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*double-ballbar,
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EVALUATION AND REDUCTION OF MEASUREMENT UNCERTAINTY OF A DOUBLE-BALLBAR WITH EXTENDED MEASURING RANGE

The double-ballbar (DBB) is a cost-effective, easy-to-automate, and fast measurement device for the kinematic calibration of machine tools and robotic systems. To extend its bandwidth of applications, a DBB with a larger measuring range has been developed. This device has now been comprehensively examined for the first time with regard to its systematic and stochastic measurement uncertainty. This paper focuses on the DBB's static behaviour – i. e. deformation due to its own weight – and on thermally induced length measurement deviations, arising from environmental conditions and self-heating due to electrical power losses. For the evaluation of a DBB with 150 mm stroke, an Abbe-compliant reference measurement arrangement with a laser interferometer was employed in an air-conditioned measuring room. Based on the results, an approach for correcting the systematic temperature-dependent length measurement deviation was implemented and validated. The DBB can thus achieve a measurement uncertainty significantly below 10 µm over a 150 mm stroke under known environmental conditions. This enables its application in the kinematic calibration of machine tools.

1. INTRODUCTION

Due to inherent limitations in manufacturing and assembly accuracy, as well as deformations caused by static, dynamic, and thermal loads, motion-guided machine systems – particularly machine tools and industrial robots – inevitably exhibit deviations of the tool centre point (TCP) from the prescribed trajectory. The imprecise ‘true’ axis or joint positions and orientations can be determined by means of kinematic calibration. A wide range of measuring devices and strategies are available for this purpose [1]. The selection of a suitable measurement approach requires consideration of several factors, including the number of recorded coordinates (one to six degrees of freedom), the realisable measurement trajectory

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and measurement volume, and the associated measurement uncertainty. In addition, the time required for preparation, execution, and evaluation, as well as the cost for purchase and operation of the measuring equipment and the qualification of personnel responsible for measurement and calibration, must be taken into account.

A cost-effective, easy to automate and comparatively fast measurement method can be realised with the double-ballbar (DBB). This device records the change in length (one degree of freedom) between a base point and the TCP with high precision. In addition, the DBB can be used for machine acceptance tests in accordance with industry standards (circularity tests in ISO 230-4, see [2]). As a result, DBB measuring devices are widely used in industry.

In order to expand the possible applications of DBB measuring systems, the Chair of Machine Tool Development and Adaptive Controls at Dresden University of Technology developed DBBs with an extended measuring range. A comprehensive overview of the work carried out to date can be found in [1] and [3]. The developed DBBs have so far been qualified for small measuring strokes in the order of a few millimetres in [1]. In [4], the uncertainty was assessed utilising the entire 150 mm measuring range, identifying the main systematic error sources. Furthermore, an approach for error correction was developed and implemented. As a result, the DBB with extended range is qualified for the kinematic calibration of machine tools.

2. DBB DEVICES AND THEIR LENGTH MEASUREMENT UNCERTAINTY

The DBB was first introduced in 1982 by BRYAN ([5], [6] and [7]). The device is based on a high-precision, high-resolution linear position transducer. According to the Abbe principle, the transducer is aligned between two precision balls. The balls are held in repeatable positions in magnetic three-point mounts at the base – usually on the machine table and at the TCP. The DBB measures the radial deviation from the target position in a workspace limited by two spherical shells. In the implementation of BRYAN, a solid-state joint is used as linear guide in conjunction with an inductive displacement transducer (LVDT – linear variable differential transformer). The measuring range is specified in [7] as ± 0.004 in ($\approx \pm 0.1$ mm). A resolution of less than $0.1 \mu\text{m}$ is achieved with an analogue LVDT-amplifier. In [6], BRYAN provides detailed instructions for manufacturing the DBB and its accessories.

In the following years, several manufacturers, including Dr. Johannes Heidenhain GmbH (Germany) and Automated Precision Inc. (USA) offered DBBs. Nowadays, ‘mechanical’ DBBs are only sold by Renishaw plc (UK) and its subsidiaries. In the 2010s, the Renishaw DBB type QC10 was replaced by the wireless (Bluetooth) version QC20 ([8], [9]). Since 2023, the RCS L-90 system with a 90 mm measuring stroke, specially tailored to robotics applications (see [10] and [11]), has become available from Renishaw. Thanks to the larger ball diameter compared to the QC20, several DBBs can be attached to one ball. This enables synchronous multiple measurement, in which two or three RCS L-90 engage the TCP simultaneously. The tripod-configuration is designated as RCS T-90 [10]. Since approx. 2019, Hexagon AB (Sweden; formerly Etalon AG, Germany) offers the “Laserbar” (see [12] and [13]), a DBB-like measuring device that performs interferometric measurements over large strokes. Unlike the well-known Lasertracer [14], the Laserbar uses telescopic tubes to

mechanically track the optics. This makes the design simpler and more cost-effective. Nevertheless, the investment required for the Laserbar is approximately five to ten times higher than that for the QC20 or RCS L-90 / RCS T-90 systems.

Table 1 lists the DBB measuring systems currently available on the market with their most important technical parameters. For comparison, the self-developed ‘DBB-1’ is included in the table.

Table 1. DBB-1 and commercially available DBB devices; *with special adapter, **depending on configuration of the telescopic extension; pictures of RCS L-90 and calibrator from [29]; picture of Laserbar from [30]

device name (manufacturer)	DBB-1 (self-developed)	QC20 (Renishaw)	RCS L-90 (Renishaw)	Laserbar (Hexagon)
literature	[1], [3], [4]	[8] p.13, [9]	[10], [11], [29]	[12], [13], [30]
photo of device				
comments	incremental linear encoder with 20 μm grating pitch	LVDT sensor, ball diameter 12.7 mm (1/2 ")	probably incremental encoder	fibre-coupled laser-interferometer
meas. radii R	from 235 mm	(30)*..100..1350 mm	240..330 mm	210..745 mm** 270..1050 mm**
meas. stroke L	150 mm	± 1 mm	90 mm	535 / 780 mm**
max. extension ratio L/R	150 mm/235 mm ≈ 0.64	2 mm/30 mm ≈ 0.07	90 mm/240 mm ≈ 0.38	535 mm/210 mm ≈ 2.54 780 mm/270 mm ≈ 2.89
meas. resolution	0.1 μm	0.1 μm	-	-
measuring uncertainty at temp. range	unknown	$\pm(0.7+0.003 \cdot L)$ μm at 15..25°C (L in μm), 95% of all readings ([8] p. 13)	± 2 μm , no temp. range given, 95% of all readings; DBB recalibration recommended for temp. change $> \pm 5$ K ([11] p. 19)	± 1 μm , no temperature range given, 95% of all readings
sampling rate	250 Hz..several kHz	up to 1kHz	up to 1kHz	-
photo of calibrator	see QC20 calibrator			-
calibrator data	see QC20 calibrator	made of Zerodur, 100 mm, 150 mm and 300 mm nominal calibration length	made of CFRP-tubes, precision balls integrated	-
calibrator accuracy	see QC20 calibrator	± 1 μm for 50 mm, 100 mm, 150 mm / ± 1.5 μm for 300 mm nominal calibration length, ([9] p. 5)	-	-

Nominally, the DBB-1 achieves a resolution of 0.1 μm , which corresponds to the commercially available devices. Typically, ± 1 digit, i. e. ± 0.1 μm , can be assumed as

uncertainty of the interpolation of the DBB-1's linear measuring system. The accuracy of the linear scale tape grating is specified as $1 \mu\text{m}/\text{m}$ at 20°C [25]. The systematic error components resulting from manufacturing and assembly tolerances, elastic deformation and thermal expansion of the CFRP tube and linear guide with scale tape are currently unknown and will be determined in the following sections.

The commercial DBBs shown in Table 1 offer an uncertainty in the range from $0.7 \mu\text{m}$ to $2 \mu\text{m}$, where the interferometer-based Laserbar is superior considering uncertainty ($1 \mu\text{m}$) in relation to stroke (up to 780 mm). The Laserbar's max. extension ratio of 2.54 is also superior, but a calibrator is not available for this device, limiting its use to relative measurement. Renishaw's mechanical ballbars can be calibrated to an absolute radius using calibration standards (calibrators in Table 1), which have a limited accuracy for themselves. Accuracy-related temperature ranges are given for the Renishaw ballbars as $15\dots 25^\circ\text{C}$ (QC20, [8] p. 13) and $\pm 5 \text{ K}$ (recommended recalibration of the RCS L-90, [11] p. 19).

3. DBB WITH EXTENDED STROKE

Based on research on the kinematic calibration of hexapods (see [15–17] and [18]), the double-ballbar device and the corresponding measuring approach were enhanced (see [1, 3], [19–21] and [22]). The DBB's design evolution led to a larger measuring range while maintaining compatibility with the DBB devices and accessories from Renishaw's types QC10 and QC20.

A total of five DBB devices were designed and built. These achieve measuring strokes from 32 mm (DBB-2) to 202.5 mm (DBB-5), equivalent to extension ratios from 0.22 to 0.66. Fig. 1 exemplifies the design of the DBB-1, which will be experimentally characterised later. Because DBB-2 through DBB-5 essentially share the DBB-1-design, differing only in the lengths of the CFRP tube and the linear guide rail, they are omitted here.

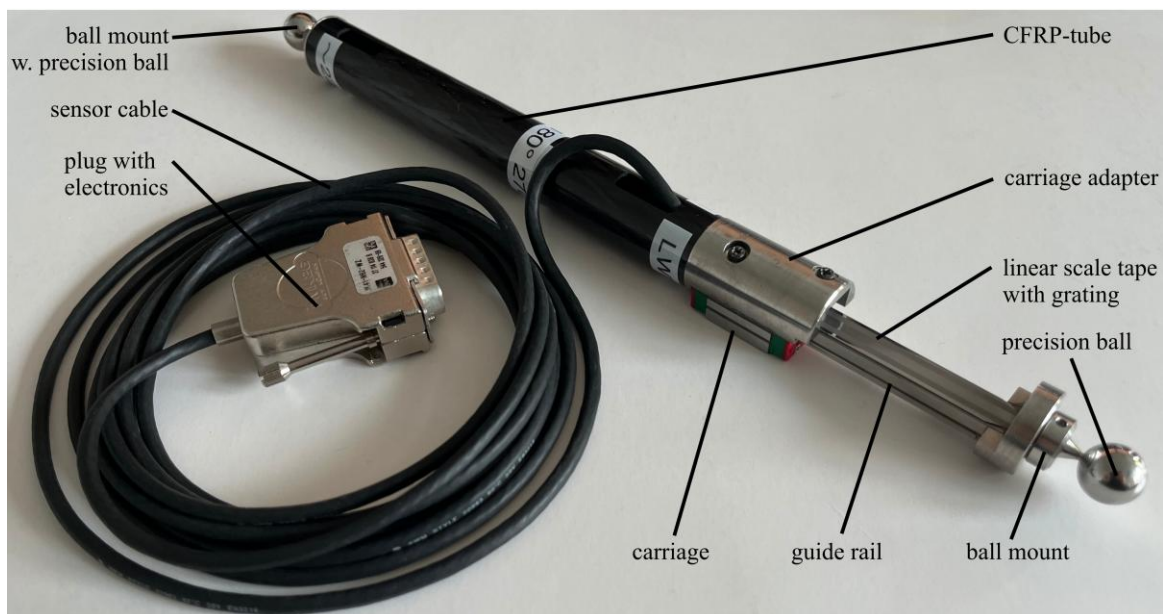


Fig. 1. Design and components of the self-developed DBB-1

A miniature ball guide (MGN9H series from HIWIN GmbH) serves as the DBB's linear guide [23]. As part of the preliminary research by KAUSCHINGER et al., different carriage lengths and three preload classes were investigated (compare [1] and [19]). KAUSCHINGER recommends the use of 'long' guide carriages and the 'backlash-free' preload class as a compromise between sufficient stiffness against tilt in the carriage and low hysteresis due to friction. The linear measuring scale tape of the incremental position measuring system is attached onto the bottom side of the linear rail by its self-adhesive backing. The arrangement ensures that the scale tape exactly lies on the connecting line between the two balls. During retraction, the linear rail plunges into a CFRP tube, which exhibits low thermal expansion. All adapter parts are made of thermally insensitive INVAR36 alloy with a linear thermal expansion coefficient of $0.8 \mu\text{m}/(\text{m}\cdot\text{K})$ [24]. Guide carriages, CFRP tubes and adapter parts are bonded with two-component adhesive. The balls (diameter 12.7 mm) are replaceable via M6 threads. Extension pieces can also be screwed in, in order to increase the measuring radius. The incremental linear measuring system was obtained from Numerik Jena GmbH. The measuring head (type LIK41-N62-WZ, see [25]) is screwed into the carriage adapter. The linear scale tape (type SINGLEFLEX MT15-10BP, self-adhesive backing, grating period $20 \mu\text{m}$, accuracy class $1 \mu\text{m}/\text{m}$, linear expansion coefficient $10.6 \mu\text{m}/(\text{m}\cdot\text{K})$, see [25]) is secured to the ball adapter with two-component adhesive (fixed point of thermal expansion of the scale tape). Interpolation to $0.1 \mu\text{m}$ incremental signals takes place in the connector. Depending on the incremental counter electronics employed, sampling rates up to the kilohertz range are achievable [1]. In the experiments presented below, a USB adapter with a sampling rate of 250 Hz was used.

4. PRELIMINARY EXPERIMENTS ON SYSTEMATIC DBB LENGTH MEASUREMENT UNCERTAINTY

4.1. EXPERIMENTAL INVESTIGATION ON DBB THERMAL BEHAVIOUR

Due to the absence of detailed documentation for the DBB-1's CFRP tube, its coefficient of thermal expansion was estimated in a simple experimental setup in [4]. A 220 mm long CFRP tube, identical to the DBB-1 tube, was placed on a flat plate and fitted with a short brass end piece. The thermally induced expansion was measured at the end piece using two precision gauges (manufacturer: TESA Technology Switzerland, type: Tesatronic TT10, resolution: $0.1 \mu\text{m}$). Heating was carried out using a hair dryer. The tube's surface temperature was measured with a non-contacting sensor (type ALMEMO 2290-4 with AMR FR260K infrared sensor, Ahlborn Mess- und Regelungstechnik GmbH). Although the experiment does not provide exact values, it revealed a positive coefficient of expansion in the order of $1...2 \mu\text{m}/(\text{m}\cdot\text{K})$. In relation to the expansion of the guide rail and scale tape, the thermal expansion of the CFRP tube will be neglected subsequently.

In order to estimate the thermally induced systematic length measurement deviation, a preliminary experiment was carried out in which the DBB-1 was placed on a QC20 calibrator's 300 mm reference distance, switched on to allow self heating and – after reaching

thermal equilibrium – switched off to observe cooling down. For comparison, a QC20 device in 300 mm configuration was placed on a second calibrator. The length measurement value and tactile as well as thermographic temperature data were recorded over a period of four hours. Temperature data loggers from TESTO SE & Co. KGaA (type Saveris E1118-F0601, see Section 5.1) were used for tactile temperature and air temperature acquisition. An infrared camera type PI450 from Optris GmbH & Co. KG was used for non-contact temperature measurement. DBB-1 data was logged at 250 Hz acquisition rate via USB adapter using a simple terminal software (see [1]). QC20 data was recorded with Renishaw's "Ballbar Trace" software at 100 Hz acquisition rate. Fig. 2 a) shows the experimental setup and three thermographically recorded temperature distributions A to C. Fig. 2 b) and Fig. 2 c) show tactile and thermographic temperature data over time. Fig. 2 d) illustrates the related DBB-1's and QC20's length deviations for the self heating phase. A magnetic tactile temperature sensor was applied at the DBB-1 guide's carriage. Another one was applied on each calibrator. Air temperatures were recorded close to each calibrator. The whole experimental setup was enclosed in a provisional cardboard housing to reduce influence of reflections in the infrared band. Adhesive tape was applied on metallic surfaces related to measuring points in order to increase the local emissivity (assumed emissivity $\varepsilon = 0.9$). The QC20 has to be switched on by hand by tightening of the battery compartment's cap. The respective short handling processes for switch-on and switch-off are visible in the thermographic data as short peaks at $t \approx 0$ s and $t \approx 9000$ s. The DBB-1 can be switched on/off by connecting/disconnecting the USB-adapter from outside the housing. Fig. 2. c) shows excess temperatures, with reference to the air temperature close to the DBB-1 calibrator for tactile temperature sensors and with reference to the thermographically measured background temperature (not shown) for all thermographically measured excess temperatures. Thus, an offset between tactile and thermographic excess temperature data occurs. This is taken into account when determining steady-state values and thermal time constants.

Just after switch-on, both DBB devices experience a temperature increase due to self heating of the electronics and the length readings begin to drift. Within approximately 11 min the DBB-1 reading decreases by 1 μm , meaning the DBB appears to become shorter (compare B in Fig. 2. a) and d). The DBB-1's length deviation reaches steady-state after 6800 s, i. e. more than two hours, at C with a 2.7 μm decrease. Related to this value, the thermal time constant is found as 1370 s (approx. 23 min) at -1.7 μm . Looking at the thermographically measured excess temperature of the guide rail close to the guide carriage (Fig. 2 c), the time constant is found as 1140 s (approx. 19 min) related to reaching thermal equilibrium after 4335 s (approx. 72 min) at 2 K excess temperature. The DBB-1 electronic compartment reaches almost 3 K excess temperature with a similar thermal time constant.

The observed decrease of the DBB-1 readings is primarily due to the self-heating because of the power loss of the measuring head of approx. 1 W (compare [25]). If the linear rail with scale tape expands when heated, assuming a coefficient of thermal expansion of 10.6 $\mu\text{m}/(\text{m}\cdot\text{K})$ [26], the grating expands from the ball end held in the calibrator towards the measuring head. This has the same effect as if the linear rail runs in, i. e. a shortening of the measured length. Based on $\Delta T_{\text{rail}} = 2$ K excess temperature of the linear rail with scale tape (see Fig. 2 c) at $t = 4335$ s) for 70 mm thermally sensitive length (300 mm DBB length on the calibrator minus 230 mm minimal DBB length), the thermal expansion may be roughly

estimated to a value of $\Delta l_{\text{rail}} = 0.07 \text{ m} \cdot 10.6 \mu\text{m}/(\text{m}\cdot\text{K}) \cdot 2 \text{ K} \approx 1.5 \mu\text{m}$, leading to an $1.5 \mu\text{m}$ decrease of the DBB reading. This value leaves $0.8 \mu\text{m}$ of unexplained length deviation regarding the observed point in time with its $-2.3 \mu\text{m}$ offset.

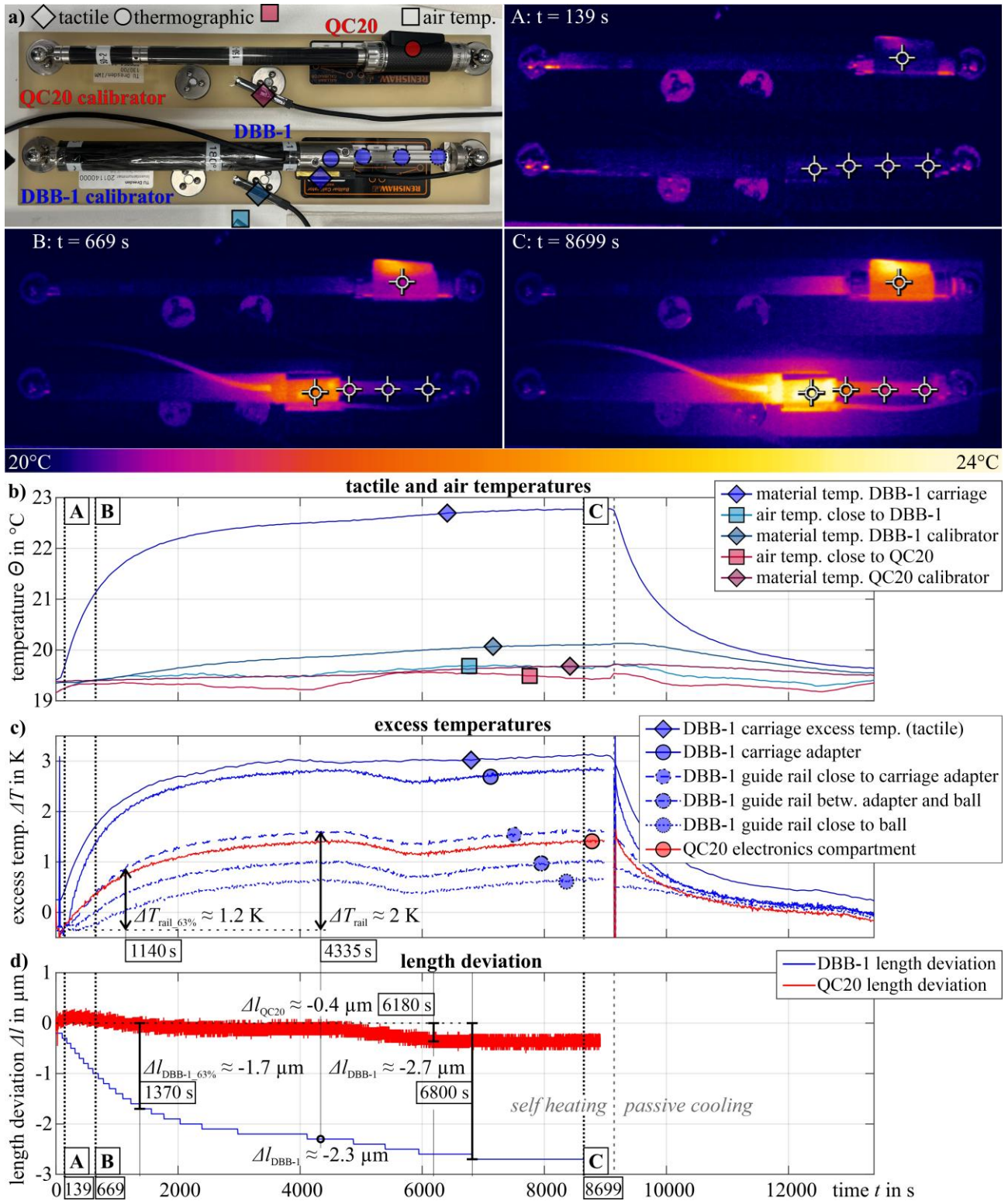


Fig. 2. Setup and result for the experimental evaluation of the DBB's systematic uncertainty due to self-heating

Probably other components affect deviation, e. g. expansion the linear scale's measuring head itself or of the CFRP tube. As can be seen from Fig. 2 a), the tube also experiences a temperature rise. Since the tube's coefficient of thermal expansion is assumed to be in the order of $1/10^{\text{th}}$ to $1/5^{\text{th}}$ ($1...2 \mu\text{m}/(\text{m}\cdot\text{K})$) according to preliminary tests) its contribution to length measurement deviation is neglected for a first estimate. Thus, the tube's temperature data is omitted. Similarly, zero expansion for the calibrators is assumed, although they experience a temperature rise.

Compared to the DBB-1, the QC20 is insensitive to thermal induced deviations in absolute magnitude. The QC20 heats to an excess temperature of less than 2 K at the surface of its electronic compartment. The length deviation reaches steady state at $-0.4 \mu\text{m}$ after approx. 100 min, which is within the specified limits of $\pm 0.7 \mu\text{m}$ (compare Table 1). The QC20 data is superimposed by a significant noise, probably related to interpolation of the analogue LVDT-signal.

Overall, the preliminary experiments reveal a notable sensitivity of the DBB-1 device to thermally induced length measurement deviations. According to the linear scale tape's coefficient of thermal expansion of $10.6 \mu\text{m}/(\text{m}\cdot\text{K})$, a scaling error in the order of several microns can be expected. Even when operated in a relatively stable thermal environment, approximately two hours are needed to reach thermal equilibrium starting from "cold", switched off DBB devices.

4.2. EXPERIMENTAL ASSESSMENT OF DBB MECHANICAL UNCERTAINTIES

In addition to thermally induced systematic DBB length measurement deviations, kinematic and elasto-static deviations are also expected. To gain an estimate, the DBB mounted in a machine tool during a calibration run was rotated in 90° steps around its longitudinal axis. Length changes of up to $2 \mu\text{m}$ were evident in the detent positions. Probably, elastic deformation and tilting of the linear rail in the guiding carriage lead to these deviations. Further research on this topic should be conducted.

Furthermore, the elasticity of the calibrator should not be neglected. It can be bent by hand to such an extent that the DBB reading changes by a few microns. This observation is plausible, as the DBB lies outside the bending-neutral fibre of the calibrator. The calibrator should therefore always be used in the same orientation on a rigid surface.

5. DBB UNCERTAINTY ASSESSMENT WITH A LASER INTERFEROMETER

5.1. EXPERIMENTAL SETUP IN THE MEASURING ROOM

Based on the approach of KAUSCHINGER [1], systematic deviations of the DBB-1 were quantified in a measuring room.[†] The room is air-conditioned to a nominal temperature of 20 °C and has a measuring track with a laser interferometer type ML10 (Renishaw) aligned (no weather station available for automatic correcting environmental data, data acquisition with 25 Hz if not stated otherwise). A carriage runs on ball bearings on the track.

Fig. 3 a) shows the experimental setup. The DBB-1 is aligned with the laser interferometer beam axis to enable reference measurements in accordance with Abbe's principle. A digital gauge is attached to the fixed ball base to detect any base displacement. The ambient air temperature is recorded at 1-minute intervals close to the ball mount on the carriage side (temperature data logger from TESTO SE & Co. KGaA, type Saveris E1118-F0601, measurement uncertainty 0.05 K in the range from 10°C to 40°C, see also [26]).

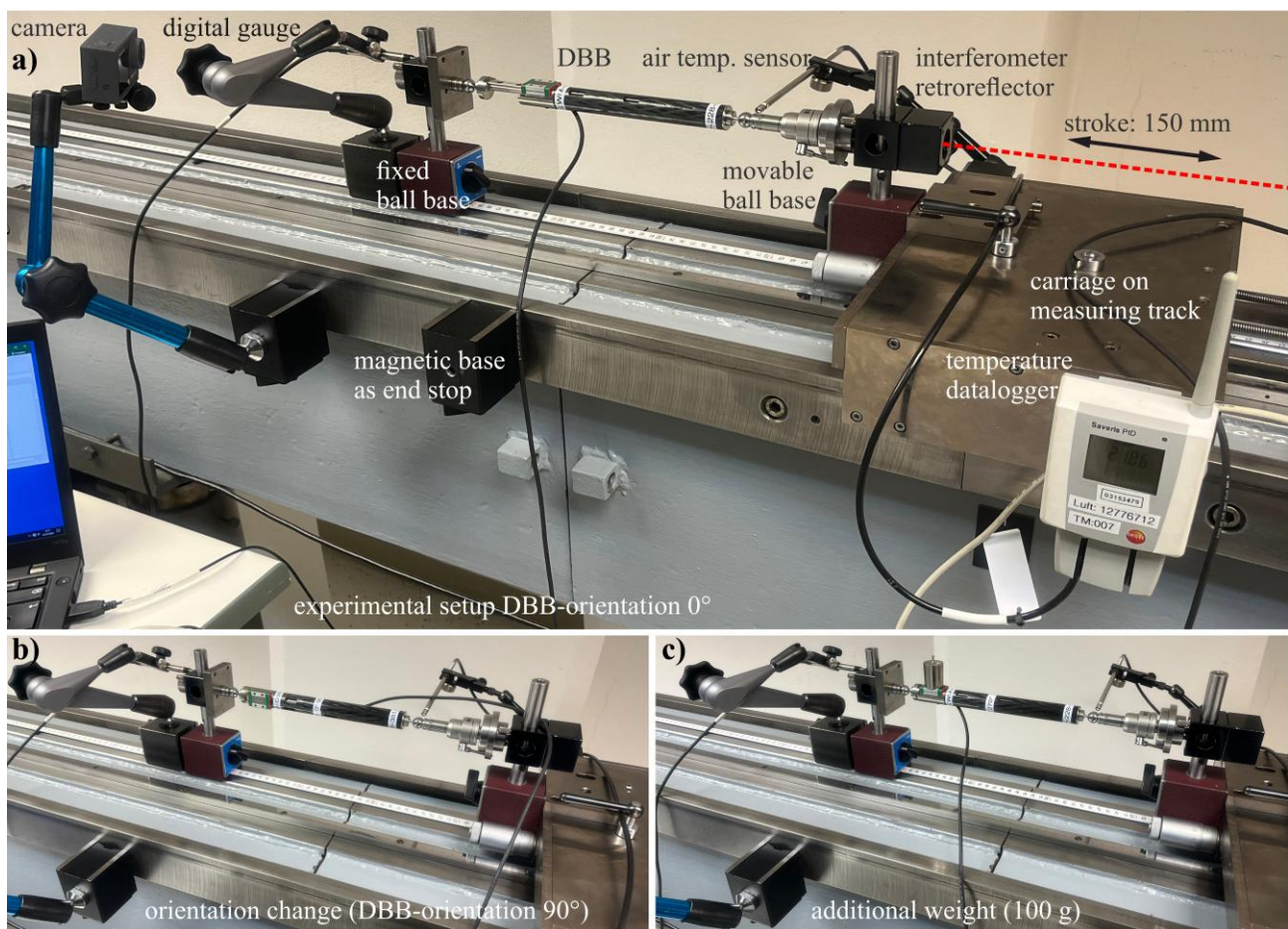


Fig. 3. Experimental setup for uncertainty assessment of the DBB-1: a) setup overview, b) orientation change of the DBB-1, c) additional weight applied to the DBB-1

[†] For this purpose, the measuring room of the Faculty of Mechanical Engineering / Process Engineering at the Dresden University of Applied Sciences HTWD (measuring room in the 'S'-building, room S065 - S073) was used, since a similar facility is not available at Dresden University of Technology. We would like to thank Prof. Dr.-Ing. Thomas Rosenbaum and Dipl.-Ing. (FH) Stefan Preuße from the Dresden University of Applied Sciences (HTWD) for enabling us to conduct the experiments in the HTWD measuring room.

For the experiment, the DBB is calibrated on the calibrator and suspended in the three-point ball mounts. The carriage is moved manually along the measuring track, stopping at detent positions. The detent positions are later identified in the data processing of the logged DBB data. The comparison between the laser and DBB measurements is performed under standstill conditions.

Fig. 3 b) and c) show the experimental setups for the estimation of the influence of DBB orientation and additional mass applied to the DBB's linear guide.

5.2. MEASUREMENT UNCERTAINTY OF THE EXPERIMENTAL SETUP

This section gives an estimate of the measurement uncertainty of the experimental setup shown in Fig. 3. All setups and measuring equipment, as well as the DBB-1 under investigation, were stored and acclimatised in the measuring room for two days before conducting the experiments. The laser interferometer was switched on for at least two days in advance to the measurement, i. e. it was also in a state of thermal equilibrium.

The roll and pitch angles of the measuring track carriage were captured using a precision inclinometer (manufacturer: Wyler AG, type: Minilevel NT). Over the measuring stroke, the maximum roll angle deviation is approximately 2 mm/m, and the maximum pitch angle deviation is less than 0.5 mm/m. The DBB misalignment due to the change in roll angle of the track's carriage is estimated for the shortest DBB-1 measuring length of 230 mm. For an offset length of 0.125 m between the track and the movable ball mount, the resulting maximum lateral displacement is 0.25 mm, assuming a deviation of 2 mm/m. This displacement causes a cosine error of 0.14 μm . The pitch angle contributes even smaller to systematic error. Both error components are subsequently neglected.

On the day of the experiment the recorded temperature in the measuring room was 21.2 °C with a maximum fluctuation of ± 0.3 K. The air conditioning was switched off during the measurement to avoid intermittent cold airflow. During each experiment, the maximum change in air pressure was below +1 mbar. To estimate the laser interferometer deviations, the laser beam's dead length of 3 m is taken into account. According to the equations given in [27] and [28], temperature fluctuations result in a systematic error contribution of $\pm 0.3 \text{ K} \cdot 1 \mu\text{m}/(\text{m}\cdot\text{K}) \cdot 3 \text{ m} = \pm 0.9 \mu\text{m}$. The maximum observed increase in air pressure leads to an error contribution of $+1 \text{ mbar} \cdot 0.3 \mu\text{m}/(\text{m}\cdot\text{mbar}) \cdot 3 \text{ m} = +0.9 \mu\text{m}$ according to [27] and [28]. It is assumed that air humidity and CO₂ concentration remained constant throughout the duration of each experiment. The maximum error contribution resulting from uncertain environmental conditions sums up to $+0.9 \mu\text{m} \pm 0.9 \mu\text{m}$, i. e. a range of 0...1.8 μm .

5.3. DESIGN OF EXPERIMENTS, EXPERIMENTATION AND PROCESSING OF MEASURED RAW DATA

Table 2 provides an overview of the experiments discussed in the following section. Exp. I was carried out to examine the self-heating of the DBB after switching on, as well as

its behaviour until thermal equilibrium (exp. II). Subsequently, the systematic deviation of the DBB reading was investigated as a function of orientation (exp. III) and additional load by applying weights (exp. IV). Finally, the DBB was extended once, with data being recorded at a higher sampling frequency of the laser interferometer (250 Hz). This exp. V is used to validate the correction approach for the systematic thermally induced length measurement deviation. The DBB-1 was not removed from the test setup throughout the whole series of experiments to avoid deviations due to mechanical inaccuracies.

Table 2. Series of experiments conducted for systematic evaluation of DBB uncertainty

no.	experiment	description
I	DBB-1_250703-1	DBB length measuring uncertainty in 0° orientation, DBB-1 switched on at ambient temperature to asses effect of self-heating, duration approximately 1 h
II	DBB-1_250703-2	DBB-1 uncertainty in 0°, including 40 min standstill to reach thermal equilibrium
III	DBB-1_250703-3	DBB-1 uncertainty in 0° / 270° / 180° / 90° orientation
IV	DBB-1_250703-4	DBB-1 uncertainty in different orientations and with additional weight applied
V	DBB-1_250703-8	DBB-1 uncertainty in 0° orientation; one pass through the whole stroke with 250 Hz laser-interferometer sampling rate

5.4. DISCUSSION OF THE EXPERIMENTAL RESULTS

Fig. 4 shows the evaluation of experiment I. The DBB-1 was switched on “cold” at ambient temperature of approximately 21.2 °C, calibrated at $l_{\text{DBB-1}} \approx 300$ mm, mounted on the test setup and cycled between extension and retraction for roughly one hour. The Z-axis in Fig. 4 presents the measurement difference between the DBB and the laser interferometer in relation to current DBB length (Y-axis) and time (X-axis). For the calibration length of approx. 300 mm, the DBB’s deviation was set to zero at $t = 0$ s, as in all other experiments.

The length offset between DBB and laser interferometer increases over time, which probably relates to the self-heating of the DBB, since ambient temperature hardly changes. Over time, a PT_1 behaviour can be assumed for this DBB offset. The increasing offset is opposite to the effect observed in the preliminary experiments (compare Fig. 2). The reason is unclear, but possibly linked to the temperature rise of the ball-mounts and laser interferometer retroreflector. A scaling deviation correlated to the stroke of the DBB is evident, which can be approximated as roughly linear to 3.5 μm over a 150 mm stroke. The scaling factor remains constant from 500...1000 s onwards while the offset still increases.

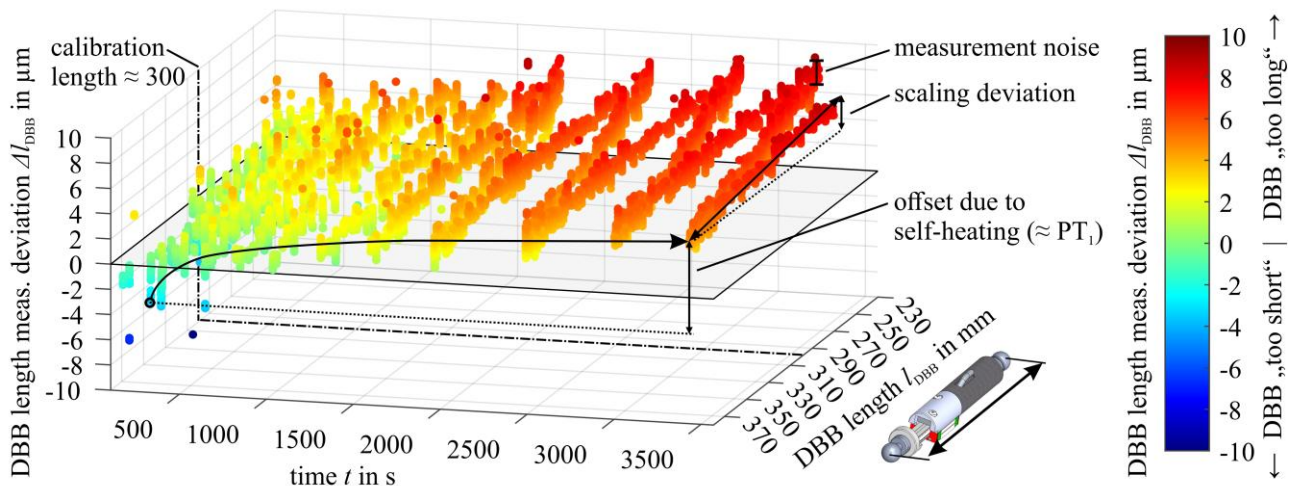


Fig. 4. DBB-1 length measurement deviation from experiment I (self-heating)

The magnitude of the scaling error in Fig. 4 is plausible. Assuming a uniform temperature increase of 1 K along the linear rail, which would relate to $t \approx 1000$ s in Fig. 2 c), the scale tape temperature becomes $21.2 \text{ }^\circ\text{C} + 1 \text{ K} = 22.2 \text{ }^\circ\text{C}$, corresponding to 2.2 K above the nominal reference temperature of $20 \text{ }^\circ\text{C}$. This leads to an estimated scaling error of $3.5 \text{ } \mu\text{m}$ ($0.15 \text{ m} \cdot 10.6 \text{ } \mu\text{m}/(\text{m}\cdot\text{K}) \cdot 2.2 \text{ K} \approx 3.5 \text{ } \mu\text{m}$). It should be mentioned, that the scaling deviation in Fig. 4 is initially ($t = 0$ s) unequal to zero. This relates to the measuring room's ambient temperature above the ideal $20 \text{ }^\circ\text{C}$ reference.

Fig. 4 clearly indicates, that DBB-1 needs at least one hour in switched on state in the measuring environment to reach a state of thermal equilibrium for the extension-retraction-cycle conducted manually during exp. I.

Subsequent to exp. I, the thermal behaviour was investigated up to thermal equilibrium in standstill in exp. II (Fig. 5). The DBB-1 was extended and retracted once, with no change in scaling error observable. Afterwards it was left stationary for approximately 40 min with a nominal length of about 300 mm. During the standstill period (750 s to 2500 s), a slight fluctuation in DBB measurement deviation is observed, associated with a length offset increase in the order of 1...2 μm . The increased offset is confirmed in the following extension-retraction cycle after standstill. The scaling deviation remains in the range of 3 to 4 μm over a 150 mm stroke. The length offset nearly does not change from approx. 2000 s onwards, so that thermal equilibrium can be assumed from this point in time onwards.

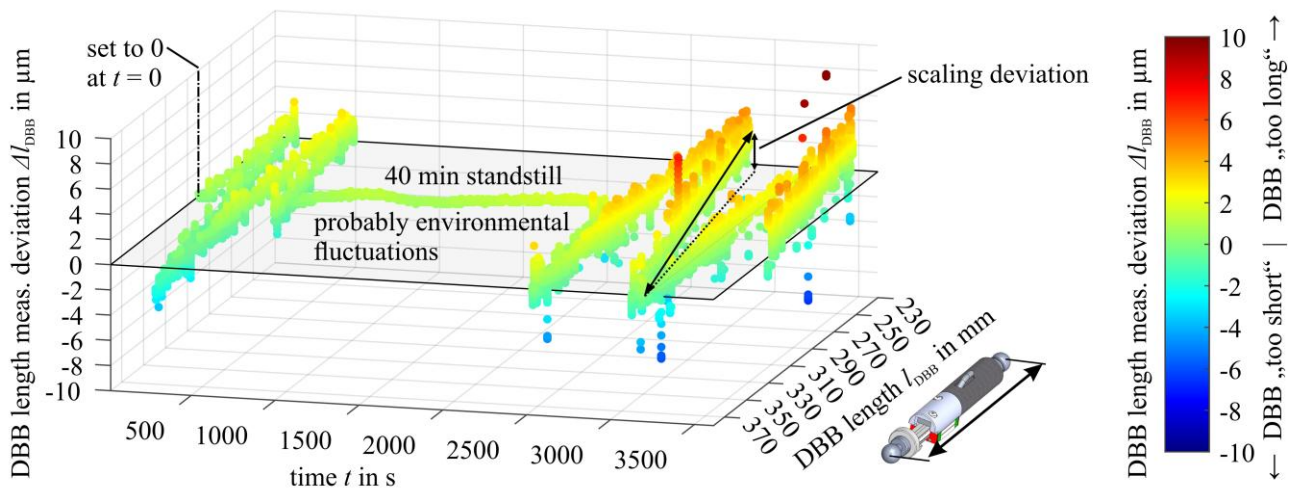


Fig. 5. DBB-1 length measurement deviation from experiment II (thermal equilibrium)

Fig. 6 shows exp. III, focused on the orientation dependence of the DBB offset. The scaling error shows no dependence on orientation. The largest shift in offset occurs while changing the orientation from 0° (horizontal orientation of guide carriage like in Fig. 3a) by rotating to 270° orientation (vertical orientation of guide carriage) and further rotating from 180° to 90°. Between opposite orientations 0° and 180° or 270° and 90° respectively, a length offset of about 4 μm occurs. After subsequent 90° rotation increments from 0° to 360° the DBB offset still differs by about 2 μm. The offset may be caused by the tensile force of the DBB cable.

Apparently, the dead mass of the DBB-1 is sufficient to traverse tilting backlash of the linear guide. Consequently, the DBB should be employed for machine calibration only in its calibrated orientation, and any reorientation should be avoided.

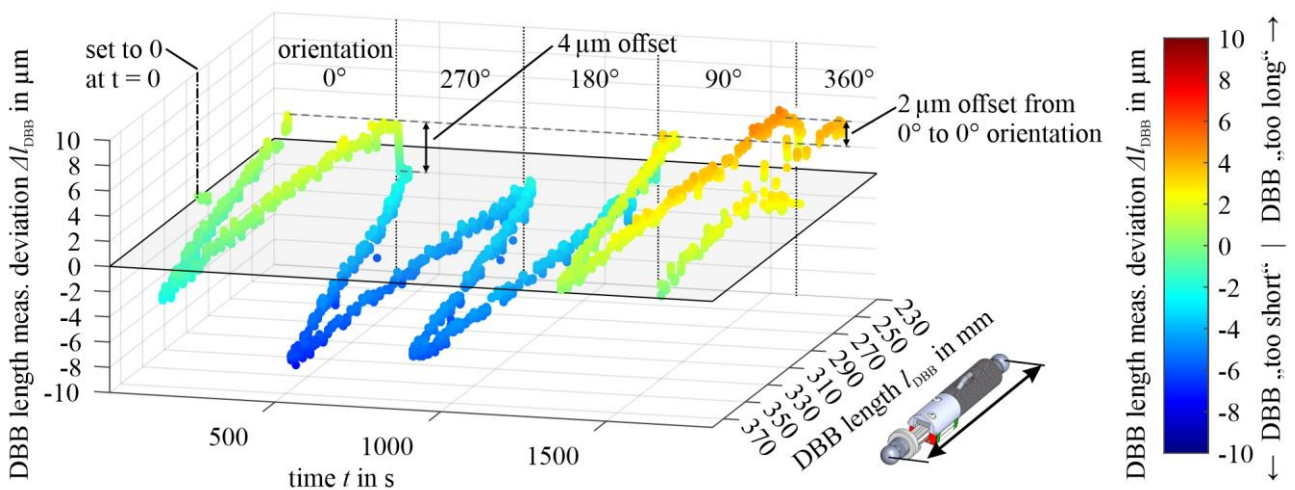


Fig. 6. DBB-1 length measurement deviation from experiment III (DBB orientation)

Influence of guide carriage deflection and tilting on DBB deviation was investigated in exp. IV (Fig. 7). The DBB was still in thermal equilibrium. Additional masses were applied on the guide carriage (see Fig. 3c). Fig. 7 shows that the scaling deviation remains

independent from the orientation and loading with weights. An increase in the load mass from 100 g to 200 g results in a slight offset increase of 1...2 μm . Subsequent rotation by -90° each to 270° orientation lead to a slight decrease in the offset. Relieving the load from 200 g to 0 g, at 270° orientation causes a significant offset change of almost $-10 \mu\text{m}$. This is probably due to the linear guide's low preload. Unfortunately no reference measurements were taken for 0 g in order to check if deviation at $t = 0$ s can be reproduced. Future DBB designs should use a higher preload class for the linear guide in order to reduce the effect of tilting in the guide carriage.

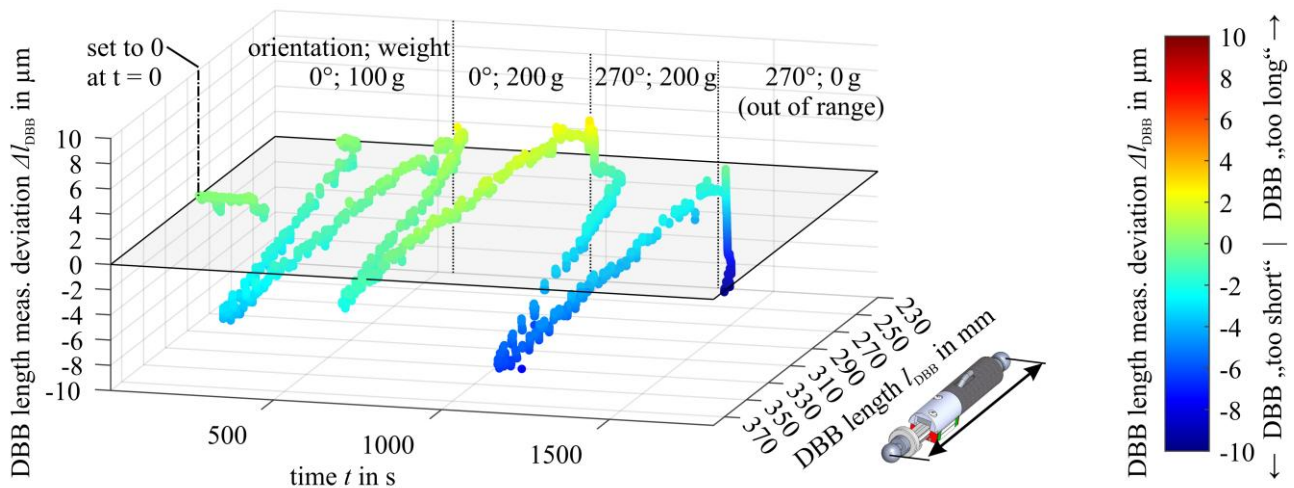


Fig. 7. DBB-1 length measurement deviation from experiment IV (effect of preload by mass and orientation change)

Exp. I to IV confirm, that the correction of the temperature-dependent DBB scaling deviation is promising – at least under defined stationary environmental conditions and constant DBB orientation. Correction of the orientation-dependent offset seems also possible. However, if the DBB-1 is calibrated in the same orientation in which it is used for measurement, this is not necessary. The following section deals with the correction of the thermally induced systematic length measurement deviation.

6. CORRECTION OF SYSTEMATIC THERMALLY INDUCED DBB LENGTH MEASUREMENT DEVIATIONS

The results discussed in Section 5 confirm that the thermally induced scaling deviation of the DBB-1 can be corrected, since scaling does not change throughout all exp. I to IV after reaching thermal equilibrium. Correction is not possible for the observed PT_1 -like-drift of the length offset (see Fig. 4), as no cause has yet been identified. In this respect, sufficient time should be allowed before the measurement to achieve thermal equilibrium in the calibration environment. The scaling deviation can then be corrected based on the equilibrium temperature at which the DBB has to be calibrated.

Fig. 8 shows DBB-1 with the dimensions relevant for correction. The measuring head of the linear measuring system acts as the main heat source with a power loss of approximately

1 W [25]. Heat is transferred to the carriage adapter and the CFRP tube, as well as to the linear rail with scale tape via conduction and radiation. To calculate the systematic, thermally induced DBB length measurement deviation, a homogeneous temperature field in the linear rail and CFRP tube is assumed for simplicity. All other components are neglected. The reference for the length measurement deviation is defined as the length during calibration with the parameters calibration length l_{CAL} and DBB temperature θ_{CAL} during calibration.

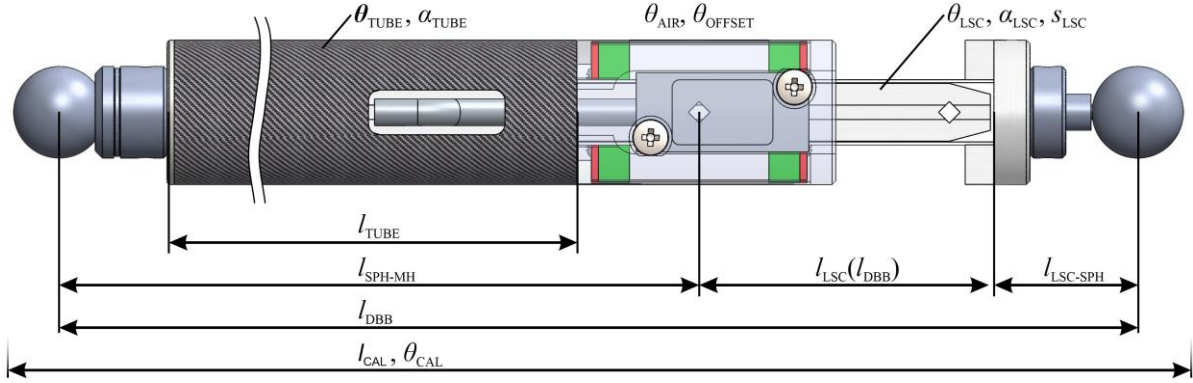


Fig. 8. DBB-1 with parameters for correction of thermally induced length measurement deviations

The thermal expansion behaviour is calculated based on the lengths shown Fig. 8. According to Eq. (1) the effective expansion-sensitive length l_{LSC} of the linear scale tape (LSC) is obtained by subtracting the offsets l_{SPH-MH} (ball centre on the CFRP tube to the sensor field of the measuring head) and $l_{LSC-SPH}$ (ball centre to the guide rail) from the current DBB-reading l_{DBB} .

$$l_{LSC}(l_{DBB}) = l_{DBB} - l_{SPH-MH} - l_{LSC-SPH} \quad (1)$$

The CFRP tube length, l_{TUBE} is also required. Eqs. (2) and (3) are used to calculate the temperature-dependent length changes of the guide rail with scale tape (index LSC) and the CFRP tube (index TUBE). A possible assembly-related scaling deviation of the scale tape is taken into account by the scaling factor s_{LSC} , adding up to the total scaling factor s_{LSC_total} .

$$\Delta l_{LSC}(\theta_{LSC}, l_{DBB}) = l_{LSC}(l_{DBB}) \cdot (\alpha_{LSC} \cdot (\theta_{LSC} - 20^\circ C) + s_{LSC}) \quad (2)$$

with scaling factor $s_{LSC_total} = (\alpha_{LSC} \cdot (\theta_{LSC} - 20^\circ C) + s_{LSC})$

$$\Delta l_{TUBE}(\theta_{TUBE}) = l_{TUBE} \cdot \alpha_{TUBE} \cdot (\theta_{TUBE} - 20^\circ C), \text{ assuming } \alpha_{TUBE} = 0 \mu\text{m}/(\text{m} \cdot \text{K}) \quad (3)$$

The change in length from calibration relative to the current thermal state, is described by Eq. (4). It is assumed, that linear scale and CFRP tube have the same temperature during calibration.

$$\Delta l_{CAL}(\theta_{LSC}, \theta_{TUBE}, \theta_{CAL}, l_{CAL}) = +l_{LSC}(l_{CAL}) \cdot (\alpha_{LSC} \cdot (\theta_{LSC} - \theta_{CAL},) + s_{LSC}) \quad (4)$$

$$+ l_{TUBE} \cdot \alpha_{TUBE} \cdot (\theta_{TUBE} - \theta_{CAL},)$$

Finally, in Eq. (5) all aforementioned length deviations are combined, wherein the first and second term define the grid surface shown in Fig. 9. The third term in Eq. (5) shifts the grid surface up-/downwards to nullify the deviation at the calibration point ($\Delta l_{DBB \text{ SIM}} = 0$ at $\theta_{DBB} = \theta_{CAL}$, $l_{DBB} = l_{CAL}$), as shown in Fig. 9. A DBB deviation $\Delta l > 0$ originating from Eq. (2) or (3) causes the DBB reading to decrease.

$$\Delta l_{\text{DBB SIM}}(\theta_{\text{LSC}}, \theta_{\text{TUBE}}, \theta_{\text{CAL}}, l_{\text{DBB}}, l_{\text{CAL}}) = -(\Delta l_{\text{LSC}}(\theta_{\text{LSC}}, l_{\text{DBB}}) - \Delta l_{\text{LSC}}(\theta_{\text{CAL}}, l_{\text{CAL}})) \quad (5)$$

$$- (\Delta l_{\text{TUBE}}(\theta_{\text{TUBE}}) - \Delta l_{\text{TUBE}}(\theta_{\text{CAL}}))$$

$$- \Delta l_{\text{CAL}}(\theta_{\text{LSC}}, \theta_{\text{TUBE}}, \theta_{\text{CAL}}, l_{\text{CAL}})$$

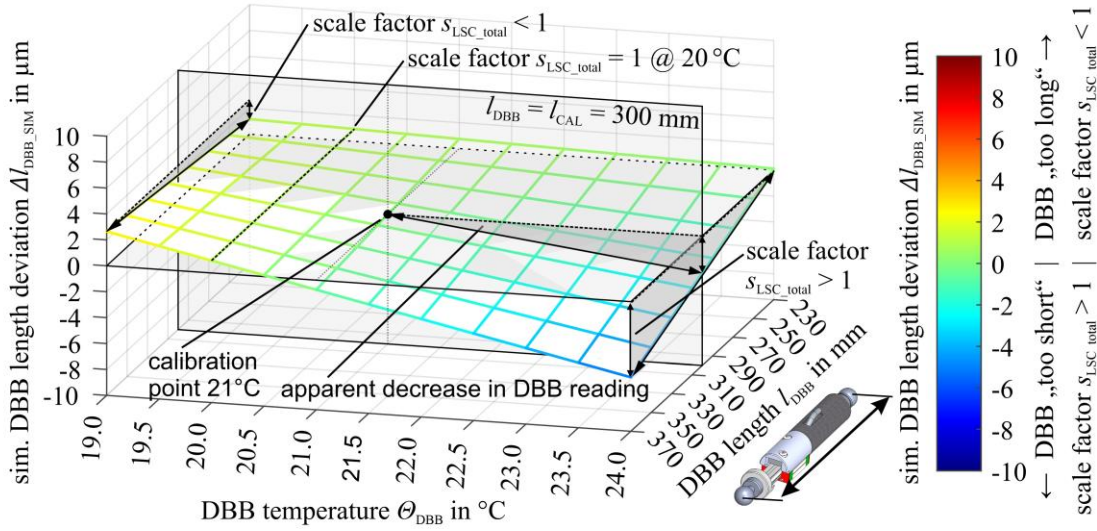


Fig. 9. Simulated DBB-1 length deviations $\Delta l_{\text{DBB SIM}}$, calculated according to Eq. (5), assuming $\alpha_{\text{TUBE}} = 0 \mu\text{m}/(\text{m}\cdot\text{K})$

Fig. 9 shows the deviations $\Delta l_{\text{DBB SIM}}$ calculated according to Eq. (5) for the DBB-1 with the parameters: $l_{\text{SPH-MH}} = 190 \text{ mm}$, $l_{\text{LSC-SPH}} = 20 \text{ mm}$, $l_{\text{TUBE}} = 155 \text{ mm}$, $\alpha_{\text{TUBE}} = 0 \mu\text{m}/(\text{m}\cdot\text{K})$, $\alpha_{\text{LSC}} = 10.6 \mu\text{m}/(\text{m}\cdot\text{K})$ and $s_{\text{LSC}} = 0$. DBB calibration temperature is set to $21 \text{ }^\circ\text{C}$ and calibration length to $l_{\text{CAL}} = 300 \text{ mm}$. The simulated deviation $\Delta l_{\text{DBB SIM}}$ is plotted against current DBB length l_{DBB} and DBB temperature θ_{DBB} . For simplicity, it is assumed that CFRP tube and linear rail have the same temperature ($\theta_{\text{LSC}} = \theta_{\text{TUBE}} = \theta_{\text{DBB}}$). For better orientation, the zero level $\Delta l_{\text{DBB SIM}} = 0 \text{ mm}$ and the calibration length $l_{\text{DBB}} = l_{\text{CAL}} = 300 \text{ mm}$ are highlighted in Fig. 9.

In Fig. 9 the function $\Delta l_{\text{DBB SIM}}(l_{\text{DBB}}, \theta_{\text{DBB}})$ is formed by straight lines in the direction of the variables l_{DBB} (Y-axis) and θ_{DBB} (X-axis) respectively. The DBB scaling deviation is visible in the direction of l_{DBB} . At the calibration temperature of $21 \text{ }^\circ\text{C}$, the DBB measures ‘too short’ when extending and ‘too long’ when retracting. This corresponds to the observations described in Section 5.4 (see Fig. 4 and Fig. 5). At $\theta_{\text{DBB}} = 20 \text{ }^\circ\text{C}$, the scaling deviation $s_{\text{LSC_total}}$ is zero because the linear scale is operating at its reference temperature. The intersection of the plane $l_{\text{DBB}} = l_{\text{CAL}} = 300 \text{ mm}$ and the function $\Delta l_{\text{DBB SIM}}(l_{\text{DBB}}, \theta_{\text{DBB}})$ clearly shows the behaviour of the clamped DBB-1 under heating: the measured length appears to decrease. This is consistent with the preliminary experiments discussed in Section 4 (compare Fig. 2).

In order to validate the model of thermally induced DBB deviations, a comparison with experiment V is performed. For model adjustment, the assumption of an excess temperature of 1.5 K relative to the measured air temperature in the measuring room has proven to be optimal, thus $\theta_{\text{DBB}} = \theta_{\text{AIR}} + 1.5 \text{ K}$ applies. The expansion coefficient of the CFRP tube was set to zero. Fig. 10, a) shows the DBB length measurement deviation relative to the laser

interferometer for exp. V. The black dots represent the simulated length deviations $\Delta l_{\text{DBB SIM}}(l_{\text{DBB}}, \theta_{\text{DBB}})$ calculated by Eq. (5).

Fig. 10 b) shows the residues between measured and simulated length deviations. The scaling deviation over the stroke is approximated very well. This is evident from the nearly constant difference between the measured and estimated DBB deviation in Fig. 10 b). Obviously, it is possible to correct the scaling error of the DBB-1.

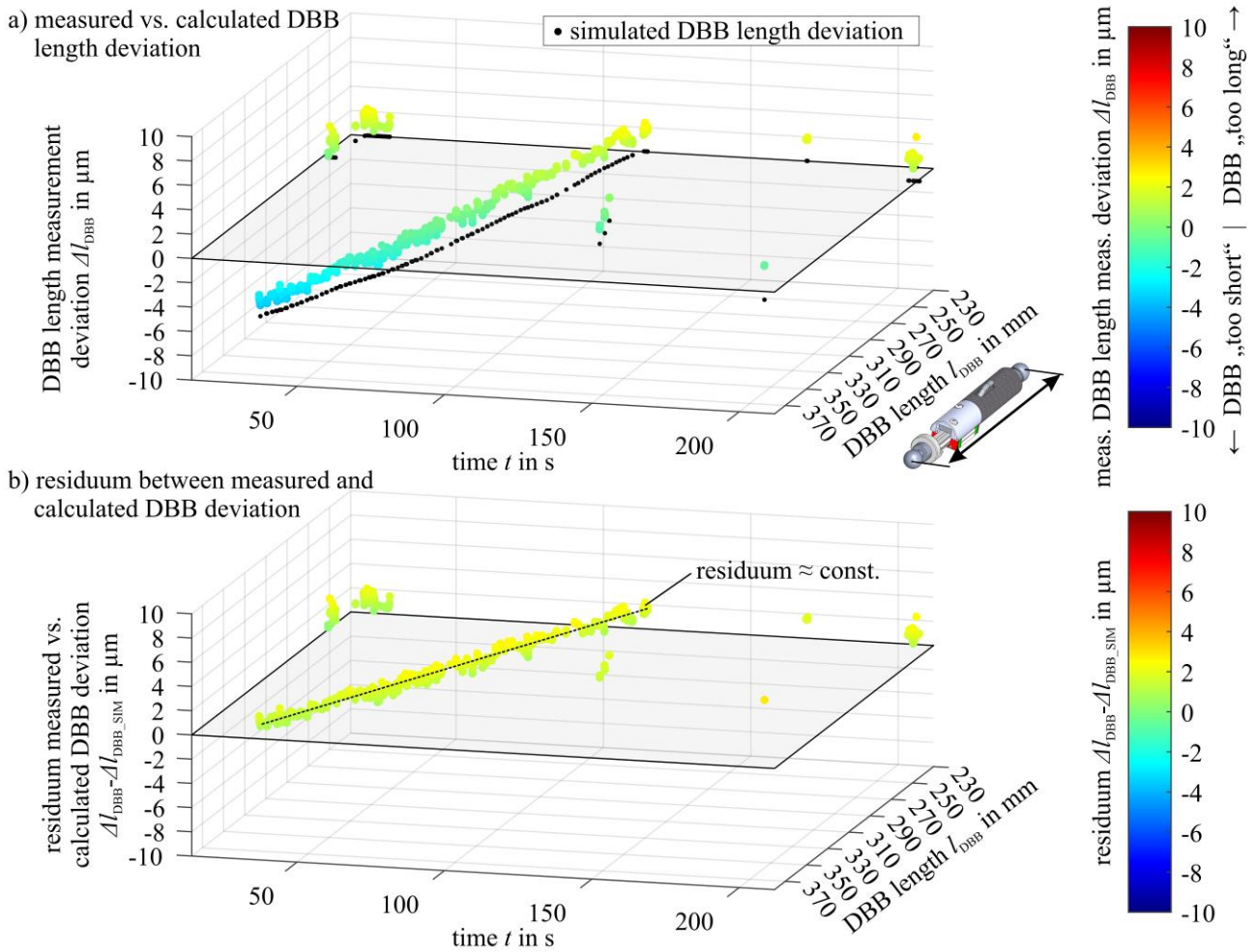


Fig. 10. DBB-1 length measurement deviation from experiment V (validation of correction approach)

In exp. I to V, a uniform temperature field for the linear rail can be assumed, since the DBB was cyclically extended and retracted, which favours a uniform heating over the stroke. However, this special case cannot be expected generally for every DBB measurement regime. Further development of the correction approach for non-uniform temperature fields is therefore necessary. The correction of statically induced deviations is also possible, but will not be discussed further here. It should be ensured, that the DBB does not change its orientation during the kinematic calibration procedure. For this purpose, it has proven effective to orient the DBB's cable outlet towards the base and point the cable downwards.

Even after extensive testing in the measuring room, it is difficult to provide a reliable indication of the DBB-1's length measurement uncertainty. In particular, the characteristic of the temperature field is uncertain. The total uncertainty of the corrected DBB-1 readings is estimated as $\pm 0.5 \mu\text{m}$ for mechanical deviations at constant orientation, increased by roughly $\pm 1.6 \mu\text{m}$ due to the temperature measurement uncertainties and unknown characteristics of the linear scale's temperature field (assuming a $\pm 1 \text{ K}$ uncertainty, for a 150 mm stroke, with $\alpha_{\text{LSC}} = 10.6 \mu\text{m}/(\text{m}\cdot\text{K})$). This results in an overall uncertainty of $\pm 2.1 \mu\text{m}$ for exp. I to V. The deviation might be higher if the temperature field is irregularly distributed. According to [9], the QC20 from Renishaw has a minimum uncertainty of $\pm 0.7 \mu\text{m}$ (compare Table 1) within a temperature range of 15°C to 25°C. For Renishaw's RCS L-90 an uncertainty of $\pm 2 \mu\text{m}$ is stated (compare Table 1). For calibration tasks, the respective uncertainties of the calibrator must be added.

7. CONCLUSION AND OUTLOOK

This paper provides an overview of double-ballbars (DBB) with extended measuring range and compares a self-developed DBB device (DBB-1) with commercially available systems. An initial assessment of the DBB-1's measurement uncertainty based on experimental investigations is presented. The results indicate that the thermally induced length deviations of the linear guide rail with linear scale tape contribute significantly to the systematic measuring deviation, primarily due to power losses in the measuring head of the linear system, which cause self-heating of the DBB. Based on these preliminary experiments, reference measurements were performed using a laser interferometer, revealing the thermally induced DBB-1's scaling deviation. Additional systematic contributions to measurement uncertainty, such as tilting in the guide carriage, were also quantified. Based on the extensive experiments, a correction approach for the thermally induced scaling deviation was derived, implemented, and validated using an independent experimental dataset. The results demonstrate that correction of systematic, thermally induced length measurement deviations is feasible – at least under constant environmental conditions and for a well-known DBB extension-retraction cycle. Under these boundary conditions, the DBB-1 achieves measurement uncertainties comparable to commercial devices, even across the whole extended measuring range of 150 mm.

Future work will focus on refining the correction approach by implementing a more sophisticated thermal model of the DBB device. Complementary, improved DBB designs incorporating temperature sensors and reduced mechanical uncertainties will be developed. These efforts aim to maintain the achieved measurement uncertainty under fluctuating environmental conditions and for arbitrary extension-retraction cycles.

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SUPPLEMENTARY MATERIAL

Additional photographs, videos, and raw data from the experiments can be accessed via <https://doi.org/10.5281/zenodo.20234573> or upon request from the corresponding author.

REFERENCES

- [1] KAUSCHINGER B., FRIEDRICH C., ZHOU R. IHLENFELDT S., 2020, *Fast Evaluation of the Volumetric Motion Accuracy of Multi-Axis Machine Tools Using a Double-Ballbar*, Journal of Machine Engineering, 20/3, 44–62, Wrocław Board of Scientific Technical Societies Federation NOT.
- [2] N.N., ISO 230-4: *Test Code for Machine Tools - Part 4: Circular Tests for Numerically Controlled Machine Tools*, International Organization for Standardization, 02/2022.
- [3] MARWITZ J. A., THEISSEN N. A., GONZALEZ BASSANTE M.K., FRIEDRICH C., HELLMICH A., ARCHENTI A., IHLENFELDT S., 2022, *Accuracy Assessment of Articulated Industrial Robots Using the Extended- and the Loaded-Double-Ball-Bar*, Journal of Machine Engineering, Wrocław Board of Scientific Technical Societies Federation NOT.
- [4] MERX M., 2025, *Identifikation Kinematischer Parameter Anhand von Messungen Mit Einem Double-Ball-Bar-Messgerät Mit Erweitertem Messbereich*, diploma thesis, HTW University of Applied Sciences Dresden.
- [5] BRYAN J.B., 1982, *A Simple Method for Testing Measuring Machines and Machine Tools – Part 1: Principles and Applications*, Precision Engineering, 4/2, 61–69, Elsevier BV.
- [6] BRYAN J.B., 1982, *A Simple Method for Testing Measuring Machines and Machine Tools - Part 2: Construction Details*, Precision Engineering, 4/3, 125–138, Elsevier BV.
- [7] BRYAN J.B., 1982, *Telescoping Magnetic Ball Bar Test Gage*, US Patent No. 4435905, granted 13th March 1984.
- [8] N.N., 2024, QC20 Ballbar, brochure of Renishaw plc, part no. L-8014-9054-01-A.
- [9] N.N., 2010, QC20-W Kabelloser Kreisformtest, Brochure of Renishaw plc, part no. L-8014-9006.
- [10] N.N., 2023, *Advancing Robotic Automation – Faster, Easier and More Accurate Commissioning and Verification of Robots*, brochure of Renishaw plc, part no. H-6827-8005.
- [11] N.N., 2025, *Rcs T-Serie - Benutzerhandbuch*, user guide of Renishaw plc, part no. H-6828-8002-03-A.
- [12] N.N., 2019, *Etalon X-AX LASERBAR*, website of Hexagon AB, <https://hexagon.com/products/etalon-x-ax-laserbar?accordId=84781290EE484905BD077196BF0CB8A6>.
- [13] N.N., 2019, *Etalon X-AX LASERBAR*, Brochure of Hexagon AB.
- [14] HÄRTIG F., KECK C., KNIEL K., SCHWENKE H., WÄLDELE F., WENDT K., 2004, *Selbstnachführendes Laserinterferometer für die Koordinatenmesstechnik*, Technisches Messen, 71, 227–232.
- [15] KAUSCHINGER B., 2006, *Verbesserung der Bewegungsgenauigkeit an einem Hexapod einfacher Bauart*, Phd thesis, TU-Dresden.
- [16] SZATMARI S., 2007, *Kinematic Calibration of Parallel Kinematic Machines on the Example of the Hexapod of Simple Design*, Phd thesis, TU-Dresden.
- [17] GROBMANN K., KAUSCHINGER B., SZATMARI S., 2008, *Kinematic Calibration of a Hexapod of Simple Design*, Production Engineering, 2/3, 317–325, Springer Science and Business Media LLC.
- [18] GROBMANN K., KAUSCHINGER B., 2008, *Räumliche Referenzierung an Werkzeugmaschinen Mit Dem Double-Ball-Bar*, ZWF Zeitschrift für wirtschaftlichen Fabrikbetrieb, 103/3.
- [19] ZHOU R., KAUSCHINGER B., IHLENFELDT S., 2020, *Path Generation and Optimization for DBB Measurement with Continuous Data Capture*, Measurement, 155, 107550, Elsevier BV.
- [20] ZHOU R., KAUSCHINGER B., FRIEDRICH C., IHLENFELDT S., 2020, *Fast Evaluation of Volumetric Motion Accuracy of Multi-Axis Kinematics Using a Double Ballbar*, Proceedings of the 10th Congress of the German Academic Association for Production Technology (WGP), Dresden, 23–24 September 2020, Lecture Notes in Production Engineering, Springer Berlin Heidelberg, 345–353, <https://doi.org/10.1007/978-3-662-62138-7>.
- [21] ZHOU R., KAUSCHINGER B., IHLENFELDT S., 2021, *Data Synchronization By Continuous Spatial Measurement with Double Ballbar*, Measurement, 174, 108909, Elsevier BV.

- [22] IHLENFELDT S., DROSSEL W.-G., KAUSCH M., FRIEDRICH C., WIESE T., JANKOWSKY L., 2022, *Seamhex – Fast 6D Additive Manufacturing Using an Innovative Screw Extruder Applied on a Hexapod Parallel Kinematic*, Special Issue: 5th International MERGE Technologies Conference (IMTC), 1st - 2nd December 2021, 5/1, Chemnitz University of Technology.
- [23] N.N., 2025, *Profilschienenführungen*, Catalogue of HIWIN GmbH. Document no. GW-12-1-DE-2501-K.
- [24] N.N., 2020, *Ni36/Invar 36*, datasheet of thyssenkrupp Materials Switzerland, https://d2zo35mdb530wx.cloudfront.net/_binary/UCPthyssenkruppBAMXSchweiz/de/downloads/werkstoffdatenblaetter-nickel/link-1.3912_ni36_invar_36.pdf.
- [25] N.N., 2017, *LIK 41 Optical Linear Encoder with Online Compensation*, Product brochure of Numerik Jena GmbH, https://www.numerikjena.com/fileadmin/Redaktion/004__PDF-Dokumente/LIK2x_4x/UM_LIK_41_eng.pdf.
- [26] N.N., 2014, *Measurement Data Monitoring System Testo Saveris*, catalogue of Testo SE & Co. KGaA. Document no. 0981 8114/msp/I/11, 2014.
- [27] CHAPMAN M.A.V., 2017, *Environmental Compensation of Linear Laser Interferometer Readings*, Renishaw plc. Technical white paper: TE329, Part no. H-5650-2050-03-A.
- [28] N.N., 2011, *Effect of Environmental Compensation Errors on Measurement Accuracy*, Documentation of Renishaw plc. Part no. H-9908-0474-01-A, https://www.renishaw.com/resourcecentre/download/application-note-effect-of-environmental-compensation-errors-on-measurement-accuracy-35093?userLanguage=de&srsltid=AfmBOoptWTUPal_7rtF5KXYc6bMsArgQLjrZ6jNQv-xDxE8wd9y7KiP1.
- [29] N.N., 2023, *Rcs L-Serie - Benutzerhandbuch*, user guide of Renishaw plc, part no. H-6827-8016-01-A.
- [30] N.N., 2026, *ETALON X-AX LASERBAR*, <https://nexus.hexagon.com/home/product/etalon-x-ax-laserbar/>.