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ANALYSIS OF MEASUREMENT SYSTEM CAPABILITY WITH NEGLIGIBLE OPERATOR INFLUENCE: A CASE STUDY USING A COORDINATE MEASURING MACHINE

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Abstract: *In modern industrial metrology, the ability to assess the reliability and precision of measurement systems is of critical importance. This study presents a measurement system analysis (MSA) focused on scenarios where operator influence is negligible, particularly applicable when using coordinate measuring machines (CMMs) operating in automated or highly standardized conditions. Unlike classical GRR (Gage Repeatability and Reproducibility) studies that assess both repeatability and reproducibility — often require multiple operators — this approach isolates repeatability as the dominant component of measurement variation.The experimental part of the research was conducted using a CNC-controlled CMM to measure key dimensional characteristics on a series of precision-machined cylindrical parts. A fixed measurement program was used to eliminate variability due to operator actions. Statistical analysis included repeatability studies, calculation of %GRR, and evaluation of measurement system capability indexes (such as P/T ratio).*

Keywords: *Product quality, Measurement system analysis, GR&R, CMM*

1. INTRODUCTION

Coordinate Measuring Machines (CMMs) represent a cornerstone of modern dimensional metrology, primarily due to their ability to minimize the influence of human operators on measurement outcomes. Traditional manual measurement techniques, such as calipers, micrometers, or gauges, are highly dependent on operator skill, consistency, and subjective judgment, which introduces variability into the measurement system. By contrast, CMMs automate the measurement process through programmable probing strategies, controlled motion systems, and integrated software environments. This automation reduces operator-dependent sources of error, ensuring that measurements are executed in a repeatable and standardized manner. From a theoretical perspective, CMMs can be considered as instruments that effectively decouple the measurement process from human factors, allowing researchers to focus on machine-related uncertainty components such as repeatability, probe performance, fixturing, and environmental stability. In industrial practice, this translates into improved measurement reliability, higher productivity, and a stronger foundation for objective decision-making in quality assurance.

In past years, CMMs have evolved from high-precision laboratory measuring devices into shop floor systems. This trend is observed in high-tech processes, a typical example being the automotive industry. Standardized procedures for quality assurance in the automotive industry require proof of the quality of the control processes and of the measuring devices, for which the MSA methodology is applied.

Measurement System Analysis has been extensively standardized and documented, most notably in the AIAG MSA manual and in ISO 22514-7 [1], which provide guidelines for evaluating the capability of measurement systems across different industrial applications. According to international standards, m*easurement system analysis* is defined as “a series of studies that explains how a measurement system performs” (ISO 13053-2 2011 [2]) and consists of “a set of methods used to evaluate the uncertainty of a measurement process under the range of conditions in which the process operates” (ISO 22514-1 2014) [3]. The core idea is to decompose total observed variation into repeatability, reproducibility, and part-to-part components, using either range-based methods or variance analysis (ANOVA). Within academic literature, several studies have emphasized the importance of adapting MSA methodologies to advanced metrology systems, including CMMs, where the traditional assumption of significant operator influence no longer applies. Instead, the focus shifts toward quantifying machine-related uncertainty sources such as probe calibration, thermal effects, and the stability of fixturing and alignment strategies. Research contributions in this field highlight that, while CMMs inherently reduce human variability, they still require rigorous system capability studies to ensure measurement validity, particularly when measurements are employed for process control or capability analysis. This dual perspective, rooted in both industrial standards and academic investigation, establishes a sound methodological foundation for applying MSA in the CMM environment.

A measurement system analysis initially aims to verify if the right measurement is being applied to the system. It evaluates if the chosen method is appropriate considering all potential variables. Next, it assesses the measuring instruments. Often, tools like gages and fixtures deteriorate or malfunction, compromising their efficiency. The MSA checks whether these tools require calibration, replacement, or an upgrade.

Furthermore, the MSA evaluates the staff's proficiency in implementing the measurement system's guidelines and any environmental elements that could impact the procedure. Inconsistencies in the process can lead to inaccurate outcomes and potentially defective products. The primary objective of the MSA is to pinpoint and reduce these inconsistencies [4].

A comprehensive review of different methods and techniques used for measuring system analysis is given as an in-depth analysis in many scientific articles. In [5] the authors discuss the sources of measurement variation, such as bias, linearity, and stability, and provide insights into how to assess and improve measurement systems.

There are also studies in which it is examined, and the impact of various factors on the quality of measurement results from a coordinate measuring machine (CMM) being explored, with a particular focus on the role of temperature [6].

Measurement system analysis methods are used to analyze measurement systems for continuous and attribute data. It is important to mention that all elements of a measurement system (gages, standards, operators, software, measurement equipment, procedures, environmental components, as well as others) can affect the variation of results and contribute to the measurement system capability. Capability of the measurement system can be characterized by quantifying its accuracy and precision [7].

Measurement System Analysis (MSA) is critical in ensuring the reliability of data used in manufacturing and quality assurance. Traditional systems often suffer from operator-induced variability. CMMs, especially in automated configurations, offer a solution by reducing human influence. This paper aims to evaluate the capability of such systems through a structured case study.

2. MEASUREMENT SYSTEM ANALYSIS

Quality control is an essential component of modern manufacturing, ensuring that products consistently meet design specifications and customer expectations. At the heart of every quality control process lies the measurement system, which provides the quantitative basis for evaluating conformity and process stability. A reliable measurement system not only enables the detection of nonconformities but also supports continuous improvement initiatives, process optimization, and cost reduction. Conversely, if the measurement system itself introduces significant variation or uncertainty, the validity of quality decisions is compromised, leading to incorrect acceptance or rejection of parts, inefficiencies, and potential customer dissatisfaction. For this reason, the evaluation and validation of measurement systems represent a critical step in establishing an effective quality management framework, particularly in industries where high precision and tight tolerances are required.

Measurement Systems Analysis (MSA) is a tool for analyzing the variation present in each type of inspection, measurement, and test equipment. It is the system used to assess the quality of the measurement system. In other words, it allows us to ensure that the variation in our measurement is minimal compared to the variation in our process.

Every day our lives are being impacted by more and more data. We have become a data driven society. In business and industry, we are using data in more ways than ever before. Today manufacturing companies gather massive amounts of information through measurement and inspection. When this measurement data is being used to make decisions regarding the process and the business in general it is vital that the data is accurate. If there are errors in our measurement system, we will be making decisions based on incorrect data. We could be making incorrect decisions or producing non-conforming parts. A properly planned and executed measurement system analysis can help build a strong foundation for any data-based decision-making process [8].

3. COORDINATE MEASURING MACHINES

A Coordinate Measuring Machine (CMM) is a device designed to measure the geometry of physical objects by detecting discrete points on their surfaces using a probing system (Figure 12). CMMs are most commonly applied in the inspection of parts or assemblies to verify whether they conform to the original design intent. They are integrated into quality assurance and quality control processes to check the dimensions of manufactured components and to prevent or resolve quality-related issues. In addition, CMMs are widely used in production and assembly operations to verify parts and assemblies against design specifications. The measured points can be utilized to validate distances between characteristic features, as well as to construct geometric elements such as cylinders or planes, enabling the evaluation of aspects like roundness, flatness, and perpendicularity. Compared to manual inspections or conventional measuring tools such as micrometers and height gauges, CMMs offer significant advantages, including higher accuracy, faster measurement cycles, and a considerable reduction of human error [9].

Although CMMs significantly reduce operator-induced variability, the application of Measurement System Analysis (MSA) remains essential to ensure the overall reliability of the measurement process. The reason lies in the fact that measurement variation is never completely eliminated; instead, its sources shift from human factors to machine- and process-related components. In the case of CMMs, repeatability is primarily influenced by probe performance, machine kinematics, fixturing conditions, and environmental stability, while part-to-part variation reflects the actual dimensional differences of the workpieces under study. By applying MSA, it becomes possible to quantitatively separate these components of variation, evaluate the proportion of measurement error relative to the studied tolerance, and determine whether the CMM system is capable of supporting process control decisions. From both academic and industrial perspectives, conducting an MSA study in the CMM environment provides a systematic framework for validating the measurement system, identifying dominant error sources, and establishing confidence in the data used for product and process quality assurance.

MSA is a process used to evaluate the suitability of a measuring system for use. A measuring system can be any combination of a transducer, signal conditioner, display, recorder, or data acquisition system used to obtain a measurement. A measuring system is capable if it meets the required technical performance specifications.

With increasing demands for accuracy and precision in industries such as aerospace, automotive, medical, tooling, semiconductor, electronics, shipbuilding, and other manufacturing sectors, it has become essential to develop new procedures and machines capable of performing complex measurements. In this context, the Coordinate Measuring Machine (CMM), due to its high accuracy and repeatability of measurement results, represents a logical choice for enhancing the quality of the production process. However, the CMM must efficiently and effectively provide the necessary information regarding part dimensions and tolerances. Furthermore, it is crucial that CMM users understand and apply proper procedures and techniques to improve the reliability of measurement results. Evaluating the performance of the CMM and determining the uncertainties associated with measurement outcomes are of fundamental importance for maintaining repeatability and reliability in measurement processes.

4. STUDIES FOR ASSESSING THE ABILITY OF THE MEASURING SYSTEM

Measurement System Analysis (MSA) is a standardized methodology used to statistically evaluate the capability of a measurement system to deliver accurate, repeatable, and stable measurement results. This analysis is essential for ensuring product and process quality, as it enables the identification of sources of variability in measurement—whether they originate from the device itself, the operator, the measurement method, or environmental conditions. In modern industrial systems, particularly in the automotive and precision manufacturing sectors, MSA is regarded as an indispensable tool for qualifying control processes [10].

MSA studies are conducted as a form of “mini experiment” aimed at assessing the overall variability within the measurement system. When a variable (quantitative) characteristic is being measured—such as length, angle, temperature, pressure, or resistance—specific MSA methods are applied depending on the study’s objective and the presence of operator influence. The fundamental types of MSA studies for quantitative data include [11]:

- Evaluation of instrument bias, linearity, and stability over an extended period of time.
- **Type I Study** – assessment of the measuring device alone (excluding the operator), where Cg and Cgk indices are calculated, analogous to process capability indices (Cp, Cpk).
- **Type II Study** – classical GR&R analysis (Repeatability and Reproducibility), in which variability is assessed by involving multiple operators.
- **Type III Study** – GR&R study without operator influence, suitable when the same operator measures multiple samples and differences between operators are considered negligible.

Type II and Type III studies utilize two primary calculation methods: the Average and

Range Method (ARM) and Analysis of Variance (ANOVA). Although the ARM method is simpler and widely used, the ANOVA method is increasingly required in practice due to its higher precision and ability to clearly isolate sources of variation [12]. The MSA methodology received its standardized form in the early 1990s, when the Automotive Industry Action Group (AIAG), in collaboration with leading American automotive manufacturers such as Chrysler Motors, General Motors, and Ford Motor Company, developed the MSA manual as the official guide for conducting these analyses. Within this manual, specific rules for evaluating GR&R (Gage Repeatability and Reproducibility) studies are defined, along with threshold values that enable straightforward interpretation of results.

Based on the percentage contribution of GR&R variation to the total tolerance, it is possible to determine whether a measurement system is acceptable, marginally acceptable, or unacceptable for a given application. This allows engineers to quickly decide whether a particular measuring device (gage) can be used in serial production, or whether replacement or further process optimization is required [13]. The most used criterion is the so-called %GRR, which represents the percentage of total tolerance "consumed" by measurement uncertainty. According to AIAG guidelines, the system is considered [13]:

According to AIAG guidelines, the system is considered:

- **Acceptable** if %GRR is less than 10% – the measurement system is suitable for use in production without further modification.
- **Marginally acceptable** if %GRR is between 10% and 30% – the system may be used, but improvement is recommended.
- **Unacceptable** if %GRR exceeds 30% – the measurement system is not suitable for the intended application and requires corrective action, such as equipment replacement or process optimization.

Total Variation (TV) of a measurement system represents the sum of several components that collectively describe the quality and reliability of the measurement process. These components include repeatability (EV), reproducibility (AV), stability, and linearity. Repeatability refers to the ability of a measuring device to consistently produce similar results under the same conditions and with the same operator, and it is quantified by the standard deviation of a set of measurements. In contrast, reproducibility reflects the variation caused by different operators, time intervals, or other external factors, thereby measuring the influence of human factors on the measurement results.

5. EXAMPLE OF A STUDY FOR ASSESSING THE ABILITY OF A MEASURING SYSTEM WHERE THE IMPACT OF THE MEASURE IS NEGLIGIBLE

Stability refers to the ability of the measurement system to maintain its accuracy over time, while linearity indicates how the instrument's deviation changes across the entire measurement range [10]. In cases where reproducibility, i.e., AV = 0, the operator's influence is considered negligible. This is a specific scenario that typically occurs with automated measuring equipment. In such cases, the adequacy of the measurement system is determined by evaluating the precision of the measuring device (EV) [14].

To successfully conduct a case study for assessing the capability of a measurement system where operator influence is negligible, the following conditions must be met [14]:

The following conditions must be met in order to successfully conduct a case study for evaluating the capability of a measurement system where operator influence is negligible:

- The measurement process must be fully automated or consistently performed by a single operator whose influence is statistically insignificant.
- The measured characteristic must be quantitative and stable over time, without significant fluctuations due to environmental or process-related factors.

- The measurement equipment must be properly calibrated and maintained, ensuring consistent performance throughout the study.
- A sufficient number of repeated measurements must be taken to allow for reliable statistical evaluation of repeatability.
- The measurement results must be analyzed using appropriate statistical methods, such as standard deviation or control charts, to assess the precision of the device.

These conditions ensure that the study focuses solely on the intrinsic performance of the measuring instrument, allowing engineers to determine whether the system meets the required standards for precision and reliability in production environments.

- Repeated measurements must be performed ($r \geq 2$).

- A sufficient number of measurement items must be included ($n = 5–25$), and the condition $n \cdot r > 20$ must be satisfied.

- All measurements must be conducted using the same measuring device under consistent measurement conditions.

Using a coordinate measuring machine (SPECIFICATION and image provided), repeated measurements ($r = 3$) of the relay housing depth were performed on a sample of 10 measurement items. The specified nominal value for the relay housing depth is 175.58 mm with a tolerance of ±0.7 mm. Based on the measurement results presented in Table 1, it is necessary to evaluate the capability of the measurement process for the intended application using the Average and Range Method.

The measurement results for the relay housing depth, obtained using a 3D coordinate measuring machine, are presented in Table 1. The numerical calculation of the study for evaluating the capability of the measurement system, where operator influence is considered negligible, using the Average and Range Method, is presented in Report (Table 2).

Table 1. Results of measuring the depth of the relay housing [14]

	Measurement results of the depth of the relay housing (mm)									
Rep	1	2	3	4	5	6	7	8	9	10
1	175.7657	175.7163	175.8471	175.8074	175.7991	175.7414	175.7898	175.8534	175.7827	175.7790
2	175.7738	175.7222	175.8507	175.8120	175.8028	175.7436	175.7928	175.8538	175.7868	175.7815
3	175.7762	175.7252	175.8515	175.8155	175.7343	175.7844	175.8489	175.8036	175.7872	175.7750

Table 2. Report on the ability of the measuring system where the influence of the measure is negligible

Statistics obtained based on measurement results: $\overline{R}$ = 0.02637 R_p = 0.12853	
Analysis of the measuring system where the influence of the measure is negligible	**% Total variation (TV)**
Repeatability - precision of the measuring device (EV) - σ_E $EV = \overline{R} * K_1$ =0.02637 * 0.5908 = 0.01558 mm	$\% EV = 100\ [EV/TV]$ = 100 * [0.01558/0.2333] = 6.68%
Reproductiveness - precision of martyrs (AV) - σ_A	

AV = 0	$\% AV = 100\ [AV/TV]$ = 0%
Repeatability and reproductive (GRR) - σ_M $GRR = \sqrt{EV^2 + AV^2} = \sqrt{0.01558^2 + 0^2} =$ = 0.01558 mm	$\% GRR = 100\ [GRR/TV] =$ 100 * [0.01558/0.2333] = 6.68%
Process variation (PV) - σ_P $PV = R_p * K_3 =$ 0.12853 * 0.3146 = = 0.04044 mm	$\% PV = 100\ [PV/TV]$ = 100* [0.04044/0.2333] = = 17.33%
Total variation (TV) - σ_T $TV = \frac{GGT-DGT}{6} = \frac{176.28-174.88}{6} =$ $0.23333\ mm$	$ndc = 1.41\ \frac{PV}{GRR} =$ = 1.41* (0.04044/0.01558) = 4

In the report (Table 2), deviations were included in the calculation. Although the measurement system is considered unreliable (since ndc < 5), the %GRR value is now within acceptable limits, i.e., %GRR < 10%. This indicates that the system, while not ideal, is sufficiently adequate for the specific application, particularly in cases where wide tolerances are defined, as in this example.

6. CONCLUSION

In modern manufacturing environments, the demand for precision and reliability in measurement processes has become increasingly critical, especially in industries such as aerospace, automotive, medical devices, and electronics. Coordinate Measuring Machines (CMMs) have emerged as a key solution for performing complex dimensional inspections due to their high accuracy and repeatability. However, the effectiveness of a CMM is not solely determined by its technical specifications—it also depends on the robustness of the measurement system as a whole.

The application of MSA methodology to a CMM-based measurement process has demonstrated the importance of evaluating system capability beyond mere equipment specifications. Through a structured study using the Average and Range Method, it was shown that even when operator influence is statistically insignificant, key metrics such as %GRR and ndc must be carefully interpreted to determine system adequacy.

Although the number of distinct categories (ndc) was below the recommended threshold, indicating limited resolution, the %GRR value remained below 10%, suggesting that the measurement system is sufficiently capable for the specific application—particularly when wide tolerances are defined. This highlights a practical insight: a system that may not meet ideal statistical criteria can still be acceptable for certain industrial contexts, provided its limitations are understood and aligned with process requirements.

The results confirm that automated CMMs can deliver highly repeatable and reproducible measurements with negligible operator influence. This enhances confidence in quality control decisions and reduces risks of Type I and Type II errors.

Automated CMMs represent a robust solution for high-precision measurement tasks. Their ability to minimize operator-induced variability makes them ideal for modern manufacturing environments. Future work should explore integration with AI-driven inspection systems and real-time process feedback.

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