Analysis of the influence of the Spherically Mounted Reflector on the measurements done with Laser Tracker

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Abstract
In the paper research conception of angular positioning change influence on measurement accuracy of Laser Tracker system was presented. The research was conducted using two retroreflector sizes. Two series of measurements were performed, the first series was conducted with fixed retroreflector while the second series was performed which changing angular orientation for each measurement. X, y and z coordinates of Cartesian coordinates system and laser interferometer distances were compared. In the study authors describe research methodology, measurements results as well as conclusion and suggest directions for further investigation.

Keywords
Coordinate measuring technique, laser tracking systems, measurements uncertainty, retroreflector impact on measurements accuracy.

1. Introduction

Nowadays dimensional metrology become increasingly known science field. Science researches conducted in the best worldwide scientific centers are more often used in industry with benefits for both sides. Devices dedicated to conduct length and angle measurements are increasingly accurate and knowledge about their operation are become much broader. Coordinate metrology has special position in this field of science due to versatility of Coordinate Measuring Machines (CMM). The possibility of multiple geometrical features measurement on single machine is desirable in the industry where low cost and quickness of metrological process are crucial. CMMs have many advantages like universality mentioned above, but also measuring speed, automation of process and more often simplicity of use. One of the common system disadvantages is limited measurement volume as well as lack of device mobility. In order to meet these requirements laser tracking systems like Laser Tracker or Laser Tracer have been developed. These system are usually small size and ensure full mobility. Also the range of measurement has been extremely increased in comparison to standard CMM measurement volume. Due to these advantages laser tracking systems are being widely applied in aviation, shipbuilding and automotive industry as well as in large-scale engineering. Considering measurement accuracy of these systems are comparable to CMM and can even exceed them in some application [1,2].

2. Laser Tracker System and measurement accuracy

Laser Tracker system operation principle relies on laser beam, which is used to measure a distance. Laser beam emitted from the source is divided and is directed to the measuring point as well as to laser interferometer. Returning laser beam, reflected at measuring point is also directed to laser interferometer, where distance from the measuring point to the known starting point (so-called birdbath) is determined. The distance is estimated by counting the interference fringes which are create by returning laser beam. These method is called incremental and ensure very high accuracy. The laser interferometer measurement itself can be described by Maximum Permissible Error (MPE) equation (1):

$$MPE = 0.000025 + 0.0007 / 1000 * L \text{ [mm]} \qquad (1)$$

where: L [mm] – distance to the measuring point

Due to its nature, the method has major disadvantage - the continuity of laser beam has to be continuous throughout entire duration of measurement performance. Laser beam, which is emitted from source, is directed to the measuring point by rotary mirror system, which is placed in Laser Tracer head. The position of rotary mirror, which targeting laser beam to any possible point in measurement volume, is determined by two motors responsible for motion in two perpendicular axles. The laser beam reflected on laser tracker head mirror reaches the measuring point, where is reflected again by group of mirror known in common version as Spherically Mounted Reflector (SMR) or simply retroreflector. The retroreflector mirrors are aligned to each other so that reflected beam always returns by parallel trajectory to the inbound laser beam. Returning laser beam is then reflected by laser tracker head mirror and then splitted. After that beams are directed to laser interferometer as well as to photosensor – Position Sensitive Detector (PSD). Any deviation of beam point in detector caused by retroreflector move is processed and become feedback for head mirror drives. These drives define position of the mirror in such a manner that the beam point in detector could shift back to neutral position. This allows to continuously track the position of the retroreflector without interruption of the laser beam. The position of the head mirror is continuously registered by the angular encoders which returns information about the horizontal angle (vertical axis of rotation) and vertical angle (horizontal axis of rotation). The two angles together with the distance information from the laser interferometer (d, θ, φ) constitute a set of necessary data to unambiguously determine the position of the measuring point in spherical coordinate system which center is located at the intersection of head rotation axis. These coordinates are transposed to the Cartesian coordinate system later [2,3]. Scheme of the system is shown in Fig. 1.

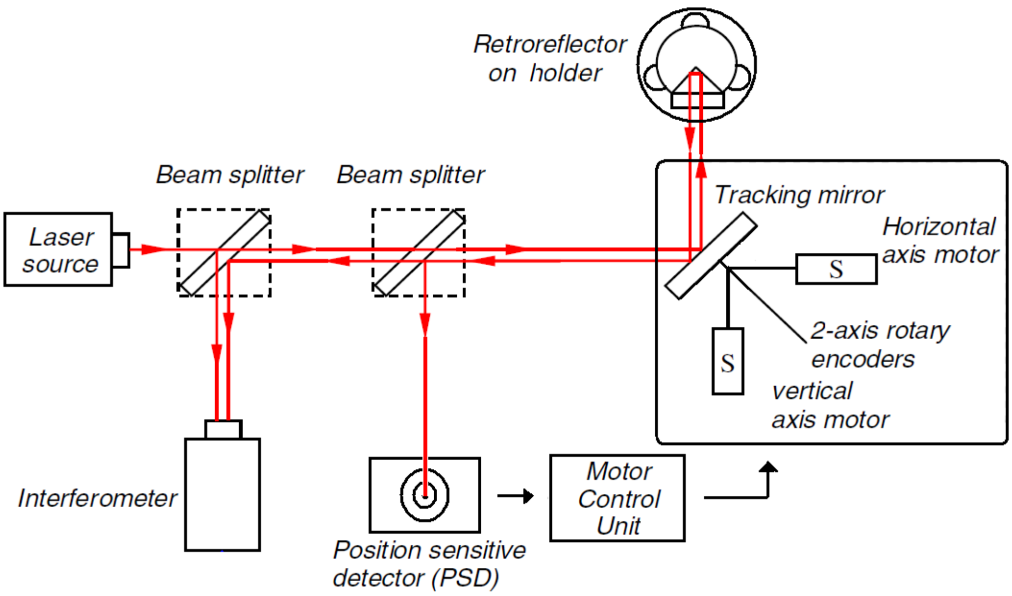

Fig. 1. *Scheme of the tested system with holder and spherical retroreflector.*

In the case of beam interruption during the measurement using a laser interferometer, which is common occurrence in practice measuring, counting interference fringes is interrupted. In this case, the procedure should be repeated guiding the beam continuously to the measuring point. Industrially, it is sometimes difficult and above all it makes measurements longer. To exclude the above disadvantage there is a possibility to use the Absolute Distance Meter (ADM) which can calculate the distance to the retroreflector for the incremental method instead of specifying it by position in the birdbath. However, this method is characterized by a lower positioning accuracy.

Retroreflector has several construction solutions. Most often it is a system of mirrors enclosed in a spherical housing of different sizes. In this case, the measurement of the coordinates of a point (the contact point of all the mirrors in the housing) occurs upon contact of the housing with the measured object. Another solution is the so-called cat's eye retroreflector type. Its characteristic feature is that it consists of spherical mirrors in the form of a hemisphere instead of the mirrors in the housing. It has the same properties and is mainly used during CMM calibration due to a much broader area of beam reflection. The most common type of retroreflector is the so-called T-probe. It consists of a retroreflector such as in the sphere form but the measuring element is the measuring tip similar to those used on CMMs but which is shifted from retroreflector by a known distance. The measurement is performed by contact measuring tip with the measured object. To define the vector of measuring tip shift relative to the retroreflector infrared light LEDs system placed on the T-probe handle has been applied. It cooperates with the camera attached to Laser Tracker system which perform similar movements such as the head mirror. Based on the LEDs distribution that is recognized by the camera the shift vector of a known dimension is defined. This system has two major advantages – it is convenient to use and allows for the measurement of features which can not be measured directly by retroreflector without interrupting the beam such as unfavorably situated cylinders or elements overshadowed by the measured object. Due to the use of additional system is also less accurate than direct retroreflector measurements. Both the retroreflector in the spherical housing and the T-probe system, it is necessary to use of adequate radial compensation of the distance between the point of the coordinate acquisition and the actual contact point which is usually performed by a dedicated software. Mentioned types of retroreflectors are shown in Fig. 2.

Fig. 2. *Retroreflector types: 1) Sphercially Mounted Refelctor 2) T-probe 3) T-Scan.*

Determining the accuracy of the laser tracking systems, such as all the measurements should be done under constant conditions in a controlled environment. A lot of environmental factors such as temperature, humidity or pressure affects the behavior of the light beam. It is important that the conditions should be unchanged for the entire length of the measurement. In order to monitoring these parameters the laser tracking systems are equipped with so-called meteo stations. This system has several disadvantages because the compensation of the environmental conditions impact is not perform continuously and the parameters measurement are pointwise what as particularly important inasmuch the longer the measurement is performed.
There is still no a public and uniform standard for determining the measurement uncertainty of the Laser Tracker system. So far there are only guidelines and recommendations made by the leading research centers [4]. Measurement uncertainty can be determined globally for a entire system by conducting a series of investigations using length standards under specified measuring conditions. So determined uncertainty omits the impact of uncertainty components for their global effects for the specified measurement task. The uncertainty for the length measurement conducted using the Laser Tracker system can be described by the equation as (2):

$$MPE = 0.025 + 0.045 / 1000 * L \text{ [mm]} \quad (2)$$

where: L [mm] – distance to the measuring point

Another approach to the uncertainty estimation problem is to determine a so-called errors budget. To determine the error budget all the components that affect the system accuracy should be defined. This is an extremely difficult task and to its implementation knowledge and experience are required. A detailed error budget is determined rarely while determination of individual factors may be useful for creating measurement uncertainty simulators. These simulators allow to determine the uncertainty of measurement task based on its multiple simulations. The process is fast and does not require detailed knowledge or extensive experience of the operator. The preparation of the input data which the simulator will be sample can be associated with a large amount of research on many component factors of uncertainty [3,5].
Further part describes a process and a research methodology of one of the factors that influence the measurement uncertainty of the Laser Tracker system proposed by the authors. This factor is the impact of the angular position of retroreflector on the system accuracy.

3. Methodology and research

Aim of the authors was to examine the influence of angular positioning of retroreflector in spherical housing on measurement accuracy. Since the results of the study should to present utilitarian value of research for the whole system measurement the assumption was using only Laser Tracker system. Additionally to assess the impact of fixing in the study an external Talycenta system and an independent thermohygrometer system for monitoring environmental conditions were used. The entire process is carried out in an air-conditioned room in Laboratory of Coordinate Metrology at the Cracow University of Technology in order to eliminate the effect of variations in environmental conditions. Environmental conditions were monitored throughout the measurement process and their variations are negligible. In the study Laser Tracker Leica LTD-840 with active meteo station was used. Measurement uncertainty of the system is described by the equation (2). The whole measuring process was held without major interruptions in measurements and was not disturbed by any additional factors. Therefore, measurement conditions were defined as permanent. Before measurements were taken, elements that have been thoroughly cleaned and the study was carried out with the exception of the factors that may cause pollution during the measurement. Measurement station which 1,5 inch retroreflector is shown in Fig. 3.

Fig. 3. *Measurement station which fixed 1,5 inch retroreflector during measurements.*

To investigate the influence of the selected factor on the system accuracy simple method of its exclusion can be used. It means two statistically representative series of measurements that differ only in the presence of the factor should conducted. In this case, the factor is the change in angular positioning of retroreflector. Therefore, the methodology of the research assumes conducting a two runs. The first series consist of measurements in which the retroreflector is motionless located (no factor) while the second series consist of measurements which the angular displacement of retroreflector only occurs (presence of the test factor). It has been established that representative sample for each series will be a fiftyfold measurement.
The first tested retroreflector had housing sphere with a diameter of 1.5 inch. For the study of angularly displaced retroreflector had to ensure such mounting that unequivocally remain housing sphere in a fixed position despite the performed revolutions. For this purpose an oval

base with three steel balls with low shape error was created. This would allow to stabilize the retroreflector on the holder always in a three points despite the rotation assuming that housing sphere is perfectly round. Since in practice, it is known that this sphere has some form error. Regarding to this the roundness deviation should be measure in order to estimate the impact of the error derived from the retroreflector fixing. The measurement was made on the Taylor-Hobson Talycenta system for measuring roundness deviation with a measurement uncertainty less than 0,5 µm. Deviation measurements in three different planes of a sphere were performed. Results were oscillated between 1 and 1,5 µm. After the analysis of the worst possible retroreflector positions on the holder can be concluded that the sphere center point offset error derived from cooperation sphere with the holder shall not be greater as 0,5 µm. Considering the MPE equation of system, its intended use and the results, this value was considered as negligible.

As the results of individual measurements x, y and z coordinates of Cartesian coordinate system were obtained. In the calculation of these coordinates angular encoders were participated and their indication error affect to the final results. Because the encoders error saddle results for the two series still should be regarded that the measurement conditions have not changed and so the procedure is correct. However, in order to consider the results not burdened with encoder errors additional measurements were conducted. In addition to the coordinates also the distances which enter directly as a parameter in a spherical system were examined.

For the better overview additional tables with increments of parameters were prepared (Table 3 and Table 6). These values are differences in the results of fixed and rotating retroreflector series. For each table showing the results of a series measurement uncertainties of each of the measured parameters were attached calculated according to the A method.

The following tables show the results for the 1,5 inch retroreflector. All values are given in mm.

Table 1. – *Results obtained for fixed 1,5 inch SMR*

Fixed position	x	y	z	distance
Standard deviation	0,00597	0,00077	0,00363	0,00388
Range	0,0267	0,0033	0,0157	0,0160
Uncertainty	0,00084	0,00011	0,00051	0,00055

Table 2. – *Results obtained for rotated 1,5 inch SMR*

Changes in orientation	x	y	z	distance
Standard deviation	0,00709	0,00423	0,00844	0,00826
Range	0,0341	0,0206	0,0409	0,0293
Uncertainty	0,00100	0,00060	0,00119	0,00117

Table 3. – *Increments between experiment stages for 1,5 inch SMR*

Increments between states	x	y	z	distance
Standard deviation	0,00111	0,00345	0,00481	0,00438
Range	0,0074	0,0173	0,0252	0,0133

The same procedure was repeated for the second retroreflector 0,5 inch in order to systematize information. It would be problematic to use the same fixing system as the retroreflector 1,5 inch due to its small size and weight. A small oval magnetic base was applied in order to stabilize retroreflector. This is a derogation from the constant measurement conditions principle by modifying the fixing system therefore the results can not be compared with each other directly. However, the nature of the increments can be compared in both tests as a indicative comparison. Also, for the small retroreflector shape deviation was measured. The measurement results performed by Talycenta system oscillate around 1.5 µm. Error caused by fixing system has been estimated at a level not exceeding 10 µm. Despite the fact that this value is relatively high from the perspective of the previous study, that was assumed negligible role of fixing error in comparison with the values of acquired data.
The following tables show the results for the 0,5 inch retroreflector. All values are given in mm.

Table 4. – *Results obtained for fixed 0,5 inch SMR*

Fixed position	x	y	z	distance
Standard deviation	0,0095	0,0013	0,0050	0,00330
Range	0,045	0,007	0,030	0,0167
Uncertainty	0,0013	0,0002	0,0007	0,00047

Table 5. – *Results obtained for rotated 0,5 inch SMR*

Changes in orientation	x	y	z	distance
Standard deviation	0,0090	0,0031	0,0176	0,01396
Range	0,044	0,012	0,069	0,0608
Uncertainty	0,0013	0,0004	0,0025	0,00197

Table 6. – *Increments between experiment stages for 0,5 inch SMR*

Increments between states	x	y	z	distance
Standard deviation	-0,00050	0,00189	0,01258	0,01066
Range	-0,001	0,005	0,039	0,0441

4. Conclusions

Firstly, it should be noted that all the measurement uncertainty are sufficiently small relative to the obtained values that the test results can be regarded as an objective in the range considered in the work. The biggest measurement uncertainty of one parameter is 2,5 μm (Table 5) while the remaining ones are much lower.

In the analysis of the coordinates can be concluded that in fixed retroreflector series the largest dispersion parameters were observed on the X-axis and the smallest on the Y-axis while in a rotating retroreflector series the largest dispersion were observed on the Z-axis and the smallest on Y-axis. This relationship can be observed for both size of the retroreflector. Analyzing increment values it can be seen that the biggest values are on Z-axis and the smallest values are on the X axis. Also in this case this relation corresponds to both the size of retroreflectors. Because of these relationships it can be draw a conclusion, firstly that these relations are valid regardless of the size of the retroreflector, and secondly it is premise about the possibility of comparing the results of research which uses various types of used retroreflector holders. This is obviously not irrefutable conclusion due to the use only two retroreflectors in the study but it can be the basis for further investigation.

The authors supposed that the results will be higher in a rotating retroreflector series and this is confirmed in the tables of increments (Table 3 and Table 6). Based on the research the assumption can therefore be confirmed that the change of the angular orientation of the retroreflector during measurements adversely affect on the system accuracy – larger impact of the retroreflector error on measurement uncertainty. Negative values on the X-axis (Table 6) suggest opposite conclusion but it should be noted that these values are very small in relation to the other – not more than 1 μm and could be the result of a residual error of performed results. Uncertainty of parameters which negative values were calculated are greater than 1 μm therefore, would be appropriate to classify them as close to zero value.

Analyzing the parameters obtained from a laser interferometer the same conclusions can be drawn. Parameters of the distance exhibit the same character as the coordinates – both the standard deviation and the range increase during the rotation of retroreflector. Slight measurement uncertainty of distance result allows to confirm the correctness of the measurements.

That should be careful in drawing conclusions due to the fact that in the study were used only two retroreflectors, in addition on the same machine. However, the results could serve as a basis for the future research. Further investigation should include measurements on other Laser Tracker systems and using other retroreflectors. A good concept for future research would be a possible shift control of retroreflector after the rotation, for example, using Coordinate Measuring Machine.

Symbols

MPE	*Maximum Permissible Error*	*(mm)*
L	*length*	*(mm)*

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