Supporting analysis of measurement uncertainty via a user-centered assistance system

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A commonly accepted method to estimate the uncertainty of a measurement result is given by the GUM (Guide to the expression of uncertainty in measurement). To ease the application of this method, several tools are available to support the mathematical evaluation. Yet, for the most crucial step, the definition of a suitable model of the measurement, there is hardly any support available. In industrial application, usually the employees who execute measurements and thus have expert practical knowledge have only very few competences regarding mathematical modeling. Therefore, measurement uncertainty is only very rarely estimated and measurement results may be incorrectly interpreted.

To ease this situation, an assistance system is developed which supports the modeling of measurements in an approach oriented towards needs, skills and specific expert knowledge of typical user groups in an organization. It is based on the graphical modeling of measurements and features a concept to enable knowledge management between employees via the definition of adaptable modular components and the entity-based description of relevant parameters. Via this concept, practical expert knowledge provided by the metrologists can be efficiently included in the estimation of measurement uncertainty, facilitating a broader spreading of measurement uncertainty in practical application and thus a more reliable interpretation of measurement results.

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NOMENCLATURE

GUM = ISO/BIPM Guide to the expression of Uncertainty in Measurement

1. Introduction

Measurements provide valuable information about the measured quantity. Yet, without knowledge about the related measurement uncertainty, this information cannot reliably be interpreted. For the comprehensive statement of a measurement result therefore it is necessary, to provide not just the value shown by the utilized measurement instrument, but to determine the best available estimate by correcting known systematic influences on the indexed value and to amend this value by an information about the uncertainty related to the measurement result together with the considered coverage factor. The statement of measurement uncertainty with a given measurement result provides valuable information about its quality and reliability. Therefore, it is demanded by standards like ISO 14253-1 consider the uncertainty of the measurement result when taking decisions about the quality of a product, especially regarding the conformity of a manufactured product with given specifications in customer-supplier relationships [1]. Besides enhancing a trustful cooperation between customer and supplier based on quantifiable information, knowledge about the uncertainty of performed measurements also provides a base for the economic setup of measures for quality control [2]. Generally, it is necessary to understand the limits of reliability of a measurement result, which are expressed by the measurement uncertainty, in order to be able to utilize it as a source of information.

A commonly accepted method to estimate the uncertainty of a measurement result is given by the GUM (Guide to the expression of uncertainty in measurement) [3]. Here, a model of the measurement, describing the relation between indicated value and measured quantity under consideration of all relevant constraints, is evaluated according to specific mathematical rules to estimate the value of the measurand and its uncertainty. As the method is defined in a general way, the evaluation of measurement uncertainty according to GUM can be utilized in every field of application. Accordingly the measurement uncertainty can be used as a universally understandable and interpretable parameter describing the quality of the measurement result and thus the determination and analysis of measurement analysis is required in various standards (e.g. ISO 9001 [4]) as a prerequisite for traceable measurement results.

Besides this demand, in industrial context measurement uncertainty still is rarely evaluated or stated with measurement results. To assure the quality of measurement processes, other parameters are used instead, based either on statistical concepts, e.g. measurement process capability c_g, or on properties of the measurement machine, e.g. MPE (maximum permissible error), or a combination of both, e.g. reliability according to MSA [5]. Yet, besides many other problems like gathering of data for new measurement methods or measurements of single specimen, these parameters do not allow for a suitable specification of the quality and reliability of measurement results, but can only be considered as rough indicators of the usability of a measurement process or machine [6]. Thus, they do not fulfill the defined requirements on traceability of measurement results and measurement results may be incorrectly interpreted.

To enable the analysis of measurement uncertainty for a broad application also in industry, it is necessary to provide a suitable support facility, considering the constraints of its application, especially the specific expertise and demand of typical users.

2. Analysis of current situation

The determination of measurement uncertainty is a complex task, which demands well funded knowledge of the metrologist performing it. In a systematic approach, the steps necessary to evaluate the measurement uncertainty can be structured in five phases (Figure 1) [7]:

1. Description of the measurement process and documentation of available knowledge
2. Definition of a mathematical model to describe the relation between the quantity and the indicated value under consideration of the influences identified in the first steps
3. Quantification of all relevant quantities, i.e. determination of an estimate for the value of the considered influences as well as for their likely deviation
4. Combination of these data according to the defined model and determination of the best estimate for the measurement result as well as the according measurement uncertainty according to given rules for calculation. [3], [8]
5. Evaluation of the measurement result and analysis of the established budget of measurement uncertainty in order to identify need or possibilities for improvement.

The performance of steps 1-3 requires the transfer of the general concepts of GUM to the given measurement task. These tasks have to be executed carefully and with results specifically defined for each single measurement task. Contrarily, steps 4 and 5 are executed based on general rules and for each measurement task alike.

2.1 User needs analysis

To gather information about influences relevant for the performing of a measurement task – regarding on the one hand the way in which they interfere with the measurement process, on the other hand the quantity they are likely to show – in depth knowledge and broad experience in the execution of this measurement tasks is needed. Additionally, to describe the measurement process and the expected appearance of influences in a way suitable for the following calculations, high competences regarding mathematical modeling and principles of physics are required.

In industrial context, the metrologists actually performing the tasks and thus being experts on the given constraints generally have only practical skills, but do not know much about the underlying principles, next to nothing about mathematical modeling and often enough are not even familiar with the idea of measurement uncertainty [9]. Also, there are experts with a sound theoretical background, who could perform the mathematical modeling of measurements, e.g. working in measurement management or at least externally available for consulting, but usually they have insufficient knowledge about the actual way, how the measurement is processed.

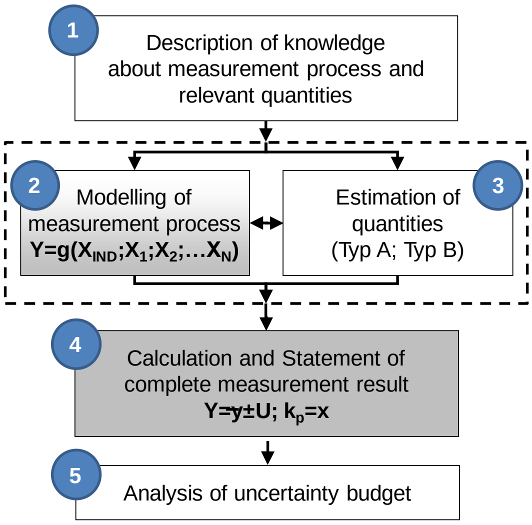

Fig. 1 Procedure of uncertainty evaluation according to GUM and need for assistance (based on [7])
Y: Measurand; X_{ind}: Indicated value; X_i: Influencing quantity
grey filling: support available; no filling: no support available

2.2 Existing support facilities

To ease the application of this method, several tools are available to support the mathematical evaluation. Yet, for the most crucial steps, the definition of a suitable model of the measurement and the estimation of quantities, there is hardly any support available.

The software available nowadays for support during the evaluation of measurement uncertainty can mainly be classified as stand-alone calculation program (e.g. GUM-Workbench [10], Uncertainty Manager [11], Uncertainty Analyzer [12]). This software is used by especially trained experts as an amendment to other tools related to measurements, e.g. for quality management or management of inspection equipment. Additionally, some providers of software for CAQ (Computer Aided Quality Management), generally supporting methods of quality management like statistical process control which are relying on measurement results, started to include components for the evaluation of measurement uncertainty. Yet, these tools are generally very simplified and do not enable a proper evaluation according to GUM – sometimes the "measurement uncertainty" specified there is not even determined according to the basic principle of GUM to consider the whole measurement process and evaluate a best estimation for the measurand, but it is calculated statistically out of deviations of the measurement instrument. Therefore, these facilities are not acceptable as support for measurement uncertainty evaluation.

Although the functionalities contained in qualified software for the determination of measurement uncertainty – providing mathematical processing of defined models according to the standard method of GUM [3] or simulations based on the Monte Carlo method according to GUM supplement [8] – are often very efficient and highly complex, they require as input a finished mathematical model of the measurement process and all considered quantities. A first approach to enhance a better comprehensibility and easy adaptability of models is the support of graphical modeling and a following automated derivation of an equation describing the measurement process, like provided by GUM CAD Software [10].

Summarizing, the currently commercially available tools for measurement uncertainty analysis support mainly tasks with a rather low level of complexity, i.e. operation with data according to given rules instead of abstract and "creative" tasks of modeling. [13]. (Figure 1, step 4 and partially step 2)

In contrast to the current possibilities of support, users usually experience the definition of the mathematical model as the most difficult part of measurement uncertainty evaluation [14]. Here, some guidance is available in literature for basic tasks, e.g. in the amendments to GUM [3], in guidelines of calibration services [15] or in general literature, e.g. [16], [17]. But the models given here are often not fully understood by typical metrologists in practical application out of a lack of basic knowledge and thus can not be properly adapted to the task at hand. The application of given simplified models, e.g. in [18], must also be considered as unsatisfactory, as the user can not really check if the model is applicable to the given situation. Thus, the inconsiderate use of such a standardized model is rather error-prone and will not lead to the required reliable, comprehensible results.

As a suitable way to support the most crucial step, the definition of a model for the measurement process, the definition of modules for specific components was established [19], [20]. Yet, the approach used so far recommends the definition of quite fixed modules for the measuring process by experts. For the actual user, the possibilities to adapt or even see the underlying model are strictly limited. During application of the defined modules, the user is only allowed to insert data requested by the modeling system. This approach neglects on the one hand the specific expertise of practical metrologists about the measurements they perform as they are not allowed to improve the model and amend or adapt it based on their own observations. Thus, such a concept that actively detains the metrologist from modeling violates a basic principle of GUM framework: The metrologist is performing the analysis, maybe supported by an expert, but in the end he is considered responsible for the stated results [8]. Therefore, although the basic principle of defining modular components to support the definition of models itself is very suitable, the implementation has to be done in a way that enables the metrologist to fully understand the defined model and amend or influence it, if necessary.

Therefore, the currently available facilities for support during the evaluation of measurement uncertainty are unsatisfactory, as the crucial step of modeling is not supported sufficiently. To ease this situation, an assistance system for the analysis of measurement uncertainty has to be developed, focusing especially on the tasks related to modeling and description of influences and considering the typical expertise of different user groups.

3. Concept of the assistance system

The main objective of an assistance system is to enhance the correct performance of the supported task [21]. This demands first of all the avoidance of errors, i.e. breaches of common rules as well as mistakes out of typical human weaknesses, such as a changing level of concentration and motivation due to personal and environmental constraints, a limited ability to oversee complex combinations or a tendency to rely on once chosen solutions without considering alternatives [22].

The second objective to be considered for the design of an assistance system is the facilitation of an efficient working progress [21]. For the support of measurement uncertainty analysis in industrial context this requires comprising adequately the different groups of persons involved in measurement processes, especially taking into account their specific competences and knowledge about the measurement process itself and the tasks related to the evaluation of measurement uncertainty.

These two main objectives of the assistance system may be subdivided into a number of different functionalities. They can be classified to three basic components [21]:

Knowledge processing offers active assistance, i.e. the component analyses input data and parameters, identifies mistakes and errors and determines presets for the current operation. It interacts with the knowledge base that stores all required information and decision rules.

Knowledge presentation offers passive assistance, i.e. the component presents required information and thus supports the decision process and execution of the individual operations. It also provides background knowledge that can be accessed on demand.

C*ommunication logic* serves for the interaction between assistance system, operator and coordinate measuring machine as well as for the data transfer with other systems relevant for the execution of the measurement task, e.g. quality-related data from a CAQ (Computer Aided Quality) system. It also comprises the user interface and presents the data that are provided by the knowledge processing and the knowledge presenting component.

For a comprehensive assistance these components have to interact well-adjusted, so that active and passive assistance complement each other.

An assistance system for the analysis of measurement uncertainty which fulfills the specifications described above should be laid out as an amendment to existing software for the calculation of measurement uncertainty. It can be expected that software offered on the market is regularly checked and continuously improved as well as adapted to new requirements and thus provides the necessary functionalities for the actual calculation steps in an acceptable quality. Additionally, by designing the assistance system as an add-on to existing software, the integration in given processes in the enterprise is enhanced and the comparability with analyses of measurement uncertainty performed without assistance is granted.

Thus, the main necessities regarding the assistance are the definition of an appropriate user interface, providing guidance for active assistance and a consulting agent for passive assistance on demand during the setup of the model and the description of quantities. To enable the exchange of knowledge between the different involved user groups, a knowledge base is required where necessary data about relevant quantities is stored and where modules are provided as a base for the definition of models.

For the assistance system, a library of modules has to be defined. Here, employees with good skills in mathematical modeling, maybe supported by external experts, can define models to represent typical components of the measurement processes in the enterprise. Out of these modules, the user later on can composite the full model of the measurement process. The physical and mathematical functions there have to be open on demand, in order to include necessary changes or amendments. To facilitate an efficient modeling process, it is recommendable to structure the modules according to physical borders of entities used to set up the measurement process, i.e. one module per components like thermometers, voltage displays etc.

This modeling component has to be embedded in a user-centered assistance system, concentrating on the support of the user to enable a correct and efficient execution of tasks. Such a system has to include on the one hand guidance for the user, providing active assistance, on the other hand a consulting agent, providing passive assistance on demand. Additionally, suitable interfaces have to be defined enabling the communication with the underlying software (figure 2).

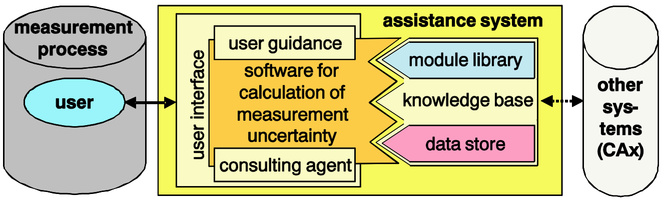

Fig. 2 Concept and structure of the assistance system

The user guidance supports the definition of a model for the analyzed measurement task and eases working with predefined modules. In the main part of user interface, dialogue between the involved metrologists and the assistance system is enabled, e.g. information for adapting implemented quantities it requested. To support also information transfer in the other direction, the consulting agent shows on demand general information about the process of measurement uncertainty analysis or structured explanations for an efficient use of the system as well as rules to be obeyed or suggestions out of best practice examples.

The setup of the assistance system has to facilitate the cooperation between different user groups in the enterprise to enhance the combination of their specific competences. Therefore, the application of the assistance system has to be embedded in a systematic workflow of knowledge management. These process and the requirements resulting from it has to be considered for the system design. Therefore, an analysis has been conducted to identify typical user groups in industrial context together with their usual expertise regarding the analysis of measurement uncertainty.

Two main user groups have been identified and their possible contribution has been systematized:

On the one hand, there are *practical metrologists*, i.e. employees planning and performing measurements in the context of production control. They know a lot about the conditions for the performance of the measurement, but typically have only few competences in mathematical modelling. Thus, they should be the main users of the assistance system to perform evaluation of measurement uncertainty. To ease the modelling, they can efficiently use the prepared modules and adapt them to include their observations and experiences into the analysis of measurement uncertainty. Yet, they typically should not be required to define new models from scratch. It is important to notice, that the adaptation of existing components to a specific situation requires a considerably lower level of competence in modelling than the new definition (level "3 – application" instead of "6 – evaluation" in Bloom's six-levelled taxonomy of learning objectives [23]). But anyway, an operator interested in the definition of a new module should be allowed to do so, but not forced to. As a benefit from working with the system, this user group may gain background information about the performed measurements.

On the other hand, there are *theoretical metrologists*, i.e. experts working in a central department, e.g. planning the outline of measurement processes and supporting practical metrologists on complex tasks when necessary. They usually are detached from the actual performance of measurements and thus do not know the constraints of the actual measurements in details, but typically they own at least basic competencies in mathematical modelling and have a more abstract overview of underlying physical principles of the implemented measurements. Thus, they should contribute to the definition of modules for the library and to the description of modelling data. If the modelling itself is experienced as too complex, support of external experts can be used. The theoretical metrologists then are needed to explain the principles of the measurement processes. As a benefit, this user group gets refined information about the actually ongoing processes from the system, provided by the practical metrologists during the application. This will help to check and improve assumptions about constraints of production control.

Thus, besides the immediate gain through a more efficient or firstly possible analysis of measurement uncertainty and the resulting more detailed knowledge about the measurement processes, the assistance system may help to improve knowledge management, being a tool to facilitate the exchange of information.

4. Inclusion in organizational processes

A workplace-integrated assistance system is an efficient possibility to reduce mistakes during the execution of complex tasks and to improve the comprehensibility and efficiency of results. Yet, guidance and support during the performing of tasks without providing a well funded basic knowledge about the underlying principles will only result in a short term success. If the user does not understand his work but just follows suggestions, tasks that are not covered by the systems, e.g. due to new development, can not be executed correctly. Also, if the reason for a suggestion or the derivation of a result is not understood or accepted, it may happen that the user is not able to use the provided support properly or even willingly neglects it [22].

Partially, this problem can be eased by integrating sufficient background information in the consulting agent. The knowledge gathered via such an integrative measures of learning is adapted very well to the specific problem at hand and therefore immediately contributes to a correct performance. Yet, an operator has to get used to the handling of the system first before using it for learning. Also, for the execution of a complex task like the analysis of measurement uncertainty without a profound preknowledge, it would be necessary for the operator to look up a lot of information for each step of the working sequence. This would be very time consuming and also frustrating for the operator as accordingly the progress of work will be very slow. Thus, during the phase of basic introduction, the productivity would be decreased considerably before the positive effect of increasing expertise sets in [24].

Therefore, it is necessary to complement the utilization of an assistance system to support the execution of complex tasks by adequate measures of preparative training, imparting the underlying principles of the topic at hand. Preparative learning offers can give a profound basis for continuous qualification via the work with the assistance system, during which additional information may be gained and the transfer of the gathered knowledge to the specific situation is supported. [25]

4.1 Requirements of knowledge management

For the successful implementation of any method of knowledge management, a triangle of areas in the enterprise has to be regarded: Technique, organisation and human being [26]. Even a good technical realisation is of no use, if the organisational constraints do not allow for a proper use and the individual employee is not able or not motivated to participate in the process of knowledge management.

If the overall situation does not enable self-guided working and a comprehensive considering of the advice offered by the assistance system, but only a strict processing of instructions, a process of learning or knowledge transfer will not be possible.

Therefore, to sustainably achieve high standards in the performance of complex processes it is indispensable to enable a sufficient degree of self-guidance for all involved employees. Complementarily, it is necessary to promote a feeling of responsibility for their specific area of duty and to show the importance of knowledge management and sharing of experience for the overall success of a specific process as well as on a long term for the whole company including all employees.

4.2 Organisational requirements

In order to enable a proper execution of a difficult task, the traceable and well-reasoned taking of decisions and their documentation and also continuous learning during the execution of work, three basic requirements have to be met [24]:

- The environmental conditions have to allow for concentrated working.
- The tasks should on one hand require transfer and adjustment of general knowledge to the actual situation in an entirely specific way, but on the other hand they should be solvable in a systematic way.
- The organisational constraints of the workplace have to allow for learning accompanying working.

In a typical working environment in industrial metrology, these requirements can be regarded as principally met. Yet, It is necessary that the management supports the process of knowledge management and individual continuing learning by using the consulting agent and therefore allows for the required freedom. Correspondingly, an active participation in knowledge management has to be rewarded by the management, whereas tendencies of non-cooperation have to be marked as undesired. This can be supported by an adept setup of a granting system in the company, i.e. a helpful contribution like the adaptation of a given module to a new measurement task or the implementation of additional, helpful modules, may be honoured by some sort of material or non-material bonus, e.g. points enabling the gathering of rewards out of the so-called “cafeteria system” [27].

4.3 Employee-related requirements

Regarding the employee, a proper use of the assistance system or any facility for knowledge management or continuous learning can only be expected, if the employee is adequately motivated. Otherwise, these tools will be ignored and remain unused. For this, it is necessary to provide some basic information on three levels:

- Handling of the system.
- Benefit of knowledge management for the company and the employee himself.
- Benefit of better results.

In order to impart the necessary competencies and understanding, a proper introduction to the assistance system will have to take place. Also, information about the policy and vision of the company as a learning community is necessary. Finally, a proper qualification of the employees together with a close involvement in a process of Life Long Learning is indispensable in order to achieve a sustainable motivation and an adequate identification with the aims of an assignment. These requirements are obviously closely related to the organisational requirements, as the latter have to encourage an according behaviour of the employees.

5. Conclusion and outlook

With an assistance system for the evaluation of measurement uncertainty, reliability and comparability of measurement results gathered in industrial context can be sustainably improved. The concept presented here, focusing on the integration of specific competences of different user groups involved in the processes related to the evaluation of measurements, provides an efficient possibility to enable practical metrologists to perform the evaluation of measurement uncertainty and enables the sensible utilization of expert support as an amendment of own knowledge instead of an imposing approach.

So far, the concept has been described and analyses have been conducted to further specify user needs regarding the design of the system, considering especially the overall situation of involved employees. Approaches for the implementation and the system set-up have been analyzed. As a next step, a prototype has to be developed and tested by interested users to verify the basic concept as well as the details of system design.

The basic concept of the assistance system is usable for all areas of application, as closed system for one enterprise or more openly by exchanging modules for specific components with other users. By building up an own library of modules, the system can be customized. By including the performance of measurement uncertainty analysis in processes utilizing measurement results, e.g. quality control, inspection for conformity, experiments for configuration of machines or tests in research and development, the quality of the measurement results becomes known. This enables the purposeful planning of measurement methods used and also the implementation of methods for continuous improvement [28]. Thus finally the efficiency and economical adequateness of the performed measurements together with eventual need for emendation becomes evident.

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