How long is a piece of string?

Some overlooked considerations for uncertainty estimation.

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Abstract

When estimating measurement uncertainty, there are some contributors that are obvious, such as the equipment and the environment. However, since the uncertainty is supposed to tell us how far away from the true value our measurement result may be, it is important to consider what the definition of the true value is. The author is involved in ISO Technical Committee 213, where a draft Technical Specification is being considered, which expands the concept of uncertainty to encompass not only the measurement itself, but also the definition of the measurand and how the measurement result relates to the function of the product.

Introduction

The International Vocabulary of Basic and General Terms in Metrology[1] (VIM) defines *measurement uncertainty* as a "parameter, associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand". It also defines *measurand* as a “particular quantity subject to measurement”. Finally, it defines *true value* as a “value consistent with the definition of a given particular quantity”.

Looking at these three definitions together, we can think of measurement uncertainty as a parameter that tells us how far the true value might be from the measured value. Therefore, using the string analogy, where we need to see the whole string including both ends in order to make an educated estimate of its length, we need to consider both the measured value and the true value for the measurand, if we are to make an intelligent statement about the difference between the two, i.e. the measurement uncertainty.

However, we are often so focused on our measurement and the elements that cause our measured values to vary, that we tend to forget what it *really* was we were asked to measure. This oversight tends to make us think our measurements are better than they really are and it really causes trouble when we start comparing our results to others, who may have a different interpretation of what it was we were supposed to measure.

ISO TC 213 "Geometrical Product Specification and Verification" has faced these problems since it was established in 1996. This is because the TC was established by merging the technical committee that was writing standards for the specification of product geometry with several technical committees tasked with writing standards for making measurements to verify that product lived up to these specifications. It turned out that the members of these different committees had very different ideas of what “size”, “form” and other geometry concepts really meant, when you have a part and a drawing and you are trying to establish whether the part is in accordance with the drawing.

Consequently, ISO TC 213 has started an effort to define a terminology that can give us words to use when we are discussing these concepts.

Expanding the concept of uncertainty

In transactions involving measurement, it is often critical that the supplier and the customer agree on what is to be measured, how good the measurement has to be and what the result of the measurement means. If there is a disagreement over any of these issues, there is a potential conflict and a costly correlation issue may be the result.

What is to be measured?

This question is not as trivial as it seems, at least not in the dimensional metrology area. If, for example, we are asked to measure a diameter, is it then the minimum circumscribed diameter, the maximum inscribed diameter, or a two-point diameter? All of these will give different results, unless the part we are measuring is perfectly round. But if we know how round the part is and we know which diameter is called for, it is still quite acceptable to measure another diameter, if we account for the difference in our uncertainty budget and find it sufficiently small compared to the tolerance we are measuring.

How good must the measurement be?

The "goodness" of a measurement is quantified in the uncertainty of the measurement. It is important that we calculate the uncertainty back to what we were asked to measure, as described above.

What does the measuring result mean?

We use the measurement result to draw a conclusion. We may accept or reject a part or a batch of parts based on our measurement, or we may adjust our manufacturing process. To get the maximum benefit out of our measurement, we need to have a clear set of rules for how we decide what to do based on our measuring result. ISO 14523-1[2] gives one example of such a set of decision rules.

New ISO work on terminology

To provide a framework and a language, ISO TC 213 has started work on terminology that covers these concepts. The terminology covers function, specification and verification/measurement and expresses the differences between them in terms of uncertainty.

Function

The function of a part can be anything from a simple: Will the pin fit in the hole? To the more complex: Will the engine run for 100,000 miles before requiring a tune-up?
Some functions, such as the pin-in-hole scenario are very easy to express in terms of geometry, whereas others, such as the engine scenario are very complex and almost impossible to express purely in terms of geometry without having to be overly restrictive, i.e. reject a significant percentage of the parts that might have worked.

The difference between the functional requirements (what it takes to make the engine run for 100,000 miles) and what is in the specification can be viewed as an uncertainty.

We may not know or truly understand these functional requirements, just like we generally do not know the true value of what we are measuring, but we can still calculate an uncertainty relative to it, just as we calculate the uncertainty relative to a true value.

Specification

The specification is what is put down in a product documentation. It often is based on international or national standards or internal company standards. Sometimes these standards are clear and unambiguous, but sometimes the language of a standard is open to interpretation or gives equal value to choices that are not equivalent. In those cases there may be an ambiguity built into the specification. This ambiguity can also be interpreted as an uncertainty.

If you can reasonably interpret a specification in different ways and reach different results, then all of these results are correct per the definition in the specification and the span between them is the uncertainty built into the specification.

Verification/Measurement

The basis for our measurement may be something else than what the specification called for. An example is measuring a two-point diameter, when the minimum circumscribed diameter is called for. Another aspect of the measuring uncertainty arises from the imperfections in our measuring equipment and our measuring process. This is often the only aspect that is taken into account when calculating measurement uncertainty, but while it is the most tangible one, it may still end up being the smallest of them all.

Terminology

The ISO/TS 17450-2[3] draft provides a terminology for the uncertainty components quantifying the difference between the function and the measurement result. Figure 1 gives an overview of all the components and their relationship.

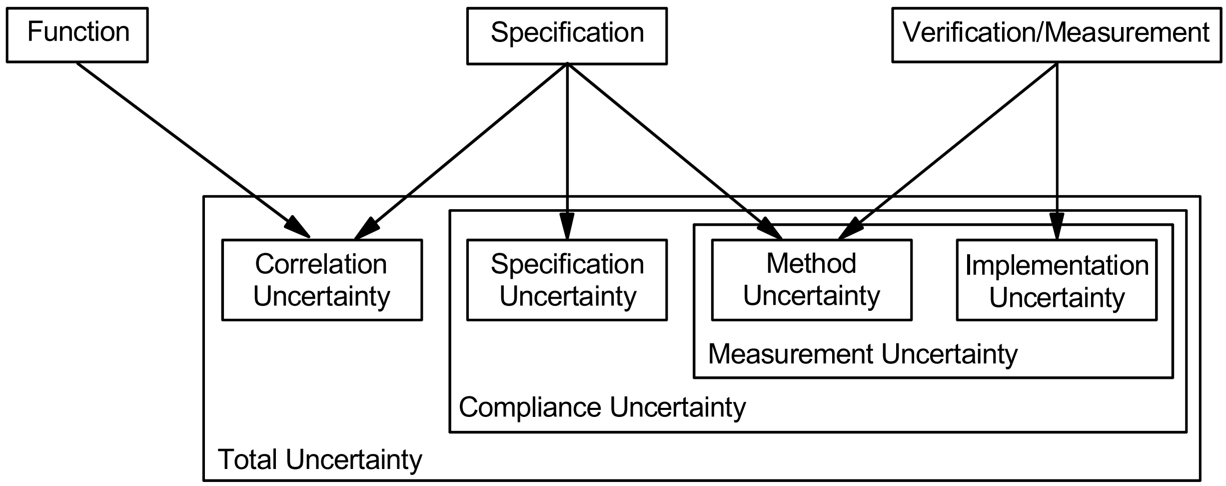

Figure 1: Relationship between function, specification, verification/measurement and various uncertainties

Method Uncertainty

The method uncertainty accounts for the difference between what the specification calls for and what is implemented in the measuring process, disregarding the physical imperfections of the measuring equipment and inaccuracies in the measuring process.

Even with perfect measuring equipment and strict adherence to the measuring procedure, it is impossible to reduce the measuring uncertainty below the method uncertainty. For example, measuring a two-point diameter when the specification calls for a minimum circumscribed diameter, results in method uncertainty if the part is not round.

Implementation Uncertainty

The implementation uncertainty covers the uncertainty arising from the physical imperfections of the measuring equipment and deviations from the prescribed measuring procedure. The purpose of calibration is to control the metrological characteristics of the measuring equipment in order to reduce, control or eliminate the implementation uncertainty. Other effects, such as environmental effects, that are not directly related to the measuring equipment may also contribute to the implementation uncertainty.

Examples of implementation uncertainty contributors are: scale error, zero-point error and linearity of the gage.

Measurement Uncertainty

The VIM definition of measurement uncertainty is given in the introduction. It is not the intent for ISO/TS 17450-2[3] to contradict this definition, but rather to build upon it. For the purposes of this presentation, measurement uncertainty can be considered as the sum (in the sense of the Guide to the Expression of Uncertainty in Measurement[4] (GUM)) of the method and implementation uncertainty.

Specification Uncertainty

The specification uncertainty is the uncertainty inherent in a specification when it is applied to a real part. Most specifications are defined such that they are unambiguous, if the part has perfect form and no roughness. However, as the part imperfections increase, the specification may be less well defined. An example is "diameter". If a part is perfectly round, no qualifiers are needed to define the diameter, but if the part has form error, then various methods of measuring the diameter will lead to different results.

For example, if the tolerance for a pin's diameter is 1 inch +/- 0.001 inch and the call-out does not specify what diameter, e.g. minimum circumscribed or two-point diameter is covered by the tolerance, then the difference between results obtained with all acceptable methods using perfect measuring equipment is the specification uncertainty.

The magnitude of the specification uncertainty depends on the particular specification and the geometrical deviations of the actual part.

Compliance Uncertainty

The compliance uncertainty quantifies the uncertainty with which it can be determined that a workpiece complies with all possible interpretations of a specification. It is the sum (in the sense of the GUM[4]) of the specification uncertainty, the method uncertainty and the implementation uncertainty.

The compliance uncertainty, rather than just the measuring uncertainty, is what has to be taken into account, when suppliers and customers try to solve a dispute over product compliance.

Correlation Uncertainty

The correlation uncertainty arises from a less than perfect correlation between a specification and the intended function of the workpiece, expressed in the terms and units of the specification. Correlation uncertainty is usually not related to a single specification item. Usually it takes a number of specification items to simulate a function (e.g. size, form and surface texture of the part).

The correlation uncertainty quantifies our ability to predict whether a part will work or fail, based on its compliance with a given specification.

In the case of the pin, this is fairly straightforward, but in the case of the engine, there are a lot of gray zones, where we do not know whether the engine will run for 100,000 miles before requiring a tune-up. To accommodate this uncertainty, we tighten the tolerances, so we reject all the engines we are not sure about, but which might run for 100,000 miles. A lower correlation uncertainty would obviously allow us to reject fewer potentially good engines.

Total Uncertainty

The total uncertainty is the sum (in the sense of the GUM[4]) of the correlation uncertainty, the specification uncertainty, the method uncertainty and the implementation uncertainty.

The total uncertainty quantifies our ability to predict whether a part will work or fail, based on the result of a measurement of the specified characteristic(s).

The next steps

Standing alone, this terminology will not solve any problems. But the awareness that it raises and the discussions that are necessary both internationally and in the individual national committees for the implementation of these concepts in future standards from ISO TC 213, may give us a better understanding of what uncertainty contributors we need to take into account when we try to solve disputes and discrepancies between measurement results and functional performance of parts and products.

It may also help us formulate some rules around what is an appropriate relationship between the various uncertainties. For example is it not useful to invest in the ability to measure a specification with very low measuring uncertainty, if the specification uncertainty is high.

Ultimately this should lead us to a better understanding of exactly what our requirements are, exactly what our measurements mean and exactly how long the string is.

References

1. International Vocabulary of Basic and General Terms in Metrology.BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML., 1995

2. ISO 14253-1:1998 Geometrical Product Specifications (GPS) - Inspection by measurement of workpieces and measuring equipment - Part 1: Decision rules for proving conformance or non-conformance with specifications

3. ISO/DTS 17450-2 Geometrical Product Specifications (GPS) - General concepts - Part 2: Operators and uncertainties

4. Guide to the Expression of Uncertainty In Measurement. BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML., 1995