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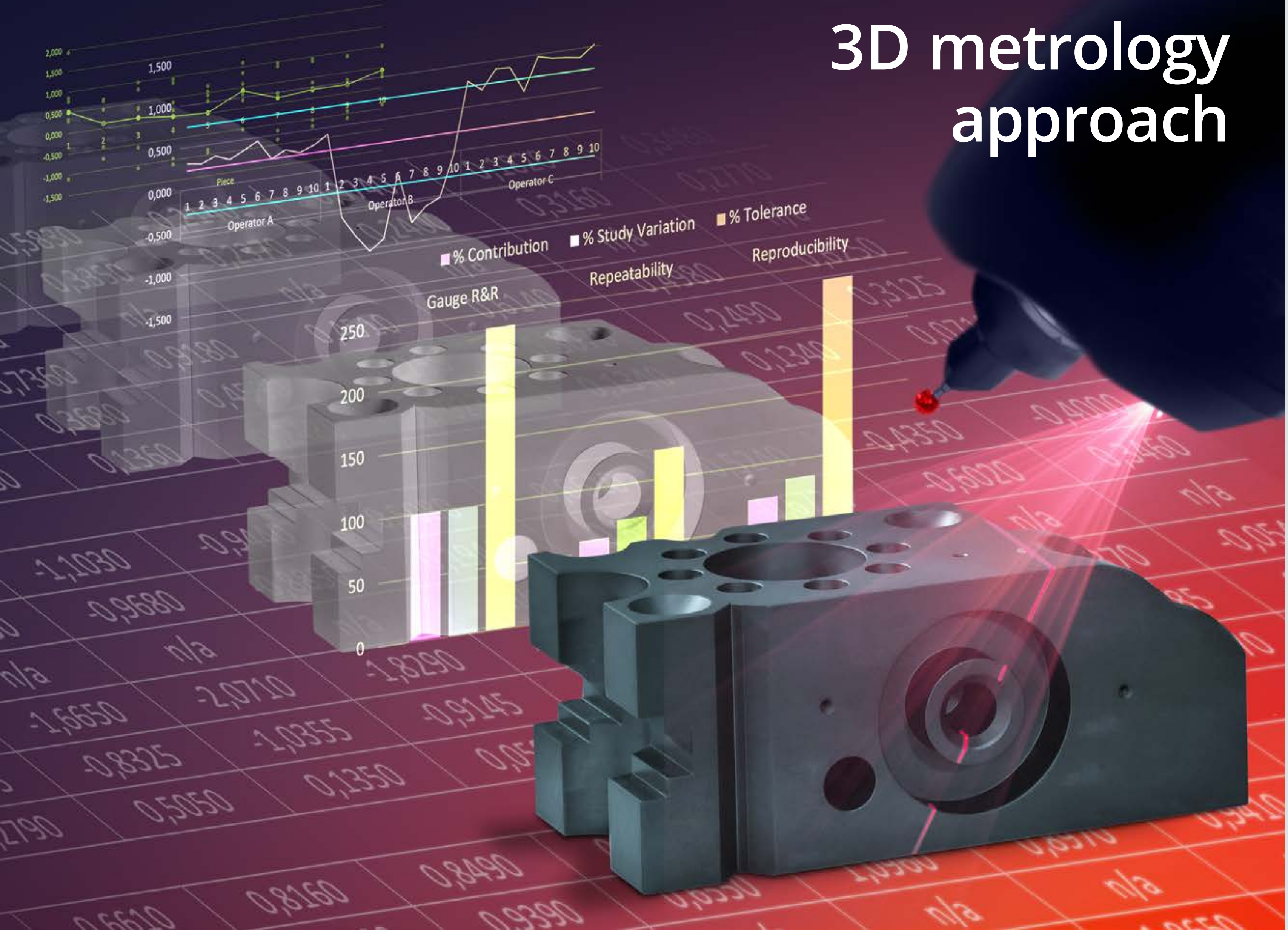
WHITE PAPER

Collecting trustworthy 3D measurements **The Smart 3D metrology approach**



Collecting trustworthy 3D measurements
The Smart 3D metrology approach

Manufacturing companies monitor product quality every day by collecting dimensional measurement data. This data is used to investigate the stability of a manufacturing process, determine the ability of the process to ensure part quality and functionality, and establish indices to quantify the capability of the process to meet dimensional requirements. It's all part of their continuous improvement process.

When introducing a new manufacturing process, problems may be perceived with the process stability without being able to pinpoint the cause and correct it. These problems are, in some cases, not related to the manufacturing process but rather to the measurement system itself.

Metrologists know that a measurement is never exact. A multitude of sources of variation affect the performance of the measurement system, leading to uncertainty in the measurement. By performing a Measurement System Analysis (MSA) through repeatability and Gauge R&R studies, the measurement system variation can be estimated. These studies allow metrologists to assess the validity of the measurement system and minimize the factors contributing to the total measured process variation that are actually stemming from the measurement system.

An MSA study can be quite complex to set up and execute - even more so in the context of 3D metrology - and requires extensive knowledge of statistics to obtain actionable data.

This white paper will:

- Explain the key concepts of Measurement System Analysis and their practical application for 3D measurement devices.
- Explore a fully digital process from the setup and execution of repeatability and Gauge R&R studies to obtain results directly in Excel for analysis and sharing.
- Provide metrologists with recommendations to analyze study results.

Understanding MSA basics

Let's examine the crucial role of the MSA in the context of the overall part inspection process. During this process, metrologists measure *key characteristics*, such as size, dimensions, positions, profiles, and orientations, to determine their deviation from nominal specifications. They assess compliance with technical specifications, as set out in the control plan, through tolerances and requirements. Every measurement is characterized by two main components: one representing the actual deviation (i.e., real value), and another that reflects the variability of the measurement system. To ensure that their measurement system is trustworthy and reliable for the task, metrologists need to identify the amplitude of the measurement system variation and ensure that it represents a maximum of 10% to 30% of the specification limits. The variability or performance of the measurement system must be proportionally small enough that it is not a significant contributor to the total measured process variation, considering both the variation of the manufacturing process and the measurement system, and does not push the process out of the specification limits (*LSL*, *USL*) or tolerances.

Figure 1 shows this interaction, where the performance of a measurement system and the measured values (x_i) has a relatively discrete and predictable contribution to the measured process variation. This variation is obtained from measured results on parts coming from the production line using SPC techniques. Usually, control limits are calculated using this data. In other words, the performance of the measurement system affects the results of the total measured process variation, and the measurement system analysis workflow helps identify this performance.

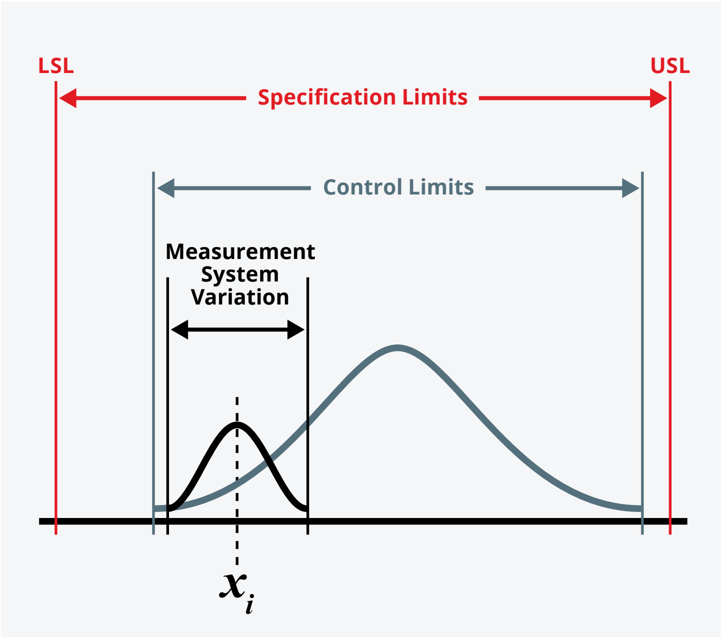
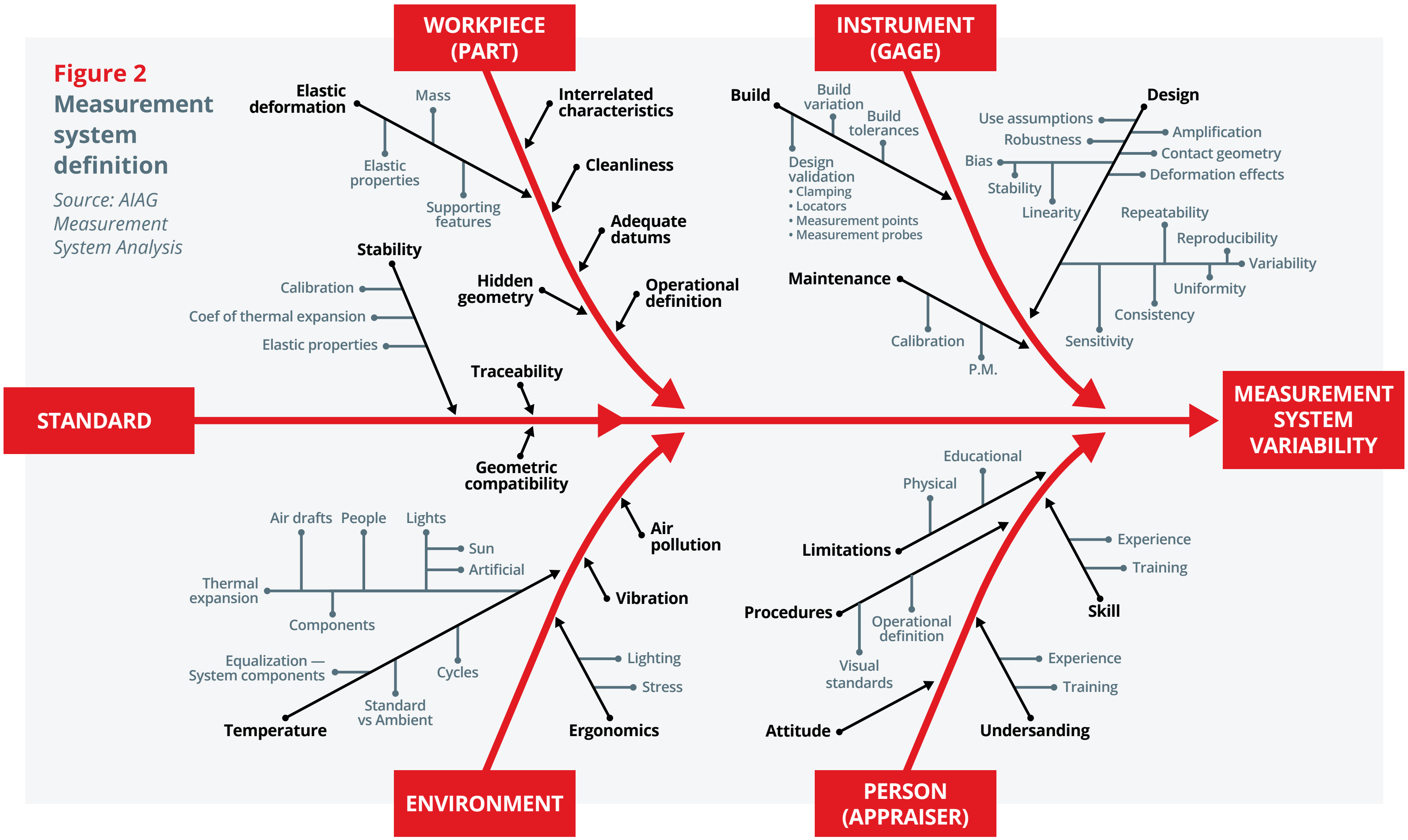


Figure 1
Performance of a measurement system regarding total process variation

Measurement system definition

Before determining the performance of the measurement system, it is critical to identify all the potential sources of variation that may affect the measurement process of a key characteristic. The Automotive Industry Action Group (AIAG) states that the measurement system is composed of *"the collection of instruments or gages, standards, operations, methods, fixtures, software, personnel, environment and assumptions used to quantify a unit of measure or fix assessment to the feature characteristic being measured; the complete process used to obtain measurements."* The MSA must consider all these factors, as detailed in Figure 2, as they influence the overall measurement system uncertainty.

Figure 2
Measurement system definition
Source: AIAG Measurement System Analysis



Measurement system performance indices

The performance of a measurement system is determined using indices that categorize and quantify the measurement uncertainty. By collecting data on the process, the metrologist can quantify the total measurement variability by determining a specific behavior associated with it. Usually, this behavior is described as a Random Variable (RV) with a Gaussian distribution (normal). Figure 3 illustrates this concept, with the black curve representing the collected data i.e., the measured values coming from the measurement process, and its distribution defined by the location (*mean*) and width parameters (*standard deviation*).

The multiple factors affecting the measurement process represent multiple sources of uncertainty that are either systematic (e.g., *average measurement value vs. actual value*) or random (e.g., *spread of measurements*). It is possible to categorize these uncertainties depending on the effect they have on the identified distribution parameters. As illustrated in Figure 4, systematic uncertainty includes bias, linearity, and stability, while random uncertainty includes repeatability and reproducibility. Each category is clearly identifiable by its unique distribution pattern.

Figure 3
Gaussian distribution

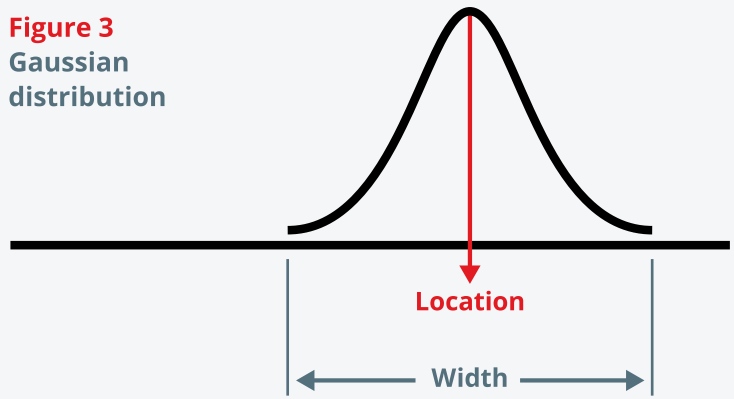
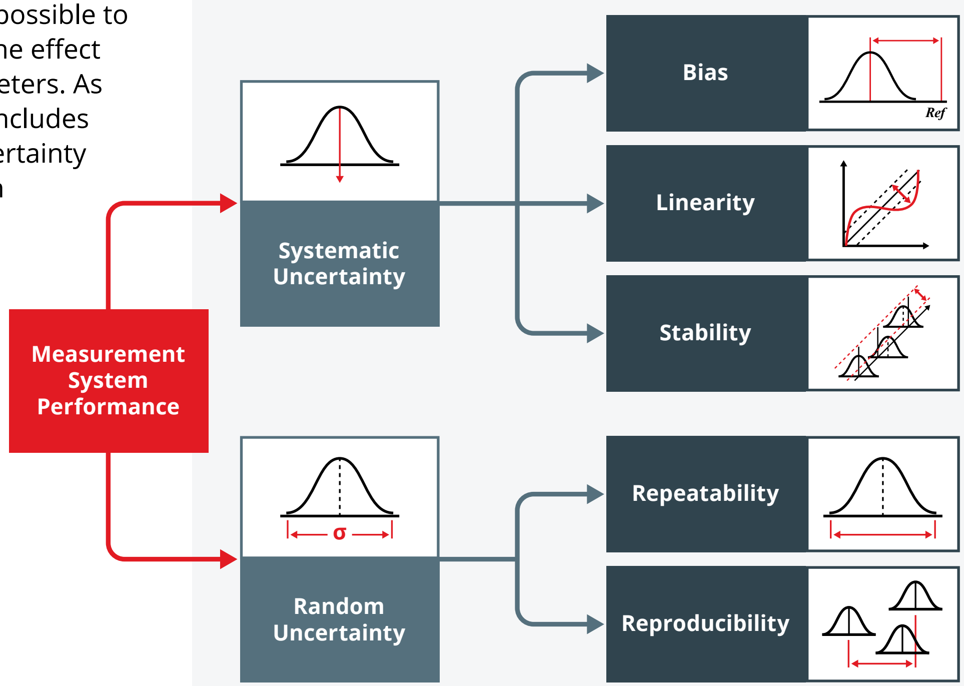


Figure 4
Performance indices



• **Systematic uncertainty**

Systematic uncertainty is the measurement uncertainty strongly associated with the position of the normal distribution regarding a known reference. Mathematically, it influences the mean value of the measured data. The common term for this is *accuracy error*. Accuracy error represents the exactness between the average of one or more measured results and a reference value. Accuracy error is generally reproducible and is often due to problems that could be quantified and corrected. The three types of systematic uncertainty are bias, linearity, and stability, with bias being the most common. *Bias* represents the distance between the average of one or more measured results ($\bar{X}$) and a reference value (Ref). Mathematically, bias is estimated by the difference between the true value (Ref value) and the observed mean of measurements on the same characteristic on the same part. *Linearity*, on the other hand, indicates how well the data gathered throughout an instrument's measurement range matches the reference value. It is the difference in bias over the entire intended measurement range of the equipment. Linearity represents the change in bias from one extreme of the measurement range to the other. The last systematic uncertainty type is *stability*. It represents the ability of a measurement system to maintain its metrological capability over time. Stability describes the variation of the bias over time, usually the time between two system calibrations.

• **Random uncertainty**

The remaining source of measurement uncertainty is random uncertainty, commonly called *precision error*. Precision error represents the statistical fluctuations in the measured data due to the limitations of the measurement system. The precision error describes the expected variation of repeated measurements over the range of measurement. The two types of random uncertainty are repeatability and reproducibility. *Repeatability* represents the width of the dispersion of measurements obtained under a set of very controlled conditions. It describes the system's ability to get the same measurement, with the same equipment, part, template, and the same environmental conditions. A narrow distribution indicates a more repeatable measurement. *Reproducibility* represents the variation between measurements made by different operators, with the same equipment and under the same conditions. Mathematically, this is the variation in the average of the readings taken by each of the operators.

Measurement system capability & performance

The capability of a measurement system ($\sigma_{capability}$), also referred to as the *total standard uncertainty*, is the combination of all systematic and random uncertainties. It quantifies the doubt associated with a measurement under known conditions and it is used to identify the total measurement system uncertainty over a short period of time. Capability can be calculated using the formula:

$$\sigma_{capability}{}^2 = \sigma_{Bias\ (linearity)}{}^2 + \sigma_{R\&R}{}^2$$

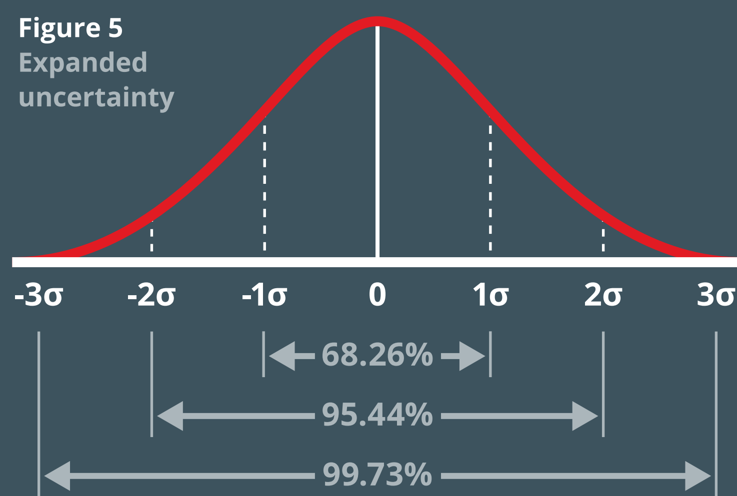
Performance, on the other hand, considers not only the sources of systemic and random variations, but also the sources of drift that occur over time. It is calculated using the formula:

$$\sigma_{performance}{}^2 = \sigma_{capability}{}^2 + \sigma_{stability}{}^2$$

Expanded uncertainty

The final step of the Measurement System Analysis process determines the *expanded uncertainty* (U) associated with the measurement system. Expanded uncertainty represents the total measurement uncertainty value that describes, within a specific confidence level, the range expected to contain the real measurement result obtained by a system. It can be expressed as: $U = \pm K\sigma_{tot}$ where U is the expanded uncertainty, K is the coverage factor that represents the area under the normal curve for a desired confidence level (e.g., $K = 3$ for 99.73% confidence level), and σ_{tot} is the total standard uncertainty of the measurement system that usually corresponds to its performance. The most commonly used confidence factors during measurement system analysis are found in the figure below.

Figure 5
Expanded uncertainty



Choosing the appropriate methodology to evaluate the uncertainty of complex 3D measurement systems

To evaluate the measurement uncertainty of a system, its measurement model first needs to be defined. This model is a mathematical representation of the relationship between the output quantity of the measurement system and the input quantities known to be involved in the measurement process. Two types of measurement exist: direct and indirect, and this will affect the way the model is defined. Direct measurement is when a measurement device directly provides the output quantity. For example, an external diameter (Y) is measured using a micrometer, which directly provides the physical value X. In this case, the measurement model (i.e., function) is identified as $Y=X$. However, most 3D measurement devices perform indirect measurement. They cannot directly provide the value (Y), but rather consider a function of several (n) physical values (X_i), $Y=f(X_1,...,(X_n)$. For example, a portable CMM uses the position and orientation of multiple encoders to obtain a specific output. These physical values, in this example the encoders' position and orientation used to calculate the output quantity, are all affected by a specific measurement uncertainty (u_{x_i}). Therefore, the measured result given by the arm (Y) is dependent on the set of values (X_i) and the associated uncertainties (u_{x_i}) used for its estimation. Ultimately, the measured value (Y) also has a total uncertainty (u_y).

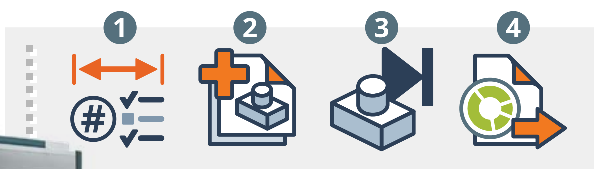
If the model representing the measurement system is explicitly formulated, it could be used to propagate the uncertainties from the input quantities to the output quantities using two strategies: a Taylor series or a Monte Carlo simulation. These strategies are addressed in depth in publications such as the *Guide to the expression of uncertainty in measurement (GUM)*[1]. On the other hand, **if the model is too complex to be explicitly formulated or when parameters are unknown, an experimental strategy should be used**. Analyzing the output quantity using statistical tools, it is possible to estimate the total uncertainty of the measurement system. For example, in a situation where a metrologist uses a portable CMM with a scanner to measure a surface profile, the measurement function is much more complex to identify. In this case, experimental analysis must be used. Since it is done directly on the measurement's results, the metrologist doesn't have to break down the complete measurement system, making it simpler, more straightforward, and easier to understand.

[1] Evaluation of measurement data - Guide to the expression of uncertainty in measurement (JCGM 100:2008) published by the Bureau International des Poids et Mesures

Conducting MSA studies using the experimental methodology and smart 3D metrology software

Performing an experimental analysis to determine the expanded uncertainty of complex 3D measurement systems requires first conducting a repeatability study followed by a complete Gauge R&R study. By collecting data on the system's measurement outcomes using different setups and trials, the metrologist can estimate the total variation using the performance indices described previously. But these studies are traditionally complex to perform and require extensive knowledge of statistics to obtain appropriate results.

Figure 6
PolyWorks MSA toolbar



PolyWorks® offers an integrated MSA smart 3D metrology software solution for conducting studies of complex 3D measurement systems within a fully digital process (Figure 6). It allows users to:

1. Specify key characteristics required by the control plan;
2. Create the study by selecting its type and defining key parameters, which are essential for quality control and traceability;
3. Execute the study by performing data acquisition for all 3D measurement device configurations and measurement contexts, within just one universal software platform;
4. Produce information-rich reports published directly in Microsoft Excel with preformatted spreadsheets linked to smart 3D inspection data; and
5. Perform sophisticated analyses in Excel without the need for advanced expertise in statistical software applications.

From the setup of the studies to the measurement acquisition and the automatically generated results, such as indices and charts, the PolyWorks MSA solution ensures that all calculations are performed within one software ecosystem and the fully digital chain ensures data integrity and trustworthy results.

Repeatability studies

The first step in conducting a measurement system analysis is a repeatability study. It assesses the variability of measurement systems (equipment variation) when affected by a minimum number of sources of variation. It is used during the initial evaluation of a measurement system to quickly compare different system configurations, such as the fixture clamping locations or the parameters of the metrology hardware.

A repeatability study is performed by:

1 - Placing a part in a fixture (when applicable);

2 - Measuring the part using a 3D measurement device;

3 - Removing the part from the fixture; and

4 - Repeating these steps one to three times, always using the same part, fixture, and measurement device.

Using the control plan, the metrologist identifies the key characteristics on which statistical analysis must be done. The part is measured a minimum of 10 times, but usually at least 30 times, in order to obtain a good estimation of equipment variation. This type of study is usually conducted by a senior metrologist who has the necessary experience to rapidly detect problems in the measurement process and easily solve them.

There are two types of repeatability studies:

Type 1 Gauge Study[2] :

- Assesses the effect of bias and repeatability on measurement
- Requires a certified reference of known dimensions
- Outputs two metrics: Cg and Cgk
- Applies when a certified reference is available, and the stability of the measurement system is not a concern

Gauge R Study[3] :

- Assesses the repeatability and stability of the measurement system
- Requires no certified reference
- Uses the I-MR chart as a basis for the evaluation of variation and stability

The main difference between them is that the Type 1 study needs a certified reference to help identify a possible bias and does not assess the stability of the measurement system.

[2] Measurement System Analysis Requirements for the Aero Engine Supply Chain (AS13003) published by SAE International

[3] Measurement System Analysis (MSA) published by the Automotive Industry Action Group (AIAG).

Both repeatability studies are facilitated by the PolyWorks MSA solution:

1 - The metrologist is guided step by step in the necessary steps of the study with the creation of an inspection project that is complete with all the required measurements, their characteristics, controls, and output metrics, as well as the number of pieces to be measured, ensuring a robust measurement template.

2 - Then, operators are guided with on-screen instructions and 3D displays throughout the measurement acquisition.

3 - Once the measurement acquisition process is completed, inspection results are automatically published to preformatted Excel spreadsheets that are dynamically linked to the inspection project's 3D inspection data.

4 - The preformatted spreadsheets provide the metrologist with automatically calculated and analysis-ready equipment variation, i.e., repeatability, performance indices, and charts.

5 - To complete this analysis and quickly optimize the measurement process, the metrologist can adjust measurement parameters in the inspection project and see their direct influence on the equipment variation, with PolyWorks automatically updating the spreadsheet index and chart values.

Gauge R&R studies

While repeatability studies allow you to analyze and optimize measurement system equipment variation, gauge repeatability and reproducibility studies, or Gauge R&R studies, are required to complete the final validation of a measurement system.

Gauge R&R studies are usually executed after repeatability studies because they require more resources, parts, and costs. Also, by doing a repeatability study first, the metrologist can correct the equipment variation before analyzing and correcting its reproducibility. Several accepted empirical methods exist to estimate the uncertainty of measurement system repeatability and reproducibility. The two most common methods are the *Average and Range Method* (X-bar R) and the *Analysis of Variance (ANOVA) Method*. In both cases, data collection follows strict rules to ensure credible results:

- **Number of operators:** A minimum of 3 operators are required and they must use the measurement system in a production context.
- **Number of parts:** A minimum of 2 parts, representative of the variations found in the manufacturing process, must be selected. If possible, the preferred number would be 10; the larger the number of parts, the better the estimate of the process behavior.
- **Number of repetitions:** Each operator must measure all the parts more than once. Usually, 2 or 3 repetitions are done.
- **Random order for measurements:** To ensure that the order of measurement does not influence the results, each operator must measure parts in a randomized order.

The PolyWorks MSA solution allows users to create and execute a complete Gauge R&R study using these two standard methods:

1 - The metrologist quickly selects the analysis method and specifies parameters such as the number of operators, repetitions, and parts.

2 - Then, PolyWorks creates the inspection project with all the necessary pieces in a specific run order.

3 - A run order sheet is then automatically exported to an Excel spreadsheet, which guides the operators during the measurement collection process, ensuring a random measurement order.

4 - A toolbar guides the operators through the inspection process, ensuring that all key characteristics are measured, and that sufficient probed and scanned data is acquired to obtain reliable measurement extractions.

5 - On measurement completion, the metrologist uses the inspection project to estimate the variability of the measurement system.

The main difference between the X-bar R and ANOVA methodologies lies in the analysis of the results. The X-bar R method makes it possible to quantify repeatability and reproducibility using control chart calculations. The AIAG's "Measurement System Analysis" guide presents the methodology in detail. Gauge R&R with the ANOVA methodology provides more information and is therefore more comprehensive.

Analysis of variance (ANOVA) is a statistical analysis that breaks down the sources of variations in a measurement system as follows:

- **Repeatability:** Variation from the measurement system that is not attributable to other sources of variation.
- **Operator:** Variation between operators.
- **Part/operator interaction:** Variation resulting from the interaction between operators and parts (when an operator measures different parts differently).
- **Part to part:** Variation coming from the parts within the study. It represents the manufacturing process variation.

Regardless of the method used, the sources of variation are considered to be statistically independent. Therefore, they are assembled on a random basis (sum of variances) to express the total uncertainty.

First, the methodology determines whether the variation resulting from the interaction between parts and operators is significant. If it is, it must be considered in the total reproducibility of the system ($\sigma_{reproducibility}$) as follows:

$$\sigma_{reproducibility}^2 = \sigma_{operator}^2 + \sigma_{interaction}^2$$

With repeatability ($\sigma_{repeatability}$) having been directly identified during the study, it is possible to determine the repeatability and reproducibility ($\sigma_{R\&R}$) of the measurement system as follows:

$$\sigma_{R\&R}^2 = \sigma_{reproducibility}^2 + \sigma_{repeatability}^2$$

Finally, the total measured process variation (σ_{total}) is obtained by adding the repeatability and reproducibility of the measurement system to the estimated manufacturing process variation ($\sigma_{part\ to\ part}$) as follows:

$$\sigma_{total}{}^2 = \sigma_{R\&R}{}^2 + \sigma_{part\ to\ part}{}^2$$

The analysis of the study results consists in:

- Ensuring that the measurement system uncertainty ($\sigma_{R\&R}$) has a small contribution to the total measured process variation. The estimated manufacturing process variation (part to part) should account for most of the variability. When the contribution from part-to-part variation is relatively higher than the rest of the uncertainty, it means that the measurement system can reliably distinguish manufacturing errors.
- Comparing the measurement system variation to the specification limits (tolerances) to ensure the variation represents a maximum of 30% of the limits.

The publishing step of the PolyWorks MSA solution converts the MSA study data into interpretable results, and actionable data, through easy-to-read tables, summaries, and charts, as presented in Figure 7. This is a powerful and important part of the digital study process as it greatly facilitates the interpretation and troubleshooting of study results. It allows users to publish results to the selected X-Bar R or ANOVA Excel template and quickly analyze the measurement error and other sources of variability. When conducting an ANOVA study for example, the metrologist can break down the variance in four categories: parts, appraisers, interaction between parts and appraisers, and replication error due to the gauge.

Gauge Repeatability and Reproducibility Report

Sources of Variation	Standard Deviation (SD)	Expanded Std Deviation (Study Variation * SD)	% Study Variation (% SV)	% Tolerance (SV/Tolerance)
1. Total Gauge R&R	0.7934	4.7602	99.87	238.01
1.1 Repeatability	0.4101	2.4608	51.63	123.04
1.2 Reproducibility	0.6791	4.0748	85.49	203.74
1.2.1 Operator	0.6791	4.0748	85.49	203.74
1.2.2 Part/Operator	n/a	n/a	n/a	n/a
2. Part-To-Part	0.0412	0.2472	5.19	12.36
Total Variation	0.7944	4.7666	100.00	238.33

Number of Distinct Categories =	1

Gauge R&R Report for Measurement

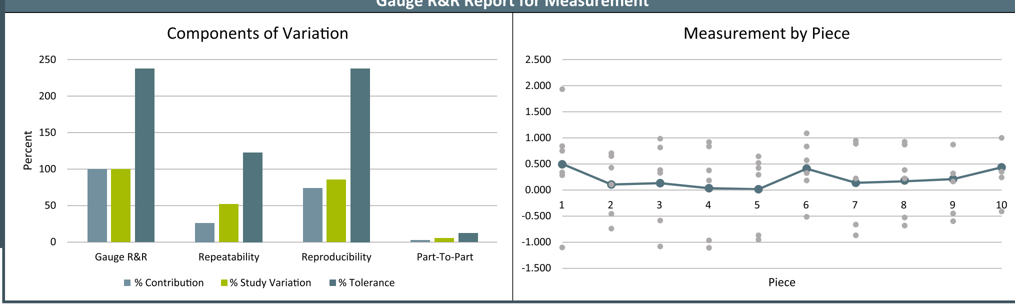


Figure 7
Gauge R&R

Recommendations for metrologists

The data collected on the system's measurement outcomes gives feedback on the effect of measurement uncertainties. Using the performance indices (page 5), the metrologist can take corrective actions to optimize his measurement process. Let's use a concrete example—a target and scatter plot of error values, as illustrated in Figure 8.

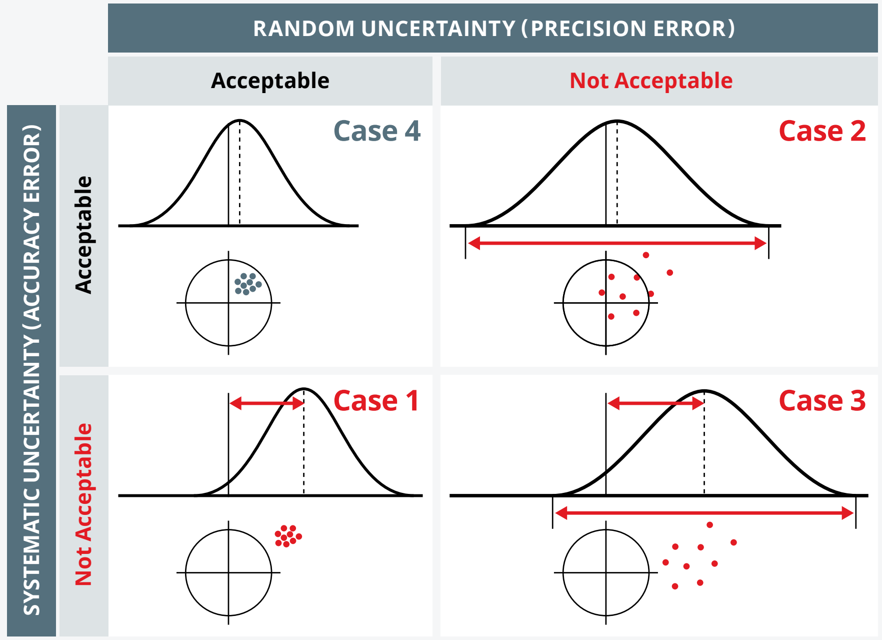


Figure 8 Accuracy & precision errors

The first problem (case 1) a metrologist can identify is if there is an accuracy error—it may come from the bias on linearity of the system, but in both cases, this error may be easily corrected. The possible causes of accuracy error may be:

- The metrology device needing calibration
- A worn device, equipment, or fixture
- An error in the reference used in the analysis process
- The measurement method (e.g., the clamping technique)

The second issue a metrologist can face is when there is a precision error (case 2). This may be related to the measurement system itself (repeatability) or be caused by the operators (reproducibility).

Possible causes of precision error may be[4]:

- Part related: form, position, surface finish, taper, sample consistency
- Instrument related: repair, wear, equipment or fixture failure, poor quality or maintenance
- Methodology related: variation in setup, technique, holding, clamping
- Operator related: technique, position, lack of experience, manipulation skill or training, feeling fatigued

If all sources of error are present (case 3), the metrologist should break down the measurement system performance using the indices and correct one type of error at a time for the measurement system to be acceptable (case 4).

[4] Measurement System Analysis (MSA) published by the Automotive Industry Action Group (AIAG)

Conclusion

An effective measurement system analysis process ensures you are collecting trustworthy 3D measurements. Today, there is no need to suffer with outdated, complex processes that require multiple third-party software solutions and advanced expertise in statistical software applications.

The PolyWorks® MSA smart 3D metrology software solution greatly simplifies the setup and the execution of MSA studies for environments with 3D measurement devices, providing reliable analysis of measurement system variations. It provides an easy-to-use fully digital workflow that ensures measurement data integrity and allows manufacturers to confidently perform MSA studies for every new part, delivering better quality control.

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