Comprehensive calibration of robots and large machine tools using high precision laser-multilateration

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Abstract

Within this paper procedures for the high precision, flexible and comprehensive calibration of robots as well as large machine tools based on laser tracking interferometers will be presented. Four tracking interferometers, so called 'Lasertracers' from the etalon AG, are used. Herewith four length measurements with uncertainties of some micrometers between the Lasertracers and a single reference mirror fixed in the machine spindle or on the robot endeffector are performed simultaneously. The commercial software outputs the 3D absolute positions of the mirror with a measurement uncertainty of about 2 µm, depending on the realized application. Subsequent data processing procedures were developed to obtain different kinematic and dynamic machine properties which can be used for calibration. These properties include positioning accuracy, repeatability, straightness, squareness, uniformity of velocity, coaxiality and 3D circularity. Current research work focuses on the fast and precise identification of geometric and kinematic model parameters of different robots types and sizes.

1 Introduction

The increasing size of energy conversion machinery like wind turbines, gas turbines or steam turbines requires large machine tools with high machining accuracies [1]. Besides this robot handling and assembly tasks getting more and more challenging concerning speed and precision [2]. To quantify as well as to improve the capability of the axis systems the geometric, kinematic and dynamic properties have to be identified metrologically [3] [4].

Due to the large variety of axes sizes and configurations, the sequential utilization of different metrology instruments is required as well as a significant time effort for the installation and alignment of the devices. This causes machine downtimes up to several days or weeks and particularly the temperature variations during these long-time measurements decrease the calibration uncertainty dramatically [5].

Within this paper the practical application of a novel metrology procedure based on the simultaneous utilization of four Lasertracer will be presented using the example of a small robot and a large machine tool. Different kinds of axis configurations can be calibrated as well as different machine and robot sizes up to a volume of 10 x 10 x 10 m³. Furthermore geometric, kinematic and dynamic properties can be quantified by demand oriented capture and evaluation of measuring points. The utilization of only one measurement setup per axis system capacitates short measurement durations as well as consistent measurement data in terms of thermal influences.

2 Metrological principles and procedures

2.1 Principle of the Lasertracer

In order to simplify and accelerate the calibration of coordinate measuring machines and machine tools the Lasertracer was developed [6]. It is an automated tracking laser interferometer that can be rotated around its reference mirror with two degrees of freedom (pitch, yaw). The reference mirror is a high precision steel ball (roundness < 0.3 µm) and is located stationary with the aid of an invar holder to minimize errors due to thermal effects. The target mirror of the interferometer is realized by a retroreflector (figure 1).

The automated tracking is controlled via the displacement of the reflected laser beam on a position sensitive diode. The uncertainty of the length measurement is 0.3 µm + 0.3 µm/m at a measurement range up to 15 m and a resolution of 1 nm [7]. Position measurement bases only on this 1D length information and not on encoder signals of the rotary axes. Therefore multiple measurements are needed to obtain complete geometric information but the measurement results are more precise than that of a Lasertracker [8].

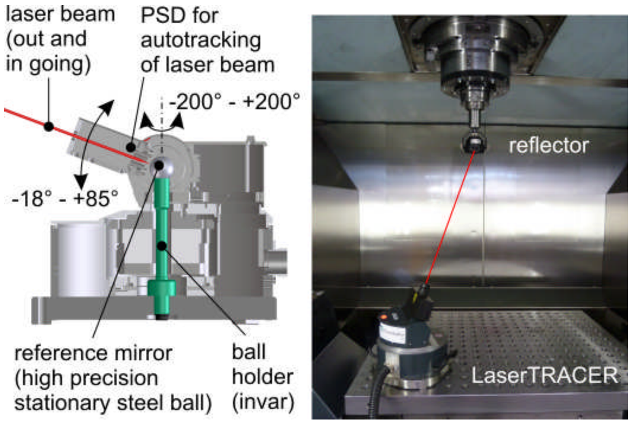

Figure 1: Principle of the Lasertracer

2.2 Metrological procedure using four Lasertracer

The spatial position of the reflector can either be determined by conducting four measurements consecutively or by utilizing four Lasertracers at the same time for a so called Multitrace procedure developed by the Etalon AG [9]. Similar to a global positioning system (GPS) working with four satellites the 3D position of the reflector can be calculated near to real-time (figure 2). The only limiting factor is the 120° angle of the reflector aperture.

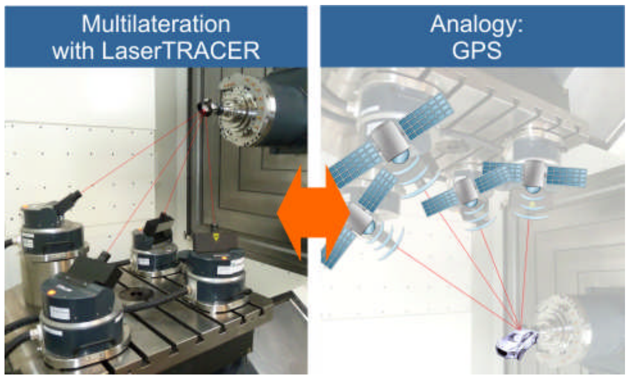

Figure 2: 3D position captured by means of four Lasertracers

Different practical trials showed that the 3D positions can be calculated with a spatial uncertainty of less than 5 µm. However, the uncertainty depends not only on the capabilities of the four interferometers but also on their spatial configuration. The more the Lasertracer positions deviate from a coplanar setup the lower the uncertainties are.

In addition to static 3D positions arbitrary spatial trajectories can be captured dynamically with a measurement frequency up to 50 kHz. Therefore a large variety of kinematic and dynamic problems can be analyzed. The most appropriate applications are the calibration of large machine tools (axis length > 1000 mm) and serial or parallel robot kinematics because the size and the capacity of the overall system.

2.3 Postprocessing of measured data

Calibration usually requires more information than the 3D positions which are provided by the so called TracCAL software (commercial product of Etalon AG). Hence, within current research projects evaluation procedures are being developed to solve specific calibration problems. For postprocessing different MATLAB® programmes are used.

The measured 3D positions are saved in a text-file in chronological order. Usually this file contains the results of three to five measurements for analysis of statistical effects. Therefore, the data sets have to be separated and correlated to the measurements. Afterwards the data sets are evaluated mathematically by means of linear algebra to obtain the desired kinematic or dynamic information.

For example diagonal and circularity test measurements can be evaluated by determining the distances of 3D positions to their line of best fit and respectively circle of best fit. Straightness and squareness analysis is based on angles between normal and direction vectors. Because of the constant measurement interval, velocities and accelerations of arbitrary movements can be obtained using differentiation, too.

The measurements results obtained via the Multitrace procedure are very close to the results of a conventional laser interferometer. Figure 3 exemplifies this fact using the measured position accuracy of a linear axis.

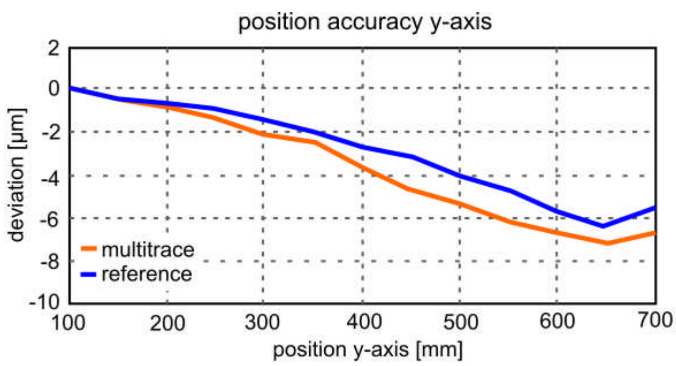

Figure 3: Comparison of laser interferometer and Multitrace results

3 Application and results of machine tool calibration

A major advantage of the presented procedure is its high flexibility and that it can be applied to many different machine tool calibration tasks or acceptance tests. Without any change of measurement equipment or setup a large variety of kinematic or dynamic parameters can be obtained. This leads to shorter breaks between measurements and therefore to less errors due to thermal changes of the environment. However, there are some challenges, which have to be considered when planning Multitrace measurements:

- The reflector aperture is limited to an angle of 120°. Especially rotational movements can cause blockage of the line of sight.
- In small machine tools an eligible nonplanar Lasertracer-setup is sometimes difficult to realize.
- Fast machine tool movements may cause beam breaks due to the limited dynamics of the automated beam tracking.

In the following several measuring procedures for an acceptance test of a large 6 axes machine tool are presented to demonstrate the mentioned versatility. The measurement setup, four Lasertracers mounted on the rotary table, was installed within two hours and used for all test. Each figure shows the results of different measurement runs indicated by colour.

3.1 Circularity test

One circularity test was executed in each of the three planes of the linear machine axes. Each test included circular movements with a diameter of 300 mm and trajectory velocities of 1000 as well as 3000 mm/min. All movements were repeated five times clockwise and counter-clockwise. The reflector was mounted on the centre of the spindle and aligned towards the four Lasertracers. Measurement data was captured continuously with frequency of 100 Hz. Figure 4 shows the results of the clockwise circular test of the XY plane at 3000 mm/min. For better presentability measured radial deviations are related to a base circle with a radius of 30 µm.

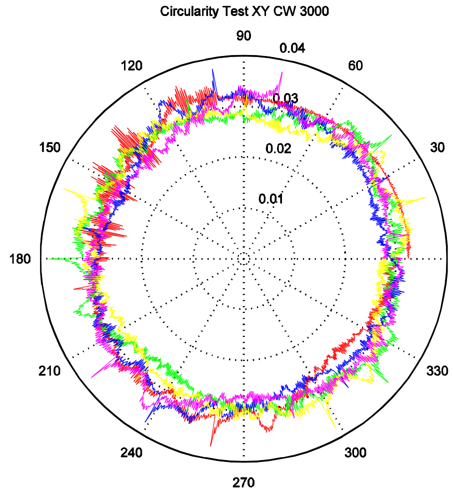

Figure 4: Circularity test of XY plane

3.2 Roundness of spindle

The reflector was mounted on a mechanically and thermally rigid arm made of carbon fibre reinforced plastic and moved by the spindle rotation on a circle with a radius of 200 mm. Measurement data was captured continuously with a frequency of 100 Hz. Figure 5 shows the determined radial deviations of the spindle movement which are related to a base circle with a radius of 10 µm for better presentability.

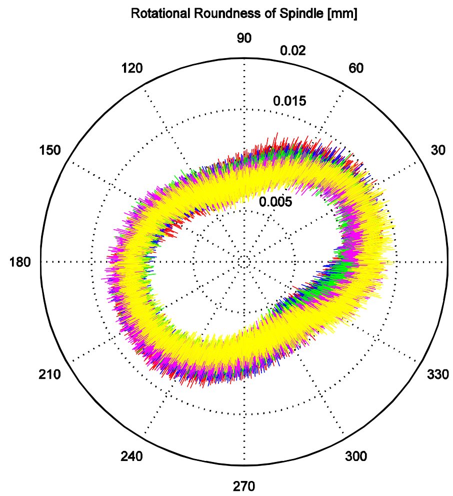

Figure 5: Roundness of spindle

3.3 Diagonal test

The diagonal tests were executed in the three planes of the linear machine axes. In each plane 3°, 45°, and 87° diagonals with lengths of 500 mm were realized with a speed of 500 mm/min. All movements were repeated three times. Measurement data was captured continuously with frequency of 100 Hz. Figure 6 shows the sums of lateral deviation of the 87° diagonal in the XY plane.

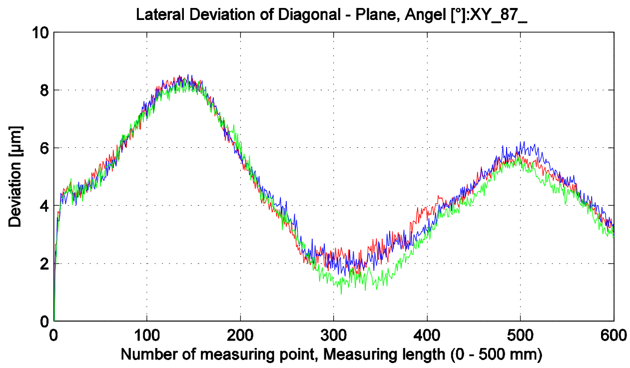

Figure 6: Lateral deviation of the 87° XY-diagonal

3.4 Orientation of axes

For determination of coaxiality and squareness all machine axes were moved separately but continuously measured in a single procedure. Based on the individual machine movements all direction vectors of linear movements and all normal vectors of rotational movements as well as the angles between these vectors were calculated. Measurement data was captured continuously with frequency of 50 Hz. Figure 7 shows one linear and one rotary axis of a large machine tool that were analysed with respect to coaxiality.

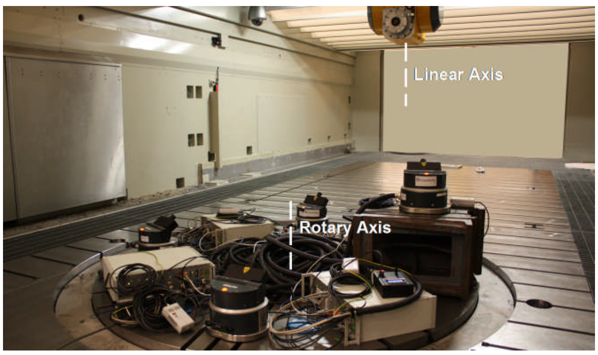

Figure 7: Orientation of two axes

3.5 Positioning accuracy of rotary axes

There are two feasible choices for the measurement setup for determining positioning accuracy of rotary axes. Depending on the size and type of the axis either all four Lasertracers or the reflector are mounted on it. Figure 8 shows the positioning accuracy of a large rotary table embedded in the machine base. In this case all Lasertracers were mounted on the rotary table. During the measurement procedure the axis was positioned every 10°. The Lasertracers automatically detected the standstill and captured the 3D position of the reflector. Based on these positions the actual rotation angles and the positioning accuracy were calculated by means of the postprocessing procedures.

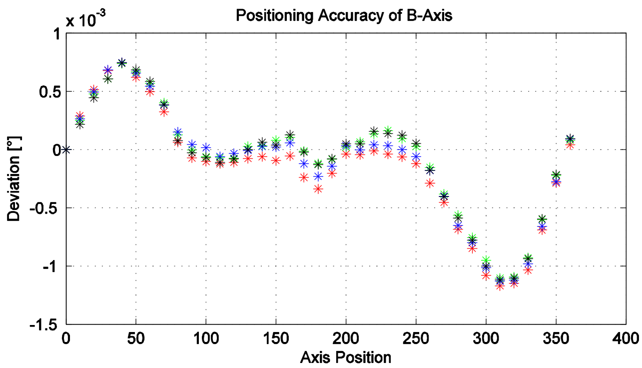

Figure 8: Positioning accuracy of rotary axes

4 Application and results of robot calibration

Robot kinematics, serial as well as parallel, are eligible for characterisation by the Multitrace system, too. However, specific measurement strategies and data evaluation procedures are necessary and are being developed within in ongoing research. The goal is to fulfil particularly the specifications of ISO 9283 [10] which main technical aspects are:

- Absolute pose accuracy and pose repeatability
- Identification of Denavit-Hartenberg parameters
- Geometric, kinematic and dynamic analysis of spatial trajectories
- Analysis of the dynamic system behaviour

Within one of the first practical trials, a 4-axis scara robot was analyzed using the Multitrace system. Figure 9 shows the application setup in the laboratory. The reflector is mounted on the endeffector and the four opposite located Lasertracers are logged in.

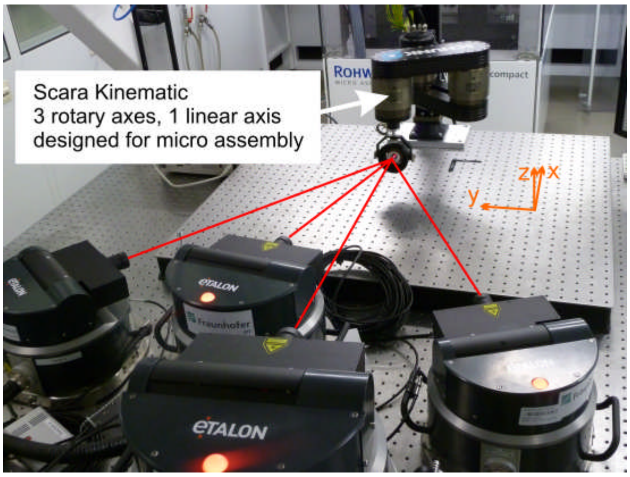

Figure 9: Robot calibration

As already mentioned above, it is feasible to capture the 3D position information with a measuring frequency up to 50 kHz. Hereby the analysis of static, kinematic and dynamic trajectories can be realized. Ongoing research work focuses on the quantitative identification of:

- Geometric trajectory accuracy and repeatability
- Dynamic behaviour at reversal points and in positioning motions
- Uniformity of track speed
- Acceleration behaviour

All the mentioned aspects will be analyzed three-dimensional. Since the Multitrace system only offers 3D position information specific data evaluation procedures in terms of post processors are being developed currently.

5 Conclusion and Outlook

Within this paper the practical application of the novel Multitrace measurement method was presented using different typical calibration tasks for machine tools robots. The Multitrace system enables the real-time measurement of 3D positions with an special uncertainty less than 10 µm. Based on the 3D position data, demand oriented evaluation algorithms were implemented in terms of post processors to calculate the required calibration results. The procedure has significant potential due to its speed and versatility.

The focus of the ongoing research work is on the implementation of further post processors for the calibration of robots and machine tools. Particularly the metrological identification of the Denavit-Hartenberg parameters for the improvement of the controller integrated robot model is one of the important challenges in the near future.

6 Acknowledgements

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