openZDM

Open Platform for Realizing Zero Defects in Cyber Physical Manufacturing

Uncertainty Management - Calibration

A measurement system **measures an input quantity and provides an output**, which can be an electrical signal (analog sensor) or a numeric value (digital sensor).

The relationship between input and output represents the model of the sensor and it can be represented by the general function given in Equation (1). This function can be determined through calibration.

Figure 1 Measurement system block diagram

(1)

In use, once the output of the measurement system is obtained, the numerical value of the input can be retrieved by applying the calibration function inverted. This value represents the measurement which has to be expressed in a measurement unit of the International System of Units and has to be associated with a measurement uncertainty.

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Measurement Uncertainty

Even after calibration, there is always some doubt about the accuracy of the measurement. This doubt is known as measurement uncertainty; main causes of uncertainty are disturbances, noise and any other sort of deviation from an ideal measurement. It represents the range within which the true value of the measured quantity lies, considering all possible errors and variations.

Measurement uncertainty arises from the inherent complexities of measurement systems, which deviate from ideal behaviors described in models. These deviations introduce uncertainty due to various factors:

- **Model-related Uncertainty:** The initial step in measurement involves modeling the quantity (measurand) to be measured. However, real-world objects rarely conform perfectly to these models, leading to uncertainties. For instance, assuming a steel bar has a perfect rectangular shape (parallelepiped) when it may deviate slightly from this ideal.
- **Disturbances:** Disturbances affect measurements by influencing the measurement system beyond the intended input-output relationship:

| **Interfering Inputs:** These add unwanted variations to the output, such as electromagnetic noise affecting sensors, thereby causing uncertainty.

| **Modifying Inputs:** These alter the functional relationship between input and output, for instance, temperature changes affecting the stiffness of a transducer.

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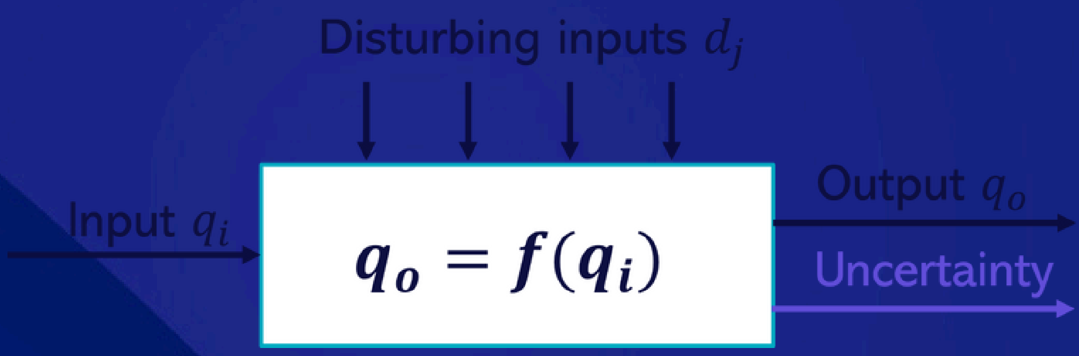

Figure 2 Disturbing inputs entering a measurement system

Disturbances can be random (causing fluctuations) or systematic (causing biases), with systematic effects potentially correctable if understood.

To mitigate uncertainty:

- Designers should minimize instruments; sensitivity to disturbances, focusing on accurately measuring the intended input quantity.
- Techniques such as input filtering and output signal filtering can be employed to reduce the impact of disturbances.

In a real world, the uncertainty can be mitigated but never completely removed and therefore it has to be estimated because it is an inherent component of the measurement like the measurement unit. **Calibration of instruments is crucial, as it determines the measurement system's model and associated uncertainty.**

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BIPM

JCGM 100:2008
GUM 1995 with minor corrections

Evaluation of measurement data — Guide to the expression of uncertainty in measurement

Évaluation des données de mesure — Guide pour l'expression de l'incertitude de mesure

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Figure 3 The Guide od Expression of Uncertainty in Measurment (GUM) ISO-GUM JCGM 100 series

In the Guide to the Expression of Uncertainty in Measurement (GUM) uncertainty is defined as **“a measure of the quality of a measurement”** ; so if the uncertainty is known, it is possible to define the confidence level on following decision.

Standards like ISO-10012:2003 emphasize the importance of calibration to ensure instruments meet required standards for accuracy and reliability. Uncertainty influences quality of measurement data and, since measured data are used to make decisions, like to assess conformity or nonconformity with specifications of a product or a process, uncertainty of measurement affects the level of confidence in decisions based on measured data.

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Figure 4 Uncertainty affecting quality of data and decision

As provided by the International Vocabulary of Metrology (VIM), calibration is the *“operation that, under specified conditions, in a first step, establishes a relation between the quantity values with measurement uncertainties provided by measurement standards and corresponding indications with associated measurement uncertainties and, in a second step, uses this information to establish a relation for obtaining a measurement result from an indication.*

A calibration may be expressed by a statement, calibration function, calibration diagram, calibration curve, or calibration table. In some cases, it may consist of an additive or multiplicative correction of the indication with associated measurement uncertainty.”

The calibration procedure consists of the following steps:

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- **Define Input Range and Reference Values:** Determine the operational range of the sensor and select N known values of the input quantity within this range. These reference values should be known with significantly lower uncertainty than the instrument being calibrated. This can be achieved using standard reference samples or specific equipment calibrated against instruments with lower uncertainty.
- **Measurement Procedure:** Measure each known input value sequentially, recording the corresponding output of the sensor. Perform measurements from the smallest to the largest values and back to identify and account for hysteresis effects. Each input value is measured twice, resulting in 2N data points.
- **Data Plotting:** Plot the measured points on a Cartesian graph, with the input quantity on the x-axis and the output quantity on the y-axis.
- **Regression Analysis:** Conduct a least-squares regression analysis to fit the data and obtain the resulting equation that represents the calibration function. Typically, instruments are designed to exhibit linear behavior, but higher-order polynomial fits may be considered for non-linear relationships.
- Residual Analysis: Compute and plot the residuals, which are the differences between the measured output values and the values predicted by the calibration function. The scatter of residuals indicates the calibration uncertainty caused by measurement errors during calibration.
- **Uncertainty Evaluation:** Assuming residuals follow a Gaussian distribution, calculate the standard deviation of the residuals. The expanded uncertainty is estimated as, providing a measure that includes a coverage factor to encompass approximately 95% of measurements. The calibration uncertainty of the instrument is then computed from.

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The calibration function is exploited to determine the input quantity from any subsequent readings of. Make certain that the calibration compensates for any systematic effects, ensuring the instrument exhibits minimal bias.

Conclusions

Quantitative data on physical quantities originate through measurement processes. Measurement instruments, because of their nature and complex interaction with the measurand and the measurement environment, produce data that are always inherently affected by uncertainty, affecting the level of confidence in decisions made based on uncertain data.

To ensure quality of measured data is paramount to understand and manage the entire measurement process; it implies always to use calibrated instruments, and to pay attention to disturbances that affect the measurement process.

In the context of Industry 4.0 and the Zero-Defect Manufacturing (ZDM) paradigm, high-quality data comes from accurate measurements. Measurement science is therefore crucial as an enabling technology for advanced manufacturing. Quality control stations, equipped with well-calibrated instruments and accurate uncertainty assessment, perform the quality control process, possibly in-line on 100% production, and support effective decisions towards Zero Defect Manufacturing. This not only improves production effectiveness and efficiency, but also improves customer satisfaction by reducing non-quality-related costs overall.

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