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Ontology development for measurement process and uncertainty of results

ABSTRACT

In future manufacturing and metrology, there is increasing demand to organize relevant metadata and knowledge to present information in semantically meaningful, reusable, easily accessible, and interoperable form. Up-to-date information on measurement uncertainty is key to interpretation of measurement results and to assessment of the quality of the measurement process. Although various technologies from knowledge engineering have been proposed to fulfil this requirement, previous work has not fully addressed the uncertainty during the measurement process. This paper presents the method to develop an ontology of the measurement process and the uncertainty of results on the example of coordinate measurements. The resulting ontology model based on a set of competency questions, including key concepts and relationships between them, is presented and discussed. The consistency of the ontology model is verified by inferencing rules and answering competency questions in Protégé software. The presented ontology will find wide applications in metrology and Industry 4.0.

1. Introduction

Measurement uncertainty is an inherent part of the measurement process. The Guide to the Expression of Uncertainty in Measurement (GUM) [1] 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 is essential to consider the uncertainty of measurement when evaluating and reporting measurement results. In dimensional measurements, where an artefact is measured by a coordinate measuring machine (CMM), uncertainty sources include environmental factors, measured artefact, CMM configuration and components, operator, methods, and calibration of references.

Detailed information (metadata) about the measurement process is required for evaluating the uncertainty of measurement. It is not uncommon to spend considerable amount of time searching for the metadata about the measurement devices, instruments, uncertainties of different sources, and other information supporting uncertainty analysis and evaluation. It has been recognised that making this information more accessible, reusable, and sharable would advance research in academia and industry [2]. This approach can be taken a step further by organising the knowledge about the measurement process in a way that enables computer-based reasoning from the semantically presented measurement information. However, constructing an ontology from scratch is a time-consuming and complicated process, as it is easy to forget valuable information, reducing the ontology's usability during its design phase. This paper attempts to close the gap by presenting a step-by-step approach to ontology development for dimensional measurements using CMMs. The CMM ontology would allow establishing a semantically sound knowledge base for dimensional measurement data.

There have been developments of several systematic knowledge bases related to dimensional metrology. National Institute of Standards and Technology (NIST) [3] developed a knowledge base for Geometric Dimensioning and Tolerancing (GD&T) using virtual objects for complex 3D geometric entities and their relationships, with visualization provided to support the understanding of different GD&T types and inspection processes. The "Onto-process" ontology [4] was developed for production design process with a case study of inspection planning for CMMs, with the informal model at both process level and planning level. The inspection planning for CMM consists of activities such as inspection feature identification, part orientation, alignment, resource selection and path planning.

Quality Information Framework (QIF) is an ISO standard that supports Digital Thread principles in manufacturing [5]. The information model and knowledge base are used to facilitate interoperability of manufacturing quality data between system software components. QIF structures the knowledge into an ontology with the concepts of features and characteristics of manufacturing quality data. The QIF standard is built on the XML that includes a Library of XML Schema to ensure data integrity, traceability, and interoperability with the system, such as web/Internet applications and other formats for Model-Based Enterprise implementations.

The Quantities, Units, Dimensions and Types (QUDT) ontology [6] developed for NASA Exploration Initiatives represents the vocabulary for various quantities and unit standards linked to many other ontologies of different domains. It facilitates unit conversions, dimensional analysis, finding similar units and quantity kind in diverse systems of units or quantities. However, QUDT does not include uncertainty of measurement and other information related to uncertainty.

To make the measurement uncertainties more findable, accessible, interoperable, and reusable in manufacturing industry, data should be presented in a knowledge base that links concepts for measurement process, including the measurement uncertainty. In the knowledge engineering process, knowledge can be modelled in structures called "ontologies" that represent the hierarchy of domain concepts and relations between them [7].

This paper describes the stages of CMM ontology development starting with the competency questions (CQs) that encompass the purpose of knowledge base and suggest the terms and relationship to be included in the ontology. The CQs are formalised in the Unified Modelling Language (UML) that represents the terms and their

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relationships in object-oriented form [8]. The UML model is than transformed into the ontology model of measurement process and uncertainty of results. The CQs are then used to validate the developed ontology model. Further applications of developed CMM ontology model and the utility of knowledge engineering methods to improve the measurement data management conclude the paper.

2. Ontology engineering for measurement process and uncertainty of results

The exponential growth of measurement data available in documents, files or digital platforms drives the need to organize and present them in a semantically meaningful way. To this end, concepts and tools from knowledge engineering such as ontologies can be utilized. An ontology is a formal description of types, properties and hierarchical interrelationships of classes that belong to a specific domain. In ontology, the first-order logic expresses the simple statements of facts, axioms and rules as logical expressions. Inference and deduction assess the logical statements against the axioms. The two ontology languages 1) web ontology language (OWL2) and 2) resource description framework schema (RDFS) can be used create semantic web ontology.

The open-source tool "Protégé" allows to expand previous ontologies or create a new one from scratch. Ontology Engineering (OE) is the process of developing ontologies that involve various activities. Fig. 1 shows the stages of the proposed ontology development adapted from the methodology in Refs. [7–9], and they will be discussed in the following sections.

2.1. Domain and scope

The Domain describes a) the use of ontology, b) what CQs the ontology will need to be able to answer, and c) who will use and maintain the ontology. In this work the domain is described in the context of a data management application for an organization where users can access the information about all the available calibrated and uncalibrated devices or artefacts to improve the quality of measurement. One way to define the scope is to define the CQs before development of ontology. These CQs can be used to check whether the ontology has enough information to answer the user queries. After the development of the ontology the CQs can be converted into a machine-readable query such as SPARQL [10].

2.1.1. Competency questions

CQs are natural language questions that define the requirements of an ontology. They also help to evaluate and validates the ontology (Stage 4). With the help of "query answering" from ontology, users and applications communicate with the ontology. SPARQL [10,11], is the common query language that can answer the CQs from ontology. A list of CQs in Table 1 has been given for this ontology model.

The listed CQs show the intention of this work to include the uncertainty in the knowledge base where all the information and sources of uncertainty can be inferred or asked from the ontology. The authorized and trained laboratory personnel can add new information to the system. In this ontology, this information must be represented and answered by the ontology, which can be changed during the design process.

Table 1
List of CQ for ontology of measurement process and uncertainty of results domain.

No	Competency Questions	Example answers
1	List of possible sources of uncertainty	From artefact, instruments, repeatability of results, referenced calibrations certificates, etc.
2	Methods of the uncertainty evaluation	GUM, Monte Carlo, Bayesian method, etc.
3	List the environmental factors that affect the measurement in a specified laboratory	Ambient temperature, atmospheric pressure, relative humidity, etc.
4	List of referenced artefacts for CMM verification.	Gauge block, a ball or hole plate, a ball or hole bar, a circular artefact, step gauge, etc.
5	Is the operator trained to use the instrument? If yes, specify the instrument and details of the operator	Yacine Koucha from Brunel University London, trained to measure gauge blocks and sphere diameter using CMM.
6	List all the instruments and artefacts store in laboratory	Leitz PMM-C Infinity CMM, ball plates, hole plates, length bars, circular artefacts and gauge blocks, etc.
7	What is resulted uncertainty expression?	Under the GUM approach, the measured length of the gauge block bar was found to be 100.001379 mm. The associated expanded uncertainty of measurement is 0.004263 mm, estimated at a level of confidence of approximately 95% with coverage factor $k = 2$.

2.2. Reuse the existing ontology

Since, to our knowledge, the existing knowledge representations such as QUDT [6] do not include the concepts of the measurement uncertainty, this ontology has been developed from scratch with an aim to close this gap.

2.3. Enumerate important terms

For ontology development it is good practice to list all terms, relations and properties related to the domain and scope of interest to ensure that the ontology represents all important terms and concepts. The presented ontology model attempts to cover all possible definitions of concepts/sub-concepts and their attributes/properties of the measurement process and uncertainty domains.

The following are derived terms from the UML diagram: *measurement planning, measurement task, measured features, measuring model, measurement strategy, measurement procedure, measurement method, measurement principle, measurement system, measuring instrument, measurement result, referenced artefact, measured artefact, geometric elements, CMM, analysis & documentation, measurement uncertainty, uncertainty budget, sources, uncertainty expression, evaluation methods, type A, type B, measurement model, standard uncertainty, combined uncertainty, and expanded uncertainty*. The object property connects two classes or individuals, while data property connects individual with literal value.

2.4. Define class hierarchy and properties with constraints

The definition of some sub-concepts can be found in VIM and GUM [1]. Classes are illustrated by rectangular boxes, while arrows define classes roles, properties, or relationships. The relation "part of" is shown by the diamond shape at the head of the arrow, and the hollow triangle shows the generalization of classes.

The ontology model for measurement process and uncertainty of

Fig. 1. Stages of ontology development.

results is shown in Fig. 2. The ontology model expresses concepts or classes of measurement uncertainty and relationships between them.

The CMM is given as an example for artefact measurement and uncertainty evaluation. To create and expand the ontology, the information flow given in the ontology model has been mapped and extended in the Protégé software. Fig. 3 shows an interactive hierarchy view of classes, subclasses and data or object properties of the ontology for the measurement process and uncertainty of results [12].

The properties have been further refined by specifying constraints on their values and cardinality. This information model captures relevant calibration and uncertainty information. It also covers the details of all artefacts and devices used in a laboratory. This information helps the user to trace the measurement results to the equipment, artefacts and measurement uncertainties specific to their laboratory workflow. The measurement data captured using this ontology are saved in XML format that provides interoperability, machine-readability and semantically meaningful structure.

2.5. Verify and validate

Our ontology organizes the measurement data in a digitalized form that clearly shows the information flow between various measurement process stages and includes uncertainty. It reduces the time required for the measurement process and provides high-quality, easily accessible, shareable data. Consistency tools such as reasoner and debugger provided by Protégé software, verify ontology for the given domain by applying the logical rule tests created by the ontology developer using the rule language SWRL [13]. The efficiency and fitness-for-purpose of the ontology are validated by answering the CQs defined in stage 1 [14]. Fig. 2 demonstrates that all CQs can be answered using the model developed. The concept "Uncertainty" is associated with "Uncertainty Sources" that give all the possible sources of uncertainty that come from "Measurement Results," "Operator," "Measurement Instrument," and "Measured Artefacts." It also includes other sources such as calibration certificates. Based on "Measurement Result" and "Analysis & Documentation," it infers the information for results and stored data in documents such as uncertainty budgets or certifications. "Evaluation Methods" lists "GUM" and "MCM (Monte-Carlo method)" evaluations. The class "Environment" lists all the sources of temperature and pressure measurements in the laboratory. The concept "Laboratory" consists of all the calibrated and uncalibrated artefact information. All the referenced artefacts and instruments can be derived from the "Measured Artefact," "Measurement Instruments" and "Laboratory". The "CMM" concept specifies the uncertainty that comes from CMM calibrations and its measurements. The concept "Operator" is linked as "operates" with "Measurement Instrument." It gives the operator information on the persons who are trained to use the instrument and measure the artefact. "Measured Artefact" and "Measurement Instrument" (CMM) are linked via "measures" relationship that contains knowledge about the features of geometry and CMM measurement algorithm, which in turn generate the uncertainty from artefacts and CMM instrument. The measuring capability of a CMM is captured in "CMM" and "Measured Artefact" concepts.

3. Discussions and applications

The definitions of concepts and relationships in the presented ontology can generate the controlled vocabulary for measurement systems and uncertainty evaluation. The knowledge representation allows easy access and interpretation of results by non-expert user. The ontology presented in this paper can generate a semantically linked, shareable, and easily editable database, with all the information required to answer the competency questions [15]. It motivates the development of an intelligent data management system for metrology or manufacturing-based organizations.

The knowledge base generated using this ontology model can infer all information necessary to answer user queries. The knowledge base can be enhanced with advanced analytics and machine learning methods to categorise the information about the measurement results and uncertainty, and to aid the operator in choosing optimal machine settings [16]. CMM ontology can be integrated with the other existing metrology related ontologies such as QIF, OntoPro, and QUDT to enhance them with the concept of uncertainty of measurement results. The merging of these ontologies can make an efficient knowledge system for manufacturing industries and wider applications.

The CMM ontology could be enriched with further concepts, actors, and properties with instances to enhance its semantic scope. The enriched ontology database would enable automation of metrology data

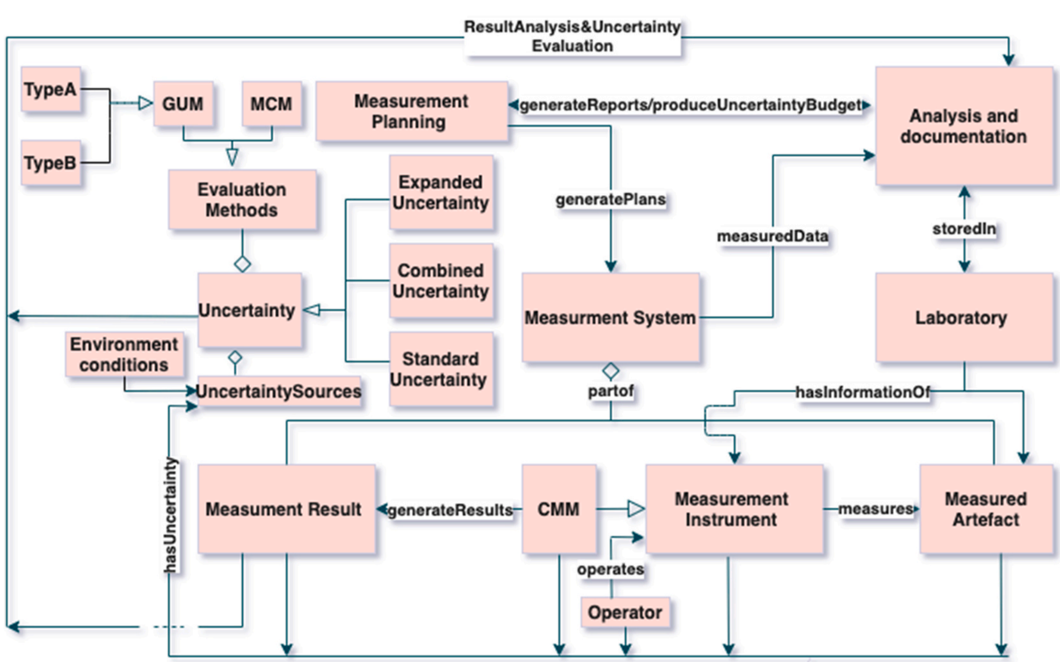

Fig. 2. Ontology model for measurement process and uncertainty of results.

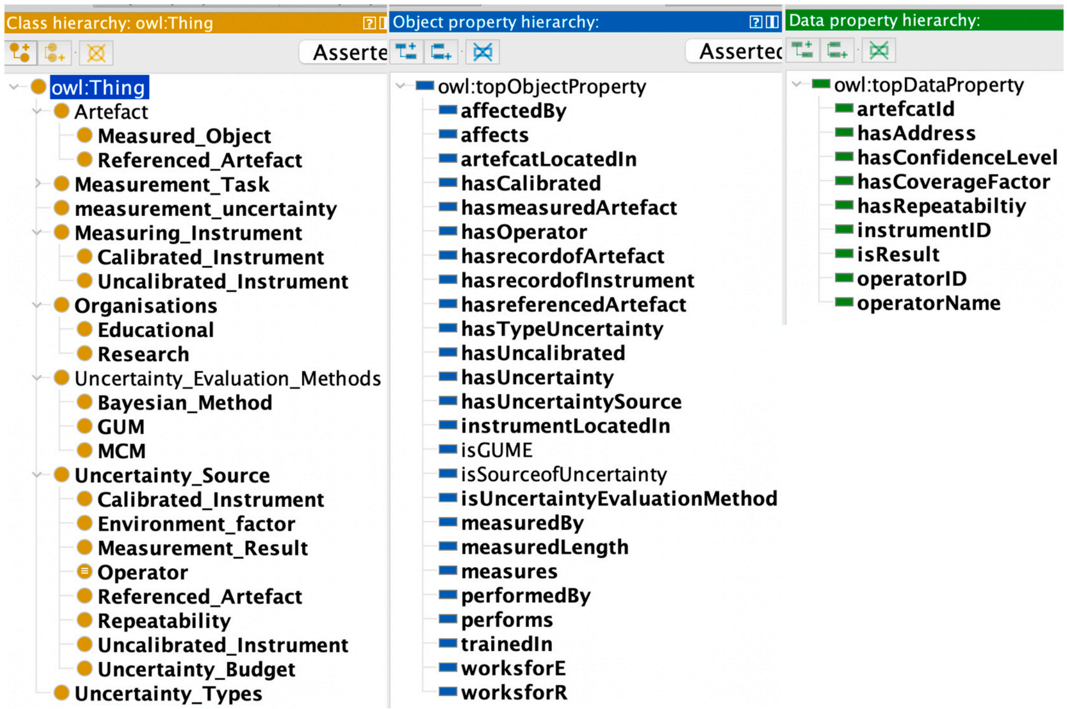

Fig. 3. Proposed ontology for CMM measurement process and uncertainty of results in Protégé.

evaluation, e.g., using natural language processing and machine learning. The ontology-based data access could be realised via Protégé software plugin, helping users to link the ontology with real-life applications. Based on the fundamental ontology of the measurement process, other ontologies can be developed for different applications, making the ontology reusable for other measurement scenarios and instruments.

4. Conclusions

Ontology-based knowledge representation is a suitable method to improve the measurement process in Industry 4.0 that enables user-driven information modelling and answering of relevant competency questions. The presented ontology enhances the previous work in this area by including the information on uncertainty of measurement process and results. The ontology can be used to create a robust database of measurement information, that includes the knowledge of measurement uncertainty. The presented ontology design method will ensure that the resulting ontology covers all relevant knowledge, is useable, can be developed in efficient manner and is easily validated via user-defined competency questions. The presented CMM ontology demonstrates how methods of knowledge engineering can be applied to metrology to enable semantic modelling, automated analysis, and discovery of traceable measurement data.

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