4..+50 °C	±0,1°C
Air pressure	800…1150 hPa	± 50 Pa
Humidity	1%...99%	±3%

3.1 Position measurement

As already mentioned, the interferometric length measurement is based on the use of the wavelength stabilized He-Ne lasers as a reference. The wavelength of the laser in air is defined as:

$$\lambda_{Air} = \frac{\lambda_0}{n_{Air}} = \frac{c_0}{f n_{Air}} \tag{2}$$

where λ_0 is a wavelength in vacuum, c_0 is a light speed in vacuum, f is a frequency and n_{Air} is a refractive index of air.

The frequency stability of the laser source of $2 \cdot 10^{-8}$ provides a negligible contribution to measuring uncertainty. The uncertainty of the measurement by laser interferometers in air depends therefore on the accuracy of the determination of the refractive index of the air along the measuring path. The refractive index of the air is defined primarily by the air temperature, air pressure and humidity. Other factors, like CO2 concentration are negligible in most cases. The optimized Edlen-formula is used for determining the wavelength in air, the Ciddor formula being also applicable for extended ranges of the state variables [4, 5]. The refractive index correction is carried out in the data processing electronics by means of values for air temperature, pressure and humidity measured by corresponding environmental sensors. For the values given in Table 1, a resulting length measuring uncertainty of ± 0.1 ppm can be achieved.

3.2 Interferometric angle measurement

As described in the first section, the alignment of the measuring reflector (starting angle) represents a possible source for measurement deviations of the angle measurements. These deviations are taken into account here, whereby it can be assumed that a PSD-based alignment of pitch and yaw angles in the range of less than 1 ° and the roll angle of the reflector can be adjusted by conventional alignment methods to the values less than 0.5 °. The relative measurement uncertainty contribution resulting from all contributions is ± 0.015%. In addition, there is an uncertainty contribution of ± 0.0085 angle seconds which is independent of the measured value, which is the result of possible linearity deviations of the interferometer.

3.3 Interferometric straightness measurement

The measurement uncertainty in the interferometric straightness measurement by the calibration interferometer consists of three parts: a constant term of measurement uncertainty, a relative measurement deviation and a contribution, that depends on the measuring distance. The constant term of measurement uncertainty, as in a case of the angle measurement, results from nonlinearities and other effects in combination with the sensitivity of the straightness measurement and is less than ± 0.1 µm. The relative measurement deviation is in the range of 0.1%. It results from sensitivity deviations due to production tolerances of the Wollaston prisms used as well as alignment errors during the measurement (maximum rotation of the straightness level of 2 ° about the travel axis).

The essential measurement uncertainty contribution follows from the topology of the applied straightness mirror. During the measurement, the measuring reflector is displaced along the linear guide to be characterized, and the measuring beams of the straightness interferometer shift over the mirror surfaces of the straightness mirror, whereby deviations of the mirror surfaces from ideal planes are directly involved into the measuring result. This contribution to uncertainty can be considerably reduced by double measuring strategy with a straightness mirror rotated by 180 °.

The uncertainty contribution by the mirror geometry was determined from the occurring limit values in the investigation of several built-up straightness mirrors and is ± 0.1 M^2 in µm, where M is the axial travel range in meters.

Table 2. Specification of the calibration interferometer

Parameter	Measuring range	Resolution	Uncertainty
Length	Maximal 50 m	0,002 nm	$\pm 0.1\ ppm$
Pitch / Yaw angle	±5°	0,002 µrad 0,0004 arcsec	$\pm 0{,}015\ \% \pm 0{,}0085\ arcsec$
Straightness	Measuring length 0,1…6,5 m, lateral 4 mm	0,01 µm (0,005 µm)	$\pm 0.1\% \pm 0.1\ M^2 \pm\ 0.1\ \mu m$

4. APPLICATION EXAMPLES AND ADVANTAGES OF THE SIMULTANEOUS MEASUREMENT OF POSITION, ANGLE AND STRAIGHTNESS

The calibration interferometers can be used for characterization of the rotational and translational deviations of linear positioning axes and of overall systems constructed from such assemblies. Figure 7 shows two typical applications. The linear axis has a large travel range and the large deviations from the ideal linearly guided movement may occur. Due to the extended measuring ranges for the angle and straightness components, the calibration interferometers are robust and can be applied easy at such assemblies. Although the main application area is in the area of precision machine tools and coordinate measuring devices, they can thus also be used for such applications of reduced precision class. The planar table in Figure 7 on the right has positioning deviations <0.1 µm and angular deviations lower than some arcsec over the full travel range.

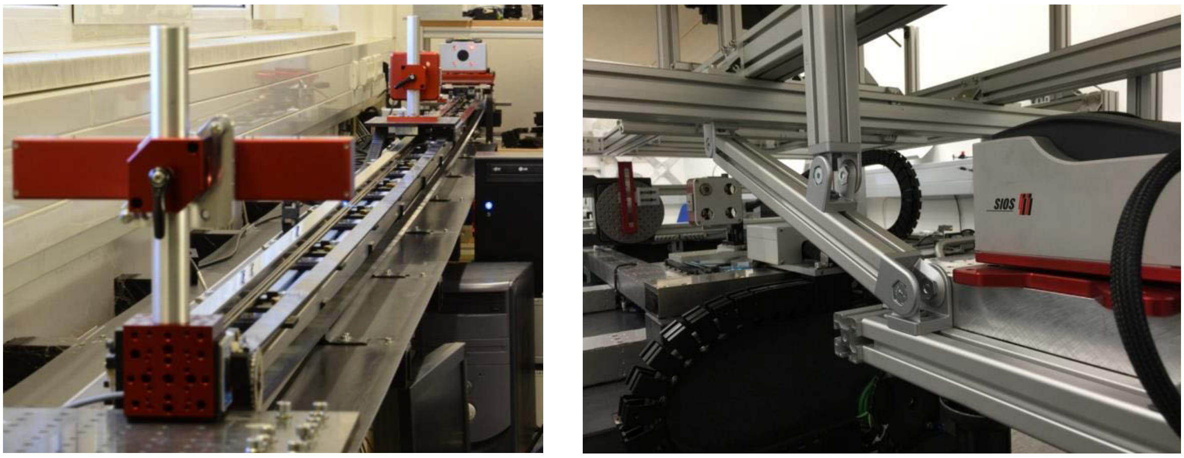

Figure 7. Measurement of a linear guide with 6 m positioning range (left); Measurement on an air bearing precision plan table with a travel range of 400x400 mm² (right)

The simultaneous measurement of several degrees of freedom reduces the required measuring time for acceptance tests, calibrations and system analyzes.

A major advantage in addition to the resulting cost reduction is the direct assignment of the measurement results of the individual measured quantities to each other. In the following, some relationships are explained with reference to a typical measurement of a linear positioning axis.

Figure 8 shows the measured values of the horizontal and vertical straightness components. The horizontal straightness has slight deviations, which are very likely to result from manufacturing tolerances of the contact surfaces. The vertical straightness clearly indicates a deflection of the guide.

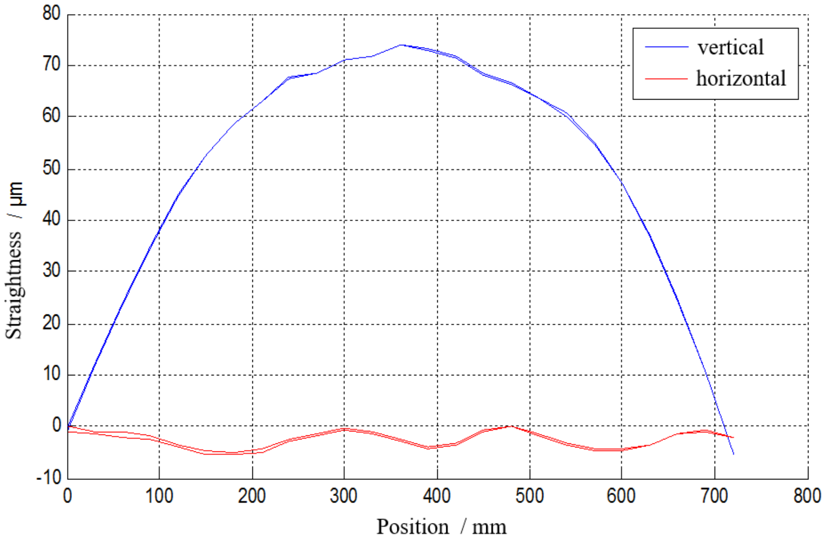

Figure 8. Horizontal and vertical straightness of the linear positioning axis

This assumption is confirmed by the measured values for pitch and yaw angles as shown in Figure 9. The yaw angle remains below seven angular seconds and qualitatively determines the source of the horizontal straightness. The linear slope indicates a slight deflection in the horizontal direction, which can also be seen in the measurement of the horizontal straightness. The pitch angle of the guide corresponds clearly to the measured horizontal straightness. In contrast to measuring methods which make use of the relationship between angularity and straightness, in the direct straightness measurement used here, the unknown effective carriage length does not influence the result of the straightness measurement. The simultaneous measurement of several degrees of freedom reduces the required measuring time for acceptance tests, calibrations and system analyzes.

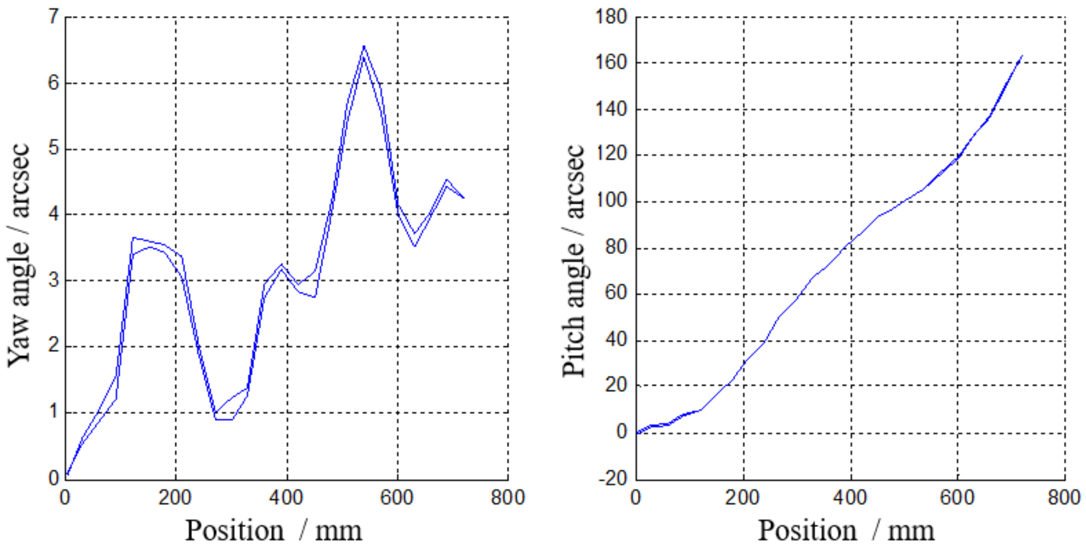

Figure 9. Pitch and yaw angles of the linear positioning axis with the range of 720 mm

The reflector used for the measurement, as well as objects to be positioned can normally not be placed in alignment with the linear positioning axis. This results in the measurement deviations of the form $\Delta l_{Abbe} = d_{Abbeoffset} \cdot \sin \alpha$ shown in Figure 10, where the Abbe-offset is defined by the distance between the measuring axis and the positioning axis, and α is a corresponding tilt angle of the guide carriage. If the angle and Abbe-offset are known, the deviation in the position measurement can be corrected. However, this is only completely possible with simultaneous measurement of angle and position, since random systematic deviations are also recorded.

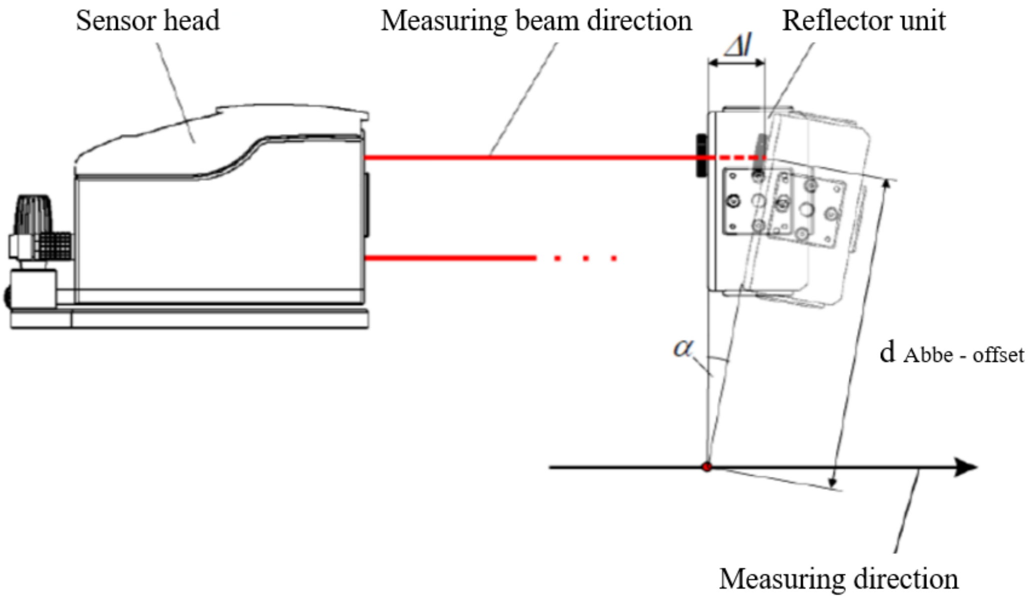

Figure 10. Measurement deviations of the linear position measurement because of the Abbe-offset

Figure 11 (left) shows the measured position deviation of the linear axis. It results from the angular movements of the guide carriage caused by the deflection of the guide and the Abbe-offset in the vertical direction, which is approximately 167 mm for the measurement setup. By correcting the angular movements, the linear portion of the positional deviation is almost completely eliminated (Figure 11, right).

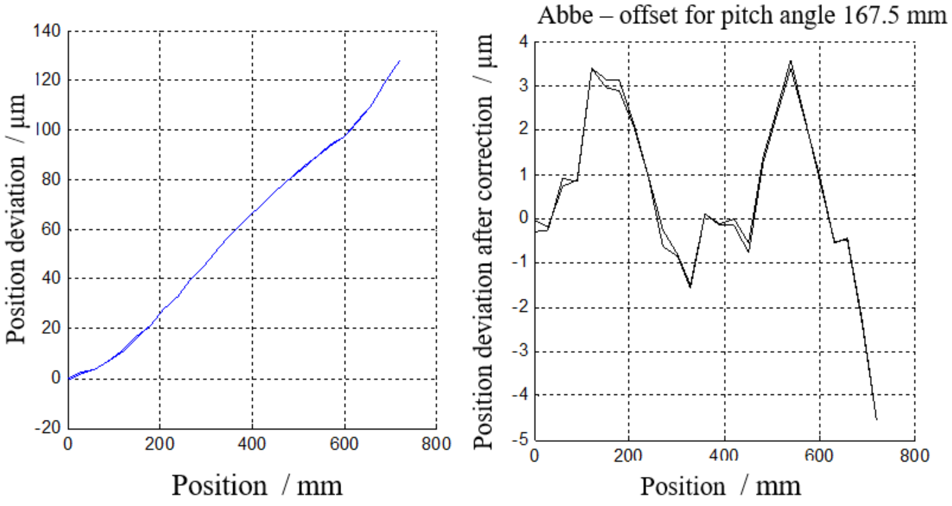

Figure 11. Measured position deviation (left); Abbe-offset corrected position deviation (right)

The positional deviation decreases from approx. 130 µm to below ± 4.5 µm. The describe correction shows that the measurement deviation was significantly greater than the actual positioning uncertainty of the guide and an evaluation of the positioning system is possible only by the simultaneous detection of several degrees of freedom.

5. CONCLUSIONS

In this article, novel calibration interferometers for the simultaneous synchronous measurement of position, pitch and yaw angles, and horizontal and vertical straightness were presented. The calibration interferometers enable position measurements up to 50 m, whereby accuracies of $1 \cdot 10^{-7}$ can be achieved based on the parameters of the environmental measurement data acquisition. The angle measuring range is 5 ° with an angle measurement resolution of 0.0004 arcsec and systematic measurement deviations less than ± 0.015%. For straightness measurement, a measuring uncertainty of $\pm 0.1\% \pm 0.1M^2 \pm 0.1\,\mu m$ is achieved in a travel range of 6.5 m (M travel range in m). The correlations of angle measurements, straightness and position measurements were discussed.

It was shown, based on the example measurement, that the simultaneous multi-degree of freedom measurements of the motion is absolutely necessary for determination of the positioning uncertainty of precision positioning axes because it allows the identification and correction of the systematic measurement deviations caused by the measuring arrangement.

REFERENCES

[1] D. Dontsov, W. Pöschel, W. Schott, “Mehrkanalige laserinterferometrische Messverfahren mit höchster Genauigkeit”. Photonik 3/2008

[2] H. Büchner, G. Jäger, “Interferometrisches Messverfahren zur berührungslosen und quasi punktförmigen Antastung von Messoberflächen. Technisches Messen 59 (1992) 2. Pp. 43-47

[3] H. Büchner, G. Jäger,” A novel plane mirror interferometer without using corner cube reflectors”. Measurement science and technology. - Bristol: IOP Publ, ISSN 13616501, Bd. 17 (2006), 4, S. 746-752

[4] Birch, K. P. und Downs, M. J., “Correction to the Updated Edlén Equation for the Refractive Index of Air”. Metrologia. 1994, Bd. 31, S. 315-316

[5] Ciddor, P. E. “Refractive index of air: new equations for the visible and near infrared”. Applied Optics. 1996, Bd. 35, 9, S. 1566-1573.

[6] VDI/VDE - Gesellschaft Mess- und Regelungstechnik. VDI Berichte 548. “Dokumentation Laserinterferometrie in der Längenmesstechnik”. Düsseldorf: VDI Verlag, 1985.

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