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.

Report Status:
PU – Public, fully open

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Publishable Summary

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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. Another objective of this project is to develop novel techniques to employ a VE to improve the data analysis required for complex measurements. This activity will explore new possible applications for 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 and 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 has been developed in the context of this project and practical guidelines will be developed. (Objective 1) Furthermore, three benchmarking scenarios have been developed and implemented in a software repository. The benchmarking scenarios are simplified VEs that are inspired by the applications TWI, CMM and FLOW, with increasing complexity. These simplified VEs are used to perform method development for novel approaches according to the JCGM:GUM framework and the Bayesian framework. Additionally, the state-of-the art uncertainty evaluation methods identified in the literature review have been implemented in the software repository and applied to the benchmarking scenarios. With these prerequisites, method development is currently ongoing, and the following results have been obtained so far:

1) An approximate Bayesian procedure using the VE of the TWI for uncertainty evaluation has been published (Marschall, Fortmeier, Stavridis, Hughes & Elster. *Optics Express*, 2024 – see list of publications below);
2) A JCGM:GUM compliant approach for uncertainty evaluation using a VE in an automated fashion has been developed for semi non-linear VEs (the respective paper by Hughes et al. has been accepted for publication in *Measurement:Sensors*);
3) A JCGM:GUM compliant approach for uncertainty evaluation using a VE in an automated fashion with unknown variance and multiple Type A quantities has been published (Marschall et al. *Metrology*, 2024 – see list of publications below);
4) A Bayesian approach to employ a VE to improve the data analysis of complex measurements with non-trivial statistical models has been submitted for publication;
5) A comparison of uncertainty evaluation methods applied to the CMM has been performed (the respective paper by van Dijk & Kok has been accepted for publication in *Measurement:Sensors*).

Currently, additional research is performed to include prior knowledge regarding the actual measurement instrument into the uncertainty evaluation to ensure trustworthy uncertainty evaluation also in the case of limited observations. On another end, the impact of different uncertainty evaluation approaches for the FLOW measurement are analysed and new uncertainty evaluation procedures are developed that include an automatic estimation of the calibration coefficient.

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 half 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. Towards the achievement of Objective 2, a formalization of the concept of DT, harmonized with the concept of VE, aligned with ISO 23247:2021 and ISO/IEC 30173:2023 and ready for metrology has been formulated. That is, a DT of measurement instrument has been identified as a time-varying VE aimed at control the physical entity (i.e. the measuring instrument). Further, for DT of measurement instruments, the virtual entity is a (time-varying) VE (Maculotti et al. *Metrology*, 2024 – see list of publications below). The project highlighted pathways to establish traceability, i.e. by calibrating sensors needed to establish the physical-to-virtual twinning and calibrating actuators needed to deploy the control implemented in the virtual-to-physical twinning. Uncertainty contributions, as pertaining to four main categories, have been classified, namely due to epistemic (modelling), diagnostic (sensing), prognosis (prediction), and actuating (controlling) error sources (Maculotti et al. *Metrology*, 2024 – see list of publications below). With respect to available approaches for modelling the predictive model of a DT, i.e. analytical, data-driven, or hybrid approaches, methods for uncertainty propagation have been defined, and applicability discussed. These can either rely on GUM-compliant methods, i.e. law of uncertainty propagation and Propagation of Distribution (PoD), non-parametric simulative methods or Bayesian methods, useful to allow an automated model update. For different applications, i.e. nanoindentation, nano-cylindricity measurement, optical measurement integrated on robot arm, and electrical measurement, influence factors and modelling parameters have been identified. Models have been established and realization of physical-to-virtual twinning achieved. For each application, the most apt method for uncertainty evaluation has been selected and the methodology for accuracy evaluation outlined. From a theoretical perspective – relying on toy examples inspired by industrial manufacturing applications – the effect of the use of proprioceptive sensors and exteroceptive sensors on uncertainty have been highlighted. In particular, a methodology to evaluate time-varying accuracy, precision and uncertainty of the DT system has been identified. For the four applications, open source software and reference dataset have been prepared and are being tested internally, before realise in open access. (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. As a first step of the validation, a list of relevant uncertainty and error sources is compiled for each of the VEs and DTs. This list will serve as an input for the validation of the VEs and DTs. Surrogate modelling is also being 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 and requirements for the surrogate models have been defined. (Objective 3)

The uncertainty evaluation methods developed for VEs and DTs will be applied in twelve case studies covering different metrological applications (dimensional, fluid, nanoindentation and electricity). Where appropriate, existing software tools will be extended based on the expected results. Furthermore, additional 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

After the first 18 months of the project, ViDiT's Stakeholder Committee consists of 19 members. Furthermore, the company EDF became a collaborator of the project. The project webpage (vidit.ptb.de) is regularly updated with news about the project's first results and activities of the consortium. Furthermore, project flyers and stickers have been distributed at different occasions (e.g. during conferences). A second e-newsletter has been created and shared with ViDiT's Stakeholder Committee as well as via the mailing lists of the EMNs MATHMET and AdvanceManu. All these documents are also available for download on the project webpage. In addition, news about the project is also distributed via LinkedIn. Results of the project have been presented at several conferences and workshops (e.g. WTP congress, IMEKO 2024, ICHVE 2024, 3DMC, etc.). Up to date, four peer-reviewed papers has been published. The consortium is in close contact with the EMNs MATHMET and AdvanceManu.

<u>Outcomes for industrial and other user communities</u>

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 18 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, four research papers have been published in the journals *Measurement, Metrology,* and *Optics Express*. 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 EMNs MATHMET and AdvanceManu has already been established and their members and stakeholders have been informed about activities of the ViDiT project. Several presentations were delivered to the metrology and scientific community at different 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. CIRP is discussing the acceptance of a keynote paper for 2029 leveraging results of the project to highlight the relevance of traceable digital twin of measurement process for quality controls in manufacturing.

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. An uncertainty-based quality evaluation tool for nanoindentation systems, *Measurement*, 225(2):113974, 2024. Available at 10.1016/j.measurement.2023.113974

Marschall, M.; Hughes, F.; Wübbeler, G.; Kok, G.; van Dijk, M.; Elster, C. Using a multivariate virtual experiment for uncertainty evaluation with unknown variance, *Metrology*, 4(4):534-546, 2024. Available at 10.3390/metrology4040033

Maculotti, G.; Marschall, M.; Kok, G.; Chekh, B.A.; van Dijk, M.; Flores, J.; Genta, G.; Puerto, P.; Galetto, M.; Schmelter, S. A shared metrological framework for trustworthy virtual experiments and digital twins, *Metrology,* 4(3):337-363, 2024. Available at 10.3390/metrology4030021

Marschall, M.; Fortmeier, I.; Stavridis, M.; Hughes, F.; Elster, C. Bayesian uncertainty evaluation applied to the tilted-wave interferometer, *Optics Express*, 32(11):18664-18683, 2024. Available at 10.1364/OE.524241

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
15. USPN, France</td><td>Unfunded Beneficiaries:
16. DUI, Netherlands
17. FLEXIM, Germany
18. GEOMNIA, France
19. KROHNE, Germany
20. Mahr, Germany
21. SICK, Germany
22. TUBITAK, Türkiye</td></tr>
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