

Toward an Industrial Uncertainty Methodology

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1 Introduction

Since the publication of the *Guide to the expression of uncertainty in measurement* (GUM) [1], the national metrology institutes (NMIs) and other organisations involved in metrology have been able to further develop common approaches and methodologies for evaluating uncertainties, promoting better understanding and communication. In view of the growing success of the GUM in promoting harmonisation of practice in the upper levels of the national measurement system, there are clear potential benefits in adopting them at all levels. All those engaged in measurement, whether in the standards laboratory, the design office or on the shop floor would have a common language for and the same understanding of statements about measurement uncertainty. Already, industrial users have been affected by the GUM in that the certificates provided by accredited laboratories for the calibration of their master artefacts or the certification of reference materials will have uncertainty statements derived using GUM principles.

Although the underlying principles of the GUM have been known and applied for many decades, its publication in 1995 has resulted in significant change in laboratory procedures. Similarly, its adoption by industry will require existing practices to be reviewed and revised. In particular, the many variants of statistical process control (SPC) implemented by industry will need to be related to or aligned with the GUM methodology.

As part of the Department of Trade and Industry's *Software Support for Metrology* programme (SSfM, www.npl.co.uk/ssfm), NPL, along with industrial partners including Rolls-Royce and GlaxoSmithKline, is undertaking a project with the objective of defining an initial version of an industrial methodology for uncertainty in quality and process improvement. In this paper, we consider existing techniques such as measurement uncertainty evaluation, measurement system evaluation, statistical process control and analysis of variance and how they can fit into a general framework. Our view is that existing techniques jointly are sufficient to enable an industrial uncertainty methodology to be established. However, work is required to seek out and explain the commonalities in the different approaches currently being used at the same time as bringing about harmonisation in areas where the techniques differ.

2 Existing Components for an Industrial Uncertainty Methodology

In this section we review current activities and techniques relevant to the uncertainty of industrial measurements.

2.1 Measurement uncertainty evaluation

The GUM gives guidelines on how one should evaluate and express the uncertainty associated with the output of a system, given the inputs, their uncertainties, and the model linking the output to the inputs [2]. For example, we may wish to determine the length of a reference artefact at 20 °C from repeated measurements. From the average of the measurements we determine an estimate of length and from the spread of the measurements we can determine an estimate of the component of measurement uncertainty. However the length estimate will need to be corrected for temperature effects and in order to do this we need to know a) the temperature of the artefact when the measurements were taken and b) the coefficient of thermal expansion for the artefact. Since neither of these quantities will be known exactly, uncertainty associated with their values will also contribute to the final uncertainty associated with the length estimate. The GUM provides a methodology for making this type of calculation based on well-established rules for the propagation of uncertainties. The GUM covers two methods of uncertainty evaluation, Type A covering statistical methods and Type B for others. The use of the standard deviation of a set of repeated measurements is an example of a Type A evaluation. If, in the measurement of the reference artefact, we know that the measurements were made in a temperature-controlled environment kept at 20 ± 1 °C, this information can be used in a Type B evaluation to estimate the uncertainty contribution arising from the possible variation in temperature. The focus of

the GUM is to take proper account of the influence of the known variations of the input quantities on the output quantity.

2.2 Assessing the accuracy of measurement methods

Although the GUM has quite general applicability, it tends to be used in the uncertainty evaluation associated with a particular set of measurements gathered by a particular measurement system, for example, in the preparation of a calibration certificate. In industrial process control, often we are concerned with commissioning measurement equipment or implementing measurement methods to meet specific metrological requirements [3]. This requires us to assess the accuracy of proposed measurement methods. ISO 5725 [4,5] addresses these issues in terms of trueness and precision. Trueness relates to the difference between the expected measurement result using the method and an accepted or reference value. Precision relates to the closeness of agreement between repeated measurements under stipulated conditions. The more the conditions are allowed to vary the larger the expected variation of results. Typical factors that affect the precision are the operator, environment, calibration of the equipment and time elapsed between measurements. The repeatability of a system is the precision when all the influence factors are held as close to constant as possible (e.g. the same operator). The reproducibility is the precision when all likely sources of variation are allowed (e.g. all operators using the equipment).

ISO 10012 *Measurement management systems* [6], currently being reissued, is intended to provide generic requirements for managing measurement systems to make sure that measurement capabilities within an organisation are fit for purpose. As a generic document, its requirements are written in very broad terms. A concern of many industrial organisations is to implement procedures that accord with ISO 10012 while being focussed tightly on the specific requirements of the organisation.

An example of the assessment of a measurement system is a gauge repeatability and reproducibility study (R&R). Gauge R&R effectively breaks measurement variation into two components. Repeatability is the inherent variability of the measurement process, where all external factors that affect variability, and which may be controlled, are kept constant. So the same operator measures the same part, with the same gauge, under the same conditions several times. The variability (sample variance) of the results is the estimate of the repeatability. Reproducibility is defined as the additional variability introduced by varying other relevant factors. Gauge R&R is defined as overall variability, taking into account both reproducibility and repeatability.

In many areas, there is a move to perform the metrology functions traditionally implemented by gauges by more flexible systems such as co-ordinate measuring machines (CMMs). These systems can be programmed to perform a wide variety of dimensional metrology tasks often with improved accuracy. A major issue in using a CMM is being able to evaluate the measurement uncertainty associated with a particular task. While the CMM manufacturer may well be able to assign uncertainty statements associated with the length measuring capability under controlled conditions (e.g. according to ISO 10360 [7]) there is no simple way of using this uncertainty statement to assess the measurement uncertainty for a more complex measurement task. Since ISO 10012 requires metrological equipment to be confirmed, a manufacturer using CMMs as elements of its measurement system has to face these difficult uncertainty evaluation problems.

2.3 ANOVA — analysis of variance

Gauge R&R is an example where we aim to decompose the observed variation in a process into a number of component factors. For gauge R&R there are just two factors: repeatability and reproducibility. Analysis of variance (ANOVA) is a more general approach that can be applied to any number of factors. The main issues in ANOVA are to be able to design the study and subsequently analyse the data in such a way that estimates of the individual contributions from each of the factors to the total variation can be determined effectively. In gauge R&R, the repeatability contribution is isolated by holding all other factors constant. For larger systems, it is inefficient to vary the factors one at a time and more effective schemes are sought.

2.4 Statistical process control

The principle behind statistical process control [8,9] is that if the manufacturing process leading to the final product is sound, then the product itself will also be sound. By means of monitoring the process at key points – extracting values at regular intervals in time of either variables (which take numerical

values) or attributes (which take values from a finite set of labels, e.g. 'high/low') – then we should be able to detect any change in the underlying system generating these values. This is traditionally done by taking statistics on short runs of the values, such as the range and arithmetic average, and comparing these to figures derived from a period in which the process is known to be functioning correctly.

If we are assured that there is a sequence of measurements when the process was operating correctly, we can estimate the population parameters (e.g. mean and standard deviation) of the statistical distributions describing the state of the controlled process. If, when we compare the running of the process at a later time, we infer that the distribution has changed substantially, then the process is said to be out of statistical control. Otherwise, it is in statistical control.

The accepted approach to SPC is to use Shewart Control Charts, whereby measures of both location and variation (e.g. mean and range) are plotted across time, and alerts (warnings or actions) are made when the charted values cross specified limits or exhibit unlikely trends, such as a specified number of consecutive increases. It is then the responsibility of the local expert to take remedial action so that the process reverts to being in-control.

The primary goal of SPC is to monitor the variation and drift in process behaviour on the basis of measurements of elements of the process and compare it with what is regarded as normal behaviour. In implementing SPC it is therefore important to ensure firstly that measurements of enough components of the system are taken in order to make valid inferences about the quality of the products and secondly that the measurements are sufficiently accurate. The implicit assumption in many SPC implementations is that all measurements are exact or at least their contribution to the observed variation is negligible.

SPC can be more diagnostic and aim to determine which factors of the process lead to most variation in the products. From this point of view, SPC overlaps closely with the objectives of ANOVA. From such a diagnosis the process can be improved to reduce the variation. As the variation in the process improves it becomes more likely that the uncertainty of measurements makes a bigger contribution to the observed variation. In fact, it is known that in quite a number of processes the measurement uncertainty is at least comparable with the variation due to the process.

2.5 Tolerance analysis

Once we have determined that a process is in statistical control, we can set about determining whether it is capable of producing parts that satisfy any constraints placed upon the end-product, such as upper and lower specification limits.

Typically, one uses some adaptation of the potential capability index as an indicator of process capability, this being defined as $C_p = (USL - LSL) / (6\sigma)$ where USL and LSL are the upper and lower specification limits, and σ is the (estimated) process variance. The adaptations tend to be motivated by the possibility of the process not being "centred" – that is, that the process is not on target. These concepts relate close to "trueness" and "precision" discussed in section 2.2.

3 Building on Existing Components

The stated objective of the SS/M project is to define a draft methodology for industrial uncertainty. The methodology should enable organisations to implement procedures that conform to international standards relating to industrial measurement including ISO 10012. It would be wrong to indicate that all issues associated with measurement uncertainty and process control have been recognised and dealt with and that an industrial uncertainty methodology can be assembled easily from what exists and is accessible at present. Indeed, the importance of quality and efficiency for global competitiveness means that organisations and economies will continue to devote scarce and expensive R&D resources to improving production methods. In terms of providing a working methodology that covers the basic concepts, we believe that the existing domains of expertise jointly are sufficient. There is no need for an intensive research effort to develop statistical techniques to solve problems unique to industrial uncertainty as a generic field of measurement.

While the basic elements of an industrial uncertainty may be in place, the benefits that can arise through a common language and understanding have yet to be realised fully. Even at the standards level, the difference between the SPC community and the metrology community is apparent. For example, ISO 10012 regards the GUM as a normative reference. However, the ISO 11462-1 *Elements of SPC* makes no reference to the GUM but references instead ISO 5725 *Accuracy (trueness and*

precision) of measurement methods. ISO 5725, published before the GUM, does not use the concept of uncertainty explicitly. On the other hand, the GUM makes very little reference to the concepts of accuracy, trueness and precision. This means that a company trying to satisfy the requirements of ISO 10012 and wanting to control its gauge measurement activities will be forced to choose between two different approaches to assessing and expressing measurement uncertainty. We think that a major element of this project is to provide industrial users with a harmonised view of ISO 5725, ISO 11462 and the GUM consistent with the overall requirements of ISO 10012.

4 Summary and Concluding Remarks

Both measurement uncertainty evaluation and SPC are concerned with modelling, describing and making inferences about the stochastic behaviour of systems. Both are concerned with taking into account variations over the short term over which only a small number of factors will have influence and variation over a longer term where more factors will have influence. In measurement uncertainty evaluation, the focus is on making inferences about the likely variation in the output if the measurement experiment was repeated many times over a long term in which all factors are allowed to operate, given information about the inputs and a model relating the inputs to the output. In SPC, the focus is at least partly on monitoring the variation of the outputs in order to make inferences about the behaviour of the inputs, in particular, identifying components that are moving out of conformance.

The main area of activities required to produce an industrial uncertainty methodology are that of a) establishing an appropriate framework, b) harmonisation and the removal of inconsistencies (mainly of in use of language rather than concept) and c) the promotion of the common concepts and understanding.

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6 References

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