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ELEMENTS OF SOFTWARE INTEGRATION OF PRODUCTION SYSTEMS IN INDUSTRIAL PRODUCT CONTROL AND DIDACTICS

The article presents the method that is used to educate students pursuing a course in Machine Design Technology. The implementation of contactless measurement technology, which is becoming increasingly popular in industrial product control, was described. The sample part subjected to dimensional control was the fastening block of a 3R system electrode. Dimensional control in order to map some geometrical features of the part was conducted on a station equipped with a coordinate measuring arm and included contact-free verification of exterior dimensions.

1. INTRODUCTION

Broadening the range of preparing an engineer for work in industry results from the appearance of new solutions in production systems. Mastery of modern techniques, methods, and tools that make it possible to raise the effectiveness and efficiency of production tasks is becoming indispensable.

Dimensional control plays an important role at every step of product manufacturing as well as at its conclusion. Universal coordinate measuring systems that adapt exceptionally well to changing tasks, degrees of complexity, differing dimensional ranges, etc. are used more and more frequently to replace conventional means of measurement. At the same time, the quality of coordinate measurement is very strongly dependent on the human factor, that is, on the method of carrying out measurements, e.g. through the selection of a measuring strategy, as well as on the method of interpretation of the obtained results. In order to minimise the influence of these factors, all engineers working in a production environment – not just metrologists – must be equipped with the knowledge required to perform such tasks.

This article presents the method that is used to educate students pursuing a course in Machine Design Technology at the Metrology Workshop of the Department of Production Systems. The implementation of contactless measurement technology, which is becoming increasingly popular in industrial product control, is described. The sample part subjected to

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dimensional control is the fastening block of a 3R system electrode. Dimensional control in order to map some geometrical features of the part was conducted on a station equipped with a coordinate measuring arm and included contact-free verification of exterior dimensions.

In order to emphasise the importance of the influence of certain factors on decision-making regarding the product compliance with requirements, a comparison and an evaluation of the quality of digital surface representation were conducted. The surface representation was prepared for the creation of a polygonal model by means of two software packages: the original PolyWorks 12.1.14 software, managing a measuring arm from the Innovmetric company, and Geomagic software from 3D Systems, that works with the arm as a ‘plug-in’.

2. COORDINATE MEASURING ARM

Modern coordinate measuring systems currently encompass an increasingly wider range of devices that differ in design, including conventional measuring machines, measuring arms, laser trackers, hybrid machines, centres, height gauges, and special measuring stations [1].

The dissemination and development of these instruments to determine a product’s geometrical shape results from the fact, that the idea realised in these tools – of interpreting dimensions as geometrical dependencies resulting from describing the body of a part into a coordinate system – is consistent with the concept underlying the generation of CNC machines. This idea has made it possible to integrate the processes of designing, production, and product quality control, where the medium for information exchange between these environments has become a common spatial model of the solid of the product resulting from the designing process.

There are various degrees of achievement of integration in practice, from the application of universal data exchange formats, e.g. IGES, STEP, between separate systems, to unified, separate software modules.

The use of mobile systems such as mobile coordinate measuring arms in product control affords great capabilities for modelling and preparing NC programs. These arms implement the main principle of coordinate measurement, which is based on determining the positions of measured points in three-dimensional space. Because the arm is equipped with an optical scanning head, it is possible to register a large number of points (a so-called point cloud) that represent the measured surface in a short time. This feature broadens the range of applications for measuring arms and enables their use in the reverse engineering process to create a digital record of the unknown surface of a tested part, which is followed by the creation of a CAD model.

Thanks to their mobility, these arms find applications in the measurement of products with large overall dimensions and surfaces that are difficult for stationary coordinate machines to access. Scanner measurements make it possible to use arms in surface measurements that are impossible to perform using contact methods, e.g. due to high temperature (in plastics processing). These measurements are most prevalent in the automobile industry and are used to determine the geometry of parts in which free surfaces are present and accuracy requirements are less strict, such as acceptance inspection and repairs of the body in automobiles.

3. MEASURING STATION

A ROMER measuring arm, model RA7220SI (Hexagon Metrology S.A.) is used at the Metrology Workshop of the Department of Production Systems.

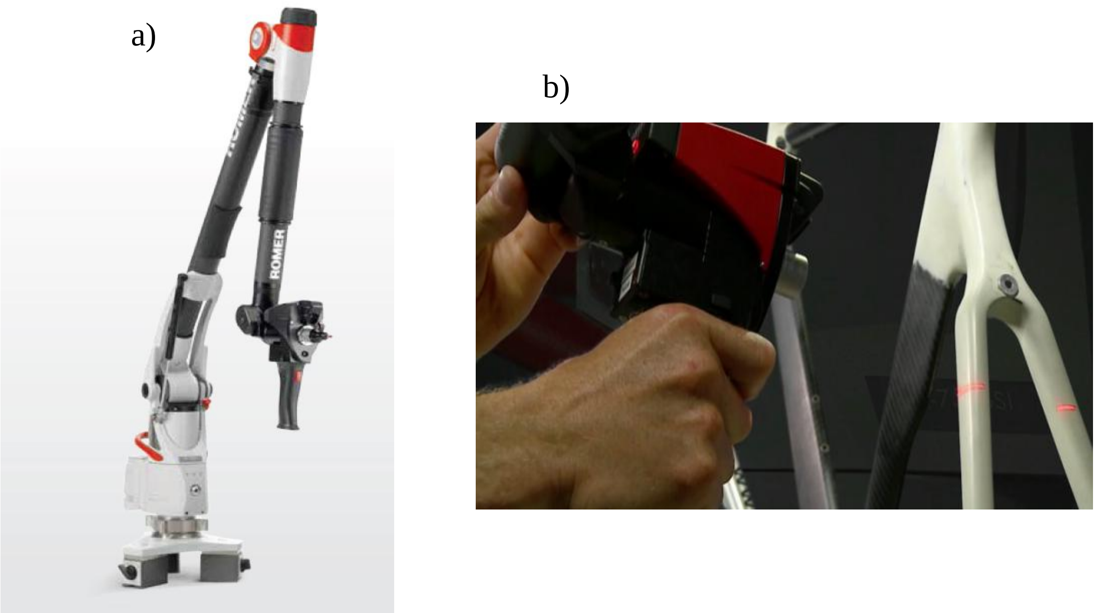

Fig. 1. ROMER measuring arm a), laser scanner b)

The arm has 6 axes of rotation and, in addition, a fixture enabling wrist control (7th axis). The range of the arm determines its radial range, which equals 2 m. The most important parameters are presented in Table 1.

Table 1. Technical data for the RA7220SI arm

Characteristics	Value [mm]
Measuring range	2000
Point repeatability	0.044
Spatial accuracy	0.061
Accuracy of the scanning system	0.079

The arm is equipped with a measuring head which consists of a 3D laser scanner integrated with the measuring system and one of three exchangeable fixed probes (with tip diameters of 15mm, 6mm, and 3mm).

The laser scanner operates based on the triangulation principle, according to which the tested surface is lit by a laser beam and a CCD camera registers the position of the beam's image. The scanner, consisting of a laser and CCD camera, proceeds to scan, using single lines with various densities of collected points – up to 1000 per line. Line scanning is possible thanks to the application of a rotating prism that gives the beam of light the form of a line. This solution significantly shortens the time of measurement: the maximum rate of data registration is equal to 30,000 points per second. Table 2 shows the characteristics of the applied RS-2 scanner.

Table 2. Specifications of the RS-2 scanner

Characteristics	Value [mm]
Resolution	0.046
Measuring range	150±50
Accuracy 2 sigma	0.030

The measuring arm is adapted for work in industrial conditions; thanks to carbon fibre materials, it is characterised by sufficient rigidity and low susceptibility to temperature changes within the range of 0–50°C.

4. METHODOLOGY OF LASER SCANNING

Scanning, in contrast to point measurements that have been arbitrarily 'distinguished' by the measuring device on a tested surface, makes it possible to obtain more information about a surface which is furnished with many registered points.

The scope of preparing measurement data after the scanning operation and the level of automation of these operations is dependent on the assumed goal of measurement. One of the two most typical applications of scanning is dimensional verification (inspect) performed in reference to an existing CAD model of a product. The second is the representation of scanned unknown surfaces of an object for the purpose of creating such a model or reconstructing its surface.

Necessary modifications, editing, and data analysis are possible thanks to advanced programming environments for the support of point clouds. These are defined as post-scanning data editing platforms, and include programs such as PolyWorks, Geomagic Studio, GOM Studio, and others.

4.1. DEFINITION OF THE COORDINATE SYSTEM

The set of points obtained as a result of a scanning operation contains the coordinates of points determined in a certain so-called local coordinate system related to the structure of the object and its arbitrary position relative to the object.

In the case of dimensional control (when there is a CAD model), important indices of the quality of free surfaces subject to evaluation are deviations of the position of individual measured points from the coordinates of points describing the ideal surfaces that constitute the model. However, most verified dimensions, including geometrical tolerances, relate to regular elements distinguished in the body of the product, so-called *associated elements* belonging to parametric surfaces, in accordance with the concept of product GPS (Geometrical Product Specification). Considering the tolerance of the product and the accuracy of the instrument, it can be assumed that some dimensions of the elements that are subject to verification (e.g. hole diameters) may be slightly dependent on the position of the coordinate system. However, in most cases, determination of the geometry of actual product surfaces requires fitting the local coordinate system, in which this geometry was measured, to the system in which the model is or will be described, so as to obtain the ‘best’ overlap of these two objects, and at the same time, to obtain the lowest values of dimensional deviations.

The definition of a correct coordinate system is an important factor that has an influence on evaluation of product quality or on the quality of the constructed CAD model. If there are base surfaces in a tested product, definition of the system is done based on the conventional measuring procedure, through measurement of these surfaces and assignment of a specified position to them.

For all measured points in a cloud, however, an accurate analytical solution of the system-fitting problem as an isometric transformation is not possible because the set of points that describes an actual surface is not a representation of the surface of the model due to the presence of deviations that occurred during production. Fitting operations are therefore implemented in software optimisation through the selection of available fitting options based on the most important points indicated by the designer or through fitting of the full set of actual points to the ideal reference surface (so-called ‘best fit’ option), in accordance with the selected optimisation criterion.

5. EDITING – OPERATIONS ON POINT CLOUDS

5.1. REMOVAL OF MEASUREMENT BACKGROUND

The result of scanning is an enormous collection containing raw points that have been registered by the camera on the head, both on the surface of the object and outside of it, or in the vicinity of the object (fixtures, supports, fragments of measuring equipment, etc.). Deciding which points belong to the measured object and which points are only the measurement background is easier if a CAD model of the product is available. If not, this decision must be made based on the subjective assessment of the measurer.

5.2. REMOVAL OF NOISE AND DISCONTINUITIES

The registered image must be subjected to further computer analysis based, first of all, on the removal of areas that can distort the result of measurement and influence further metrological analysis.

Other possible procedures making it possible to obtain data which provides the most reliable representation of the measured surface include filtering of measuring data. This procedure enables the elimination of accidentally registered points and outlying points that should not have an influence on the assessment of shape, and to remove small local noise remaining in the area of the cloud.

5.3. EXTRACTION OF PARAMETRIC SURFACES

Advanced elements of the strategy of processing point clouds into a different type of information are detection, identification, and measurement of objects corresponding to regular geometrical elements on a plane and in space. They may constitute a reconstructed 3D model of the measured parts, or they may be required to check the correctness of production of a inspected part.

In element extraction operations, it is helpful to distinguish sub-areas of the cloud in which their edges or parts of their surfaces are present. The first step of the process is contour detection, i.e. identification carried out by the algorithms present in the software. Algorithms perform image analysis and most often determine the locations of edge points by fitting the image to the parametric model or standard (imported 3D model). Approximation of an edge and surface with a selected function that describes the parametric surface, e.g. a straight line, curve, or plane, enables determination of the values of the features of the approximated shape.

5.4. DIMENSIONAL ANALYSIS

A digital model of free surfaces or actual values of the features of parametric surfaces can be used as a representation of measured surfaces. Dimensional analysis is based on determination of deviations according to the GPS tolerance model, which describes the geometry of a product with a system of acceptable deviations of dimension, shape, and position.

A convenient method of analysis is to present calculated deviations in the form of a coloured deviation map of controlled cross-sections at specific, characteristic points or geometrical reports.

6. MOST IMPORTANT FACTORS INFLUENCING THE ACCURACY OF RESULTS OF SCANNER MEASUREMENT

The final step of measurement is to elaborate the results. This is a very important step in the field of machine design and operation, because the results of scanner measurements that represent the shape of machine parts must correspond to high quality requirements imposed by designers. For machine parts, shape and dimensional accuracy of representation is essential above all.

The unlimited versatility of coordinate measurements comes at the cost of their complexity. Interpretation of results of measurement often leads to individual analyses of obtained results. This is because a result obtained on the basis of data directly coming from the coordinate-measuring machine is processed by its software, often based on complex optimisation procedures. Thus, the result is obtained by means of an indirect method, its accuracy is dependent not only on the accuracy of directly measured quantities but also on the form of the equation of the measurement from which the result was determined as well as on many other factors accompanying the measurement [3].

One practice that is sometimes applied, in which evaluation of the accuracy of the actually performed task is replaced by the accuracy of the coordinate measuring machine, is based on a complete misunderstanding. This is because the value of this characterisation was evaluated as a result of machine calibration by performing the appropriate procedure of standard distance measurement [4], as recommended in the standards, whereas the performed task may be based on completely different mathematical conversions of the data.

Based on the generally applicable document BIMP [2], inaccuracy of measurement can be specified by determining the expanded uncertainty of measurement using the method of partial uncertainty propagation. The influence of identified factors on which the result depends is expressed by the share of component uncertainties evaluated in this method on the basis of knowledge or a conducted experiment.

In coordinate measurements, the factors influencing uncertainty of measurement are classified according to five main categories, each one related either to the environment, the equipment, the measured part, the measuring strategy, or the operator. This division makes it easier to identify the enormous number of sources of uncertainty and to select the appropriate method of evaluation.

7. THE CONCEPT OF SIMPLIFIED SCANNER MEASUREMENT ACCURACY ANALYSIS

7.1. COMPARATIVE METHOD

The method of determining uncertainties according to [2] can be rather complicated in practice, [6] and the reliability of the results obtained on this basis is, in essence, a function of our imperfect knowledge about the measuring process.

To obtain a reliable result of measurement evaluation, the calculus of uncertainty must be preceded by careful analysis of the measuring process, which will make it possible to distinguish all input quantities that have an impact on or contribute to the measuring process, after which their character and intervals of variation are determined. According to the basic principles of processing the results of measurement, the influence of certain factors can be determined and accounted for as a correction in the measurement equation. Other factors must be accounted for in the uncertainty budget [2].

Another, simpler method that always gives realistic evaluations is the method of comparing actual results to values accepted as reference or standard values (‘*Although in some methods the true value cannot be known exactly, it may be possible to have an adopted reference value for the measured properties*’, [2]).

The problem with this approach is the need to obtain information about reference values. The source of such information could be measurement with an instrument of a better class, e.g. a coordinate measuring machine.

‘Calibration’ measurements of the same measured part performed by a coordinate measuring machine should take place according to repeatability principles, that is, under the same environmental conditions, according to the same strategy, with a coordinate system based on the same base surfaces, etc.

The results of a comparative measurement can be used in two ways. They can be directly accounted for in the comparison as reference values, or they can be used to construct a CAD model that will be interpreted by the arm’s software environment.

7.2. PROPOSAL OF AN INDEX OF THE QUALITY OF RECONSTRUCTION OF MEASURED QUALITIES

The measure of inaccuracy that determines the level of discrepancy between values measured by means of laser scanning and the reference values corresponding to them is the metric. This is the index of the quality of a selected attribute or property of the measuring system or of its specifications.

In geometrical product inspection, two problems are evaluated based on scanner measurements: detection of elementary shapes and representation of free surfaces in a digital or polygonal model (*polygonal mesh*). The metric must be defined for a selected attribute of the measured object so as to make it possible to evaluate the quality of its representation.

A factor that has an obvious impact on the correct reconstruction of the qualities of a measured product is the number of points. This factor should be taken into consideration during the process of measurement and should be reflected in the defined quality index. A sufficient resolution of the point cloud results in good ‘fitting’ of the object, and at the same time does not excessively prolong the time of measurement and analysis. When the points in a cloud are too numerous and fail to give important information about the measured surface, the number can be reduced arbitrarily during preliminary processing. Conversely, if the cloud resolution is too low and data is not representative, a supplementation procedure is carried out by means of scanning of additional fragments of objects or parts of the product’s surface.

Two metrics are proposed.

1. The accuracy of detection of elementary shapes can be evaluated by determining average deviations calculated on the basis of measurements of values of the attributes (ρ) of the product's geometry from the reference values corresponding to them (1).

$$MM_{\theta} = \frac{1}{m}\sum_{j=1}^{m}\left|\theta_j - \theta_{ref}\right|, \tag{1}$$

where: θ is any measured attribute of geometry.

2. The measure of the accuracy of surface representation by coordinate values can be defined by the geometric mean of the distance (ρ) between every point registered on the surface, one of the points in the point cloud, and a point in its vicinity that belongs to the surface of the model (polygonal) generated on the basis of reference values.

$$MSE_{\delta} = \frac{1}{n}\sqrt{\sum_{i=1}^{n}(\delta_i)^2}\ , \tag{2}$$

where: $\delta_i = \rho_i - \rho_{ref}$.

Metrics express 'misfit' errors of measured surfaces relative to surfaces accepted as reference surfaces as defined by formulas (1), (2).

Metric (1) is, in essence, the mean value of residual points on the actual surface relative to the reference surface, and metric (2) is determined by means of the L2 residual norm. In both cases, the metrics defined by simple mathematical operations will enable a clear geometric interpretation.

7.3. VERIFICATION OF COMPLIANCE WITH REQUIREMENTS

Individual deviations δ_i are calculated as the differences between the values of quantities measured (calculated) by the machine, e.g. the values of a measured attribute, point position, etc., and the reference values corresponding to them, according to general dependency (3).

$$\Delta = X_{ind} - X_{ref}, \tag{3}$$

where: Δ – deviation, X_{ind} – measured value, X_{ref} – reference value.

The metric values calculated on their basis do not directly give an answer to whether the obtained values are acceptable until they are verified by means of reference to accepted numerical criteria [5].

Evaluation of whether the quality of surface representation is satisfactory requires not only the establishment of a limit of acceptable value of the error of machine readings but also consideration of the uncertainty of the measurement that 'calibrates' the measured product [7], in accordance with the expression:

$$|\,X_{ind} - X_{ref}\,| \leq MPE_{ind} - U_{ref,\,0.95}, \tag{4}$$

where: MPE_{ind} is the acceptable limit of errors which can be specified by the manufacturer or user for a given attribute depending on the purpose of the conducted test and $U_{ref,0.95}$ is the uncertainty evaluated by the method of repeated multi-positional measurements on a coordinate measuring machine for a 95% confidence level.

8. EXAMPLE

8.1. GOAL AND MEASURED OBJECT

The product subject to inspection was one element of the fastening block of a 3R system electrode, Fig. 2. This system provides automated operation of an electrical discharge machining work center integrated with the coordinate measuring machine by means of *PCDMIS EDM Preset and Measure* software.

The goal of the measurement was to test whether the measurement provides sufficiently accurate reconstruction of the geometry of the base element of the fastening block, which is subject to wear during use.

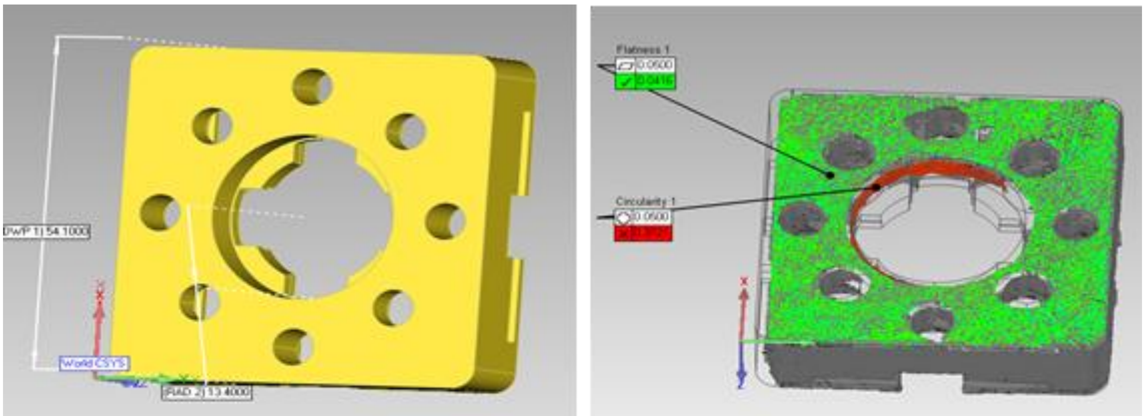

Fig. 2. Measured element

Because CAD documentation did not exist for the measured element, it was necessary to reconstruct the drawing. The fastening element was measured at a measuring station. Point clouds obtained from individual scans were then cleaned up by rejection of unearmarked scanned regions and then compiled. The created final point cloud served to create a CAD model that was converted into the IGES format.

This model was used for further measurements on the coordinate measuring machine and measurements with the application of the measuring arm.

First, base planes were selected and measured by a contact probe, which made it possible to position and determine a common coordinate system for the CAD model and the measured element in the workspace of the arm.

Next, the element was scanned by the RS-2 scanning laser in one fixture. The point cloud was cleaned up several times using the *Disconnected Components* and *Outliners* functions, which significantly reduced noise and artifacts that occurred during scanning. Fragments that were irrelevant to further processing and that could have had an influence on the quality of results were also removed.

Attributes were selected and created for the CAD model, which allowed for the calculation of their actual values on the scanned object. These attributes were used to perform realignment.

After the model was prepared, it was possible to make a 3D comparison and to conduct 3D and 2D analysis (in the appropriate cross-sections), as well as a comparison of attributes. Also were performed analyses of the flatness of selected planes, of the roundness of holes, etc.

Two software packages dedicated for processing of measuring data were used to process the point clouds and for data analysis: PolyWorks v.12.1.14 from the Innovmetric company, and Geomagic from 3D Systems. During this stage, selected processing parameter values were set identically.

8.2. CALIBRATION MEASUREMENTS

The ‘calibration’ measurements were possible thanks to a Global Performance DEA (Hexagon Metrology) measuring machine equipped with an SPX Leitz scanning head, Fig. 3, [8]. Its performance is shown in Table 3.

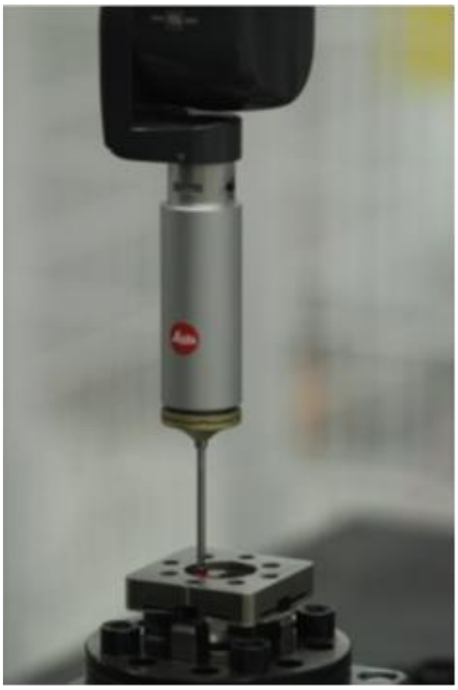

Fig. 3. Measurement of the element on
the Global Performance machine

Table 3. Selected attributes of the Global Performance coordinate measuring machine

The performance specification	
Measuring range	500x700x500m[3]
MPE_E	1.5+L/333µm
MPE_p	1.6µm
Head configuration	
Motorized rotating head	TESASTAR-sm
Probe type	LSP-X1
Tip	Length 50mm, diameter 2.5mm

8.3. METHOD OF MEASUREMENT

Selected surfaces of the block element were measured in 8 measuring cycles and in two positions, which was intended to enable determination of the uncertainty of the ‘calibration’ measurement for individual attributes of the tested part. Uncertainty evaluation methodology, with the use of uncalibrated measured objects and a multiple-repetition measuring strategy, was applied [9].

Calculated mean values constitute the best approximation of the actual values of the selected geometrical attributes of the measured part. These ‘standard’ reference values are shown in Table 4.

Table 4. ‘Standard’ results of block parameters

Parameter - nominal value [mm]	Average value [mm]	Uncertainty *u* [mm]
Diameter Φ26.800	26.765	0.00134
Flatness ◊0.001	0.003	0.00041
Distance 54.000	54.069	0.00075

Evaluations of the quality of measured surfaces were carried out using the two defined metrics, (1) and (2).

Table 5. Values of metrics (1), (2) in [mm]

Metric	PolyWorks	Geomagic
MM_θ (1)	–0.0320	–0.0808
MSE_δ (2)	0.1434	0.1749

8.4. RESULTS AND DISCUSSION

From the results shown in Table 5 above, it can be seen that the values of metrics of data analysis performed by means of the functions of the PolyWorks and Geomagic software packages are similar (of the same order).

Deviations of points of scanned surfaces in each environment were calculated relative to reference surfaces of the same CAD model. The maximum values of differences in individually calculated deviations are one order lower than the scanning accuracy of the measuring system.

The existing discrepancies between the values of metrics indicate the influence of several factors. The most significant is the influence of the subjective evaluation by person which performs the processing of point cloud from source to final set that will be used as the basis for calculation of quality indices: MM_θ and MSE_δ The selection of points means making the decision regarding which of them will be eliminated and which should be involved in the elaborating of the result of measurements. An inappropriate decision may lead to the removal of ‘good’ measuring data or to incorrect evaluation of the measured product based on false readings.

It should be noted that the two applied programming environments in which data analysis is conducted are, in essence, two different applications, although in relation to the class of the discussed problems and the precision of the scanner, this should not be overemphasised. For example, the edges of holes, upon which the beam of light is scattered, could be detected by a function performed by two different algorithms for obtaining spatial information from the point cloud, which would, in effect, give differing readings. This factor is important mainly in the dimensional inspection of elements of product geometry, generated basing on the point cloud.

8.5. GRAPHICAL ANALYSIS

The final part of the study was to perform a quick practical evaluation of the quality of measurement through the visualisation of the results. For this purpose, a coloured deviation map was generated (automatically) and superimposed on the image of the measured surfaces, Fig. 4.

The distribution of the deviations of measured surfaces from reference surfaces was also studied for individual points. The figure below shows a histogram presenting the error distribution, in mm, of misfit ting to ideal surfaces.

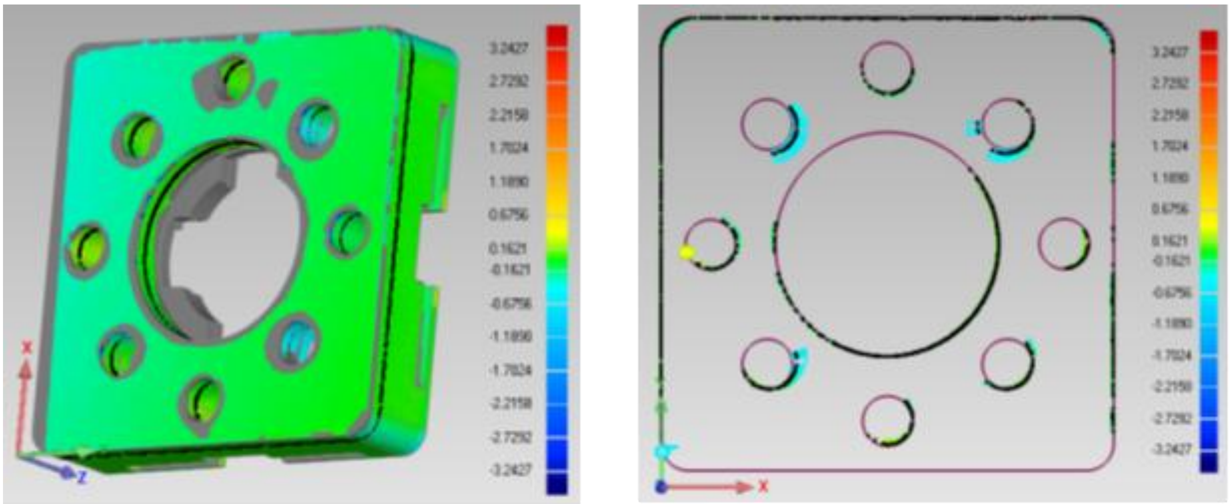

Fig. 4. 3D and 2D cross-sectional deviation maps

Deviation Distribution

>=Min	<Max	# Points	%
-2.7085	-2.2797	124	0.0205
-2.2797	-1.8508	157	0.0259
-1.8508	-1.4220	184	0.0304
-1.4220	-0.9931	1596	0.2634
-0.9931	-0.5643	9992	1.6488
-0.5643	-0.1354	47212	7.7903
-0.1354	0.1354	527301	87.0085
0.1354	0.5643	17502	2.8880
0.5643	0.9931	1166	0.1924
0.9931	1.4220	260	0.0429
1.4220	1.8508	144	0.0238
1.8508	2.2797	288	0.0475
2.2797	2.7085	107	0.0177

Out of Upper Critical	0	0.0000
Out of Lower Critical	1	0.0002

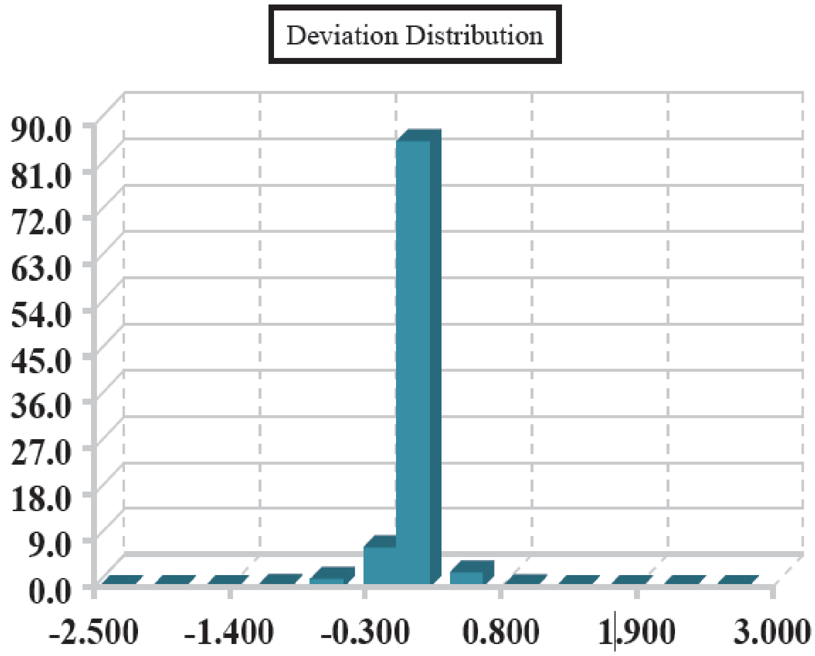

Fig. 5. Distribution of deviation values

In addition, deviation values for standard probability intervals can be read from the density curve superimposed on the histogram.

9. CONCLUSION

A method for processing and evaluating the accuracy of the results of contactless measurements performed by a measuring arm equipped with a laser head by means of so-called laser scanning was presented, giving the example of measurements of an element of a fastening block of the 3R system electrode.

The reference values for results obtained from laser scanning were the results of 'calibration' measurements performed on a coordinate measuring machine. Cloud editing and data analysis were performed by means of two different software packages. The results obtained by means of these two methods were compared, and differences were analysed.

The algorithm presented as a diagram in Fig. 6 illustrates the ultimate process of measurement and data analysis that is performed at the Metrology Workshop during metrology classes.

The multi-step methodology of measurement by means of laser scanning is labor-intensive and requires appropriate qualifications on the part of the measurer.

However, the ability to collect an enormous amount of spatial information about an object over a relatively short time and the capability of measuring objects that are difficult to access for contact methods ultimately prove the usefulness and advantages of such measurements.

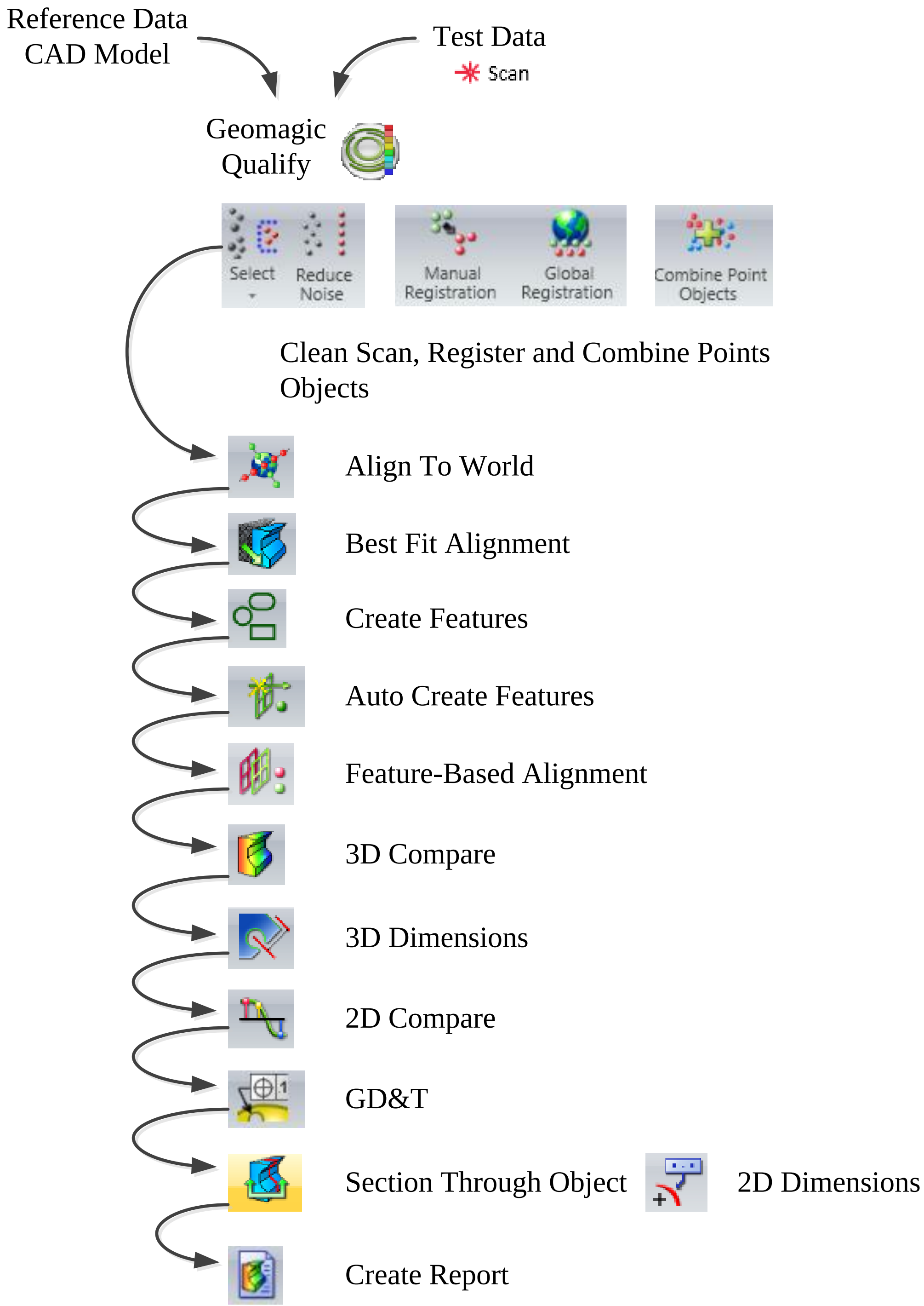

Fig. 6. Schema of the procedure of laser scanning and analysis

The introduction of elements of laser scanning methodology to didactics is an important supplement to the preparation of engineers for work with modern technical, computer, and experimental resources in the area of skills related to the use of advanced techniques in the integrated environments of production systems.

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