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Danuta OWCZAREK, Ksenia OSTROWSKA, Jerzy A. SŁADEK
Laboratory of Coordinate Metrology, Faculty of Mechanical Engineering, Cracow University of Technology, Poland
danuta.owczarek@mech.pk.edu.pl, kostrowska@mech.pk.edu.pl, sladek@mech.pk.edu.pl

EXAMINATION OF OPTICAL COORDINATE MEASUREMENT SYSTEMS IN THE CONDITIONS OF THEIR OPERATION

Key words: optical coordinate systems, optical scanners, laser triangulation, structural light, algorithms for work with points cloud, structural resolution.

Abstract: Intense advancement of optical measurement techniques, which is accompanied by the development of new calibration technologies and accuracy assessment methods determine new fields of necessary research and verification tests. In the Laboratory of Coordinate Metrology of the Cracow University of Technology (LCM CUT), works have been conducted for years dedicated to optical coordinate measurements. It was observed that certain external factors have a dominating influence in the context of value of received results. As a result, a cycle of research in operational conditions was performed, and the most important of them undergo a thorough analysis for exerting influence on the measurement result.

Badanie optycznych współrzędnościowych systemów pomiarowych w warunkach ich eksploatacji

Słowa kluczowe: współrzędnościowe systemy optyczne, skanery optyczne, triangulacja laserowa, światło strukturalne, algorytmy do pracy z chmurą punktów, rozdzielczość strukturalna.

Streszczenie: Intensywny rozwój techniki pomiarów optycznych, któremu towarzyszy opracowywanie nowych technologii wzorcowania oraz metod oceny dokładności pomiaru, wyznacza nowe obszary koniecznych badań i testów weryfikacyjnych. W Laboratorium Metrologii Współrzędnościowej na Politechnice Krakowskiej (LMW PK) od lat trwają prace poświęcone współrzędnościowym pomiarom optycznym, podczas których zaobserwowano dominację pewnych czynników zewnętrznych w kontekście wartości otrzymanego wyniku. W następstwie przeprowadzono cykl badań w warunkach eksploatacyjnych i poddano szczegółowej analizie kluczowe z nich pod kątem wywierania wpływu na wynik pomiaru.

Introduction

The Coordinate Measurement Technique (CMT) originates from the necessity of performing complex measurements of outlines with different curvature and indirect measuring methods. Due to its versatility, the CMT has a broad use in practically every branch of industry. Currently, it is used in the automotive industry, the aerospace industry, the military industry, and the medical industry, as well as in archaeology, the protection of historical monuments, and even in show business (computer animations). CMT is based on contact or contactless measurement of points on the surfaces of objects and uses the Coordinate Measurement Machine (CMM) for this purpose, which is shown in literature [1–5].

Currently noticeable is the significant expansion of the field of the application of optical coordinate measurement systems. Their intense advancement, which is accompanied by the development of new calibration technologies and accuracy assessment methods, determine new fields of necessary research and verification tests. In the Laboratory of Coordinate Metrology of the Cracow University of Technology (LCM CUT), works have been conducted for years dedicated to optical coordinate measurements. The research is oriented on the recognition of the influence of specific factors that occur at optical coordinate measurements and on the still insufficiently examined issue of measurement uncertainty, without the provision of which the sole measurement result has a minimal meaning from the metrological point of view. The authors of this development have observed a dominance of certain external factors in the context of result values. As a result, a cycle of research in operational conditions was performed, and the influence values of specific factors were determined.

1. Optical coordinate measurement methods currently used in production engineering

The dynamic advancement of electronics, optoelectronics in particular, as well as the advancement of microprocessor techniques and computing power of computers gave the possibility of progress in techniques using light as a data carrier. The contactless measurement systems are mostly based on the measurement of light reflecting off the surface of the examined object. Currently, numerous optical methods are applied to identify spatial objects. Their basic division covers active and passive methods. Passive measurement methods are used in natural light conditions, while the active methods use additional light sources: non-coherent (project and projectors) and coherent (lasers) (Fig. 1). The use of additional light sources in passive methods, in order to highlight characteristic points to speed up the measurement process or collect a bigger collection of points, is also practiced. However, the role of introduced lighting in this situation is completely different from the role in active methods [6, 7, 8].

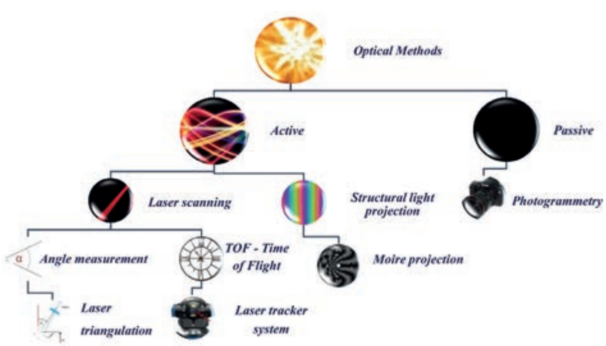


Fig. 1. Division of optical methods
Source: Authors [8].

2. Characteristics of optical coordinate systems used in research

In the Laboratory of Coordinate Metrology, works have been conducted for years with the purpose of examining the occurring dependencies and to improve the accuracy of measurements performed with the use of optical systems [8–12]. Research is performed on modern systems that are the measurement base of LCM and which also include the system made available to the Laboratory under agreements. Three of the mentioned systems are presented in Fig. 2: The Nikon Metrology brand LK V10.7.6 SL Coordinate Measuring Machine, The Romer Absolute Arm Coordinate Measuring Machine (both CMM and the AA CMM are equipped with probe heads operating by way of laser triangulation), and The Smarttech 3D SCAN3D qualify 10 Mpi optical system operating with the use of white light. The measurements are performed according to the procedures developed on the basis of standards and the longstanding experience of the accredited LCM staff [8–9].

The LK V 10.7.6 **Coordinate Measuring Machine** is a product of the Nikon Metrology Company. It is located in the LCM as a result of cooperation with the Smart Solutions Company. The machine is used both in contact and contactless measurements. For research on the LK V 10.7.6 Coordinate Measuring Machine, Focus software dedicated for contactless quality control with the use of laser scanning probe heads is used. The tests were performed on three types of Nikon probe heads selected due to the precision and specificity of work, i.e. LC60Dx, LC15Dx, and InSight L100 that are used in surface measurements, in reverse engineering, and in the inspection of moulds, tools, pressed sheets, and turbine blades [W1]. The specifications of the L100 probe head [W1] are presented in Table 1.

Table 1. L100 probe head specification [W1]

Model	Field of View / mm		MPE_P (1σ)	Amount of points per 1 sec
	Width	Depth		
L100	110	60	6.5 µm	200 000

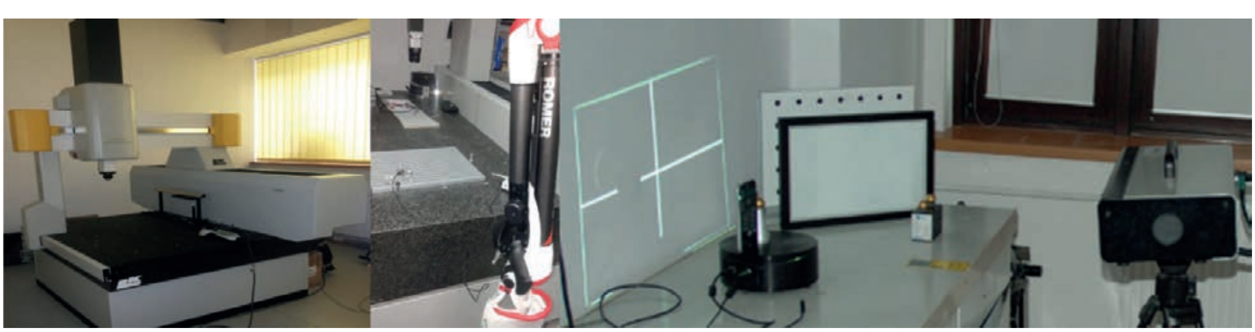


Fig. 2. Nikon Metrology brand LK V10.7.6 SL Coordinate Measuring Machine, b) Romer Absolute Arm CMM, c) SMARTTECH 3D SCAN3D qualify 10 Mpi system
Own work [8, 11].

In the Laboratory of Coordinate Metrology, research works [PB1, PB2] in the field of **Articulated Arms CMMs** [13–15] have been conducted for years. The articulated arms are currently one of the most often used solutions in the production environment. The advantage of arms is the ability to use them in various measurement tasks, because they are handheld devices, which are portable and easy to use. The probe heads most often used in arms are the solid-contact and contactless probe heads, i.e. laser scanning probe heads. Currently, in LCM, the ROMER Absolute Arm CMM (Fig. 2) integrated with a laser scanner is used. Its technical specifications are included in Table 2 [W2].

Table 2. Articulated Arm with integrated measuring probe head technical specifications [W2]

Model	Measurement scope / mm			Accuracy / µm	Amount of points per 1 sec
	X	Y	Z		
7320SI (R2)	2000	2000	2000	±79	50 000

In the Laboratory of Coordinate Metrology, works also dedicated to the determination of the measurement uncertainty with the use of optical systems operating **on the basis of structural light** [10] are performed. As a result of cooperation with the Smarttech Company, the LCM staff conducts research by using a "Scan3D Qualify" 3D Scanner (Fig. 2). The technical specifications of 3D Qualify Scanner are included in Table 3.

Table 3. 3D scanner technical specifications [W3]

Model	Measurement scope / mm^2 (white or blue light)	Accuracy / µm	Amount of points per 5 sec
3D Qualify	80 x 100 – 1200 x 1600	to 10	to 10 000 000

3. Optical coordinate measurement systems in variable conditions of their operation – key factors determining the result

During the conducted research, the dominating influence of certain external factors on the value of measurement results was observed when using optical coordinate measurement systems. A cycle of research was planned and focused on the examination of key factors from them, starting from the ones generating the biggest errors, including lighting, resolution, software, operator, and the measurement method.

Figure 3 presented below shows the Ishikawa diagram developed for the measurements performed with the use of optical coordinate systems that shows

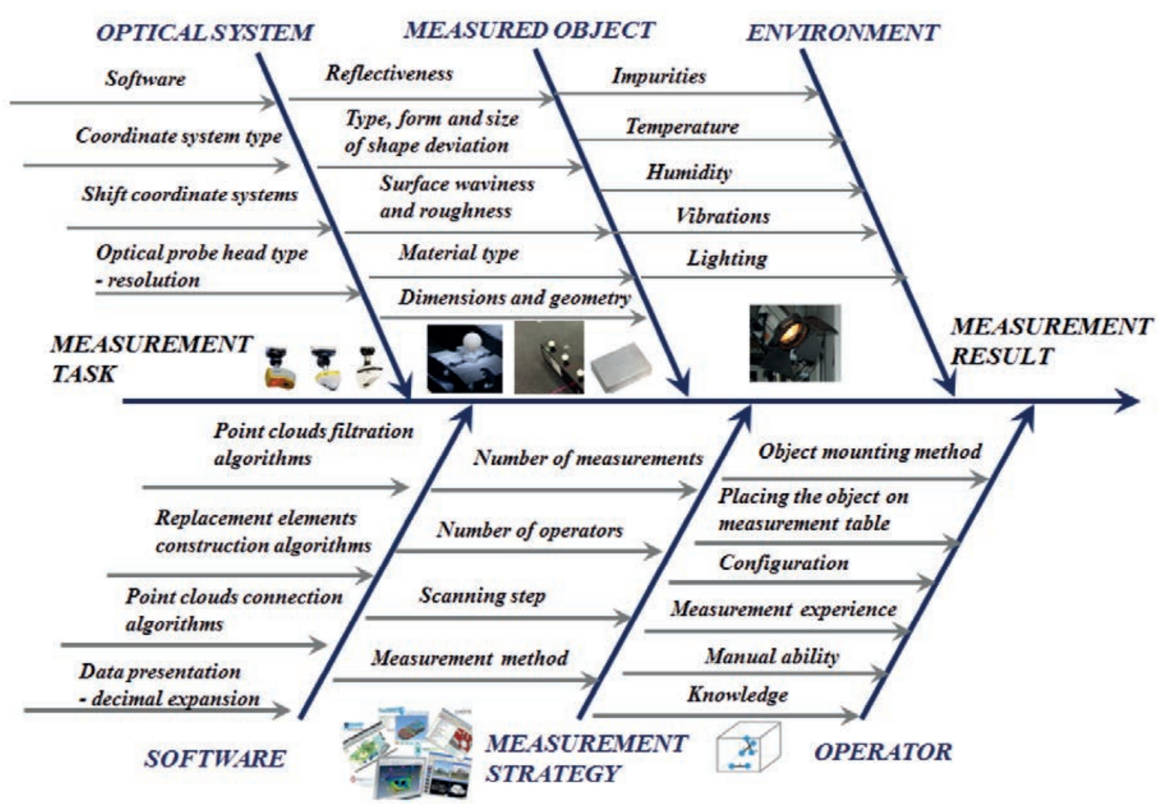


Fig. 3. Ishikawa Diagram – external factors influencing the result of optical coordinate measurement
Source: Authors [8, 11, 17].

the main sources of errors that determine the result. It can be observed that certain external factors that mutually overlap, e.g. used software, is both a part of the measurement system and a separate part of the diagram (due to the impact force), and the operator's knowledge and the experience at work in a given software also have a significant meaning. Similarly, the type of probe head, reflectiveness, and lighting are strongly connected to each other. Because of these factors, the above diagram should be treated as a certain representation as a whole with the awareness of the bigger or smaller correlation of specific factors [8].

In case of optical systems, it should be expected that the operator's experience and reliability has the biggest effect, because it has an influence on both the levelling the influence of environment (e.g., lighting) and influences originating from the measured object (e.g., reflectiveness), as well as the development of results from the so-called "points cloud" [16] and, which is very important, the selection of the measurement system to the chosen task or measurement method and program for data analysis, along with key parameters.

3.1. The influence of lighting on measurement using an optical coordinate system

In the Laboratory of Coordinate Metrology, tests were performed in order to check the behaviour of optical coordinate systems when two key parameters of ambient light change, i.e. the colour temperature and luminous flux intensity. For this investigation, a system operating by way of structural light and a system operating by way of laser triangulation were chosen. The purpose was to determine to what degree the ambient light, i.e. the change of its two parameters mentioned above influences the measurement result and assessment on the basis of research results and the usefulness of optical machinery in the measurements in non-laboratory conditions [8].

The research procedure covered the organisation of research strategy adapted to selected optical coordinate systems, the determination of data acquisition form method, the development of measurement procedures adapted to both measurement positions, the development of results, and the formulation of findings. The research positions consisted of the following elements: the position for measurements with the use of structural light – Smarttech 3D brand "Scan3D Qualify" 3D scanner with Mesh 3D software, and the position for measurements with the use of triangulation based laser scanning – ROMER Absolute Arm CMM integrated with laser scanner with PC-DMIS Reshaper – Hexagon Metrology software, and, for the generation of well controlled ambient light, the Arri Daylight Compact 1500 HMI Fresnel 6000 K lamp, Tungsten Fresnel 2000 W Junior 3200 K lamp, Arri lamp Regulator: HMI Electronic Ballast 575/2 Kw Freesun, Tungsten lamp Regulator: 1-channel Agat KRC-1 (1 x 2,2 kW), Pyrometer Voltcraft IR-1200-50D, 50:1, and Luxmeter Sonopan L-50 [8].

Tests were performed with the use of 25 mm reference sphere (LMW_OPT_25) with a diameter of 24.9805 mm and 0.0013 mm shape error. The reference sphere is made of steel with a special AuNPs covering. The sphere had been covered with white powder before tests. The sphere was illuminated by using two separate lamps with different colour temperatures. The incandescent lamp emitted a light with warm colour (yellow) with a colour temperature of 3200 K, while the gas-discharge lamp emitted a light of white colour (light similar to daylight) with a colour temperature of 6000 K. During the measurements, the intensity of lights was changed in the scopes of 0 (without lighting), 120, 2000, and 4000 lx, and its measurement was performed using a luxmeter. The measurements were repeated in a sequence of six times for every standard, every lamp,

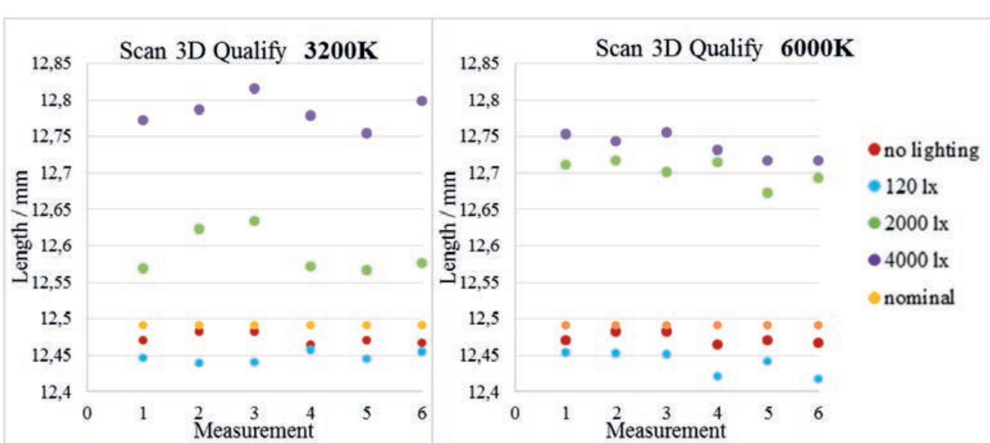


Chart 1. The change of radius of reference sphere depending on the intensity of luminous flux for 3200 K and 6000 K lamps for the "Scan 3D Qualify" 3D scanner

Source: Authors [8].

and every light intensity. During the performance of tests, special attention was paid to levelling the external light sources and limiting the influence of lamps on the temperature of measurement standard [8].

Below, a summary of charts is presented showing the changes of the reference sphere radius and the value of shape error and the amount of collected points for three scopes of light intensity between the two lamps with colour temperatures of 3200 K and 6000 K, respectively, for the "Scan 3D Qualify" 3D scanner and for the RS-2 scanning probe head [8].

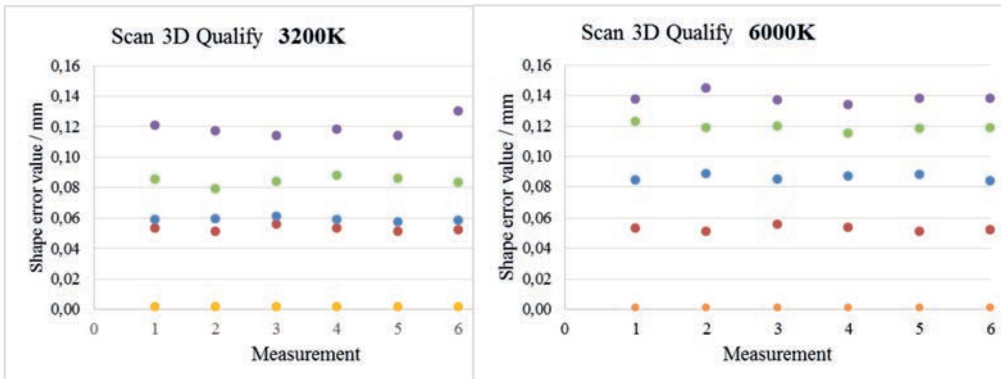


Chart 2. The change of shape error depending on the intensity of luminous flux for 3200 K and 6000 K lamps for the "Scan 3D Qualify" 3D scanner

Source: Authors [8].

On the Chart 1 is shown the change of the radius value of the reference sphere for two different colour temperatures in relation to the nominal value. The results closest to the actual value were received at the measurement performed without lighting and then for the 120 lx light intensity, regardless of the colour temperature. An increase in shape error was observed along with the increase of light intensity (Chart 2), which may be caused by the decreasing amount of acquired points. However, on Chart 3, it can be observed that the decrease of acquired points is related to the increase of light intensity, where the tendency is stronger for the higher colour temperature [8].

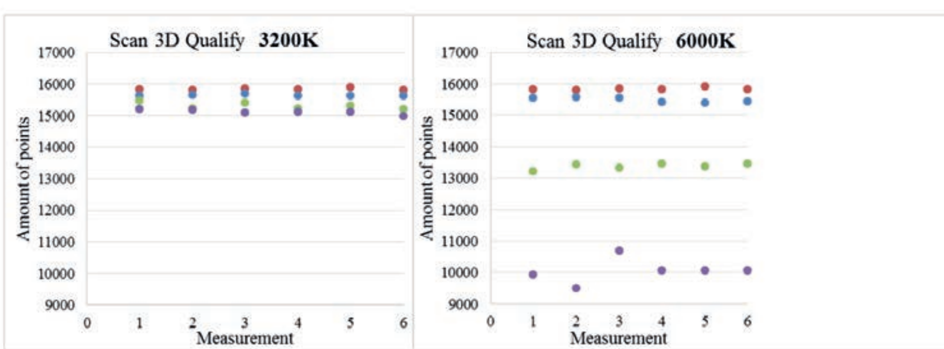


Chart 3. The change of amount of acquired reference sphere points depending on the intensity of luminous flux for 3200 K and 6000 K lamps for the "Scan 3D Qualify" 3D scanner

Source: Authors [8].

During tests, the settings of the scanner were kept constant for all measurements despite the changing illumination. Here, the situation is presented when the measured object was overexposed, which caused significant reflections on its surface. At the maximum light intensity value, they look like white or black spots on the scan picture (Fig. 4).

In the context of coordinate measurements using the laser triangulation method, the light intensity and colour temperature turned out to have a significantly smaller influence in relation to the measurements with white structural light. The acquired results of sphere radius (Chart 4), and shape error (Chart 5) at the change of conditions do not show significant differences. During

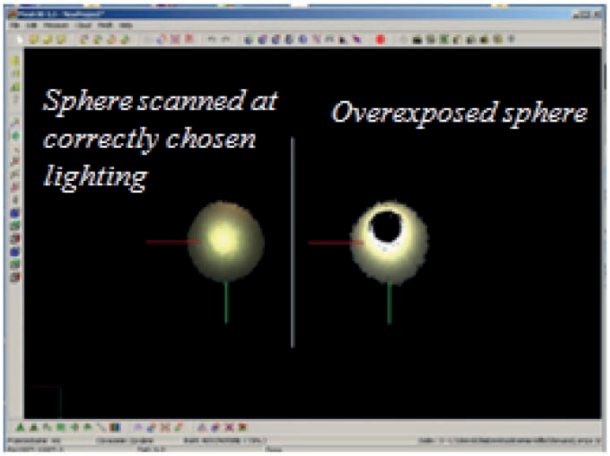


Fig. 4. Points cloud acquired from the scanning of the reference sphere at various lighting conditions
Source: Authors [8].

these tests, the settings of the probe head were also kept constant for all measurements, despite the changing illumination. The shape errors, along with the increase of intensity, increase by an insignificant value when illuminated with both white and yellow colour. When measured using the RS-2 laser probe head, the influence of variable lighting conditions on the size of the points cloud cannot be clearly shown [8].

The performed tests have shown an increased measurement accuracy when using the structural light, but only when appropriate lighting conditions are maintained, so only when the external light sources are limited to a minimum. At variable lighting conditions, the more correct results were acquired when scanning using the laser triangulation method, which simultaneously confirms the validity of commonly used Articulated Arms equipped with probe heads of this type in a production environment. In the context of the relevance of the influence originating from the applied lighting, the performed research confirms the influence of lighting on the measurement result, especially when using optical systems of structural light (similar results can be expected for corresponding projections of white light) [8].

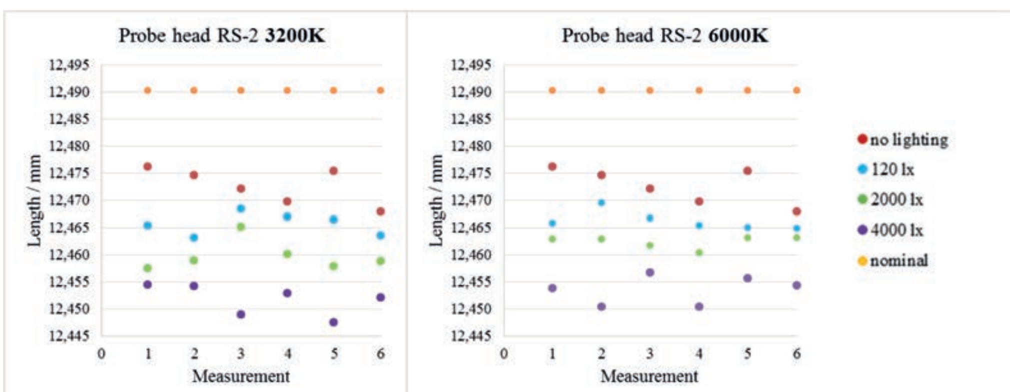


Chart 4. The change of radius of reference sphere depending on the intensity of luminous flux for 3200 K and 6000 K lamps for the RS-2 scanner probe head
Source: Authors [8].

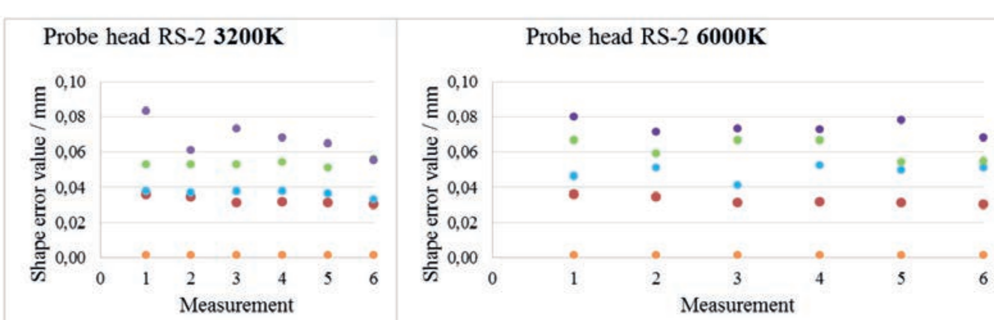


Chart 5. The change of shape error depending on the intensity of luminous flux for 3200 K and 6000 K lamps for the RS-2 scanner probe head
Source: Authors [8].

3.2. The influence of structural resolution on measurements using the optical coordinate system

The structural resolution is strongly connected to the scanning speed, and it is understood by the authors as the amount of collected points of a given surface during one pass of the measurement probe head. It has been decided that the resolution understood in this way will be called "structural resolution." During the research, the results of measured features as a function of the changing amount of points have been acquired [8].

In the research, the standards presented in Table 4 were measured using for the Nikon LK V-SL10.7.6 CMM equipped with a NIKON LC15Dx laser probe head (thanks to the selection of one probe head type, the burdening of results with errors originating from the construction of probes was avoided). The point clouds varying in terms of the amount of points were acquired through the change of *Stripe distance* parameter value. This parameter indicates the distance between subsequent shown lines, on which the coordinates of points are collected [8].

Table 4. Standards used for tests – values from the certificates of calibration [8]

Standards used in tests		Measured feature	Measured value / mm	Measurement uncertainty / mm	Material and surface condition
Flatness standard		Flatness deviation	0.00170 mm	0.0006 mm	Stell
Reference sphere		Diameter	24.9809 mm	0.0006 mm	Ceramics, application of white powder
		Shape deviation	0.0013 mm	0.0006 mm	
Ball-bar		Distance between ball centres	99.8773 mm	0.00066 mm	Ceramics, application of white powder

The performed tests were preceded by a series of initial measurements, and the purpose was to confirm the assumption that the amount of acquired points depends on the *Stripe distance* parameter. On Chart 6, the change of number of acquired points along with the change of the *Stripe distance* parameter is presented. As its value decreased, the density of shown lines increased, and, at the same time, the probe head registered a higher number of points [8].

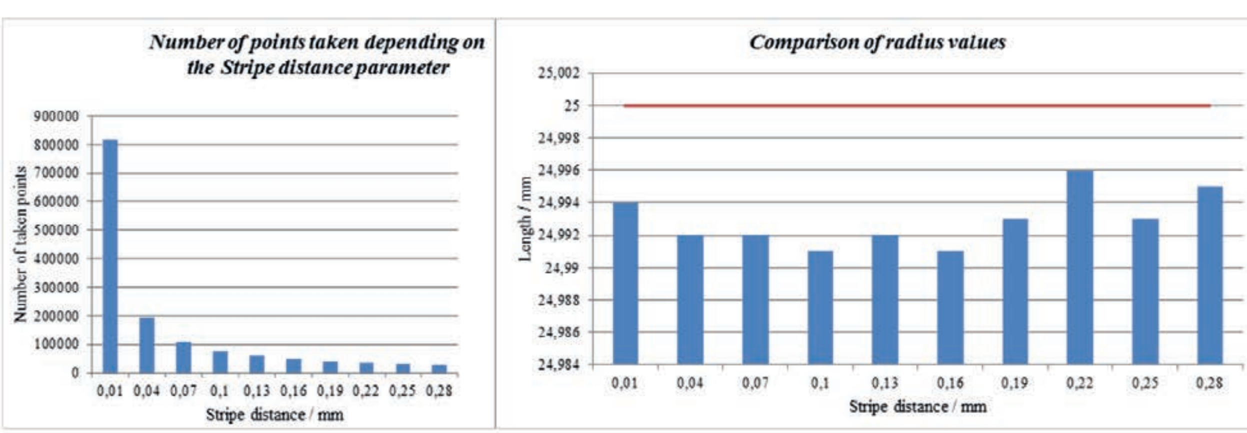


Chart 6. a) The number of acquired points in the function of Stripe distance parameter change, b) The value of diameter from measurement in relation to the nominal value (red line)

Source: Authors [8].

The initial tests have not shown a visible tendency of the influence of the amount of acquired points on the result quality (Chart 6). Only the result closest to the nominal value can be indicated at the value of the *Stripe distance* parameter of 0.22 mm. Nonetheless, in order to formulate clear conclusions, the previously mentioned cycle of tests that takes into account the series of measurements of selected standards (Table 4), i.e. three calculation methods (comparative, multi-positional, and OPTI-U) [2, 8, 10, 18], and the change of *Stripe distance* parameter in the scope of 0.05 mm, 0.125 mm, and 0.2 mm (Chart 7) was planned and conducted. Conclusions from the conducted research point to the generation of bigger errors at higher structural resolutions, i.e. at a higher density of points on a given surface. This regularity has also been observed during corresponding tests with the use of structural light systems. The increase of the number of points is accompanied by a higher probability of the occurrence of points originating from reflexes that distort the information about the actual dimensions of the object. At the smaller number of points on a given surface, the texture of cloud is simplified and the measurement goes quicker and smoother. For the performed measurements, the best results were acquired for the *Stripe distance* 0.125 mm parameter. In the tests, attention was paid to the influence of the operator, which significantly exceeds the influence of resolution. The operator "cleaned" the points cloud by indicating areas created due to the incorrect light reflection and then choosing the correct filtering algorithms. During the cloud cleaning stage, an attempt was made to apply a certain consequence when selecting the areas intended for removal. It was concluded that this activity is deciding in terms of the quality of received results [8].

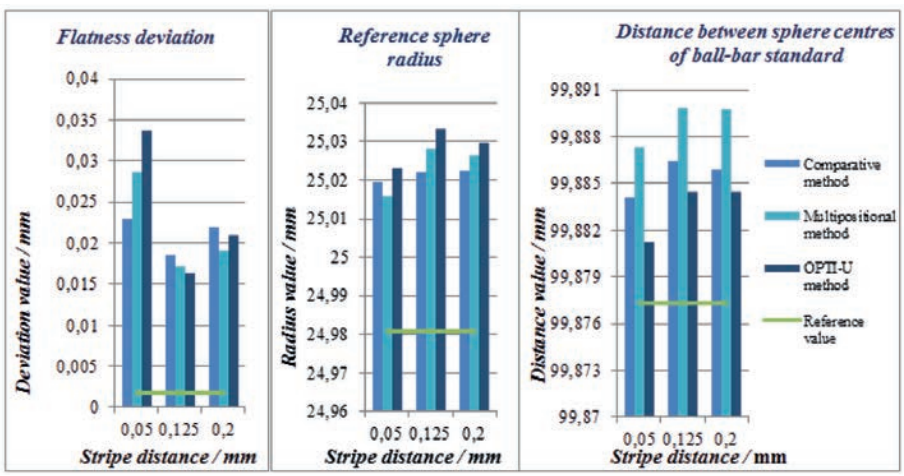


Chart 7. Summary of results of measured features in the function of Stripe distance parameter change along with reference to nominal values

Source: Authors [8].

4.3. The influence of the operator on the measurement using the optical coordinate system

4.3.1. The influence of factors originating from the applied filter algorithms on the measurement result

The influence of the operator, especially in the area of optical coordinate measurements, for years, has been considered as one of the key factors affecting the measurement result. It includes the operator's work with the measuring device and, to a significant degree, with the software (work with points cloud), i.e. the filtering of the points cloud performed by inexperienced operator may result in the loss of information on the actual shapes of the measured object. The research at LCM dedicated to the influence of the operator on the measurement result were started for the work of operator with the 3D Reshaper software and later were expanded to the work with Focus 10 software. The Focus 10 software offers three basic filtering options that operate on the basis of separate criterion and are characterised by specific properties [8, W1].

When using the *Scatter* filter (Fig. 5), the individual points that are away from others are removed. Around the points, zones with a given radius are constructed. The operator also sets the amount of points in a zone. The point will be removed, if the number of points within its zone is below the set value. When using the *Grid* filter (Fig. 5), the cloud area around the points is divided into small cubes with side length determined by the operator. In every cube, one representative point remains, which results in a points cloud with uniform density. In contrast, the *Curvature* filtration "thins out" points from flat areas and leaves them on the areas with bigger curvature. The filter has the automatic adjustment option, and the result of its application is a points cloud with a diverse density of points.

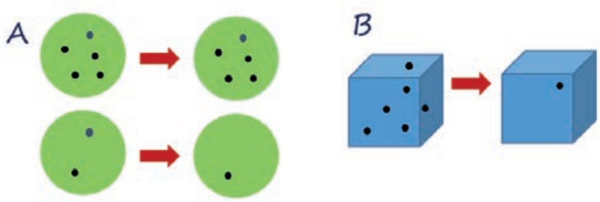


Fig. 5. Graphical interpretation of filters a) Scatter and b) Grid
Source: Authors, based on [W1].

The research of operator's influence on the measurement result was performed using the Focus 10 software for point clouds acquired from the measurement on LK V 10.7.6 CMM equipped with an LC60Dx linear scanner. During the research, the compilation of received point clouds using the available filtering options for the acquisition of standard's internal diameter was among the operator's tasks. During all filterings, the operator adhered to the amount of points in a cloud, while maintaining certain regularity and removing the similar amount of points when using all filters. At the beginning, there was 100% points, and, in every subsequent ten trials, the points were removed by every 5% (100% → 95% → 90% → 85% → 80% → 75% → 70% → 65% → 60% → 55% → 50%) (Chart 8) [8].

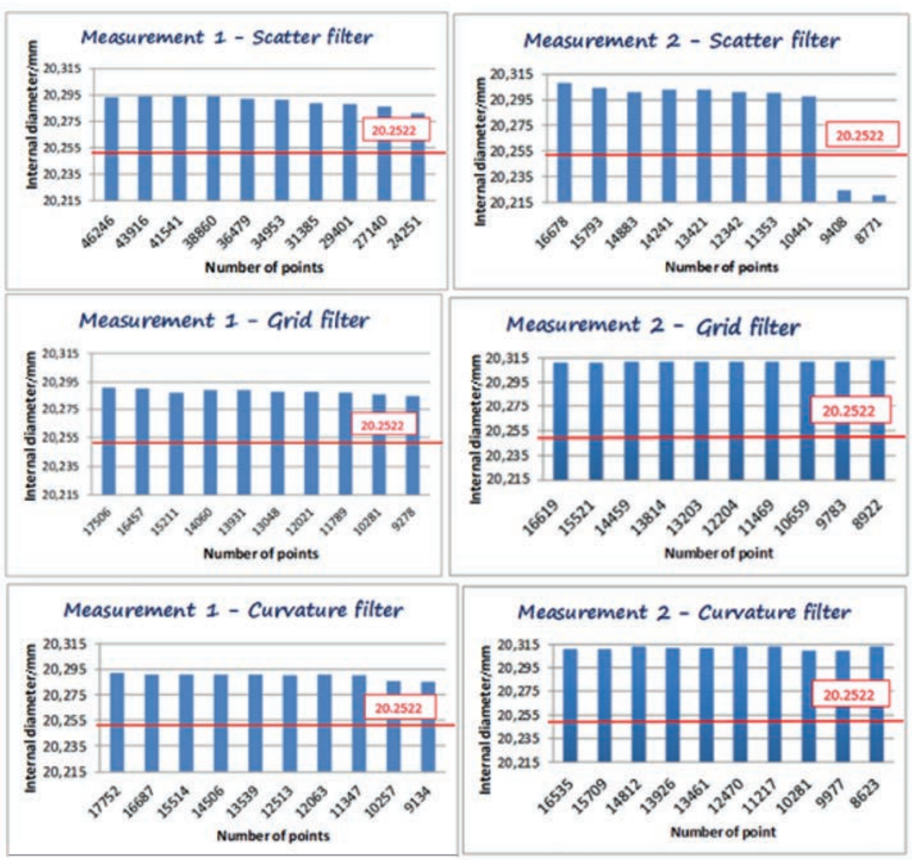


Chart 8. The internal diameter value of the standard in the function of decreasing amount of points along with the application of filters
Source: Authors.

The filtering changes the nature of input data without leaving the final inspection result without an influence. The biggest influence on the result has been observed during the application of the *Scatter* filter followed by the *Curvature* filter. The *Grid* filter turned out to be the least invasive. The change of the number of points causes the change of value for given elements indicated using the method of the least sum of squares (deviation). The influence of filtering has also been observed during corresponding tests for structural light systems. The standards and recommendations concerning the calibration of optical systems indicate the amount of points possible to remove and suggest the method for the generation of associated elements; however, the system calibration results performed by few operators significantly differ from each other. Therefore, it was decided to associate this influence to a greater extent with the operator rather than with the software itself. The optical measurement device, along with the operator and software, should be treated as a whole measurement system during the calibration [8, 14, 18, 19].

4.3.2. The influence of factors originating from the operator on the measurement result

When studying the influence of the operator on the measurement result, it has been decided to list the measurement results performed with the use of an Articulated Arm, which was equipped with both optical and contact probe heads, by using the elements of the R&R (*Repeatability and Reproducibility*) method. The R&R method consists of calculating the repeatability and reproducibility of measurements, where the repeatability (E.V.) depends on the measurement equipment and the reproducibility (A.V.) depends on the adopted variable conditions (the operator is treated as a variable factor). The measurements were performed using the AA CMM with a solid-contact probe head, and the results were developed in the PC-DMIS metrology software [W2]. Next, a similar measurement was performed using the AA CMM with integrated R2 triangulation probe head. As a result, in the co-operating 3D Reshaper software, a points cloud was acquired that was then imported into the GOM brand GOM Inspect software in which the data were developed. The R&R method parameters for the contact probe head were, respectively, E.V.% = 0.0310%, A.V.% =13.9950%, R&R% = 13.9951 and E.V.% = 0.2110%, A.V.% = 22.5700%, R&R% = 22.5701% for the optical probe head. Regardless of the applied probe head, the operator's influence is significant in both cases (this is justified by the fact that AA CMMs are handheld machines). Nonetheless, the almost two-fold increase of error originating from the operator after the connection of optical probe head is significant in the light of carried out contemplations [8, 20].

4.4. The influence of used software on the result of optical coordinate measurement

In LCM studies [9], the influence of algorithms used in metrology software on the development of measurement results were performed on the example of selected systems. The measurement was performed using the AA CMM optical system with an integrated optical probe head and according to the VDI/VDE recommendations [N1]. The results were developed in four different software packages dedicated to the surface analysis, i.e. 3D Reshaper [W4], Mesh 3D [W5], PolyWorks [W2], and PowerInspect [W6]. According to the recommendations [N1], in these studies, a reference sphere was used that was measured in 10 settings in the whole measurement space followed by a ball-bar type standard measured in 7 settings and a flatness standard in 6 settings. The standards used are metal, and the reference sphere and ball-bar have a special covering of AuNPs. Before tests, standards surfaces were covered with white powder.

The same clouds were developed in each of the four programs, and the probe head system error, length reading error, and flatness error (Chart 9) were indicated respectively and according to [N1]. It is possible to observe the close sphere construction algorithm using the method of the smallest sum of squares for software numbered 1 and 2 and, respectively, for software numbered 3 and 4. However, bigger differences occur between them. The biggest difference between the results is on the level even of 0.1 mm. Similarities in algorithms for Software 1 and 2, respectively, can again be observed for the length error. When determining the flatness error, the results for Software 3 significantly differ from the rest [8, 9].

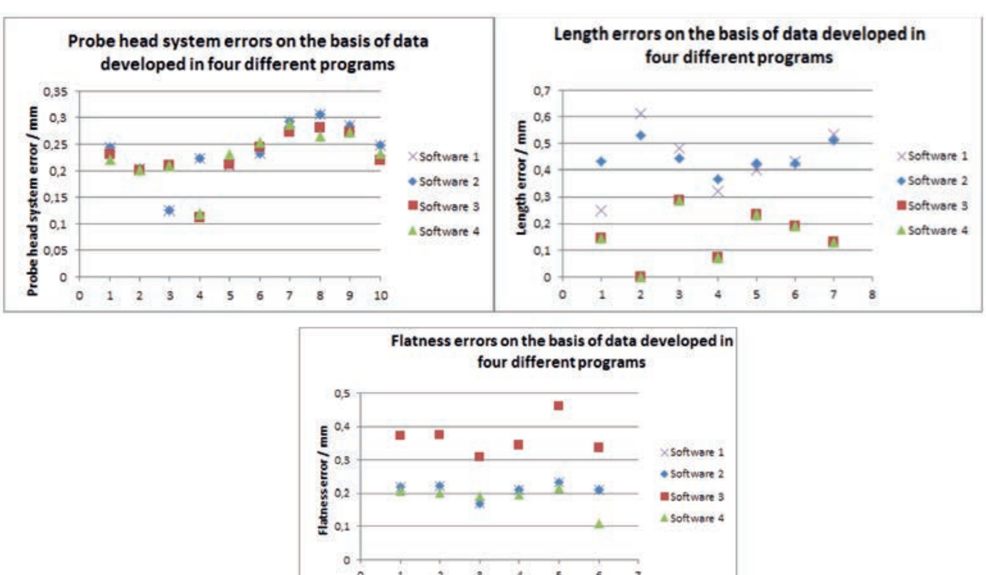


Chart 9. Influence of used software on the indication of error of a) probe head system, b) length, c) flatness [8, 9]
Source: Authors.

The acquired results have shown alarmingly large differences between each other while suggesting that, unless all software providers will unify their algorithms allowing mapping the element, even basic one such as a sphere or surface, the user of a given system will not be able to compare its accuracy with another system. In order to improve the quality, it is necessary to perform the validation of metrology software [8, 9].

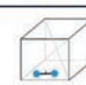
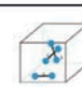
4.5. The influence of measurement method on the result of optical coordinate measurements

In order to check the influence of the measurement method on the result of optical coordinate measurement, studies with the use of a selected system were performed. The change considered only the measurement method (multipositional method, comparative method, and OPTI-U method that was developed at LCM and is dedicated for optical measurements) [8].

In the research, the standards presented in Table 6 (reference sphere, ball-bar, flatness standard) were measured using for the Nikon LK V-SL10.7.6 CMM equipped with a NIKON LC15Dx laser probe head and acting according to the methods used at LCM.

On Chart 7, significant changes in the results are visible at the change of measurement method while maintaining the other measurement conditions. The biggest acquired differences reach up to 0.01 mm for the measurement of sphere diameter (comparative method 25.022 mm, OPTI-U method – 23.032 mm) and flatness deviations (comparative method – 0.023 mm, OPTI-U method – 0.033 mm). In both cases, the comparative method gave a result closer to the nominal value. However, the biggest acquired difference for the distance measurement is on the level of 0.006 mm (multipositional method – 99.887 mm, OPTI-U method – 99.881 mm), and, in this series of measurements, the results closest to the nominal value were acquired using the OPTI-U method. And so, it can be said that a given method for the set measurement parameters will result in closer/further results in relation to the nominal value. Similarly, the relevance of used method has been observed in studies performed with the use of structural light systems. Thus, the task of the operator is to choose the correct method using experience and expert knowledge [8].

Table 6. Optical measurement accuracy assessment methods used in LCM [8]

Method	Number of settings		Number of repeats at a given arrangement		Orientation of object and standard in the measurement space
	Object	Standard	Object	Standard	
Multipositional	4	4	3	3	
Comparative	1	3	10	10	
OPTI-U	3	3	6	3	

Conclusions

The optical coordinate measurement systems have an increasingly large scope of use in industrial conditions due to the speed and uncomplicated nature of work. However, their limitation is, in case of systems the result of which are point clouds, the lower accuracy in comparison to contact systems. The performed studies in the operation conditions of optical systems allowed one to identify certain regularities concerning the received results. The structural light projection method is characterised by the increased accuracy, while maintaining appropriate lighting conditions; however, only when the external light sources are limited to a minimum. At variable conditions, it is beneficial to scan using the laser triangulation method, which also confirms the validity of the common use of arms equipped with probe heads of this type in the production environment.

At the same time, the higher structural resolution interpreted as a bigger density of points on a given surface contributes to the generation of greater errors. Along with the increasing number of points, the probability of occurrence of points originating from reflexes that distort the information about the actual dimensions of the object also increases. At the smaller number of points on a given surface, the texture of the cloud is simplified and the measurement goes quicker and smoother. It is necessary to optimally choose the correct measurement probe head parameter settings to the performed task.

Moreover, the operator has a significant influence on the measurement results, both during the operator's work with the measurement device and, to a significant degree, with the software (measurement result in the form of points cloud), because the filtering of the points cloud performed by an inexperienced operator may result in the loss of information on the actual shapes of the measured object. A clear influence of software on the measurement result performed using optical coordinate system is noticeable. The filtering changes the nature of input data, thus causing an influence on the final measurement result. The change of the number of points causes the change of the value for given elements indicated using the method of the least sum of squares. Unless all software will be validated, the user of a given system will not be able to compare its accuracy with another system.

The object measurement results acquired while maintaining the constant environmental conditions, and the ones acquired using various measurement methods (multipositional method, comparative method, OPTI-U method), also significantly differ from each other.

The performed studies and formulated conclusions draw a broad area of subsequent studies and analyses in order to improve the accuracy of measurements performed using the optical coordinate systems. Further works are subject to the determination of the size of coefficients for presented factors in the context of their influence on the optical systems' measurement uncertainty. The performed studies and analyses presented in [8] focused around the statistical analysis and multiple regression have allowed the determination of the level of influences on the uncertainty respectively for measurement method – 6% and for the CMM – 9% during the mentioned studies turned out to be decisive the influence of the measured object itself – 49%, its size – 7%, and measured feature – 18%. The mentioned studies are dedicated to the development of uncertainty in models of optical measurements estimation, the special matrix of intelligent selection, and the parametric method for calculating the measurement uncertainty on the basis of significant knowledge about specific factors. These issues are currently developed at LCM, and their presentation is planned in the upcoming cycle of publications.

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References

1. Augustyniak M., Baczewski M., Andrzejewski J.: „Wykorzystanie współrzędnościowej techniki pomiarowej w badaniach tworzyw sztucznych", Pomiary Automatyka Robotyka, 2012.
2. Sładek J.: „Coordinate Metrology – Accuracy of Systems and Measurements", Springer, 2016.
3. Jakubiec W., Malinowski J.: „Metrologia wielkości geometrycznych", WNT, Warsaw 2004.
4. Jakubiec W., Płowucha W., Starczak M.: „The estimation of coordinate measurements uncertainty in industrial conditions", International Scientific Conference Coordinate Measuring Technique, Akademia Techniczno-Humanistyczna w Bielsku--Białej Zeszyty Naukowe 22, Bielsko-Biała 2006.
5. Ratajczyk E.: „Współrzędnościowa Technika Pomiarowa" Oficyna Wydawnicza Politechniki Warszawskiej, Warsaw 2005.
6. Kupiec M.: „Optyczno-stykowa metoda pomiarów współrzędnościowych", PhD Thesis, Cracow University of Technology, Cracow 2007.
7. Schwenke H., Neuschaefer-Rube U., Kunzmann H., Pfeifer T.: „Optical methods for dimensional metrology in production engineering", CIRP Annals: 51, 2002.
8. Owczarek D.: "Model niepewności we współrzędnościowych pomiarach optycznych" – monograph, Cracow University of Technology, Cracow 2017.
9. Ostrowska K., Szewczyk D., Sładek J.: „Wzorcowanie systemów optycznych zgodnie z normami ISO i zaleceniami VDI/VDE", Technical Transactions, 2012.
10. Ostrowska K., Szewczyk D., Sładek J.: „Determination of geometric elements measurement uncertainty with the use of optical system operating based on structured light", XIth International Scientific Conference – Coordinate Measuring Technique, Szczyrk 2014.
11. Owczarek D., Ostrowska K., Harmatys W., Sładek J.: „Estimation of measurement uncertainty with the use of uncertainty database calculated for optical coordinate measurements of basic geometry elements", Advances in Science and Technology Research Journal, t. 9, 2015.
12. Sładek J., Ostrowska K., Kohut P., Holak K., Gąska A., Uhl T.: „Development of a vision based deflection measurement system and its accuracy assessment", Measurement 46, 2013.

13. Ostrowska K., Gąska A., Sładek J.: „Determining the uncertainty of measurement with the use of a Virtual Coordinate Measuring Arm", International Journal of Advanced Manufacturing Technology, t. 71, nr 1–4, s. 529–537, 2014.
14. Sładek J., Ostrowska K., Gąska A.: „Modeling and identification of errors of coordinate measuring arms with use of metrological model", Measurement 46, 2013.
15. Ostrowska K.: „Ocena dokładności pomiarów realizowanych przy zastosowaniu Współrzędnościowych Ramion Pomiarowych", PhD Thesis, Cracow University of Technology, Cracow 2009.
16. Ostrowska K., Gąska A., Szewczyk D., Sładek J.: „Determination of factors affecting errors of measurement done using optical scanners" – Conference proceedings – 11th International Symposium on Measurement and Quality Control, 2013.
17. Owczarek D., Ostrowska K., Sładek J., Gąska A., Harmatys W.: „Parametric method for estimation of the uncertainty of multi- sensor coordinate measurement with the use of intelligent matrix", IMEKO XXI World Congress, Praga 2015.
18. Ostrowska K., Gąska A. Szewczyk D., Sładek J.: „Determination of uncertainty of measurement done using optical scanners" – Conference proceedings – 11th International Symposium on Measurement and Quality Control, 2013.
19. Baldo C.R., Donatelli G.D.: „Measurement uncertainty combined with the model of product and measurement realization in 3D Metrology", XX IMEKO World Congress Metrology for Green Growth, Busan, Korea, 2012.
20. Ostrowska K., Szewczyk D., Sładek J.: „Determination of the operator's impact on the measurement done using coordinate technique", Advances in Science and Technology – Research Journal, vol. 7, no. 20, 2013.
21. [W1] www.nikonmetrology.com.
22. [W2] www.hexagonmetrology.pl.
23. [W3] www.skaner3d.pl.
24. [W4] www.3dreshaper.com.
25. [W5] www.smarttech.pl.
26. [W6] www.autodesk.com.
27. [PB1] N505 255935 „Metoda oceny dokładności pomiarów realizowanych redundantnymi systemami współrzędnościowymi (RSW)".
28. [PB2] LIDER/024/559/L-4/12/NCBR/2013 „System Oceny Dokładności Pomiarów Współrzędnościowych On-Line Realizowanych Urządzeniami Redundantnymi".
29. [N1] VDI-VDE-2634 Blatt 3:2008-12 Optische 3-D-Messsysteme – Bildgebende Systeme mit flächenhafter Antastung in mehreren Einzelansichten.