Laser based measurement system for calibrating machine tools in 6 DOF

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Abstract

The purpose of this abstract is to give a brief survey of a measuring device which is based on laser interferometry. The system consists of either three or six plane mirror laser systems and a reflecting reference structure. The laser systems are attached to the moving platform of a machine tool structure, preferably clamped onto the main spindle. The reference structure is fixed in the working area and provides three reflecting plane mirrors which are oriented in a Cartesian manner. Each reflecting plane mirror is either scanned by one or two laser beams. One laser beam delivers information on a translational deviation referring to a starting position. The use of two beams also allows for the determination of the rotational degree of freedom.

The measuring system can be used for gathering geometric information of the entire working area of a machine tool, and can especially be used for the calibration of parallel kinematic structures.

1 Introduction

The accuracy and reliability of machine tools have a decisive influence on the manufacturing accuracy of workpieces. In the past 10 to 15 years, the accuracy of machines has clearly improved [1]. Deviations in the accuracy of a machine tool, and consequently in the geometry of the completed workpiece, may be due to a variety of reasons. Causes in the machine tool may include errors in the geometry due to tolerances in the manufacturing and assembly of the machine parts, as well as deformation due to (static and dynamic) loads or thermal deformation. The newly developed laser measurement system is primarily geared to capturing geometric parameters such as angles and positions.

2 Methods of Machine Acceptance Tests

To ensure a high degree of machine accuracy, various measurement systems and processes have been created, and standards governing machine tool acceptance tests have been published, such as [2, 3, 4, 5], to name but a few. Methods of machine acceptance can basically be broken down into indirect and direct processes to identify machine properties.

In the indirect identification of machine accuracy, sample workpieces with defined geometric formal characteristics are manufactured using the machine tool to be tested so as to draw conclusions about machine accuracy on the basis of deviations between the required and actual geometries, cf. [3]. However, as several causes of errors overlap, the clear attribution of deviations in the dimensions of a sample workpiece to individual machine properties is possible in exceptional cases only. Thus, indirect processes will be more suited for final functional tests to determine the accuracy of a machine tool and are therefore preferably used in acceptance tests. If the acceptance criteria are not fulfilled, direct processes will usually be applied for more detailed examinations.

The direct determination of machine property allows for the identification of error impacts. Parameters are determined directly on the machine with the help of suited measurement instruments, and today, tests of individual criteria or individual degrees of freedom can be carried out to respond to more demanding accuracy requirements. In this context, it should be pointed out that the results may be processed further in various ways, depending on the kinematic structure. In machine tools with serial Cartesian kinematics, the results of measurements are used to re-adjust the machine. This is possible because, at least theoretically, there is an unequivocal connection between or identity of each axis of the system of coordinates of the workpiece and the corresponding actuation axis of the machine tool. Parallel kinematic machine tools are calibrated after assembly in a process that is generally significantly more complex. It comprises parameter identification and error compensation. Parameter identification serves the purpose of accurately determining the geometric parameters of parallel kinematic machine tools (e.g. actual leg lengths or joint positions), so the algorithms for the transformation of actuation and workpiece coordinates in the machine control can be modelled with greater precision. Parameter identification serves the purpose of identifying, as directly as possible, the connection between the cause and effect of an error while also finding the decisive reasons underlying the error. In the framework of a sensitivity analysis, complex computation models are used to relate position data measured in the Tool Center Point (TCP) to underlying causes in the geometric structure of the machine. Parameter identification is based on methods for the minimization of errors [6]. It is characteristic of parallel kinematic structure that all geometric errors are superimposed in the TCP. In general, measurement requirements for the identification of the actual machine parameters are usually less complex than those for non-parametric calibration because it is mostly sufficient to measure only one degree of freedom of a machine tool. The measuring points do not have to cover the entire working area of the machine tool (cf. [7]).

Non-parametric calibration or error compensation can be carried out independent of the kinematic situation. By means of error compensation, the actual TCP position is determined from the positional value measured on the basis of the system of coordinates of the machine, and a correction value. The correction values are from a compensation table included in the machine control system, and are determined dependent on the position. For the first-time determination of the values in the compensation table, deviating positions in defined locations throughout the entire working area have to be determined. The position-specific correction value is then calculated by means of an interpolation algorithm on the basis of the known points in space (see space-error compensation in [8]).

As all degrees of freedom of the machine tool in the working area have to be captured point by point, measurement becomes considerably more complex as the number of degrees of freedom rises.

3 Measurement Processes

Various measurement methods are available to capture the degrees of freedom; in this context, a rough distinction can be drawn between one-dimensional and multi-dimensional measurement systems. For sufficient accuracy of the machine tool, measurement systems are usually required to have measuring accuracy that is one power of 10 higher and resolution that is two powers of 10 higher [6]. A degree of accuracy to be realistically aimed at in machine tools is roughly 10µm. Therefore, the measurement system should have a measurement accuracy of 1µm and a resolution of 0.1µm (up to 0.5µm) [9].

3.1 One-Dimensional Measurement Systems

One-dimensional measurement systems cover one degree of freedom. Well-known measurement systems include shaft encoders and linear scales working according to inductive, magnetic or photo-electric principles. The laser interferometer has made its mark as the most accurate means of measuring one degree of freedom in machine tool building. Taking into account the parameters air pressure, temperature and humidity, which have a strong bearing on the quality of measurements, manufacturers state accuracies of up to ±0.7μm/m and a resolution of 1nm [10]. Thus, laser interferometry is able to fulfil the above-mentioned requirements. However, one-dimensional measurement systems come with the drawback that setting them up and aligning them is a time-consuming process, especially when the entire working area needs to be measured. To keep machine downtimes as short as possible, a system for capturing several degrees of freedom simultaneously with the above-mentioned accuracy would be purposeful.

3.2 Multi-Dimensional Measurement Systems

Multi-dimensional measurement systems are combinations of conventional one-dimensional measurement systems. The measurement uncertainty of the total measurement system is composed of the measurement uncertainties of the individual measurement systems and is thus always lower than that of the individual system.

The double-ball bar [11, 12] and the grid encoder [13] are customary measurement appliances for two-dimensional measurements. However, they are much rather used in the quality assessment of a machine tool than for the purpose of calibration; in general, they are not suited for servicing the entire working area of a machine tool, either.

Three-dimensional measurement systems and other multi-dimensional systems can largely be broken down into two groups, those of optical and mechanical measurement systems.

Optical systems include laser trackers, the HexScan [14], the Imetric single camera system [15] or the coordinate measurement appliance K-400CMM [16] although this list is by no means exhaustive. With the exception of the HexScan, these systems come with a drawback, i.e. their degree accuracy is insufficient for the purposes of machine tool building.

Laser trackers are preferably used to acquire measured values for the three positional degrees of freedom. Suppliers of laser tracker systems state that accuracies of about 10µm can be attained [17, 18, 19]; in this context, the accuracy in distances measured by means of interferometry would actually be about 1ppm, whilst inaccuracies are mainly due to the angle position sensors. Values of about ±5ppm are given for 95.5% of the measured values in case of static measurements [20], this corresponds to ±5µm/m.

In the framework of a study of interior geometries carried out at the Institute of Production Engineering of the Vienna University of Technology three laser trackers were examined for variations in the acquisition of positional values (Figure 1) and the range of accuracy stated by suppliers was confirmed. In the series of tests, diameters in a pipe with various given diameters (60, 200 and 160mm) were determined at various depths (3000/8500mm, 1500/7700mm and 3000/8500mm) on the basis of two opposite points.

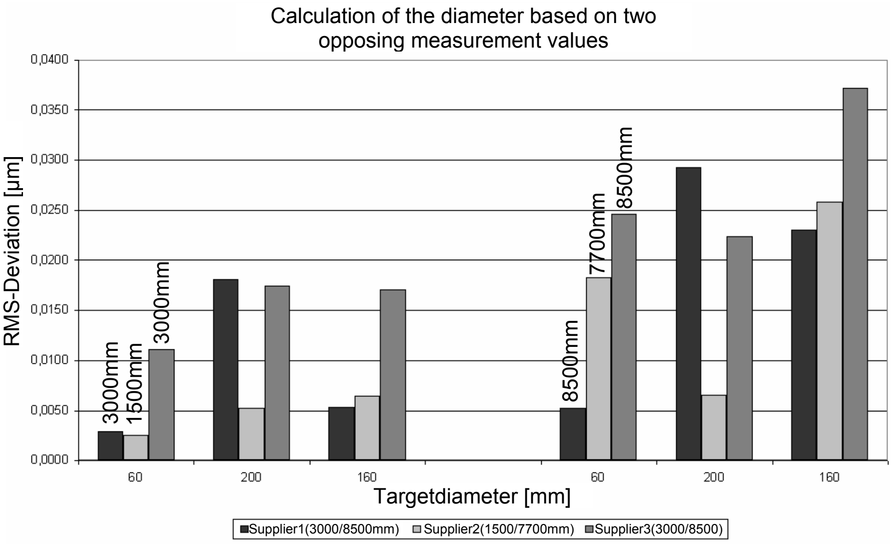


Figure 1: *Comparison of three laser trackers*

The SmartTRACK© add-on modules [21] and the XD Laser manufactured by API should be given special mention here (Figure 2). In combination with the supplier's laser tracker the SmartTRACK© module allows for acquiring values concerning the position and orientation of a measurement point. The system is characterized by an accuracy restriction of ±(25µm+2.5ppm) in 95.5% of the measured values [22]. The XD Laser "6D" series enables measurements of position, straightness, pitch, yaw, roll and squareness. Accuracy in the regular version, is stated as 0.5ppm for position, ±(1+0.1/m)angular seconds or 1% for pitch and yaw, ±1angular seconds for roll and as ±(1μm+0.2μm/m) for straightness and ±1angular seconds for squareness [23]. In Cartesian systems, the measurement system allows for the quick measuring of the degrees of freedom; in parallel systems, however, it is suited for parameter identification rather than for compensation.

a) b)

***Figure 2**: a) XD Laser b) SmartTRACK Sensor [19]*

The accuracy stated for the HexScan system, which determines position and orientation via the shadows cast by three cylindrical test pieces, is 1 to 2μm [14]. However, the working area and pivoting angles are very small if compared with the working area of a machine tool.

The Imetric single camera system is characterized with a large working area it can service but at ±10μm/m its accuracy is fairly low for the calibration of machine tools. The coordinate measurement appliance K-400 uses three CCD infrared cameras for triangulating the positional value, offering a modest degree of accuracy at 60-90μm in a working area of $6m^3$. Examples of mechanical systems include, to name but a few, Omnigage [24], Unisquare [25], a measurement tripod devised by the University of Technology of Hamburg-Harburg [26] and the QCM [27].

The QCM (the acronym stands for "Quickstep Calibration Machine"), including its analysis algorithms, was developed at the Institute of Production Engineering in close cooperation with the Krause & Mauser co. and used for measuring the parallel kinematic machine tool Quickstep©. The concept and algorithms were already described in a publication [27]. The fundamental idea was to realize a mechanical system with three passive axes docked onto the main spindle via the tool holding fixture. The machine tool drags the measurement system along in the positioning movement path. The TCP position is determined via 5 linear scales, two each for the z- and x-axes, and one for the y-axis. The use of two linear scales on the x- and z-axes serves to compensate any yaw deviation of the slide and is reflected in the so-called phantom-scale model. Due to the fact that the measuring scale of the y-axis is directly located at the QCM docking point no second measurement system is required to compensate yaw deviation.

Considering the phantom-scale model and compensation of sagging, in particular on the z-axis, comparative measurements using a coordinate measuring machine resulted in a positional accuracy of 12.2μm at a positional variation of 1.7μm and a variation of orientation of 6.3 angular seconds. In view of the requirement that, to attain an accuracy of the machine tool of 10μm, the degree of accuracy of the calibration measurement system should be one power of 10 higher, further tests and conversions were initiated.

Figure 3: *Quickstep Calibration Machine [27]*

FEM analyses of the structure and supporting measurements identified room for improvement: The stiffness of the substructure for the rails of the z-axis is low. With two guide carriages, the slide on the y-axis was not sufficiently stiff in responding to pitch and yaw, and has meanwhile been replaced by a version with four guide carriages. The slides on the z- and x-axes are very stiff structures and can be considered sufficiently rigid in the relevant range of forces. The dead weight forces of the structure dominate, with masses being 91.9kg for the carriage on the z-axis, 24.2kg for the carriage on the x-axis and 1.9kg for the carriage on the y-axis. The remaining stochastic error is thus primarily due to stiffness problems of the guide carriages. In this context, guide carriages with a prestress of 0.02·C and 0.08·C were compared. The differences between breakaway forces under stress (160N) and in an unstressed state were examined, and it was found that there are hardly any differences between the various prestress categories in both states (≈1N).

Based on the insights gained in the QCM tests, research for a suited alternative measurement technique, preferably one that uses laser measurement technology and allows for the simultaneous acquisition of values for several degrees of freedom with a high degree of accuracy, started.

4 Multi-Dimensional Laser Interferometer

The basic concept developed for the multi-dimensional laser interferometer envisages a laser source that can be moved with the TCP. A stationary reflector is placed in the working area. There is no mechanical coupling by means of transmission links between the moving and the stationary part of the system. Conventional laser measurement systems with a retroreflector are unsuited for this application because the retroreflector would have to follow the moving laser beam, and would have to be moved mechanically. The new application uses a laser system in which the laser beam is reflected by a front-surface mirror. Due to this laser system it is possible to measure the distance of a point across a reflecting surface as a reference plane.

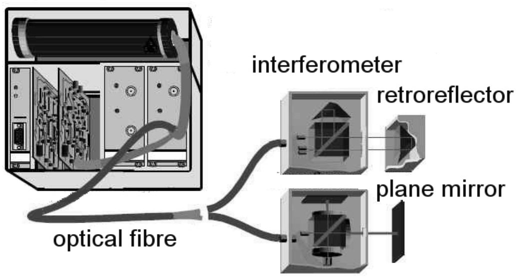


Figure 4: *Comparison of retroreflector- and plane mirror interferometry [28]*

Relevant laser systems using helium-neon lasers are available on the market, covering measurement ranges of up to 2000mm at a resolution of up to 1nm. The maximum tilting range is ±2 angular minutes (e.g. Renishaw RLE10, SIOS SP 2000). To reach the accuracies stated by suppliers, appropriate tolerances in the quality of the reflecting surface must be adhered to. Parameters given for the flatness of the mirror surface are local and global flatness. Local flatness is defined as the value measured between the highest peak and the deepest valley of the profile, comparable to surface roughness R_y. Global flatness is determined in the same way, only the reference distance is clearly longer. Local flatness should be around λ/10 over a distance of 10mm. The wavelength λ of a helium-neon laser is 632.8nm. Global flatness describes distortions over the entire mirror. Deviations of around λ/4 cause errors of around 158nm [29].

If the reflecting surfaces are mounted appropriately, global deviations can be reduced and deducted from the result by compensation; for this reason, they are of rather secondary importance. Due to an angular difference α between the normal line on the mirror and the incident laser beam, the measuring error is:

$$\Delta s_{\alpha} = -s \cdot (1 - \cos\alpha) \tag{1}$$

Errors due to an angular deviation β between the measuring movement and the normal line on the mirror can be expressed in the same way:

$$\Delta s_{\beta} = -s \cdot (1 - \cos\beta) \tag{2}$$

At a maximum admissible deviation of 2 angular minutes, the resulting greatest possible measuring error is ±0.085µm over a distance of 500mm.

The concept is based on Abbe's comparator principle whereby the distance to be measured should be positioned in alignment with the scale embodiment. A significant benefit of this measuring principle is the method by which the reference body is manufactured as today's manufacturing processes allow for clearly more narrow tolerances to be reached in a plane surface than in spatial geometry.

4.1 Identifying a Suitable Reflector

First of all, investigation for the most cost-effective front surface reflector covering the required measuring range of about 500mm lateral length started. The reference body for the analysis of the laser measurement technology was a front surface mirror of high optical quality which had been supplied by the laser manufacturer and could be considered as meeting the requirements of flatness accuracy. The dimensions of the reference body were 220x20x20mm. First, a hand-polished steel plate was used as a front surface mirror. To keep the guiding movement of the plane mirror laser as regular as possible and within narrow limits in respect of rotation around the axes as well as positioning accuracy, the basic tests were made on a coordinate measuring machine, type Zeiss WMM 850 (Figure 5).

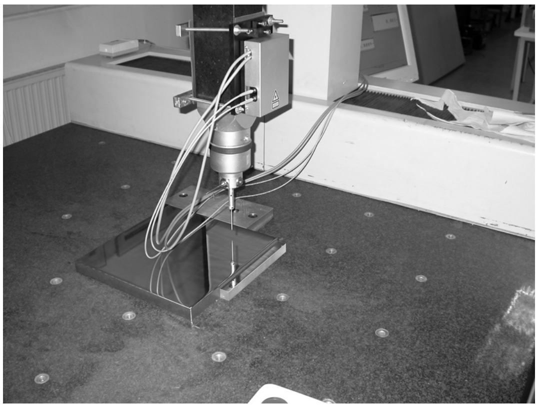


Figure 5: *Measurement setup, polished plate on the CMM*

The plane mirror laser manufacturer stated that the required laser beam intensity is 50%. A software package for the determination of beam intensity is supplied with the laser. In the tests with the polished steel plate, beam intensity was markedly below 50% in many cases so that the measured values cannot be considered as sound.

In a further measurement setup, a front surface mirror made of chromium-coated conventional float glass was tested on the coordinate measuring machine. The test setup was similar to the one used in the test involving the polished steel plate.

The mirror dimensions were 500x500x6mm. No special requirements had to be fulfilled in respect of surface flatness. Mirrors of this quality are available from the optical industry as semi-finished goods of almost any dimensions, causing relatively cost-effectiveness. The basic tests showed that the intensity of the reflected laser beam was clearly higher, as can be seen in Figure 6. The required beam intensity of 50% was exceeded markedly.

In an analysis according to VDI/DGQ 3441 a mean measurement variation P_{smean} of 1.662µm and a measurement accuracy P of 3.427µm were determined on the coordinate measuring machine WMM 850 along a mirror-parallel path over a measuring distance of 400mm.

In the third measurement setup, a front surface mirror made of Borofloat 33$^{©}$, dimensions of 500x500x25mm was tested (Figure 7).

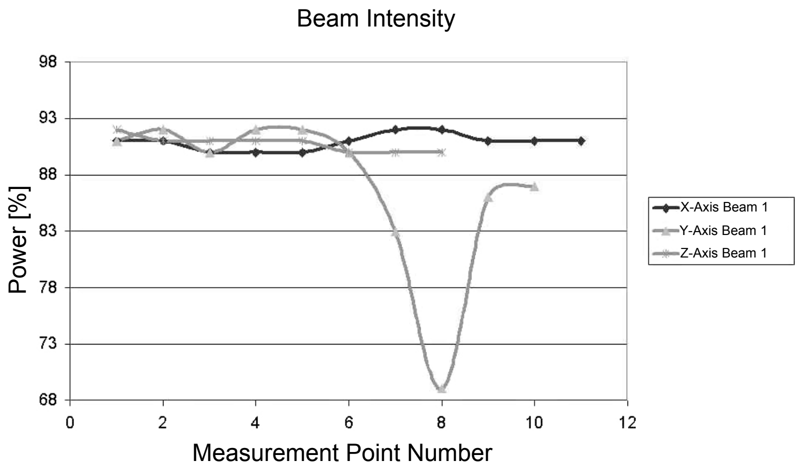


Figure 6: *Beam Intensity relating to the working area, conventional plane mirror*

The surface was highly polished, sputtered with a layer of aluminium and covered with SiO_2 protective coating.

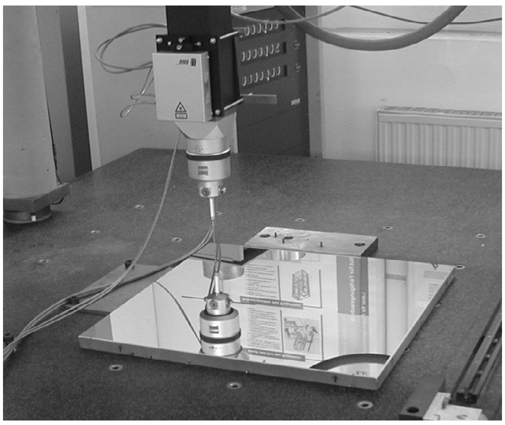


Figure 7: *Measurement setup, high precision plane mirror*

The protective coating makes the reflector surface considerably more resistant to abrasion, which makes the mirror suitable for use in a rough environment.

The mirror flatness across the entire surface was λ/2, which corresponds to about 315nm. As can be seen in Figure 8, laser performance is constantly at a high level and thus allows for high-quality measurements.

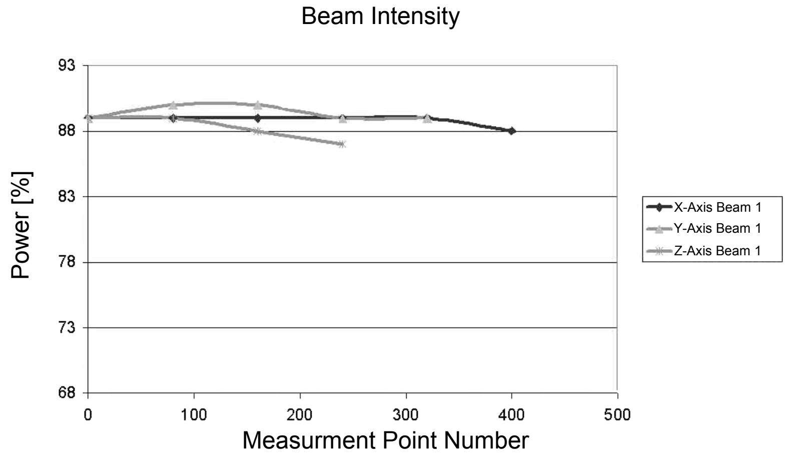
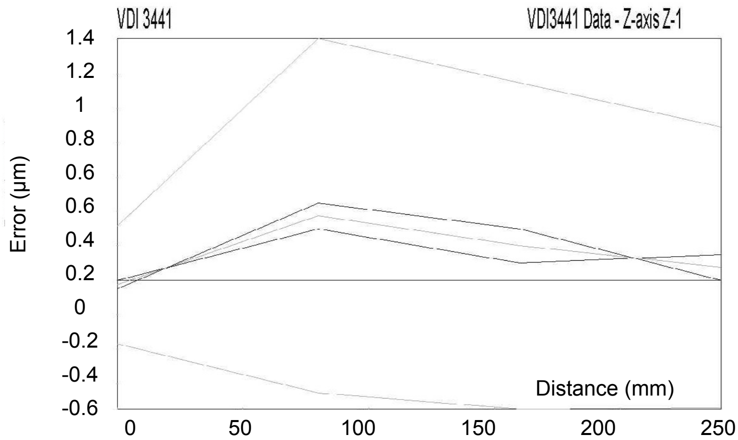


Figure 8: *Beam Intensity relating to the working area, high precision mirror*

In an analysis according to VDI/DGQ 3441 mean measurement variation P_{smean} of 1.432µm and a measurement accuracy P of 2.153µm (Figure 9) were determined along the z-axis. These measured values were lower than those of the conventional mirror.



U_{mean} = 0.325	U_{max} = 0.450	$P_{s\,max}$ = 2.546
$P_{s\,mean}$ = 1.662	P = 3.427	P_a = 0.900

Figure 9: *According VDI/DGQ 344, conventional plane mirror X-Axis*

To determinate the quality of measurements in beam direction for the plane mirror interferometers, another test was set up (Figure 10). To exclude the impact of the coordinate measuring machine, the reference system was a conventional Michelson-Interferometer which allowed for checking the movements of the plane mirror interferometers.

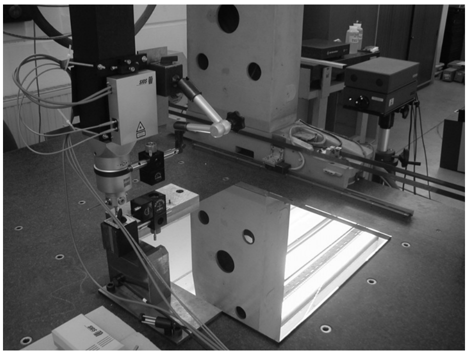


Figure 10: *Measurement setup to compare conventional- and plane mirror interferometry*

The slope of the three measuring curves in Figure 11 results from the cosine error which is caused by the fact that the two laser systems were not exactly parallel in position. The conventional laser was misaligned by about 15.98 angular minutes vis-à-vis the plane mirror laser. If this error is taken into consideration in the measured value, the remaining deviation amounts to a maximum of 0.4µm, which is quite normal for a given measurement uncertainty of ±0.7µm/m in a laser interferometer.

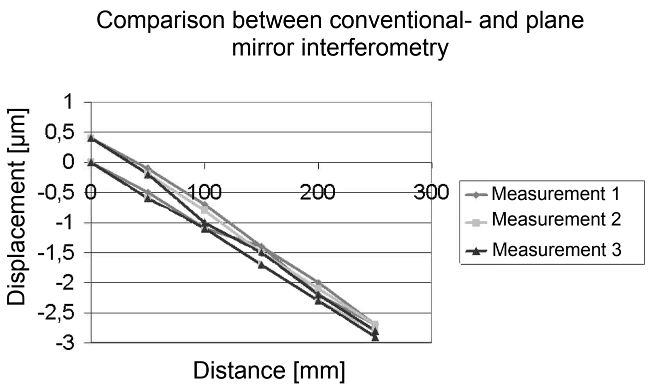
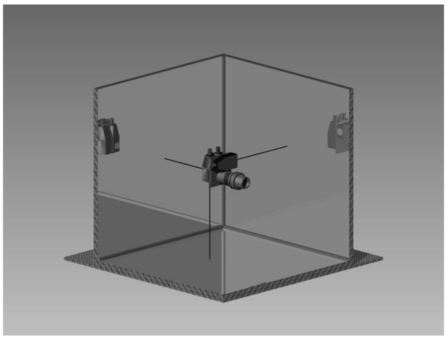


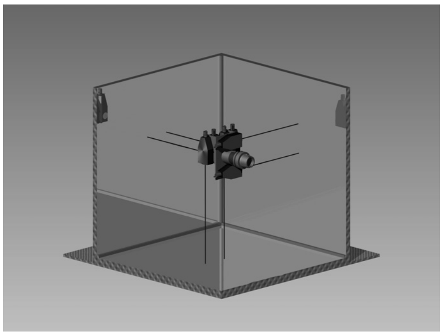
Figure 11: *Results of comparing conventional- and plane mirror interferometry*

4.2 Measurement Setup for Multi-Dimensional Measurements

Individual systems are combined so as to enable simultaneous multi-dimensional measurements. To determine the position in space, three laser systems have to be



a)



b)

Figure 13: *Measurement system for a) three and b) six DOFs*

positioned in such a way that the measuring laser beams coincide with the basic vectors of the Cartesian system of coordinates. The origin of the coordinate system should ideally be identical with the TCP. The adapter thus consists of three laser systems and can be directly clamped onto the main spindle, as it is shown in Figure 14 below for the single-laser system, or alternatively be attached to the moving platform.

The front surface mirrors are mounted immovably in the workspace on the basis of a Cartesian system of coordinates. The reflecting surfaces each correspond to the basic planes of the coordinate system. The body on which the mirrors are mounted with as little warp as possible can e.g. be made of composite material such as carbon- or glass-fibre reinforced plastics with the lowest possible thermal expansion coefficient. It is important that the mirror surfaces are as precisely aligned towards each other as possible. Figure 13 shows two possible configurations of measurement systems with three and six beams, respectively.

The reference body can be mounted on a pallet and placed in the workspace of the machine tool to be calibrated by means of a pallet-changing system. To define a reference point for the laser measurement system, "blind spots" or marked geometric changes such as grooves can be integrated in the front surface mirrors.

Two-beam laser systems are well suited for determining angular shifts around the individual axes along with positional measurements. The measuring beams are aligned in such a way that they scan a front surface mirror from a defined distance in pairs. The pairs of measuring beams must be aligned as symmetrically as possible around the basic vector. Remaining angular deviations can be compensated. The actual position is determined on the basis of the mean value of the measuring distances. The angle of inclination α is determined from the difference between the two measuring beams ΔL and the beam distance a by means of the following formula:

$$\alpha = \arctan \frac{\Delta L}{a} \tag{3}$$

In accordance with the above results concerning the accuracy of a front surface mirror laser interferometer an angular accuracy of 0.852 angular seconds at a resolution of 0.2 angular seconds can be realized, with the beam distance being 100mm.

4.3 Machine Test

First tests of practical application involving a one-axis system were directly made on the Quickstep parallel kinematic machine. The two-beam plane mirror interferometer with a laser beam distance of 12.5mm was directly attached to the tool spindle of the machine by means of an adapter and the spindle was locked in its angular position (Figure 14).

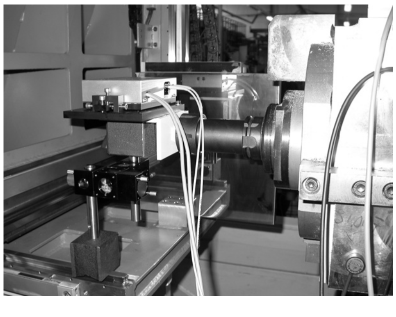


Figure 14: *Measurement setup on the Quickstep*

The measured results show that the accuracies obtained in the basic tests on the coordinate measuring machine were reproduced in the application test.

5 Summary and Outlook

Tests carried out in the course of development of the measurement system presented here indicate the potential possibility of covering three to six degrees of freedom simultaneously with a high degree of measuring accuracy. A comparison with systems available on the market shows that there is great potential in respect of accuracy and flexibility. The benefit of greater cost-effectiveness compared with current multi-dimensional measurement systems makes its industrial use seem realistic. Due to the measuring concept used, rotational degrees of freedom can only be covered in a narrow range of angles. In this respect, the measurement system fulfils the requirement of controlling an oriented position via Cartesian movement. This should ensure excellent suitability for many applications in the metrological analysis of machine tool structures, especially of three-axis kinematics. Further tests aim at the simultaneous use of three two-beam laser systems and the development of a suitable reference body made of composite materials.

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