



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

**Report Status:**  
**PU – Public, fully open**

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European Partnership  Co-funded by the European Union

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The project has received funding from the European Partnership on Metrology, co-financed from the European Union's Horizon Europe Research and Innovation Programme and by the Participating States.

**METROLOGY PARTNERSHIP**



Issued: April 2026

## 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*

Three existing freeform measurement standards have so far been identified that will be used within the project to further develop the mathematical models for D-MTs: (i) a large hyperbolic paraboloid freeform standard (HP300), (ii) a smaller spiral shaped andromeda and (iii) a knee implant. Additional freeform geometries will be made available from the newly designed freeform artefact which has been designed based on a review by the consortium and stakeholders on complex geometries representing products in advanced manufacturing: aspherical lenses, air foils, and canal surfaces. The newly designed freeform artefact is ready to be manufactured.

Methods for virtual measurement standards are being further developed based on skin models and applied to data from a ring gauge and from the HP300 freeform standard. The progress made with these physical and virtual measurement standards is needed for the development of appropriate mathematical models for D-MTs of CMMs and MTs which is now in progress. A draft version of the glossary of terms and definitions of D-MTs for freeform metrology is currently under review. This document will be the first of its kind to present in a

well-structured way relevant terms related to freeform metrology in advanced manufacturing. The glossary will be published and presented this coming summer.

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

The optical sensors to be used by the consortium have been characterised and subsequently the characterisation data is being used to create models that can predict measurement errors based on sensor principle and measured geometry. These models will allow more accurate uncertainty estimates and changing measurements strategy so that measurement uncertainty can be minimised for the most important measurement parameters of CMM-sensor-sample combinations. The models contain influence factors such as the tilt of the surface and position of the surface within the field of view of the sensor. In turn the sensors have been divided to four sensor groups each defined by the measuring principle and covering different manufacturers.

#### *Traceable parametrisation of D-MTs for measurement uncertainty evaluation*

Different available physical standards with prismatic and freeform geometries have been identified, and procedures for the measurement of the selected standards have been evaluated. Procedures for the determination of D-MT parameters are being developed and will be used to ensure traceability in the estimation of measurement uncertainties in CMMs and MTs with integrated tactile and optical sensors for prismatic and freeform features. Traceable measurement techniques have been selected for the identification parameters following D-MT parametrisation strategies for geometric errors of measurement machines. Furthermore, new measurement standard designs have been identified for future applications in advanced manufacturing.

#### *Optimisation and case studies verifying the developed D-MTs*

Following a literature review, a strategy to quantify the cost of performing uncertainty simulations using existing D-MTs has been defined. The strategy provides a reference point for the costs of those D-MTs currently under development in the project. A framework for quantifying the computational costs of D-MTs has also been created. Once the models are finalised, their costs for typical measurement tasks can be estimated. Furthermore, the costs of performing the new freeform D-MTs are under observation, as the influence of the complex geometry and the convergence of the evaluation algorithms for these objects might have an impact on the performance of the models. The costs of the measurement standards required for parametrisation will only become visible once the models for the D-MTs have been created.

Frameworks for both, the case studies in which the D-MTs will be evaluated and for the validation of the models have been established and are being aligned with the availability of suitable artefacts that meet the requirements of the tactile and optical measurement capabilities within the project. After a suitable selection of artefacts, an efficient exchange of objects and/or data will be organised to ensure a consolidated evaluation and validation of the models used throughout the project. The test results will then be used to develop 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**

### Key dissemination and communication activities

One peer-reviewed publication has been published to date and several manuscripts are in preparation. The output of the project has also been disseminated to the scientific community through 10 oral and poster presentations at various national and international conferences as well as workshops. The project has organised three workshop and training activities including the 3D CMM Workshop on Freeforms and Digital Twins for stakeholders and end-user communities, the 2nd International Workshop on Metrology for Virtual Measuring Instruments for the scientific community, and a four month one-to-one researcher exchange between UNIPD and PTB to strengthen consortium expertise. Additional dissemination and communication activities have included the project website, LinkedIn communication, partner website articles, stakeholder information meetings, and engagement with the European Metrology Networks (EMN AdvanManu and EMN MATHMET), thereby helping to increase the visibility of the project among industrial, scientific and wider public audiences.

### 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 will 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 currently establishes 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 is working 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 is constantly seeking input from industrial stakeholders in its stakeholder committee and through the EMN Advanced Manufacturing.

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 and a glossary on relevant terms and definitions in virtual metrology for freeform geometries 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 has developed 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 has developed a design for a new measurement standard (i.e. a freeform artefact design) and a prototype has been manufactured after consulting with the stakeholder committee about their needs, 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 are 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 engages 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, ISO/TC 39 Machine tools, ISO/IEC JTC 1/SC 41 Internet of things and digital twin, VDI/VDE GMA TC 4.31 Coordinate measuring machine and GMA FA4.32 Optical 3D metrology and DIN NA 152-03-02-12 UA Coordinate Metrology and NA 122-02-01 AA Overall evaluation of machine tools .

Further to this, the project has proposed 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.

**List of publications**

[1]. Schmelter, S., Fortmeier, I., Heißelmann, D. (2025) 'Metrology for Virtual Measuring Instruments Illustrated by Three Applications', *Metrology*, 5(3) p. 54. Available at <https://doi.org/10.3390/metrology5030054>

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

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|--|-----------------------------|-----------------------------------|--|
| Project start date and duration:   |                             | 01 September 2024, 36 months      |  |
| Coordinator: Daniel Heißelmann, PTB  |                             | E-mail: daniel.heisselmann@ptb.de |  |
| Project website address: <a href="https://www.adam.ptb.de">https://www.adam.ptb.de</a> |                             |                                   |  |
| Internal Beneficiaries:  | External Beneficiaries:     | Unfunded Beneficiaries:           |  |
| 1. PTB, Germany  | 8. DTU, Denmark             | 16. eumetron, Germany             |  |
| 2. CMI, Czechia  | 9. ENS Paris Saclay, France | 17. Hexagon, Germany              |  |
| 3. GUM, Poland   | 10. IDEKO, Spain            | 18. Mitutoyo, Germany             |  |
| 4. LNE, France   | 11. PK, Poland              | 19. Zeiss, Germany                |  |
| 5. RISE, Sweden  | 12. POLITO, Italy           |                                   |  |
| 6. VSL, Netherlands  | 13. RWTH, Germany           |                                   |  |
| 7. VTT, Finland  | 14. TEKNIKER, Spain         |                                   |  |
|  | 15. UNIPD, Italy            |                                   |  |
| Associated Partners: 20. AIST, Japan   |                             |                                   |  |