



Publishable Summary for 23IND12 ADAM

Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing

Overview

Advanced manufacturing enables novel design and production techniques for industrial products with complex freeform geometries. It also meets the increasing demand for fast and contactless measurements in industrial quality control using optical sensors. However, current simulation-based methods using Digital-Metrological Twins (D-MTs) to determine measurement uncertainty do not cover such developments in advanced manufacturing. To address this issue, this project will develop reliable model descriptions, accurate mathematical models for use in D-MTs, traceable parametrisation methods for measurement uncertainty evaluation in D-MTs. The project will also optimise the performance of the developed D-MTs for advanced manufacturing applications, as well as producing case studies comparing optical and tactile measurements using complex freeform geometries and guidance for D-MT use in advanced industrial applications.

Need

Advanced manufacturing, and hence industrial metrology, are consistently evolving. However, such developments produce demands for new and improved technology, assembly concepts and designs, more accurate measurement methods and improved quality assessments of freeform geometries. Thus, better knowledge of measurement uncertainties is vital for the evaluation of product quality and for time and cost savings in advanced manufacturing.

The need for time efficiency in industrial metrology supports the use of simulation-based uncertainty evaluation (e.g. D-MTs). Indeed, D-MTs play an important role in measurement uncertainty determination in industry. However, currently D-MTs are only available for a limited number of measurement tasks and do not cover the full spectrum of part geometries demanded by users of coordinate measuring machines (CMMs) and machine tools (MTs) in advanced manufacturing.

In addition, the proper use of D-MTs in industrial metrology also depends on the quality of the D-MT results, which are dependent on (i) the quality of the models available (i.e. the description of the measurement device, the measurement process, the specimen under test and their mutual interaction), and (ii) the parametrisation of the model (crucial for the traceability and reliability of the measurement results). Therefore, methods for high quality D-MTs with robust parameterisation need to be developed.

Recent developments in sensors and sensor systems in industrial quality control have enabled the substitution of classical tactile CMMs with more versatile multi-sensor CMMs with different, interchangeable sensors. Similar developments have also been observed for MTs. In particular, the use of optical sensors has increased in popularity as they can be used to capture large areas of a parts' surface in a fast and cost-efficient manner, and they are suitable for measurements of delicate parts that cannot be probed tactilely. However, current D-MTs for CMMs or MTs are predominantly limited to tactile probing. Therefore, the rapidly growing number

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of machines that use contactless (optical) sensors lack models (e.g. D-MTs) that cover the numerous error sources typical to these systems.

Objectives

The overall goal of the project is to provide methods and tools in metrology for advanced manufacturing processes to suit the needs arising from a paradigm shift in part properties and measurement techniques. In particular, mathematical descriptions will be developed for optical sensor technologies and freeform-shaped workpieces that take into account the relevant uncertainty contributions. The mathematical models will be usable for D-MTs and represent measurement processes, CMMs, MTs, and workpieces in industrial applications.

The specific objectives are:

1. To determine the measurement uncertainty sources attributed to **freeform geometries**, and to develop accurate mathematical models for use in D-MTs. This includes the (i) evaluation of the D-MTs, (ii) the experimental comparison of the deviations of freeform geometries to prismatic standards, and (iii) the creation of virtual reference artefacts for representative freeform standards.
2. To evaluate the behaviour and inherent properties of at least 3 different types of **optical sensors** integrated in CMMs and/or MTs. This includes the determination of the influence of (i) surface characteristics, (ii) surface tilt and (iii) curvature on the interaction between the optical sensors for freeform and prismatic geometries, as well as the development of reliable mathematical models for D-MTs.
3. To develop methods for the **traceable parameterisation of models** used for measurement uncertainty evaluation in D-MTs. This includes the identification of suitable measurement standards and procedures for the parameterisation of D-MTs and the development of parameterisation strategies for (i) freeform geometry measurements and (ii) for optical sensor measurements.
4. Using the D-MTs developed in Objectives 1-3, to optimise their performance for economically efficient application in advanced manufacturing. This will include **case studies** comparing optical and tactile measurements using freeform geometries and prismatic parts in order to (i) verify D-MT application and (ii) to produce good practice guidelines for D-MT use.
5. To **facilitate the take up of the technology and measurement infrastructure** developed in the project by the EMN Advanced Manufacturing, the measurement supply chain, standards developing organisations (e.g. ISO, VDI/VDE-GMA), and end users (e.g. automotive, machine industry, micromanufacturing, renewable energy and medical sectors).

Progress beyond the state of the art and results

This project will build upon the results of previous projects 17NRM03 EUCoM, 19ENG07 Met4Wind and 20IND07 TracOptic. In 17NRM03 EUCoM, the uncertainty determination through comparison measurements was investigated for tactile measurement of selected prismatic and freeform geometries, however optical sensors and D-MTs were not considered. Through investigations of optical measurements of blades, 19ENG07 Met4Wind focussed on metrology for wind energy systems, but neither a range of optical sensors, nor other freeform geometries were within its scope. In 20IND07 TracOptic, physical models of selected sensors were developed, but data-driven models were not considered.

Mathematical models for measurement uncertainty determination of freeform geometries by D-MTs

D-MTs and numerical simulations play an important role in measurement uncertainty determination in industry, however the currently available methods do not cover the full spectrum of part geometries demanded by users of CMMs/MTs in advanced manufacturing. This project will go beyond the current state of the art by developing validated D-MTs that describe freeform geometries, and their measurement. In addition, the project will develop physical and virtual measurement standards to ensure traceable parametrisation for the D-MTs' application. Terminology for freeform measurements will also be established in order to provide consistency across the metrology and scientific communities and standardisation organisations. This project also intends to extend the applicability of D-MTs to measurements of complex freeform geometries across all areas of advanced manufacturing.

Mathematical models for D-MTs of optical sensors integrated into CMMs/MTs

Current D-MTs for CMMs or MTs are predominantly limited to tactile probing. In contrast there is an increasing demand for the use of optical sensors in advanced manufacturing, as these sensors enabling fast capture of high-resolution data and help to expand the range of measurable parts. This project will create validated D-MTs for the uncertainty determination of optical sensors commonly used in coordinate metrology. The results will expand the state of the art to emerging production methods and current industrial demands for solutions to metrological challenges and help to support faster, reliable, and more cost-efficient measurements.

Traceable parametrisation of D-MTs for measurement uncertainty evaluation

Currently, the traceable use of D-MTs to determine measurement uncertainties requires the identification of all significant contributions and the parametrisation of their influence via dedicated measurement routines. Routines and measurement standards already exist for tactile measurements of prismatic parts on CMMs, however few methods are available for MTs. The project will go beyond the current state of the art by developing procedures for the traceable parametrisation of D-MTs for tactile and optical probing of prismatic and freeform geometries on CMMs and MTs. This should then enable their application to a wide range of measurement tasks in advanced manufacturing.

Optimisation and case studies verifying the developed D-MTs

Simulation techniques, such as D-MTs, used for the determination of measurement uncertainties currently require 10^4 to 10^6 iterations and must be accompanied by detailed parametrisation measurements of the D-MTs. In contrast, cost-efficiency demands in industrial applications require a reduction of the number of iterations to only a few hundreds, which creates a significant gap between the requirement for the trustworthy use and the practical application of D-MTs. The project will address this issue by developing good practice guidelines for the cost-efficient, and traceable use of validated D-MTs. The guidelines will be made available to end users and standardisation committees and are intended to support the trustworthiness and sustainable dissemination of D-MT technologies.

Outcomes and impact

Outcomes for industrial and other user communities

This project's development of D-MTs for the measurement uncertainty evaluation of freeform geometries and the use of optical sensors in coordinate metrology should provide industry with improved measurement capabilities for complex geometries and the use of increasingly fast, accurate, reliable, and versatile measurement technology to advanced manufacturing industries.

The project will establish validated D-MT models for tactile and optical measurements of complex freeform geometries and commonly used optical sensors. The project's development of the D-MTs models will greatly extend the range of their application in CMM and MT measurements to cover complex freeform geometries and delicate objects (that require optical probing). The increased measurement capabilities in MTs will also contribute to faster and more cost-efficient production lines in manufacturing industries. The D-MT models are expected to be integrated in CMM software as part of the virtual coordinate measuring machine (VCMM), originally developed by PTB. This D-MT updated VCMM will then be made available to users from advanced manufacturing industries and other communities. To help ensure that the D-MT updated VCMM is suitable for end-users in industry, PTB will work closely with industrial participants Hexagon, Mitutoyo, Zeiss, who have previously been involved in the integration of PTB's VCMM into their own systems. Further to this the project will benefit from input from industrial stakeholders in its stakeholder committee.

Finally, the project will create 2 good practice guidelines for the reliable and trustworthy application of traceable D-MTs for both freeform measurements and optical sensors in advanced metrology applications. The guidelines will be made freely available to end users via the project website and an open access repository. The results of the project will also be provided to the EMN Advanced Manufacturing, so that they can be promoted widely to their stakeholders in the European advanced manufacturing industry.

Outcomes for the metrology and scientific communities

The project will develop a glossary for relevant terminology of freeform geometries and the use of D-MTs for the uncertainty evaluation. The glossary will help to establish consistency across the metrology and scientific communities. The glossary will be disseminated to the metrological and scientific communities together with the project's good practice guidelines via the project website and an open access repository. This should

support an increase in the use and understanding of D-MTs by calibration laboratories and less experienced users in the scientific community.

The project will also develop a new measurement standard (i.e. a freeform artefact design), together with methods and routines for the parametrisation of the D-MTs, which can be used by stakeholders to enable traceable measurements and uncertainty determination. The design of the freeform artefact will be made publicly available in an open access 3D cloud repository, such as “Reality Cloud Studio” such that all users from the scientific community can access it.

During the project, close ties to the EMNs for Advanced Manufacturing and MATHMET will be sought so that the outcome of this project can be used in outlining roadmaps and updating the EMN's existing strategic research agendas documents and consequently stimulating additional related research.

Further to this, the project will engage with the metrology and scientific communities via the publication of joint research papers in high impact peer-reviewed journals, through the presentation of the project at conferences and as part of the knowledge transfer the project will host 3 stakeholder workshops, as well as a special session dedicated to using D-MTs at the “International conference on Digital Twins” 2026.

Outcomes for relevant standards

The project will provide input to several international and national standards bodies and their guidelines dealing with coordinate metrology using CMMs and MTs. These include EURAMET TC-Length, BIPM's Consultative committee for Length (CCL), ISO/TC 213 Dimensional and geometrical product specifications and verification WG 4 Uncertainty of measurement and decision rules, WG 10 Coordinate measuring machines and Advisory Group (AG) 12 Mathematical support group, ISO/TC 39/SC 2 Test conditions for metal cutting machine tools, ISO/IEC JTC 1/SC 41 Internet of things and digital twin and VDI/VDE GMA TC 4.31 Coordinate measuring machines.

Further to this, the project will develop a proposal for the establishment of a working group devoted to the application of D-MTs in advanced manufacturing.

Existing standards for geometric product specification only sparsely cover the use of D-MTs in coordinate metrology. For example, ISO/TS 15530-4 describes the use of numerical simulation for the uncertainty determination in a general manner, while ISO 23247-1 covers Digital Twin (DT) systems in automation and manufacturing and providing definitions for general terminology. The ISO 230 series covers the determination of parameters describing geometric errors of MTs and provides a set of basic equations for the estimation of measurement uncertainty for MTs. The project's glossary for the use of D-MTs in coordinate metrology will provide information for future extensions of the ISO 10360 series and support more consistent terminology for DTs in advanced manufacturing. Furthermore, the project's good practice guidelines for the reliable and trustworthy use of D-MTs in advanced manufacturing will support the extension of standards in the ISO 15530 and ISO 230 series.

Longer-term economic, social and environmental impacts

In the longer-term this project's improved capabilities for the use of D-MTs for the measurement of freeform geometries and the exploitation of optical measuring systems in industrial applications will support future progress in advanced manufacturing, such as fast, versatile, and traceable quality control processes. The developed D-MTs will help to strengthen the European manufacturing industry's ability to innovate products (e.g. novel product designs required for energy-efficient aircraft and electric vehicles), as well as to make manufacturing operations more time, cost and energy efficient (helping with the mitigation of climate change).

The project's guidelines for D-MT use and trustworthiness will help to increase long-term end-user confidence in metrology devices and to support the competitiveness of CMM and MT manufacturers and the spectrum of calibration services offered by laboratories, mainly SMEs. The project will also help MT producers to be able to offer products for fast and flexible on-machine and in-process measurements thus closer to the manufacturing process and reducing waste material and the re-working of workpieces. This will benefit European citizens by supporting employment and ensuring higher quality products.

Finally, the project's outcomes should have a longer-term impact on the provision of new calibration services for CMMs, MTs and optical sensors in. This will support, for example, medical implants, electric mobility applications, and non-contact calibration of femoral implants. Such developments should open up new or enable the extension of existing Calibration and Measurement Capabilities (CMCs) for NMIs/DIs.

Project start date and duration:		01 September 2024, 36 months
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