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Method for Accuracy Assessment of the Length Measurement Unit of Laser Tracking Systems

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Abstract: Laser tracking systems are widely used in large-scale metrology of geometric quantities. Their importance is confirmed by the fact that one of the parts of the ISO 10360 series of standards has been devoted to the issue of assessing their accuracy (ISO 10360-10). A laser tracker is a device whose final measurement result is calculated using indications from various subsystems included in it, such as devices for measuring length and angle. The analysis of these individual impacts can be useful in creating simulation models of accuracy which, in regard to the Industry 4.0 concept, seem to be the most justified in terms of speed of operation and ease of use. For this reason, it may be particularly important to undertake research on the accuracy of this component in isolation from other factors affecting the measurement of the coordinates of the point. The article describes a method that allows separation of the length measurement error from the other components. The method uses a high-accuracy interferometer which is treated as a reference system that allows for the comparison of indications obtained using the tested distance measurement system. Thanks to the proposed method, it is possible to minimize errors from the optical system and other measuring systems. The use of a precise linear guide allows the reduction of errors related to the implementation of linear motion. The article presents the test method and the results obtained from performed experiments, as well as formulates conclusions and the directions of further development.

Keywords: laser tracking systems; laser tracker; accuracy; interferometer; virtual model

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1. Introduction

In accordance with the assumptions of the Industry 4.0 concept, increasing production efficiency is to take place, e.g., by optimizing the quality control process [1]. Metrology of geometrical values also follows this trend by improving both the methods and technology. Part of the geometric values of metrology is coordinate metrology, which has been developing very dynamically since the end of the 20th century. A specific part of this field of science is large-scale metrology, which is used where standard coordinate systems are not able to meet the requirements set for them. Devices with the largest measurement area use laser interferometers in their operation. Skillful use of the phenomenon of wave interferometry, through observation and counting of the interference fringes, allows for performing length measurements in the measurement space of up to several dozen meters.

One of the most popular systems in the sector that uses a laser interferometer is the laser tracker. This system uses an interferometer to determine the distance of the measurement point from the reference point. There are solutions that use an interferometer (IF) and a fixed reference point (birdbath), but also those that use an absolute distance meter (ADM) instead of a reference point. The latest systems now use only ADM for distance measurements. Appropriate aiming of the laser beam towards the measuring point is achieved by means of a rotating mirror or the right angular setting of the entire interferometer. In both cases, rotation in two perpendicular axes is performed by integrated drives. The angular positions of the mirror (or interferometer) are read by angular encoders and most often marked as the horizontal angle H and vertical angle V.

Like any measuring device, laser tracker systems should be periodically checked and calibrated. A calibration certificate issued by appropriate institutions is a guarantee of the correct operation of the device and allows for assuming that the system performs measurements with the expected accuracy. Institutions dealing with such activities are either state-owned bodies responsible for ensuring measurement consistency at the national level (e.g., in Poland, the Central Office of Measures, in Serbia, the Directorate of Measures and Precious Metals), or bodies with an appropriate accreditation certificate (such as the Laboratory of Coordinate Metrology at the Cracow University of Technology).

Several facilities around the world are engaged in research on methods of assessing accuracy in large-scale coordinate metrology. These include the University of North Carolina, where the general concept of laser tracking system is given by Lau et al. in [2] as well as its application in industrial robot accuracy assessment, while in [3], Morse focuses on the dynamic errors of laser trackers which occur during measurements of a moving target; the National Physical Laboratory, where, in [4], the methodology of obtaining a geometrical model of tracker errors is presented by Hughes et al., which is based on measurements of a target set in predefined positions from different tracker locations, while [5] describes practical aspects of trackers calibration; the University of Zaragoza, including method for the optimization of tracker location during machine tool verification, which is presented by Aguado et al. in [6], and a technique for forecasting the optimal distribution of trackers during multilateration measurements is shown by the same team in [7]; the Cracow University of Technology, where Gruza et al. in [8] discuss the influence of point averaging which occurs during laser tracker measurements on the measurement uncertainty, while in [9], a tracker is treated as a reference instrument for checking the accuracy of large-scale optical measuring systems and others. Moreover, there are valuable scientific papers that fully or partially present the discussed issues together with the results of the research carried out. These papers constitute a valuable source of knowledge in studies on the accuracy of measuring devices used in large-scale metrology, in particular based on laser interferometry. In [10], Clarke et al. describe methods of accuracy assessment in systems used in large-scale metrology, while in [11], Zhuang et al. present, e.g., a method of modeling the errors of the axis of rotation in a mirror tracking the measuring point. Conte et al. in [12] describe the procedure for identifying kinematic errors in laser tracking systems. The procedure for identifying errors coming from the angle measurement system in a laser tracker is described in [13] by Gassner et al., while the procedure for determining the errors in angular encoders using the geometric model of the laser tracker system is described by Lewis et al. in [14]. In [15], Yan et al. describe a method for correcting errors originating in a retroreflector tracking system. In [16], Sawyer et al. describe a method for calibrating the laser tracker system using a reference interferometer. Haitjema discusses laser interferometer calibration methods in [17]. The methods presented in this paper allow for testing different phenomena related to laser interferometer operation (laser frequency, counting system) and assessing the impact of various components on the accuracy of a measuring system.

Based on the presented analysis of the state of art, it should be noted that, to date, the interferometers included in the laser trackers have not been tested separately. Accuracy tests of interferometers in laser tracking systems carried out to date are burdened with errors related to the research methodology, which the authors try to describe and estimate. Others describe the accuracy related to the whole system or to a complex system by giving its sum error. This article aims to develop a method of checking errors in laser interferometers used in laser tracking systems as one of the main sources of errors in such systems. The method allows for determining the share of errors coming from the interferometer independently of other systems, while minimizing the number of potential sources of errors in the test in relation to known methods. Moreover, all other methods of error determination of length measurement devices used in laser tracking systems that are based on comparison with reference interferometric systems use two or more separate retroreflectors, which brings additional errors caused by geometrical errors attributed to the system responsible for translating the retroreflectors. In the method presented in this paper, those errors do not occur.

The experiments included in the developed method can be used to acquire input data for the interferometer error module of the virtual model of the laser tracker system. Implementing simulation methods is particularly justified in the case of large-scale metrology, both due to the time spent on measurements and the availability of appropriate standards. A very small number of institutions have standard lengths that allow for measuring distances of 3 m and more. The concept of the virtual laser tracker was described in [18] by Huo et al., while Wang et al. in [19] describe the methodology for estimating laser tracker uncertainty based on the Monte Carlo method. The authors of [20,21] describe simulation software that can be used to estimate uncertainty of large-scale measurements carried out with laser trackers using simulation software. The concept of the virtual laser tracker developed at the Cracow University of Technology includes three main modules responsible for simulating the operation of the device's main components: interferometer module, angular encoder module and environmental conditions module. Each module will contain information on the spread of results in the form of probability distributions. In order to ensure the possibility of sampling error distributions, the Monte Carlo method (MCM) will be used, which was successfully used in simulation methods developed for other measuring systems such as CMMs [22,23] and AACMM [24]. It will allow for obtaining values from the modules by simulating the response of individual parts of the system to the acquisition of a measuring point. The values thus obtained will be used to calculate the coordinates of a new (simulated) measuring point. A sufficiently large number of such simulated points will be used to estimate the uncertainty of a measurement task after conducting a single measurement using statistical methods.

2. Materials and Methods

The subject of the research is the Leica Laser Tracker LTD 840 laser tracking system. It is a device that utilizes both a laser interferometer (IF) and absolute distance meter (ADM) separately. In this particular model, the distance measurements are always carried out using IF, while ADM is used only for obtaining a start value for IF, for example, when the connection between the device and a target has been lost. The software used for control during the tests was the emScon program provided by the manufacturer. Due to the fact that it was not possible to access the length values and the values of the horizontal H and vertical V angles from the software level (alternative programs were also checked), and due to the need to automate the measurement process, a new program was created to acquire the values sent to the controller. The program was written using the libraries included in the Software Development Kit provided by the manufacturer. According to the latest calibration certificate, the maximum permissible errors of the tested system are defined by Equation (1) for the maximum permissible error (MPE):

$$MPE_{\mathrm{E}} = (25 + 35 * L/1000)\ \mu\mathrm{m}, \quad (1)$$

where:

L—measured length in millimeters.

The equation above determines the accuracy of the entire system, but the accuracy of the interferometer itself has not been determined—it has never been calibrated separately as a system component. The chosen parameters describing the system's accuracy are shown in Tables 1 and 2.

Table 1. The manufacturer specifications of length unit of laser tracker Leica LTD 840.

Manufacturer Specifications of Length Unit	
wavelength	633 nm
distance accuracy (±1 °C, ±3 mmHg)	±2.5 pm

Table 2. The manufacturer specifications of angular unit of laser tracker Leica LTD 840.

Manufacturer Specifications of Angular Unit	
angular resolution	0.14 arcsec
measurement accuracy (of a static target)	±10 µm/m

Since the accuracy of the interferometer in the laser tracker system is unknown (it is known to be much better than the accuracy of the entire system), no condition can be formulated as to the requirements of the reference device. For this reason, one of the most accurate systems available on the market was used. The reference interferometer used in the study is the Renishaw XL-80 (after retrofitting the system from the ML10 Gold model), whose length measurement uncertainty is defined as 0.5 ppm, which can be represented by Equation (2):

$$\mathrm{U(L)} = 0.5 * L/1000\ \mu\mathrm{m}, \tag{2}$$

where:

L—measured length in millimeters.

The Renishaw interferometer was calibrated in Polish NMI both in terms of frequency and measured length. Due to the assumptions regarding a virtual machine for the laser tracking system, described in Section 1, the interferometer responsible for determining the distance had to be tested independently of the other systems included in the laser tracker system. Therefore, it is not enough to use a standard calibration method used for laser tracking systems such as the methodology described in tenth part of the ISO 10360 series [25] as they are focused on the accuracy of the entire system, and not separating specified components. All procedures described in this document involve angular movements of laser tracker components, so it was not suitable for conducting the research that is presented in this paper.

To achieve the desired effect, it was necessary to ensure a fixed value of both angular encoders and the environmental conditions correction system. As the values of the horizontal H and vertical V angles are part of the set of parameters, based on which the coordinates of the measuring point are calculated, they cannot be excluded from the test; however, ensuring their fixed values allows the measurement result to be independent of errors coming from the angle measuring system. The fixed value of encoders was ensured by switching off the motors responsible for the rotation of the mirror directing the beam to the measuring point.

The measurement setup used in the experiment is similar to the setup described in [17], in which the displacement of one retroreflector is measured by both reference and tested systems. The second experimental setup presented in [17] utilizes two retroreflectors, however, one of the objectives of the developed method was to eliminate the adverse effects of using two retroreflectors in the study. This solution introduces many errors to the study, related to, e.g., the movement of the platform the retroreflectors are mounted on, or the non-parallelism of the axis of movement of the two reflectors. Moreover, it should be noted that both systems cooperate with other retroreflectors. Even if they are of the same type, their accuracy may differ. The process of determining these errors is long and complicated and the results may have a significant impact on the test result, as described in [16]. In order to eliminate these effects, a method was developed in which both the tested and the reference system work with the same retroreflector. A precision guide with a mobile platform was used as the system implementing the retroreflector's movement, but in this case, there is no need to estimate errors related to the platform's movement, mainly caused by geometric errors of the guide, since the effects resulting from the movement affect both the tested and the reference system in the same way.

The use of a common retroreflector also required using a common beam splitter. To this end, a splitter was used, constituting the instrumentation of the reference interferometer with an attached reference beam retroreflector. The splitter was set at an angle to the measurement axis to facilitate establishing the base point in the laser tracker system. Due to the different method of guiding the beam to the retroreflector in both systems, there are no disturbances in the wave interference of these systems.

The experimental setup diagram is shown in Figure 1 while the test station with the measuring track is shown in Figure 2a,b.

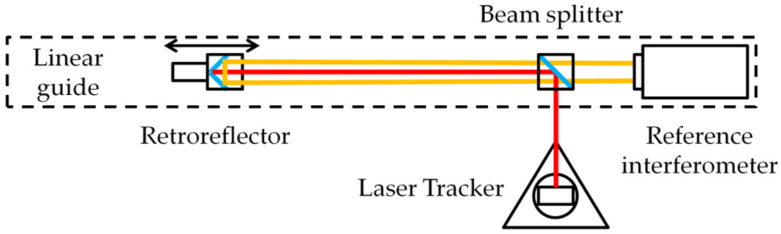
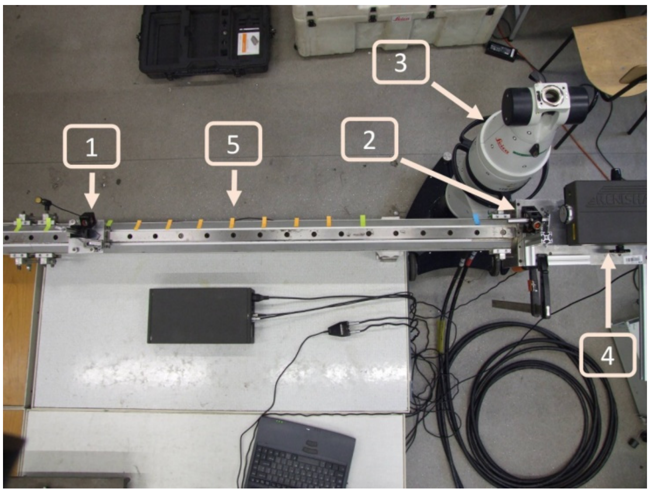
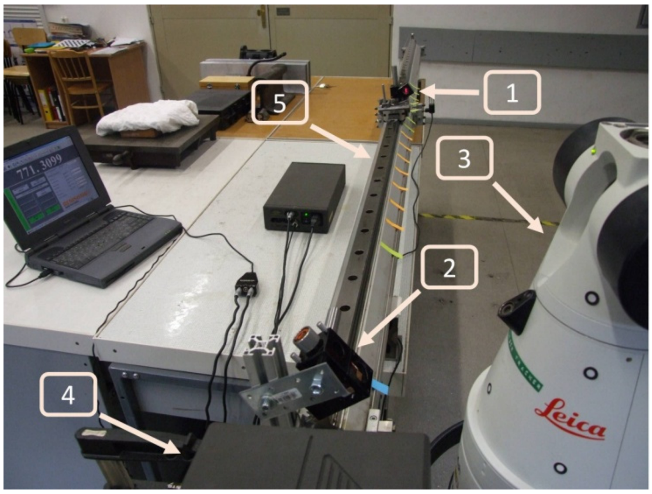


Figure 1. The simplified diagram of test station: red line—laser tracker beam, orange line—reference interferometer beam.



(**a**)



(**b**)

Figure 2. Test station—retroreflector (1), beam splitter (2), tested system (3), reference system (4) and linear guide (5); (**a**) top view; (**b**) view from the reference system side.

The study was carried out in an air-conditioned room at small intervals during one day. During the tests, the values of environmental parameters were monitored using an external thermohygrometer and additional temperature sensors along the measurement path. The average values of the environmental parameters recorded during the test were as follows: temperature 21.11 °C, humidity 55%, pressure 993 hPa. The changes in humidity and pressure were negligible, and the temperature fluctuations did not exceed a value ±0.3 °C from the average, while the temperature distribution was the same along the measurement path.

The study range was 0 to 1500 mm with measuring points spaced every 50 mm. In order to test the hysteresis, the heading on the points was carried out successively until the end of the measuring range, and then the points were measured in the opposite direction. After the final point was measured in the "increasing direction", an auxiliary movement was carried out for 1550 mm (without measurement at this point), then the measuring reflector was moved by a distance of 1500 mm (the opposite way—decreasing direction) and the first measurement was made at this point concerning the "decreasing direction". This cycle was repeated ten times. Once the platform stopped at the measuring point, the researchers waited until the indications of both systems stabilized (usually a few seconds) before taking the measurement.

In the first stage, the tests described above were performed with the laser tracker system motors turned off. With this, the influence of changes in the horizontal and vertical angles and thermal effects from LT motors were separated. However, since the virtual model of the laser tracking system is to work primarily in the standard operating mode in which the motors are turned on, it was decided to conduct additional tests with the same research methodology but with head rotation motors active.

After research on the accuracy of the interferometer, a test of correction of the LT interferometer indications using a simple mathematical model was performed. The mathematical model is based on the use of the interefeometer error approximation using a second order polynomial function. The measurements using a reconfigurable ball-bar standard were performed. The methodology and test results are presented in the next sections of the article.

3. Results

The results of both experiments (motors inactive and motors active) are presented in the diagrams below.

The results shown in Figures 3–5 show that the individual error values of the laser interferometer used in the tested laser tracker system range from −1 µm to 1 µm. Additionally, the vast majority of the range values presented are smaller than 1.5 µm or slightly higher than that value. It should also be noted that the distribution of errors for all measurement series is similar. A distribution of the measurement errors together with the spread values can be used to simulate the measurement of a point in a virtual machine model for a laser tracking system.

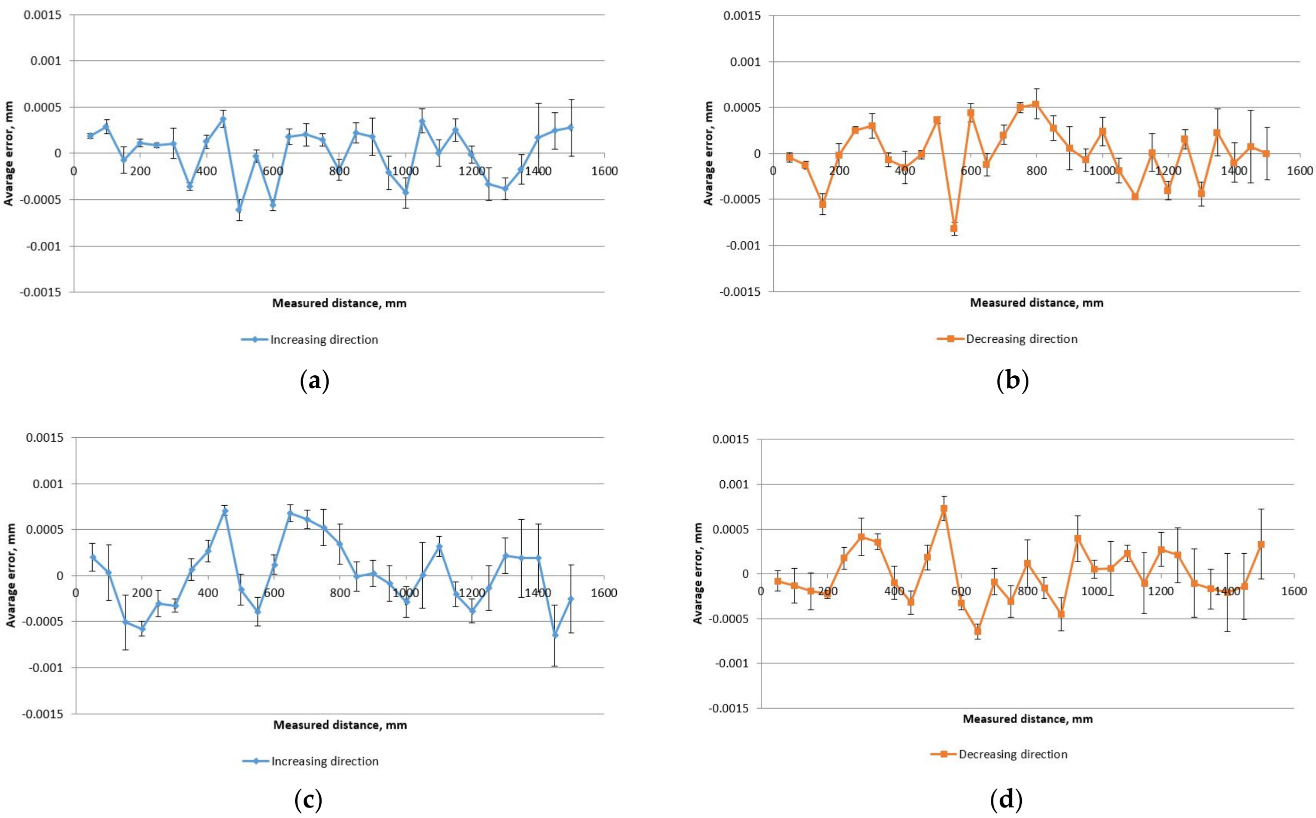


Figure 3. Averaged error values during measurement: (**a**) increasing direction, inactive motors; (**b**) decreasing direction, inactive motors; (**c**) increasing direction, active motors; (**d**) decreasing direction, active motors. Error bars show the standard deviation value.

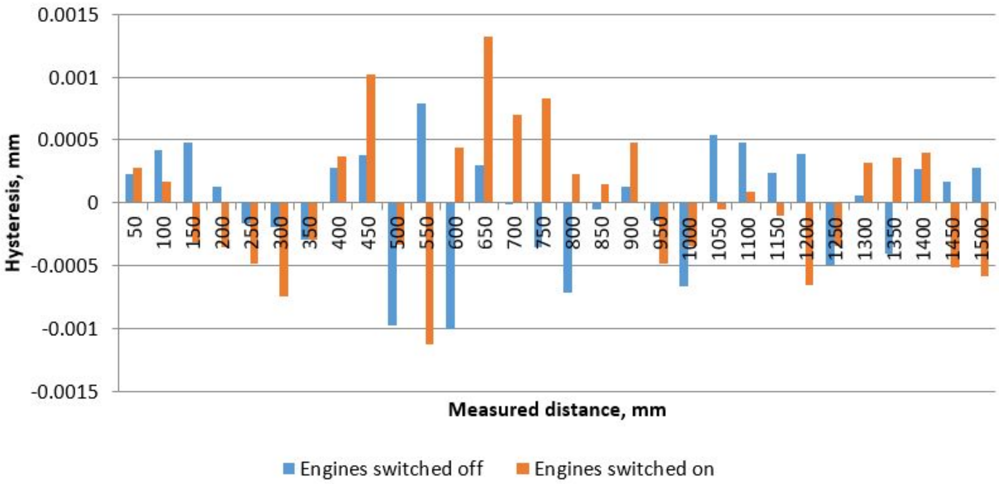
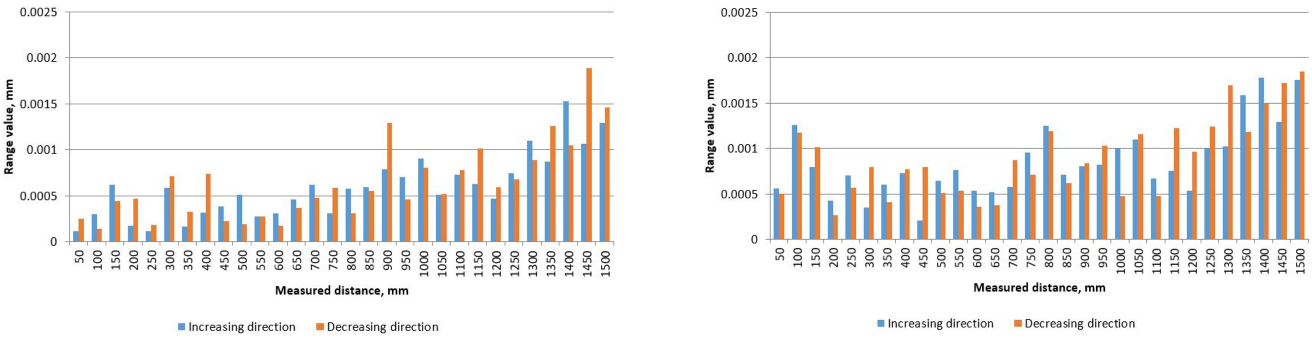


Figure 4. Hysteresis error for measurements with motors turned off and on.



(**a**) (**b**)

Figure 5. The values of the intervals between cycles in both directions: (**a**) inactive motors; (**b**) active motors.

As can be seen in Figure 3, similar characteristics were obtained for both measurement directions as well as for both tested states of the motors. In all cases, the dispersion of obtained results increased with an increase in the tested length, however, bigger dispersion values can be observed for the active state of the motors.

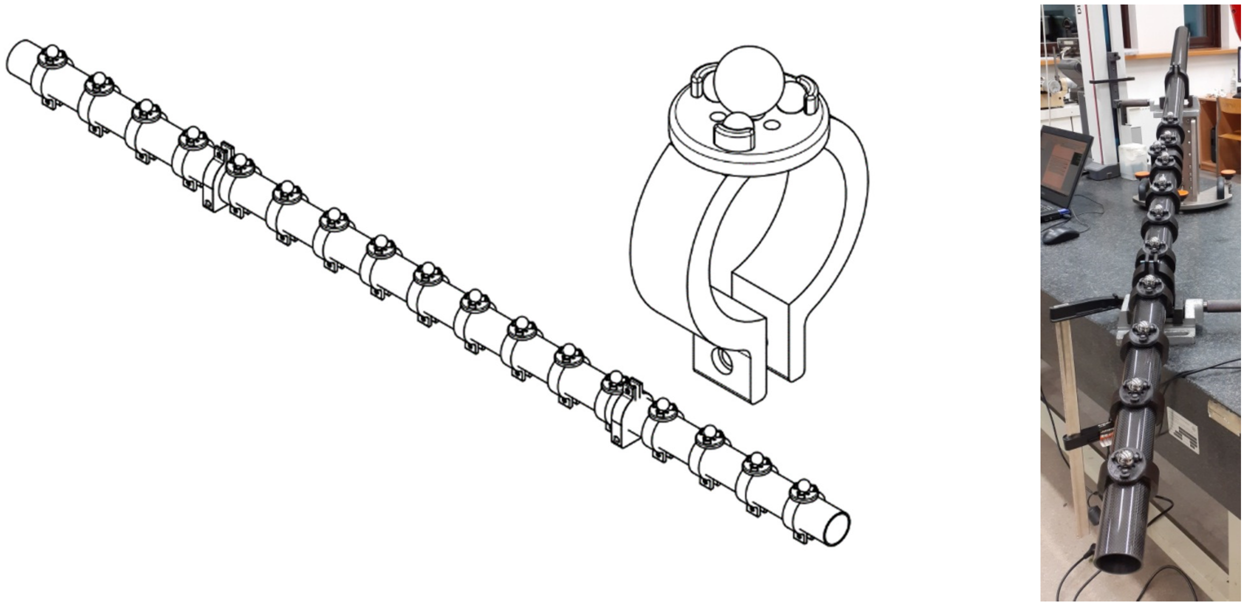
It can be observed in Figure 4 that the hysteresis practically does not exceed more than 1 μm and generally bigger values can be obtained in an inactive state of the motors. Analyzing the results shown in Figure 5, it can be concluded that range values grow with increasing length and, again, generally, they are bigger for the active state of motors. Therefore, it can be assumed that switching off the motors during the tests may increase the stability of the obtained results.

Based on the above model and the data obtained in the described research, which will serve as input data for the Monte Carlo method simulations, it is possible to simulate the distance measurement of the laser tracker interferometer. Multiple sampling from the obtained distributions allows the determination of the uncertainty of a single measurement based on the standard deviation from the simulated series of measurements. Monte Carlo method simulations use as an input the experimentally determined parameters of probability density function. For lengths in which the interferometer error was not determined directly, the data from the nearest length that was used during experiments will be taken (for example, if the simulation is carried out for L = 523 mm, the input data obtained experimentally for L = 500 mm will be used). The scaled and shifted t-distributions can be used as probability functions due to the small amount of input data.

Simulated uncertainty values attributed to laser interferometer may be used as one of the uncertainty contributors in a virtual model of the laser tracker system.

The method of simulating the uncertainty of laser interferometeter measurements with the Monte Carlo method and the results obtained with its application are presented below.

For this purpose, a reconfigurable ball-bar was used. One of its main features is the possibility of using laser tracking systems equipped with a spherical retroreflector (SMR) for research. For this purpose, special sockets were designed that are mounted on a thermally non-expandable base pin. Each socket consists of three fixed centering balls and a central sphere that can be detached from the socket (Figure 6). The size of the central sphere corresponds to the size of the retroreflector used in the test (1.5 inches).



(**a**) (**b**)

Figure 6. The reconfigurable ball-bar standard: (**a**) the technical drawing; (**b**) real specimen of reference object.

Central spheres mounted on sockets along the bar allow the performance of calibration on a standard high-accuracy CMM. The developed standard was calibrated on the reference PMM 12106 coordinate machine with the measurement uncertainty for the longest calibrated distance equaling 1.2 µm.

The central sphere in each socket can be replaced by a spherical retroreflector. In addition, thanks to the special design of the socket, it is possible to move the retroreflector between the sockets without interrupting the laser beam. Three distances between the central points of successive sockets were measured, which are: 100 mm, 500 mm and 900 mm. Each distance is determined between socket "zero" and the appropriate socket offset from it by an appropriate distance. Only readings from the laser tracker's interferometer were used to calculate measured length. The procedure was repeated ten times then the A type uncertainty was estimated. For each distance measured on the ball-bar standard, a simulation of uncertainty with the Monte Carlo method was applied. The simulation is based on 10,000 Monte Carlo repetitions. The t-distribution was used for all three considered distances. The mean values and standard deviations which are the input data for simulation were calculated on the basis of results obtained during previous parts of the experiment (the results for the inactive motor state were used for both measurement directions). The results obtained experimentally and by means of simulation are presented in Table 3.

Table 3. The uncertainties obtained with simulation and on the basis of ball-bar measurements. All values given in mm.

Uncertainty Estimation Method	Measured Distance		
	100	**500**	**900**
Type A	0.0004	0.0005	0.0009
Simulation	0.0002	0.0003	0.0005

4. Discussion

When analyzing the presented results, it should be noted that there is no significant difference in the nature of the error distribution between the errors obtained with active and inactive motors. This fact may suggest the correctness of the solutions used in the research methodology. However, the difference in values is clearly noticeable (Figures 3–5). Comparing the standard deviations (Figure 3) and the ranges (Figure 5), it can be seen that the activation of the motors caused greater values of both parameters, and particularly large values occur (with active motors) at the beginning of the measuring range. It is most likely caused by the beam tracking system, which has the greatest impact on the result at short distances. It is clearly visible that it does not occur in tests with inactive motors. The values of the mean errors (Figure 3) were increased in the case of a postive direction for active motors. Although the differences between the values are not great, an increase in the values can be observed in relation to the reference values. When trying to estimate the influence of active motors on the measurement accuracy based on the test, it can be assumed that the active LT motor system increases both the indication errors and the spread, and this value usually does not exceed 0.5 µm. When analyzing the overall influence of the angular position measuring system, it should be noted that its influence has been eliminated with the motors off, because there is no rotation of the mirror positioning the LT measuring beam. On the other hand, in a situation where the LT motors are working, this influence is minimal due to the use of a very small operating range of the angle measurement system. Research on the influence of the angle measurement system basically differs from the research methodology presented above and offers direction for further work.

The analysis of the hysteresis value also confirms the above theorem, as it is visible (Figure 4) that greater values were obtained during the tests conducted with active motors. The maximum hysteresis values in the case of active motors oscillate around ± 1 µm. The mean absolute value of hysteresis for inactive motors is 0.36 µm, while for active motors it increases to about 0.5 µm.

Results of conducted experiments can be utilized for simulating the uncertainty of the LT's intereferometer measurements. Comparing uncertainties estimated using experimentally obtained data and by means of simulation, it can be seen that the simulation method generally gave slightly smaller values then the second considered method. However, the results obtained with both methods indicate that the uncertainty of laser interferemeter measurements grows almost linear with an increase in measured length.

One of the directions of further work on the presented method will be enlargment of the measured range that can be tested. This will require finding a new way to move the reflector, as the linear guide in the LCM practically does not allow tests to be carried out beyond 1.5 m. One potential option is to use a large CMM for this purpose, but it requires additional research and adjustment of the experimental setup.

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