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Assessment of Influence of Sample Averaging on Accuracy of Point Coordinates Measurement Performed Using Laser Tracking Systems

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ABSTRACT
Laser Tracking systems are commonly used in all branches of industry, which requires accurate large-scale measurements for instance aviation, space and shipbuilding industries. Laser Trackers belong to the group of non-Cartesian Coordinate Measuring Systems. Determination of the measured point coordinates involves the measurements of distance using laser beam and two angles recorded by horizontal and vertical encoders. Additionally, the environmental conditions are monitored and used for compensation of measured distance. The coordinates of single measured point are estimated using the results obtained from a series of samples taken in a short time period. The average value obtained from a sample is given as a result; additionally, the dispersion parameters are calculated which can be used to evaluate the probing process. This paper presents the research procedure which allows assessing the influence of chosen dispersion parameter related to the sample averaging on accuracy of the measurements performed with laser tracking devices. The procedure involves standard elements measurements during which the points with similar level of RMS parameter are used for the calculation of the measurement result. Such approach allows simulating the increasing dispersion of points taken into account during sample probing. The results presented in the article can be helpful to the operators of laser tracking systems to assess the influence of the probing process on the measurement accuracy.

Keywords: Laser Tracker, measurement uncertainty, accuracy

INTRODUCTION

The requirements formulated by customers in the era of Industry 4.0 revolution cause the continuous development in the field of the metrology of geometric quantities and in particular of highly accurate mobile systems, with an extended measuring range comparing to the standard measuring systems. Additionally, the short measurement duration is one of the most important requirements which establish the directions for changes in the construction of measuring systems. In order to meet these requirements, new coordinate measuring systems have been developed, such as: Articulated Arm Coordinate Measuring Machines (AACMM) equipped with triangulation heads, structural light scanners, multi-sensor Coordinate Measuring Machines and laser tracking systems. Especially the latter group offers versatility combined with high accuracy of measurement. Additionally, the development of the measuring technology allows significant improvement of the already existing solutions that are widely used in industry.

Laser tracking systems are commonly encountered in industry in such branches as: automotive, robotics, aerospace, shipbuilding and energy industries, as well as in all the areas where large size measurements are needed. Due to the utilization of a laser interferometer, it is possible to measure distances up to several dozen meters depending on the class and generation of a system. Laser interferometer allows precise measurement of distance, while the beam is directed to the measuring point using a head equipped with a mirror, which can be rotated in two perpendicular axes – horizontal and vertical. The orientation of the mirror is determined by angle encoders. The beam at the measurement point is reflected back to the source by a retroreflector which is installed in a spherical housing. Depending on the measurement task, various types and sizes of retroreflectors can be used. Measuring point tracking is possible using the beam deflection detection system and rotary motors in the device head. The distance to the measuring point as well as the horizontal and vertical angles are the basic data set necessary to unambiguously determine the position of the measuring point in the spherical coordinate system. Due to the influence of the environmental conditions on the operation of the laser interferometer, distance compensation is applied which takes into account the changes in temperature, humidity and pressure in the measuring volume of a device. More information on laser tracking system devices, their measurement uncertainty and their application can be found in [7,8,11–13].

In the majority of laser tracking systems applications, the system is operated manually by the operator. It is possible to exclude the human influence in some measurement tasks, such as verification tests of machines and industrial equipment. Although the classic laser interferometer is still the most commonly used solution in such situations [9,14], there are laser tracking systems capable of performing the accuracy tests of industrial equipment with similar accuracies [3,4].

Generally, one or two operators are required to conduct the measurement on laser tracking system when it is operated manually. The measurement is performed by calling out the measuring procedure in the metrological software during the contact of the retroreflector with the measured object. The measurement of single point coordinates consists of an automatic measurement of a group of many points which then are the basis for determination of one averaged point, stored in the software as a measured point. The time interval of measuring the group of points during the abovementioned procedure can be changed, but usually the default value is set to 500 ms. The change of the time interval determines the number of the measured points included in the group from which the coordinates of the stored measured point are calculated. Due to the utilization of multiple measurements, statistical calculations are possible, the results of which provide information on the quality of the point acquisition process. The most important parameter from the operator's point of view is the RMS (Root Mean Square) value, which is displayed with the coordinates of the measured point immediately after the measurement procedure. The RMS parameter values indicate dispersion of individual results in the group of points and it can be a direct measure of the quality of the measurement process achieved by the operator handling the retroreflector. For the medium class system with the retroreflector set stationary at a stable point, the RMS parameter will fluctuate within a few micrometers. The same retroreflector set on a flat surface, held still by the operator, generates approximately ten times larger RMS parameter value. However, in the case of typical measurements, and in particular when difficult elements are measured, such as spheres or freeform surfaces, the RMS parameter can reach the value of hundredths of a millimeter or even tenths of millimeter in extreme cases. Proper selection of the time interval for measurement of a group of points during a single measurement constitutes an optimization task. From the operator's point of view, the measurement should be as short as possible to minimize the operator's influence, but from the point of view of system accuracy, the measurement should be as long as possible to minimize the impact of the system's natural repeatability.

The authors decided to check the impact of the value of the RMS parameter on the measurement uncertainty of measurement performed by means of the Leica Laser Tracker LTD840 laser tracking system. It is an important step in formulating the fully functional metrological model of the measurements performed using laser tracking systems that could be utilized for the system accuracy modelling. Such approach fits in with the trend of reducing the manufacturing time which includes also time needed for accuracy assessment of the measurements results obtained during the quality control stage. The so called "Virtual models" of different systems were successfully developed for different measuring systems [5,10]. During development of such models several challenges must be overcome, including: identification and modelling of main sources of errors during measurements [2] and proper model validation [6]. In the case of laser tracking systems the operator influence is one of the key factors affecting the overall accuracy of the measurement, but in fact there are almost no studies that undertook this subject. The research methodology and the results of the experiments presented below would be the basis for the future development of the model of operator influence on the measurement results that could be included in the virtual model of the laser tracking system.

EXPERIMENT AND RESULTS

In order to determine the measurement uncertainty, it was assumed that the measurement tasks will include the measurement of the point-to-point distance as well as the diameter and form deviation of the sphere (roundness). It was assumed that the minimum number of measurements should be 10, so it would be possible to determine the measurement uncertainty using the A-method without using the expansion factor as a function of the number of measurements. This method is well-known and generally accepted, while its description and examples of its application can be found in literature, among others in [1, 13, 15]. Point-to-point distance measurement has been selected as one of the most common measurement tasks performed by the laser tracking systems and due to relative small influence of retroreflector handling on the measurement. Sphere measurement was chosen as one of the most difficult task considering the influence of operator and due to the usage of more complex calculation algorithms. A gauge block of 500.0013 mm was used as a standard in the distance test, while a reference sphere with a diameter of 24.9925 mm and a 0.0009 mm form deviation was used as a standard for the diameter and shape measurements. The tests were carried out over a single day in the air-conditioned room at Laboratory of Coordinate Metrology of the Cracow University of Technology and the environmental conditions were monitored continuously during the whole measurement. Radial compensation was disabled in the software during the measurement to eliminate the possibility of applying wrong vector direction. All results were corrected by the value of the retroreflector diameter after measurements. In order to minimize the influence of the environment, especially the vibrations, both the Laser Tracker system and the mounting system of the standard and the reference sphere were fixed on the CMM measuring table. The research methodology as well as experiment set-up are shown in Figure 1 and Figure 2

In order to test the influence of the RMS parameter on the uncertainty of measurement, it was necessary to ensure that each measuring point included in the measurement task had the same or very similar value of RMS parameter. In

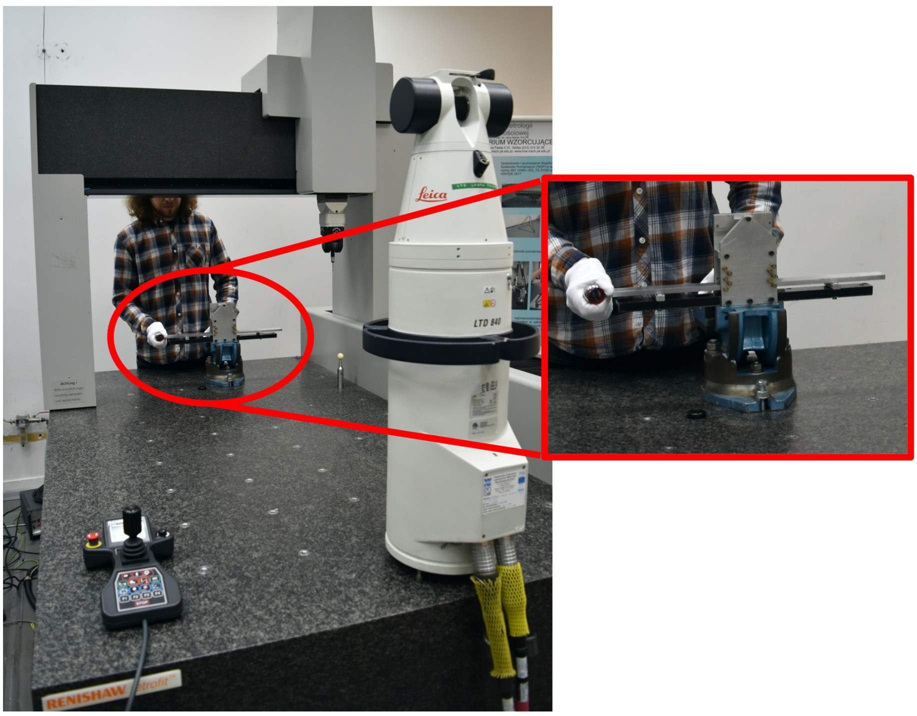

Fig. 1. The research station for distance measurement – Laser Tracking system, gauge block and its mounting system on CMM table

Fig. 2. The research station for form and diameter measurement – Laser Tracking system, reference sphere and its mounting system on CMM table

order to achieve this effect, it was decided that each point in the measurement task will be measured 100 times and then combined in groups so that the difference between the values of the RMS parameter for each of point in measuring task is as small as possible. The methodology described above was applied to both the distance measurement (2 points for measuring task) and the sphere measurement (5 points for measuring task). In the first case, combining the measurement points in a pairs was not a problem and the difference between the RMS parameter values fluctuated from 0 to 3 μm. In the second case, the set of points with the same RMS parameter increased to 5, which made the adjustment more difficult and the differences in the RMS parameter values varied between 0 and 8 μm.

In rare cases, especially in the group of points with the highest RMS parameter values, the differences were greater. After combining the points into groups, the distance along the main axis of the gauge block as well as the diameter and the form deviation of the reference sphere in the PC-DMIS software were evaluated. The results were divided into groups according to the value of the RMS parameter. For distance measurement:

1. < 0.015
2. 0.016 – 0.030
3. 0.031 – 0.045
4. > 0.046

And for roundness and diameter measurement:

1. < 0.030
2. 0.031 – 0.060
3. 0.061 – 0.100
4. > 0.100

The mean value and measurement uncertainty (estimated according to the A-method) were calculated for each group. The results of the performed experiment for distance measurement are presented in Table 1, for form deviation measurement in Table 2, while for diameter measurement in Table 3. All calculated uncertainties are expanded uncertainties with the expansion coefficient k = 2.

Table 1. Results obtained for distance measurement. All values given in mm

RMS range	< 0.015	0.016 – 0.030	0.031 – 0.045	> 0.046
Mean value	500.033	500.033	500.026	500.029
Uncertainty	0.0017	0.0024	0.0037	0.0069

Table 2. Results obtained for form deviation measurement. All values given in mm

RMS range	< 0.030	0.031 – 0.060	0.061 – 0.100	> 0.100
Mean value	0.004	0.004	0.005	0.006
Uncertainty	0.0023	0.0015	0.0017	0.0028

Table 3. Results obtained for diameter measurement. All values given in mm

RMS range	< 0.030	0.031 – 0.060	0.061 – 0.100	> 0.100
Mean value	25.004	25.005	25.001	25.002
Uncertainty	0.0025	0.0021	0.0023	0.0012

CONCLUSIONS

While analyzing the uncertainty values in Tab. 2 and in Table 3, it can be observed that the relationship between the RMS parameter and the measurement uncertainty cannot be indicated; however, it can be seen that the mean values for both form deviation and diameter measurements are maintained at a satisfactory level. The changes of uncertainty values obtained in both cases have a random character. A possible explanation of this phenomenon is double averaging which was present in both form deviation and diameter measurements. The first averaging occurs when the measured point coordinates are determined as the mean of the group of points collected during the time interval which can be set in the system software. The second averaging takes place during the calculation of the center and the diameter of the sphere from 5 points using the least-squares method. In this case, the impact of the RMS parameter on the uncertainty of the measurement task is minimized. The influence of the RMS parameter on measurement uncertainty could be greater in the case of sphere construction utilizing 4 points; however, the authors deliberately reject such solution due to the generally accepted measurement practice which assumes the measurement of geometric elements in a greater number of points than the mathematical minimum. Additionally, in the case of such constructed sphere, it would be impossible to determine the roundness error. In the case of measurements that use a greater number of points than the mathematical minimum for geometry determination, the influence of the RMS parameter on the measurement uncertainty should be considered as negligible.

However, outside the aforementioned circumstances, in the case of laser tracking systems, it is common practice to measure distances based on two points measurement – i.e. the strategy used in research, the results of which are presented in Table 1. On the basis of the results presented in the previous chapter in Table 1, a clear tendency of increasing measurement uncertainty can be notice for increasing values of RMS parameter. Taking into account the accuracy of utilized laser tracking system, all obtained mean length values should be considered as satisfactory. In the case of a measurement task realized with the use of individual measurement points (being a result of measurement), the influence of the RMS parameter on measurement uncertainty is clearly noticeable. Additionally, based on the presented results, a hypothesis that it increases exponentially can be formulated – consecutive uncertainty increases to 0.7; 1.3 and 3.2 µm; however, further research is necessary to confirm such dependence.

To summarize, the impact of the value of the RMS parameter obtained during the acquisition of measurement points on measurement uncertainty exists and is particularly noticeable in the case of measurement tasks based on measurement of single points, whereas this influence decrease in the case of the measurements that utilize geometrical features calculated using the least square method. As the direction of further research, the authors indicate the research that allows quantitative estimation of impact of RMS value on measurement uncertainty, which would enable utilizing this parameter to estimate the uncertainty of a single point measurement performed using laser tracking systems.

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