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Application of the R&R method to determine the operator's influence on measurements made with a coordinate measuring arm

The article presents the methodology to estimate the operator influence on measurements performed with a coordinate measuring arm. The research was based on the R&R analysis, adapted to the specifics of redundant devices such as ACMM (selection of a test object difficult to measure). The method provides for measurements by three operators, who measure ten parts in two or three samples (measurement data developed in the article relate to the three measurements of holes). The methodology is designed to identify which operator has the best predisposition to perform measurements (generates the smallest measurement errors). Statistica software was used to analyse and visualize measurement data.

1. Introduction

Coordinate measuring arms as a mobile device are widely used in the industry wherever it is necessary to take measurements directly on the production hall. When equipment is used at the production environment, it carries many risks related to the decrease of accuracy of the measuring system (operator – measuring device). The reason is that the system is working in difficult conditions (exposure to: mechanical damage, temperature changes, dustiness).

AACMM requires frequent monitoring, especially when used outside the measurement laboratory. In the field of performance verification of coordinate measuring arms, there are several standards and recommendations that the laboratories use. There are three recommendations: VDI / VDE 2617-part 9 [1], ASME B89.4.22 [2] and ISO 10360-12 [3]. Before the preparation of part 12 of the above-mentioned

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standard, part 2 and 5 were also used, due to the lack of ISO standards dedicated to AACMM.

It is equally important to consider the operator's influence on the measuring results [4]. The specificity of redundant measurement systems (such as coordinate measuring arms) indicates that the most important aspects are: the method of locating measuring points, measuring force [5, 6] and the methodology used by the operator (for example the number of measuring points and their distribution on the surface of the measured element [7]).

This article focuses on the issues related to determining the operator's influence on measurements. The R&R methodology base on measurements of 10 elements, which were measured by three operators with different experience in the use of coordinate measuring arms. One looks into it from the point of view of a reliable determination of which the operator has the best qualifications in the implementation of measurements (which carries out measurements with the smallest mistake). The most important was the selection for measurements such objects that challenge the measuring device related to motor coordination when the operator collects the points on measuring surfaces [8].

2. Methodology to determine the capability of measurement systems in accordance with the R&R method (Ford-type 2 full version)

The Ford-Type 2 method [9, 10] allows one to determine the repeatability and reproducibility of a measuring system separately.

The method provides for measurements by three operators, who measure ten parts in two or three samples (measurement data developed in the article relate to three measurements).

The procedure includes:

- Measurement of parts randomly selected from the production process. It is recommended to use parts with different dimensions, measurements should be made in conditions close to production.
- The calculation of the range for each operator as the difference between the largest (P_g) and smallest values (P_d) measured for a given part in accordance with the formula (1)

$$R_j = |P_g - P_d|. \quad (1)$$

- Calculation of the sum of individual ranges for operators: A, B, C ($\sum R_A$, $\sum R_B$, $\sum R_C$).
- Calculating of the average value of the sum of the ranges of individual operators (2) and calculation of the average range (3),

$$R_{Aav} = \frac{\sum R_A}{L}. \quad (2)$$

$$R_{av} = \frac{\sum R_{iav}}{3}. \quad (3)$$

- Calculating the average value based on the calculated sum ($\sum X_A$, $\sum X_B$, $\sum X_C$) and the number of measurements of all trials for each operator (4),

$$X_{av} = \frac{\sum X_{iav}}{I}. \quad (4)$$

- Calculation of the range of average values according to the equation (4),

$$RX_{av} = \max X_{av} - \min X_{av}. \quad (5)$$

- Calculation of the upper control line UCL (6) assuming that the coefficient D_4 according to Ford-type 2 R&R [9], for the number of repeats equal to 3 is 2.58,

$$UCL = R_{av}D_4. \quad (6)$$

- Calculation of the repeatability of the measuring instrument (7) assuming that the coefficient K_1 according to Ford-type 2 R&R [9], for the number of repeats is equal to 3, it is 0.5908 and the percentage repeatability of the measuring instrument according to (8), where T is the manufacturing tolerance

$$E.V. = R_{av}K_1, \quad (7)$$

$$E.V.\% = 100 \frac{E.V.}{T}. \quad (8)$$

- Calculation of reproducibility of the measuring instrument (9) assuming that the coefficient K_2 according to Ford-type 2 R&R [9], for three operators, is equal to 0.5321, for n parts and r repetitions of measurements. The percent reproducibility of the measuring instrument is calculated in accordance with the formula (10),

$$A.V. = \sqrt{(RX_a K_2)^2 - \frac{E.V.^2}{nr}}, \quad (9)$$

$$A.V.\% = 100 \frac{A.V.}{T}. \quad (10)$$

- Calculation of the repeatability and reproducibility of the resultant measuring instrument (11) and the percentage value (12),

$$R\&R = \sqrt{(A.V.)^2 + (E.V.)^2}, \quad (11)$$

$$R\&R\% = \sqrt{(A.V.\%)^2 + (E.V.\%)^2}. \quad (12)$$

- Interpreting the results: $E.V.\%$ applies to the instrument (repeatability), $A.V.\%$ refers to the operator (reproducibility), $R\&R\%$ refers to the instrument and the operator in total (repeatability and reproducibility).

If the values are below 10% – the errors are acceptable, 10% to 30% – the errors may be acceptable depending on the type of measurements carried out or other factors (e.g., the cost of repairing the instrument or for a new one), above 30% – the errors are too big, the measuring system should not be allowed to be used [11–15].

3. Research and analysis of results

The research was carried out using the Romer Omega 2025 – coordinate measuring arm (Fig. 1). Measuring range of the AACMM is 2500 mm, the diameter of measuring tip has 6 mm (Fig. 1 – 3). The measuring arm used in the tests has an MPE of 0.06 mm (in accordance with the recommendations of ASME), moreover, according to ISO standards, the mathematical model of the maximum permissible error can be given by the formula (13), where L is the measured length in millimeters.

$$\text{MPE} = 0.016 + \frac{L}{2800} \leq 0.068 \text{ [mm]}. \quad (13)$$

A steel measuring table and magnetic fastening were used to eliminate errors resulting from the method of mounting the arm (Fig. 1 – 2). Measured elements were placed on the same table and fixed with clamps to eliminate errors resulting from moving objects (Fig. 1 – 1). During the measurements the temperature was 23.5°C, with deviation less than 1°C. In the illustration (Fig. 2) additionally, the elements which were measured during the measurement procedure were marked. The object was made of aluminium PA9 with a hole tolerance of $T = 0.6$ mm. The measured holes are set vertically (nominal diameter 21 mm) (Fig. 2 – 2), horizontally (nominal diameter 20.7 mm) (Fig. 2 – 3) and at an angle of 45° (nominal diameter 20.7 mm) (Fig. 2 – 1).

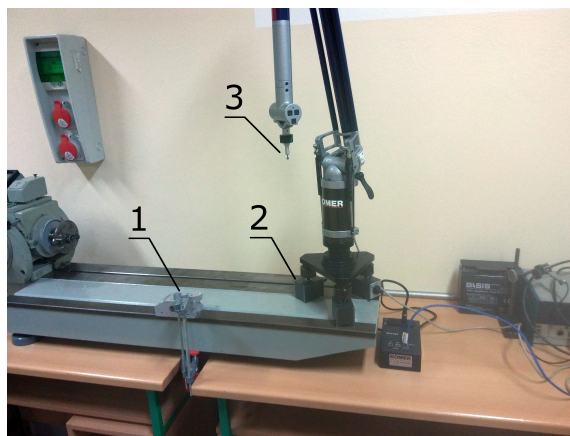


Fig. 1. Coordinate measuring arm Romer Omega 2025

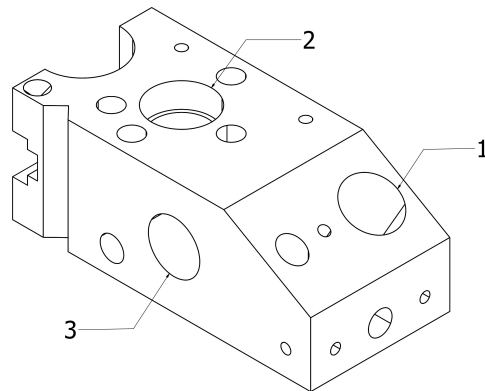


Fig. 2. Measured object

The selection of elements forces different trajectories of approach to particular measurement points, the minimum mathematical number of measurement points at which the software is able to calculate the replacement element. In this case, this element is the cylinder describing the hole, and the number of points is 6. Regardless of this, the measuring procedure for the roller enforces the measurement of points at different depths of the hole.

The operator's task was to measure the diameter of individual holes. In addition, the measurement of each object had to be made three times. In order to eliminate the operator's fatigue effect during measurements, each of them performed the first measurement series in a random order of parts, then the second series of measurements was carried out, etc. In this arrangement, each operator had the opportunity to rest when the other two operators were working. The results of the measurements presents Table 1.

Table 1.

Results of the measurements [mm]

Operator-Try	Summary of research for the project R&R									
	1	2	3	4	5	6	7	8	9	10
1-1	20.78	20.73	21.09	20.70	20.11	21.12	20.78	20.76	21.09	20.78
1-2	20.79	20.75	21.11	20.79	20.11	21.14	20.72	20.82	21.09	20.78
1-3	20.86	20.74	21.09	20.76	20.11	21.14	20.76	20.78	21.09	20.76
2-1	20.78	20.74	21.08	20.76	20.12	21.13	20.78	20.74	21.08	20.76
2-2	20.77	20.75	21.11	20.76	20.11	21.09	20.90	20.80	21.08	20.76
2-3	20.83	21.07	21.11	20.72	20.12	21.09	20.81	20.79	21.11	20.77
3-1	20.72	20.77	21.13	20.75	20.78	21.08	20.76	20.72	20.93	20.82
3-2	20.75	20.79	21.07	20.75	20.76	21.07	20.78	20.73	21.09	20.69
3-3	20.80	20.72	21.12	20.77	20.73	21.14	20.76	20.74	21.09	20.58
Nominal	20.7	20.7	21.0	20.7	20.7	21.0	20.7	20.7	21.0	20.7

Table 2.

Comparison of R&R parameters

Parameter	Operator 1	Operator 2	Operator 3
E.V.	0.02	0.04	0.05
E.V.%	3.63	7.15	7.70
A.V.	0.03	0.03	0.03
A.V.%	5.51	5.39	5.37
R&R	0.04	0.05	0.06
R&R%	6.60	8.95	9.39

The Statistica computer program was used to plan measurements and analyze measurement data [12]. The software package has a set of tools for industrial statistics, among which the six-sigma group has an editor for analysis R&R.

The results of the measurements are shown in the summary table. All operators obtained acceptable results (R&R parameter below 10%). It can be noticed that in the case of operator 1, the measurement system obtained the best results (the R&R% parameter is 6.6%). For other operators, the results are close to the limit of 10%. When analyzing the indicators, it can be noted that A.V. are almost the same for all operators. Significant differences can be seen in the E.V. (operator 1 obtained about twice as good result compared to other operators). The specificity of the coordinate measuring arms means that the measuring device itself is responsible not only for the repeatability of the measuring system, but also for the operator.

The graph (Fig. 3) presents one of the basic methods of visualization of measurement data obtained in the R&R method. The interpretation of the chart consists first of all in analyzing deviations of individual measurements from the average

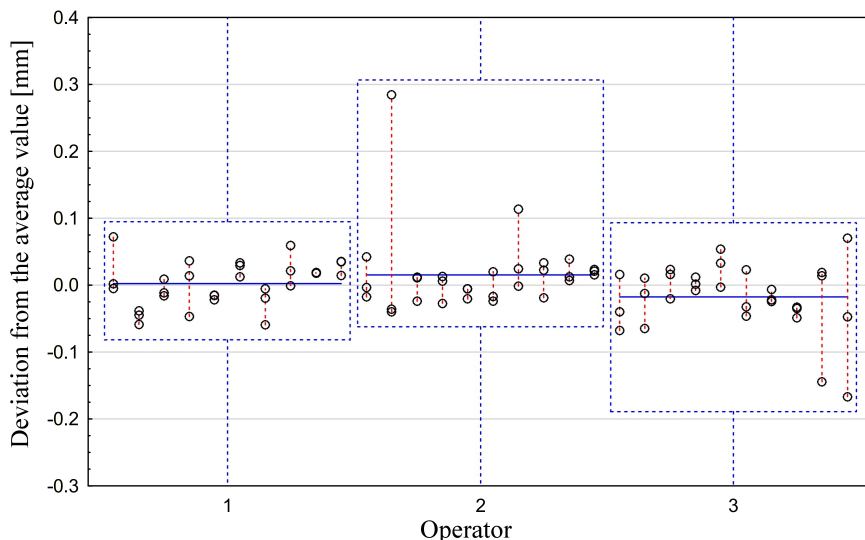


Fig. 3. Repeatability and reproducibility chart

value calculated individually for the part being measured (for each hole separately). For a measuring process free from errors both systematic and accidental, measuring points for individual parts would overlap. In the case described for operator 1, one can notice that lines connecting points for a given part are relatively short, which indicates a small variability of the operator when measuring a single part. For other operators one can notice a large variability of operators when measuring parts. It is indicated by long sections connecting points in the case of measurements of parts 2 and 7 for operator 2 and parts 9 and 10 for operator 3.

The position of the frame around the average value is another aspect of the graph analysis. The applications consist in identifying a general tendency for the operator to overestimate or lower the results. Operator 1 in this case has a symmetrically placed frame around the average – this indicates a random variation. On the other hand, the two remaining operators due to the errors in the measurement performance tend to overestimate results (in the case of operator 2) and understate the measurements (operator 3). Trends for operators 2 and 3 are also confirmed by the positions of average values.

From the point of view of the usefulness of the measurement system for the purpose of verifying the correctness of the production of manufactured parts, a very important issue is the estimation of the uncertainty [16, 17]. It is connected with the possibility of qualifying a part whose dimensions exceed the tolerance limits as correctly produced and released to the next phase of the production process.

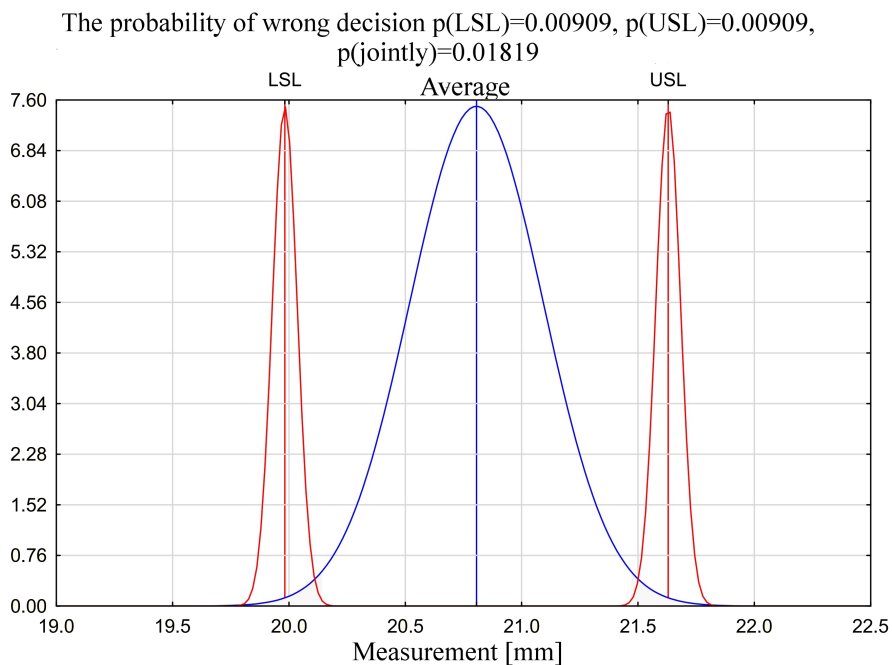


Fig. 4. Chart of incorrect MSA ratings for parts

The threat resulting from an incorrect decision may not only result in the financial losses but also threaten the safety of the user of the product (depending on the area of application of the parts) if the error remains undetected. For the tested measurement system, the probability of issuing an incorrect decision is below 2% (Fig. 4).

4. Summary and conclusions

In the methodology of operator influence assessment for measurements carried out with the use of a coordinate measuring arm, there are many important aspects that make redundant systems to enforce the use of measuring elements with features allowing to visualize measurement errors depending on the degree of training of operators. The analysis shows that the biggest problems for inexperienced measuring engineers are elements requiring the location of measurement points in uncomfortable hand settings in which the operator holds the measuring head.

For the test object, such features could be found in the opening designated as 3 (Fig. 2). The horizontal axis of the element forces the operators wrist to bend in an unusual way (or change the handle from right to left hand or vice versa). This is the case when measuring the hole 1 (Fig. 2 – 1) measured at an angle of 45 degrees, at which the largest deviation were recorded for operators 1 and 3 (Fig. 3 – 1, 3) (left-handed operation required). The second reason for obtaining greater deviation is locating the measurement points without seeing the place where the measuring tip contacts the surface of the element especially it can be see for operator 3 and ninth measuring hole (Fig. 3 – 3).

The results of the R&R analysis showed that operators 2 and 3 generate errors of greater value than operator 1 (this confirms the level of their training). For the practical purposes of the analysis, they require measurement uncertainty analysis to be carried out. The Statistica software allows to quickly create a graph from which the most important parameter can be read, which is the probability of error when assessing whether the element was made correctly or not (Fig. 4).

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