Publishable Summary for 22DIT01 ViDiT
Trustworthy virtual experiments and digital twins

Overview

The use of virtual experiments (VEs) and digital twins (DTs) in metrological applications (e.g. coordinate measuring machines (CMM), tilted wave interferometer (TWI), flow measurement (FLOW), nanoindentation, 3D robotic measurement, electrical measurement) requires uncertainty evaluation methods, as well as reliable validation procedures, to make them fit, e.g. as substitutes or extensions, to certified measurement devices. This project will develop these methods and procedures to ensure the reliability and trustworthiness of VEs and DTs in metrology. In addition, this will enable the traceability of modern measurement systems and it will boost and strengthen the European lead in this field. To facilitate the uptake of the developed methods by NMIs/DIs and industrial stakeholders, three good practice guides (GPGs) will be written, and the applicability of the methods will be demonstrated in twelve case studies covering the aforementioned industrial metrology applications.

Need

VEs and DTs are key enabling technologies to achieve and realise European strategic policies devoted to sustainability and digitalisation within the complex framework of Industry 4.0 and the European Green Deal. VEs and DTs are both simulation models that accurately replicate physical systems and characteristics in a virtual environment. DTs further include dynamic updates of the virtual model according to the observed state of its real counterpart. Hence, they consist of two parts, a Physical-to-Virtual (P2V) connection that models the considered system and a Virtual-to-Physical (V2P) connection that implements prevention and control strategies to achieve the target accuracy in the physical system.

VEs, in combination with Monte Carlo simulation methods, are used for evaluating measurement uncertainties. However, the outputs of these approaches generally differ from an uncertainty evaluation that is compliant with the “Guide to the expression of Uncertainty in Measurement” (JCGM:GUM). Such a JCGM:GUM-compliant uncertainty evaluation is needed to facilitate the use of VEs in traceable measurement chains and to ensure trust in the stated uncertainties.

For DTs, in addition to this, time-dependent influences need to be considered. Hence, DTs need to be updated with data from actual measurements that are collected in real-time, and the evaluation of measurement uncertainty needs to be adapted accordingly to be compliant with the JCGM:GUM.

To trust the outcomes of VEs and DTs, a reliable validation procedure needs to be developed. Differences between calibrated standards (or measurement data obtained with calibrated instruments) and the corresponding data from the virtual counterpart need to be analysed and quantified to make VEs and DTs fit for use in metrology, e.g. as substitutes or extensions to certified measurement devices.

To ensure the uptake of the developed mathematical and statistical methods and procedures by industry, their applicability needs to be demonstrated, using case studies that cover several metrological applications. These case studies need to be defined and planned in close collaboration with industrial participants to ensure the effective uptake of the proposed methods in industrial setups.

European Partnership Co-funded by the European Union

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METROLOGY PARTNERSHIP EURAMET

Uncertainty evaluation and validation of VEs and DTs are essential parts of the strategic research agenda of the European Metrology Network (EMN) MATHMET. This research agenda is based on a survey of European NMIs and stakeholder consultations that identified virtual metrology as one of their priorities in the field of mathematics and statistics for metrology. This emphasises the need for this project.

Objectives

The overall objective of this project is to develop methods and tools that will ensure the reliability and trustworthiness of VEs and DTs in metrology in order to support digital transformation within Industry 4.0 and the European Green Deal.

The specific objectives of the project are:

1. To develop methods for evaluating the uncertainty associated with real measurements for three different applications (CMM, TWI, FLOW) by using the results from corresponding VEs in line with the current state-of-the art for uncertainty evaluation, such as Bayesian or Monte Carlo approaches or documented in the JCGM:GUM. An open access software repository including the implementation of the methods, and a FAIR data set developed for the uncertainty evaluation of VEs, will be provided.
2. To develop methods for uncertainty quantification for DTs representing complex measurement processes and mechanisms for four different applications (nanoindentation, NanoCyl, 3D robotic measurement, electrical measurement), in each case including the effect of dynamic influences on the digital model such as thermal drift or vibrations. The model will be updated based upon data obtained during the project's lifetime. The open access software repository created in objective 1 will be extended by including the methods, and a FAIR data set, developed for the uncertainty evaluation of DTs.
3. To develop approaches for the validation of VEs and DTs for all applications of objectives 1 and 2, using statistical procedures for the assessment of differences between calibrated standards and corresponding data from their virtual counterpart. Methods include accounting for errors, specifically for computationally expensive systems, where surrogate models need to be used.
4. To demonstrate the practical applicability of the developed methods, using twelve different case studies covering six different metrological applications (coordinate measurement, optical form measurement, flow measurement, nanoindentation, 3D robotic measurement, electrical measurement). Guidance will be documented on how to employ the methods in other cases and reports will be drafted in collaboration with industrial participants and stakeholders and disseminated within e.g. European industry, Consultative Committee for Length (CCL), EURAMET TC Length (TC-L) and ISO communities.
5. To facilitate the take up of the technology and measurement infrastructure developed in the project by the measurement supply chain (NMIs/DIs, accredited laboratories, material testing laboratories, calibration laboratories), standards developing organisations (ISO, IEC) and end users (advanced manufacturing, personalised health care and urban planning).

Progress beyond the state of the art and results

As a VE usually produces virtual data rather than virtual values for the measurand, the uncertainty evaluation methods described in the JCGM:GUM cannot be directly applied and extra steps have to be taken to obtain a JCGM:GUM-compliant uncertainty estimate. Recently, a JCGM:GUM-compliant uncertainty evaluation has been reached for linear models in an automatic way by using the output of a VE. However, no procedure exists to derive the uncertainties for the result of a measurement, by automatically using virtual data when the model for the measurand is nonlinear. One objective of this project is to progress beyond the state of the art by developing such an approach. This will allow an automated uncertainty evaluation for general models using the outcome of a VE.

To this end, a literature review of state-of-the art methods for uncertainty evaluation methods involving VEs and real measurement data has been performed. This review also establishes a vocabulary and mathematically concise description of VEs in terms of input-output relations. Subsequently, different classes of uncertainty evaluation methods were identified. In particular, the review distinguished between Linear Propagation of Uncertainty (LPU) methods, Propagation of Distribution (PoD) methods and Bayesian approaches for uncertainty evaluation. In the next step, requirements, constraints, and challenges were identified for each method. Currently, an assessment of JCGM:GUM-compliancy for the methods identified is being performed. For such an assessment, a precise and practical definition of the term JCGM:GUM-compliancy will be required in the context of this project and practical guidelines will be developed. (Objective 1)

Very few examples of DTs are reported in the literature for measurement instruments or measurement processes, and there is even less literature on the uncertainty evaluation of DTs. Currently, available methods for uncertainty evaluation often neglect the coupling of a DT with its different parts, especially those linked to the control and the V2P connection. Moreover, a rigorous definition and evaluation of the metrological characteristics of the DT are missing. This project will progress beyond the state of the art by delivering different methods to evaluate the uncertainty of DTs for several measurement processes, for which JCGM:GUM-compliancy will be analysed and reported. Additionally, the coupling with the modelling, and the control feedback deployment strategies, will be included in the uncertainty evaluation.

In the first nine months of the project, an extensive literature review has been performed to identify main applications and examples of measurement instrument DTs and corresponding uncertainty evaluation methods. A definition of DT was developed that is coherent with the recently published standard (ISO 23247:2021) and with the definition of VE. Accordingly, a DT consists of a physical asset and a virtual asset twinned by means of a bi-directional connection, i.e. the physical-to-virtual (P2V) and the virtual-to-physical (V2P) twinning. The former aims at updating the virtual asset and the latter to control the physical part. The definition identifies the DT as *a simulation model that accurately replicates physical systems in a virtual environment and includes dynamic updates of the virtual model according to the observed state of its real counterpart to achieve a physical control of the latter, wherein the virtual asset is a time-varying VE.* The literature review showed that, in the implementations of DTs, the bi-direction twinning is often disregarded. Towards meeting Objective 2, the main sources of uncertainty have been identified, namely due to diagnosis (sensors and P2V connection), prognosis (the virtual asset prediction) and epistemic (modelling) errors. Similarly, the main influence factors, namely sensor traceability, task-based influence factors, and environmental contributions, and methods to evaluate metrological characteristics, i.e. accuracy (by calibration on reference artefacts), precision/uncertainty and traceability, have been identified. In particular, methods to establish traceability have been identified, i.e. by calibrating sensors, actuators and characterising virtual asset modelling performances. Furthermore, criticalities in the propagation of uncertainty in the DT and its different parts, i.e. the physical and virtual assets, have been highlighted depending on the control strategies and the available sensors. Specifically, control strategies might be implemented depending or not on the current state and relying on sole proprioceptive sensors or leveraging data fusion through exteroceptive sensors. Theoretical propagation of contributions according to the law of uncertainty propagation has shown that the only methods that avoid an increase in the uncertainty in the state estimation are those relying on data fusion. Different applications are being developed to demonstrate the applicability of the uncertainty quantification methods, and the main parameters have been selected. (Objective 2)

Currently, there are no general guidelines for the validation of VEs/DTs. This project will progress beyond the state of the art by developing these guidelines with a special focus on their applicability to metrology. The validation will include both the measurement estimate obtained by the VE/DT, as well as the uncertainty associated to it. Knowledge and experience from existing applications of VEs in metrology (e.g. virtual coordinate measuring machine (VCMM)) will be applied in other applications that are new to the adoption of VEs/DTs (e.g. nanoindentation). Attention will be given to the broad applicability of the validation guidelines and also to non-standard measurements, e.g. measurements of freeform artefacts. Surrogate modelling will also be investigated as it has the potential to replace the VE/DT in online applications. A literature review of available methods for surrogate modelling has been performed. (Objective 3)

The uncertainty evaluation methods developed for VEs and DTs will be applied in twelve case studies covering different metrological applications. Where appropriate, existing software tools will be extended based on the expected results. For other applications, new environments will be created, such as DTs for a commercial nanoindentation platform or a traceable commercial robotic 3D scanning system. Guidance will be given on the practical applicability of the developed uncertainty evaluation methods when applied to industrial case studies. The reports will be drafted in close collaboration with the industrial participants and stakeholders. The results will be disseminated within the relevant European industry as identified by the EMNs AdvanceManu and MATHMET, as well as by the consultative committees of the CIPM (e.g. CCL), EURAMET technical committees (e.g. TC-L) and ISO communities. (Objective 4)

Outcomes and impact

In the first nine months of the project, a Stakeholder Committee has been established consisting of 17 members so far. Furthermore, a meeting with a potential collaborator was held. A project webpage (vidit.ptb.de) has been created and is regularly updated with news about the project's first results and activities of the consortium. Furthermore, key information about the project has been summarised in a project flyer, a project poster, a press statement, and a first e-newsletter. These documents have been distributed at different occasions (e.g. during conferences and workshops or via the e-mail lists of *Metrology News* and the EMN MATHMET) and they are all available for download on the project webpage. News about the project is also distributed via LinkedIn, where a group for the ViDiT project has been created. First results and an overview of the aims of the project have been presented at several conferences and workshops (e.g. MSMM 2023, ENBIS 2023, 3DMC, etc.). A first peer-reviewed paper has been published. The consortium has informed JCGM WG1 about the start of the project and is in close contact with the EMN MATHMET.

Outcomes for industrial and other user communities

The outcomes of this project will include the provision of methods for the JCGM:GUM-compliant uncertainty evaluation of VEs and DTs, as well as procedures for their validation. Furthermore, the newly developed approaches will be applied to a variety of industrially relevant test cases. These methods, procedures and case studies will enable the industry and users of VEs and DTs to e.g. optimise meter design or to improve the efficiency of welding processes. This will provide the basis for gaining traceability in several metrological applications, where VEs/DTs are employed (e.g. asphere and freeform metrology, nanoscale mechanical characterisation, the quality control of welded parts). This will lead to a reduction in the production time as well as to parts being manufactured with better surface quality.

Industrial stakeholders will be involved in defining case studies to ensure the transferability of the developed methods and procedures for uncertainty evaluation and validation in industrial setups. First meetings with stakeholders took place within the first nine months of the project. The GPGs that will be written in this project will be disseminated to industrial stakeholders to further support the uptake of the developed methods in these and other fields of application. Additionally, representatives of industry (both manufacturers and users) will be invited to a workshop on uncertainty evaluation for VEs and DTs, which will be organised and held by the project. Members of the consortium participated in seminars and workshops to present the project and its impact on industrial applications, e.g., in the field of precision engineering and quality control.

Outcomes for the metrology and scientific communities

The outcomes of this project will provide a common understanding among European NMIs/DIs on how to make VEs and DTs fit for use in metrological applications. The methods for assessing the uncertainty will be summarised and published in GPGs so that they can be easily adapted by the metrological and scientific communities. Up to now, one research paper has been published in *Measurement*. By the end of the project, more results will be published in high impact peer reviewed journals, and as part of the knowledge transfer, a workshop on uncertainty evaluation for VEs and DTs, will be organised and held, to which representatives of academia and NMIs will be invited. Results will be disseminated to the EMNs AdvanceManu and MATHMET as well as to the International Academy for Production Engineering (CIRP), which will make them accessible to a wider audience including stakeholders from all these networks. Contact with the EMN MATHMET has already been established and its members and stakeholders have been informed about the start of the ViDiT project. Five presentations were delivered to the metrology and scientific community at MATHMET and ENBIS conferences and workshops. The collaboration of European NMIs and DIs in this project will increase their visibility and authority in drafting common regulations and guidelines. This will improve the competitiveness of the European economy and it will lead to a more intense international cooperation.

Furthermore, the project's results will provide high performance and robust methods that have the potential to be used in different applications, for example freeform optical surface measurements. The optical scientific community will be able to make use of these advancements and benefits in their research, e.g. with regard to the need for highly accurate complex optical systems in research fields such as lithography (e.g. extreme ultraviolet lithography), synchrotron, astronomy, ophthalmic, medical devices and many more. The benefits will also be valid for the scientific communities that are involved in electrical measurements, flow measurements, nanoindentation measurements, etc.

Outcomes for relevant standards

The consortium will promote the results and outcomes of this project within the standardisation community and will provide input into the standardisation process. The participants of the project are active in the JCGM WG1, which has responsibility for the JCGM:GUM and its supplements. These documents mark the de facto standard for uncertainty evaluation in metrology and are used worldwide at all levels of the measurement chain, from NMIs to industry. Furthermore, the results of this project will be disseminated to DIN, ISO and CEN working groups. For ISO, the relevant standards that are in preparation/revision will be identified, and the work on these standards will be suggested to the appropriate working groups or committees. The participants will also present the outputs of the project to College International pour la Recherche en Productique (CIRP), EURAMET TC Length (TC-L), IMEKO, EURAMET and other networks, where they are active. All these activities will ensure the uptake of the project's outcomes by the metrological community.

Longer-term economic, social and environmental impacts

The improved capabilities at NMIs and DIs, which will be provided by this project, will enable industries to reduce the number of iterative steps that are required in product design, production and testing. This will lead to a drastically reduced production time and cost per part. The latter will allow the production of new products and the development of novel applications and systems in several sectors including aerospace, the automotive and the naval industry, medical, optical and precision instruments, as well as computer, audio, video and telecom equipment. The improvements in the reliability, efficiency and speed of production processes will also significantly decrease the scrap rate and reduce the energy needed for production. The corresponding energy savings will help to reduce Europe's CO_2 footprint.

Positive social effects will result from the impact of high-end optical components on the production of new information technology components, mobile electronics and medical devices. Better mechanical alignment through new robotic 3D scanning system tools will be used in advanced particle beam therapies resulting in treatments with higher cure rates. In electrical measurement systems, the project's outcomes will help to better estimate over-voltages and unwanted induced currents in HV lines, as well as in the use of adapted control solutions. This will drastically reduce the loss of electrical energy, which is highly valuable and in high demand in Europe.

The enhancement of advanced manufacturing will help to keep highly skilled jobs in Europe and, hence, it will enhance the employment and wealth of the EU.

List of publications

Maculotti, G., Genta, G., Galetto, M. (2024) 'An uncertainty-based quality evaluation tool for nanoindentation systems', *Measurement*, 225(2) p. 113974. Available at https://doi.org/10.1016/j.measurement.2023.113974

This list is also available here: https://www.euramet.org/repository/research-publications-repository-link/

<table>
<tr><td colspan="2">Project start date and duration:</td><td>1 May 2023, 36 months</td></tr>
<tr><td colspan="3">Coordinator: Sonja Schmelter, PTB   Tel: +49 30 3481 7766   E-mail: vidit@ptb.de
Project website address: vidit.ptb.de</td></tr>
<tr><td>Internal Beneficiaries:
1. PTB, Germany
2. FFII, Spain
3. GUM, Poland
4. LNE, France
5. VSL, Netherlands
6. VTT, Finland</td><td>External Beneficiaries:
7. ENS Paris-Saclay, France
8. IDEKO, Spain
9. INTI, Argentina
10. PK, Poland
11. POLITO, Italy
12. TEKNIKER, Spain
13. UNIPD, Italy
14. UPM, Spain</td><td>Unfunded Beneficiaries:
15. DUI, Netherlands
16. FLEXIM, Germany
17. GEOMNIA, France
18. KROHNE, Germany
19. Mahr, Germany
20. SICK, Germany
21. TUBITAK, Türkiye</td></tr>
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