Measurement Uncertainty: Literature Review and Research Trends

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***Abstract*—This paper reviews and analyzes studies concerning measurement uncertainty, examining 114 papers published between 2004 and 2010 in the following international journals: IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, *Measurement*, *Flow Measurement and Instrumentation*, and *Precision Engineering*. The papers were classified according to six different approaches identified during the research and six different methods of calculating uncertainty used by the authors of the researched articles. This paper provides a short summary of the state of the art of measurement uncertainty, analyzes the research scenario on the theme, and, finally, brings suggestions on future work based on the analysis.**

***Index Terms*—Fuzzy sets, measurement, Monte Carlo, review, uncertainty.**

I. INTRODUCTION

IT IS extremely important to express the quality of results obtained from measurements and tests, not only as a means of comparing different laboratories but also to estimate the doubt in a given result, thus allowing results to be compared. Measurement uncertainty is the most simple and widely accepted way of stating the reliability of results [1] and is also demanded by international quality standards. It consists of a parameter associated with the outcome of a measurement, which determines the dispersion of possible values relative to that measurement [2].

In 1993, when the International Organization for Standardization (ISO) published the Guide to Expression of Uncertainty in Measurement (GUM) [2], a universal method for estimating measurement uncertainty was established which has been widely employed by the industrial sector, particularly during calibration. However, there are some cases in which the GUM method is not the most suitable or is simply not viable, either because of the complex calculation it involves or because the prerequisites of the method are not satisfied [3].

The ISO itself recognized the methodological gaps in GUM and published the Evaluation of Measurement Data—Supplement 1 to the "Guide to the expression of uncertainty in measurement"—Propagation of Distribution Using Monte Carlo Method [4] in which they recommend the Monte Carlo simulation for measurement uncertainty determination. The suggested method does not require the same prerequisite originally imposed by GUM and operates through experimental simulations, instead of mathematical models. GUM and Monte Carlo provide widely acknowledged tools used by both the industrial sector and the scientific community, but there remain some specific cases in which neither of these methods provides a reasonable expression of measurement uncertainty. New methodologies, employing different mathematical approaches, are therefore emerging which are adapted to more restricted applications than the traditional methods and which aim to overcome these deficiencies in industry [5].

Several published papers bring new methods for use with these applications; others revisit established methods or suggest unfamiliar applications for them. The purpose of this paper is to review papers concerning measurement uncertainty published from 2004 to 2010 and to classify them according to their approach, their calculation method used, and year of their publication.

This paper is divided in five sections. Following the introduction, a short theoretical discussion is given on measurement uncertainty; Section III explains the procedural methods used to develop the bibliographic review. The analysis and categorization of selected papers are shown in Section IV, and the final section summarizes the conclusions drawn from the results obtained.

II. MEASUREMENT UNCERTAINTY

Since the publication of GUM, there has been an increasing acknowledgement that the measurement uncertainty is as important as the measured value itself [6]. Apart from being widely used in the field of metrology and tests, it can be applied in several other areas as the main parameter to compare different methods, as suggested in [7] and [8]. Furthermore, [9], [10], and [11] showed that measurement uncertainty can also be very useful in validating new methodologies.

A. GUM Method

GUM, the most widely used method for estimating uncertainty in measurement, consists of a procedure based on statistical knowledge and experimental analysis of measured data.

In most cases, the measure is not obtained directly; it is obtained from other variables (that are measured) and then related to each other through a function, according to

$$Y = f(x_1, x_2, \dots, x_N) \tag{1}$$

where f is the mathematical model representing the Y variable as a function of x_i inputs.

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Uncertainties in each of the model inputs are evaluated and introduced into the measurand following the law of propagation of uncertainty, given by

$$u_c^2(y) = \sum_{i=1}^{N} \left(\frac{\partial f}{\partial x_i} \right)^2 u^2(x_i) + 2 \sum_{i=1}^{N-1} \sum_{j=i+1}^{N} \frac{\partial f}{\partial x_i} \frac{\partial f}{\partial x_j} u(x_i, x_j) \tag{2}$$

where $u_c(y)$ represents the standard uncertainty of the measure, $\partial f / \partial x$ denotes the sensitivity coefficients of each variable calculated from partial derivatives, and $u(x)$ represents the uncertainties of random variables by which the measure is influenced.

Finally, the expanded uncertainty in measurement is the result of the standard measurement uncertainty multiplied by a coverage factor, according to

$$U = k u_c. \tag{3}$$

The coverage factor k is obtained from the degrees of freedom for each input and the coverage interval required.

Certain conditions must be satisfied for the use of GUM to be appropriate. When expanded uncertainty U is determined, the following four requirements must be satisfied [12].

1) Conditions appropriate for the central limit theorem must be satisfied, characterizing the distribution of Y as normal or student's t-distribution.
2) The equation should be suitable for calculating the effective degrees of freedom when one or more inputs have an associated finite number of degrees of freedom.
3) Inputs must be independent when the degrees of freedom associated to their uncertainty are finite.
4) The model must have sufficient linearity, to allow a first-order expansion in Taylor's series.

GUM describes the objectives to be reached when determining measurement uncertainty, together with the main directions to be followed to achieve them. However, considering the practical problems and the wide variation in the situations encountered, different methods with different degrees of complexity may be necessary [13].

References [14] and [15] show aspects of GUM that might make its application difficult, including the problem of knowing if the model is linear enough or the problems of calculating the degrees of freedom for correlated input variables, while [16] discusses the difficulty in fitting certain cases into GUM's requirements. Reference [17] highlights situations in which the GUM method, although adequate, is capable of improvement. Also, [14] states that the application of GUM can become difficult and exhausting if some simplifications are not adopted.

B. Monte Carlo Simulation

To overcome the difficulties in certain areas of using the GUM method, the Supplement 1 to GUM [4] was published in 2008, recommending the use of Monte Carlo simulation as an alternative for evaluating measurement uncertainty.

Monte Carlo simulation uses *a priori* information about inputs that influence uncertainty through their probability distributions, generating random values from these distributions and thereby obtaining an *a posteriori* distribution of results [4].

Supplement 1 proposes the use of the input variables' probability distributions, instead of including only their variances, as described in GUM. This method consists of defining a probability density function for each input, which is then used together with the sensitivity coefficients that relate them to the variable of interest Y, using numerical simulations. Measurement uncertainty is defined according to the desired coverage interval (usually 95%) after a large number of repetitions.

The operation by Monte Carlo simulation does not require the calculation of sensibility coefficients through partial derivatives, which can be one of the factors complicating the use of GUM in many cases [18]. Apart from this advantage, it is also possible to obtain asymmetrical probability distributions, which would not fit the requirements for GUM use.

Monte Carlo can be used independently to calculate uncertainty but can also be employed to validate computations obtained from GUM, since the propagation of probability distributions is the broadest form of the law of propagation of uncertainty [18]. Reference [19] used Monte Carlo simulation to compare different methods and also compared their results obtained with those obtained from GUM, as a validation.

Extra care should be taken, when this method is to be applied, concerning the quality of random-number generating algorithm and the size of the random seed. Such factors may directly affect the quality of the simulation result [15].

C. Other Methods

Some cases cannot be dealt with appropriately by either GUM or Monte Carlo simulation. Each scenario then requires a different scientific method for estimating uncertainty, appropriate to its circumstances. Reference [20] suggests that GUM's restriction sometimes makes it impracticable and that many other methods have been proposed in the literature for measurement uncertainty, while [15] shows that GUM can under- or even overestimate uncertainty in some cases.

On the other hand, some studies propose methods that do not conflict with GUM or are complementary to it, for the purpose of refining the methodology for situations in which traditional methods do not apply. On this subject, [6] states that the increase in resolution and sensitivity of measurements now requires more sophisticated physical models. Alternative methods have been developed to overcome these problems, of which can be cited the numerical integration through Fourier and Mellin transforms [15], [18] and the use of fuzzy variables [20].

III. Methodological Procedures

The study was structured in five phases: 1) selection of journals to be included; 2) choice of scientific papers published from 2004 to 2010 in the selected journals; 3) analysis of selected articles according to predefined criteria; 4) classification of papers according to criteria obtained in step 3); and 5) identification of trends and opportunities for research.

The journals were selected from the virtual databases Science Direct Online, Emerald, and SciELO. A search for papers published on the seven-year range and which had the expressions "measurement uncertainty" or "uncertainty of measurement" in their title or keywords was performed. From the results of this search, the following four journals had highest numbers of publications on the theme: IEEE TRANSACTIONS ON INSTRUMENTATION AND MEASUREMENT, *Measurement*, *Flow Measurement and Instrumentation*, and *Precision Engineering*. Journals with fewer than five publications on measurement uncertainty over the study period were not included nor were publications from scientific conferences, books, and theses. In this step, the excluded journals were the following: *Analytica Chimica Acta*, *Journal of Chromatography A*, *Atmospheric Environment*, *International Journal of Pure and Applied Analytical Chemistry*, *Applied Radiation and Isotopes*, *International Journal of Mass Spectrometry*, *Journal of Hydrology*, *Journal of Sound and Vibration*, *Remote Sensing of Environment*, *Clinical Biochemistry*, *Optics and Lasers in Engineering*, and *Radiation Physics and Chemistry*.

The second step consisted of a new search of the selected journals, for papers published between 2004 and 2010, expressing the word "uncertainty" on title or keywords, followed by a manual screening of results so that only those papers in which the measurement uncertainty was actually the main theme and not papers in which the measurement uncertainty was simply calculated for a particular case. Articles that did not clearly state which method was used for uncertainty calculation were also excluded. Using these rules, 114 papers were acceptable for further study. This interval of seven years was chosen due to the quick decrease in the number of publications regarding the theme from 2003 to 1990, according to the selected virtual databases.

When analyzing the papers, attention was focused on identifying criteria that distinguished between them in terms of scope and methodology, so as to identify present trends in the area and possible prospects for future research. The approach and method of calculation were then taken as criteria together with the year of publication. The following approaches and uses for measurement uncertainty were identified: parameter of quality, presentation of methodology, suggestions for improvement, comparison of methods, methodological deficiencies, and risk analysis. For the calculation method, the following were recorded: GUM, author's own methods, fuzzy variables, multiple methods, Monte Carlo, and others.

In the fourth phase, each paper was classified according to each of the criteria selected on the previous step.

Finally, an analysis based on these data was performed which sought to identify what trends can be detected in measurement uncertainty over the researched period and which are the most deficient sectors in this field, suggesting the need for future research.

IV. Classification of Papers

In Section IV-A, the selected papers were classified according to the approach used, namely, parameter of quality, presentation of methodology, suggestions for improvement, comparison of methods, methodological deficiencies, and risk analysis, while in Section IV-B, they were classified according to the calculation method employed, namely, GUM, author's own methods, fuzzy variables, multiple methods, Monte Carlo, and others. In each section, a few papers are described as an example of the reason to classify them as such.

A. Classification According to the Approach

Table I shows the distribution of the approaches identified, within the selected journals, and their years of publication. An enumeration of the papers according to the criteria selected is given in the Appendix.

1) Papers Using Measurement Uncertainty as a Parameter of Quality: The most common approach found in the papers was the use of measurement uncertainty as the main parameter for comparing different methods of measurement, calibration, or test. Reference [21] described a new calibration method for thread rings, compared it with two traditional methods, and chose the most appropriate based on the analysis of the uncertainty in each method. A method for reconstructing 3-D shapes was proposed by Merkac and Acko [22] who also compare uncertainties of two different methods. Similarly, [23] analyzed calibration methods for high-voltage resistors in the Italian National Institute of Metrological Research, [24] suggests that a new international standard for measuring angles should be created, and [25] analyzed different ways of measuring Cartesian coordinates.

2) Papers Suggesting New Methodologies: Twenty six papers suggested new methodologies for calculating uncertainty, of which five used the theory of fuzzy random variables (three based on the theory of possibility and two based on the theory of evidence), two used polynomial chaos, and one employed Monte Carlo. Reference [26] used a method based on bootstrapping techniques to evaluate cylindricity. Using fuzzy variables based on the theory of possibility, [27] proposed an improved method for determining uncertainty in 2-D measurements, while [28] used them to evaluate uncertainty in measurements of harmonic distortion. Reference [29] developed a method for evaluating uncertainty with which the cutting tool is placed in high-precision metal turning.

3) Papers Suggesting Methodological Improvements: Some papers focused on presenting improvements and modifications to well-established methods so as to extend their use in nonstandard situations. Eighteen of these studies suggested improvements to GUM, three suggested improvements to fuzzy theory, and two suggested improvements to Monte Carlo. References [30] and [31] discussed the best way to define the coverage factor in GUM. In agreement with this methodology, [32] showed how to assess modular measurement systems, and [33] identified a more adequate handling for data acquisition systems. Concerning fuzzy variables, [34] suggested changes in the way that system information is used regarding the theory of evidence, whereas [35] introduced triangular norm operators for modeling certain systems using the theory of possibility.

4) Papers Comparing Different Methods: Nine papers set out to compare two or more existing methods and to identify which was the best or simply to illustrate differences between

TABLE I
CLASSIFICATION OF APPROACHES AND YEARS OF PUBLICATION

Approach	2004	2005	2006	2007	2008	2009	2010	Total
Parameter of quality	2	7	3	6	6	14	10	48
Presentation of methodology	1		6	3	3	8	5	26
Suggestion for improvement	6	4	3	3	2	3	2	23
Comparison of methods	2	1	2	1		2	1	9
Methodological deficiencies		1	2			1		4
Risk Analysis	1		3					4
Total	12	13	19	13	11	28	18	114

TABLE II
CLASSIFICATION OF METHODS OF CALCULATION AND YEARS OF PUBLICATION

Methodology	2004	2005	2006	2007	2008	2009	2010	Total
GUM	8	11	10	6	6	13	9	63
Author's own			3	2	3	4	4	16
Fuzzy variables	2	1	1	1	1	3	1	10
Multiple methods	2	1	2	1		2	1	9
Monte Carlo			2	2	1	3		8
Other			1	1		3	3	8
Total	12	13	19	13	11	28	18	114

them. Reference [36] discusses the differences between GUM, Monte Carlo, and fuzzy methods applied to state variables in power systems, whereas [1] suggests several alternatives to determinate uncertainty in situations where GUM is not suitable. Reference [37] studied differences and restrictions of GUM and Monte Carlo and developed an optimization algorithm for these situations.

5) Papers Pointing to Methodological Deficiencies: Four papers addressed only the deficiencies in methods for estimating uncertainty. Reference [38] showed limitations of GUM for qualitative variables, while [39] points to gaps in the epistemology of metrology, which affect the estimation of uncertainty.

6) Papers on Risk Analysis: Four papers applied measurement uncertainty to the field of risk analysis and decision making. Reference [40] explores the relationship between costs of uncertainty analysis and the consequences of an inaccurate decision, whereas [41] proposes a method that relates risk analysis to measurement uncertainty. Reference [42] considers the impact of measurement uncertainty on the quality control of a product.

B. Classification by Method

Table II shows the methods used to determine measurement uncertainty and how they were distributed amongst studied journals.

1) Papers Using the GUM Method: The methodology most frequently found in the papers was the GUM. Reference [43] emphasizes that uncertainty in the calibration of Computer Numerical Control machines should not be calculated using ISO 230-2 but that GUM should be used instead, so that there is an agreed international standard. Along with that, [44] suggests a calibration method using international standards as a means of acceptance. In another work, [25] used GUM methods in a probabilistic multivariate analysis.

2) Papers Using Authors' Own Methods: Sixteen papers used the methods suggested by the authors themselves. When proposing new methods for measuring exposure to electromagnetic fields, [45] did not find anything suitable amongst traditional methods and developed a new procedure for determining uncertainty. For cases in which the GUM assumptions are not appropriate, [46] developed equations for calculating uncertainty that included second- and third-order terms with moments of higher order than those given in GUM.

3) Papers Using Fuzzy Variables: Reference [47] introduced the use of random fuzzy variables based on the theory of evidence for calculating measurement uncertainty, used later by [34], [84], and [114], and other authors ([27], [48], and [28]) have also reported works using other fuzzy methods. Also, [49] used a fuzzy linear predictor of fuzzy state variables to model uncertainty in a power system.

4) Papers Using Monte Carlo: Nine papers used Monte Carlo to determine measurement uncertainty. References [50] and [51] remarked that, for 3-D ball plates, several factors external to the measuring process itself influence uncertainty, making the Monte Carlo simulation necessary. Reference [52] used Monte Carlo since it is better at propagating uncertainties where the distribution of each contribution is known, and [19] analyzed the effect of correlated variables on the uncertainty in electric variables in fuel cells.

5) Papers Using Multiple Methodologies: Some papers used more than one calculation procedure, particularly those comparing different methodologies. Reference [53] proposed methods for application in the environmental sector, and [54] states that, amongst different methodologies analyzed, only the probability determination is in agreement with the classical laws of logic. Even though they used Monte Carlo, [37] drew a parallel with GUM and illustrated their differences in the calibration of platinum resistance thermometers. Reference [55] also discusses the differences between GUM and fuzzy variables in their analysis of signals based on wavelet transforms.

6) Papers Using Other Methodologies: Papers using different methodologies from those cited earlier were also examined. Reference [56] used the EURACHEM/CITAC methodology in spectrometric measures, while [57]–[59] used chaotic polynomials in their work. Reference [60] also used the relative uncertainty method in his determinations.

TABLE III
CLASSIFICATION OF METHODS OF CALCULATION AND APPROACH

Approach	GUM	Author's own	Fuzzy variables	Multiple methods	Monte Carlo	Other	Total
Parameter of quality	37	1	2		4	4	48
Presentation of methodology		15	5		2	4	26
Suggestion for improvement	18		3		2		23
Comparison of methods				9			9
Methodological deficiencies	4						4
Risk Analysis	4						4
Total	63	16	10	9	8	8	114

C. Analysis

For the approaches identified in Table I, the most widespread use of measurement uncertainty is as a parameter of quality for comparing different metrological methods having a common objective. The second largest number of papers was concerned with methodologies for determining uncertainty. Together, these approaches represent approximately 65% of the papers analyzed.

Table II shows that GUM is the most frequently used method in all the journals consulted, corresponding to more than half of all selected papers. There is no single leader amongst the other methods, although fuzzy variables appear in a considerable number of papers despite being relatively new.

Table III compares the approaches as identified by authors' calculation methods. Although GUM is used very frequently, it was the more criticized by the authors of the mapped articles: Many papers suggest improvements or draw attention to problems in this methodology. The methods based on fuzzy variables, particularly the ones based on the theory of evidence, are clearly still in development but show a trend toward becoming a robust alternative to GUM, which can be seen by the number of papers published and explained by the robustness of the method regarding available information, which is often the case in industry [34]. Several new calculation methodologies were also described but their application remains limited or underexplored, and they have not been cited in subsequent publications.

The analysis of the 114 papers on measurement uncertainty revealed that GUM, presented more than a decade ago, is still the most frequently used (55.3% of studied publications). Despite its limitations and the fact that other methods have been described in recent years, authors generally still choose to use it. However, although it is the most widely used, GUM is also the most criticized method. The description of alternative methods for uncertainty determination was also frequent (22.8% of the papers studied), and results using fuzzy variables, described in 2004 by [46], appear to be very promising since they do not necessarily conflict with the GUM but encompasses it as a particular case [34].

For future studies, some topics show particular promise. There are few studies in which risk analysis uses techniques for measuring uncertainty, and all the papers that did so used GUM, so that there are opportunities for using other methods of calculation, potentially Monte Carlo evaluation. There are also few papers about the characteristics of methods other than GUM. The interface with other statistical methods for estimating uncertainty has also been little explored. Certain gaps in the literature were also identified: Apart from metrology, risk analysis was the only sector using the theory of measurement uncertainty. The impact of uncertainty on economic and manufacturing indicators was not addressed in any of the papers studied nor were topics such as the analysis of measurement uncertainty in quality-control procedures and nanotechnology.

V. CONCLUSION

Measurement uncertainty is currently very important in the industrial sector and is considered as important as the measurement itself. Hence, several methods for determination of uncertainty in a variety of areas have emerged. The purpose of this study was to analyze the existing literature on this subject and to categorize articles according to their approach and method.

One hundred and fourteen scientific papers, published in four international journals between 2004 and 2010, were analyzed. The articles were classified according to six identified approaches and six different mathematical methods. The numbers of papers in each approach and method were assessed together with the number of publications per year and per journal.

The approaches most commonly found were the parameter of quality for method comparison and methodology description (together, a total of 64.9%). Very few publications were found on measurement uncertainty in other scientific areas except for risk analysis, with 3.5% of papers. The most widely used method was GUM (55.3% of papers), followed by methods designed by authors themselves (14%). Amongst alternative methods, the most frequently used was fuzzy variables, appearing in 8.8% of the papers.

Studies concerning the use of measurement uncertainty in other areas have been suggested, particularly combined with quality-control procedures such as control charts and capability indices.

TABLE IV
PAPER CLASSIFICATION ACCORDING TO APPROACH

Approach	Papers		
Parameter of Quality	[19], [21], [22], [23], [24], [25], [43], [44], [48], [52], [53], [57], [61], [62], [63], [64], [65], [66],	[67], [68], [69], [70], [71], [72], [73], [74], [75], [76], [77], [78], [79], [80], [81], [82], [83], [84],	[85], [86], [87], [88], [89], [90], [92], [93], [94], [95], [96], [97].
Method Demonstration	[17], [26], [27], [28], [29], [45], [46], [47], [50], [51], [58], [59],	[60], [91], [119], [120], [121], [122], [123], [124],	[125], [126], [127], [128], [129], [130].
Improvement Suggestion	[5], [30], [31], [32], [33], [34], [35], [103], [104], [105],	[106], [107], [108] [109], [110], [111], [112], [113]	[114], [115], [116], [117], [118].
Method Comparison	[1], [6], [36],	[37], [54], [55],	[56], [101], [102].
Methodological Deficiencies	[38], [39]	[99], [100].	
Risk Analysis	[40], [41],	[42], [98].	

APPENDIX

See Table IV.

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