euspen's 26th International Conference & Exhibition, Krakow, PL, June 2026
www.euspen.eu

Glossary of terms and definitions of digital metrological twins for freeform metrology

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Abstract

This paper aims to introduce the "Glossary of terms and definitions of Digital-Metrological Twins (D-MTs) for freeform metrology" (Glossary) compiled for the purposes of the 23IND12 ADAM: Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing, a Joint Research Project (JRP) within the European Partnership on Metrology (EPM). The main objective of the Glossary is to unify technical terminology and enable precise and unambiguous communication between partner institutions. A number of ISO standards and scientific papers have been studied in order to select clear and consistent definitions of key terms and concepts that are essential for the correct understanding and implementation of advanced models, methods and technologies used in the field of D-MT freeform metrology. The terms and definitions in the Glossary are accompanied by a number of original images for better understanding, hyperlinks and an alphabetical index for easy navigation. In September 2026, the Glossary will be published on the 23IND12 ADAM project website https://www.adam.ptb.de.

Digital metrological twin, freeform metrology, advanced manufacturing, coordinate measuring, freeform surface

1. Introduction

The project 23IND12 ADAM: Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing (ADAM) aims to develop reliable mathematical models and traceable parameterisable methods for evaluating the measurement uncertainty applicable in Digital Metrological Twins (D-MTs), with an emphasis on industrial products with complex freeform geometries [1]. This paper presents the "Glossary of Terms and Definitions for D-MTs for Freeform Metrology" (Glossary), compiled within the ADAM project, which collects established and defines new terms in the field of D-MT for freeform metrology. The Glossary enables unification of terminology and definitions, which is crucial for accurate communication and understanding among all involved experts as well as less experienced users in the field of advanced manufacturing engineering, metrology and digital twin development. The Glossary provides a basis for standardising D-MTs terminology, thereby increasing the scientific accuracy and practical applicability of D-MTs across industries.

The paper is organized as follows: Section 2 describes the structure of the Glossary. Section 3 provides some examples of the most important terms used in the interdisciplinary field focused on the mathematical-geometric theory of freeform surfaces design and inspection with the application of D-MTs. Section 4 concludes the paper and discusses the possible impact of the Glossary on the metrological and scientific community, as well as on relevant standards.

2. The Glossary structure

The Glossary is represented by a pdf document where the terms and definitions are listed together with important textual and visual information as well as with the references to the relevant ISO standards or scientific papers where the original description can be found, see example in Fig. 1. Where necessary or appropriate for better understanding, the original description is expanded with broader explanations, notes, examples, formulas, images, etc.

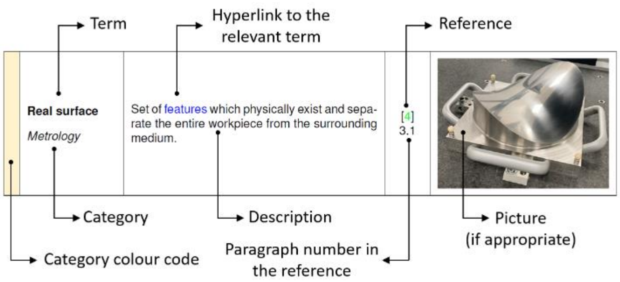


Figure 1. Information structure used to present terms and definitions

All terms in the Glossary are divided into the following five categories (distinguished by colour codes for better orientation):

- *General* (green) for terms or expressions used in scientific and technical disciplines for precise and unambiguous communication between experts,
- *Metrology* (yellow) for specific terms or expressions used in the field of coordinate metrology to ensure the accuracy and reliability of measurements,
- *Virtual geometry* (pink) representing Computer Aided Design (CAD) models of physical or non-physical 3D objects or abstract mathematical representations of 3D objects,
- *Numerical simulations* (orange) involving processes, algorithms and computational methods to analyse and model various systems and phenomena that would be difficult or impossible to analyse analytically, and
- *Advanced technology* (blue) for tools, equipment and systems designed to improve manufacturing processes.

All the main terms are listed in an Alphabetical index and a number of hyperlinks ensure easy navigation.

3. Examples of terms and definitions important for D-MTs

This section provides examples of several Glossary terms that are important for D-MTs developed for advanced industrial applications of complex freeform geometries.

3.1. Digital twin, digital metrological twin

The terms *Digital twin* (DT) and *Digital metrological twin* (D-MT) undoubtedly represent the most important terms in the ADAM project. While the concept of digital twin as a virtual model of a real object or system enabling its monitoring, analysis and optimisation in real time is introduced in ISO standards and currently widely used in various areas of technical practice, the definition of D-MT is not defined in ISO standards yet. Therefore, in the Glossary, the definition of DT is taken from the ISO/IEC 30173 [2] and formulation published in [3] is used as the definition of D-MT:

Digital twin is a digital representation of a target entity with data connections that enable convergence between the physical and digital states at an appropriate rate of synchronisation [2]. DT has some or all of the capabilities of connection, integration, analysis, simulation, visualisation, optimisation, collaboration, etc. DT can provide an integrated view throughout the life.

Digital Metrological Twin [3] is a numerical model that depicts a specific measurement process and indicates an associated measurement uncertainty for a specific measured value, which is traceable to the units of the International System of Units (SI). Moreover, it complies with the requirements that

- the measurement uncertainty is calculated according to recognised standards and guidelines,
- all input parameters are traceably determined and are stated with the corresponding measurement uncertainty,
- the calculated measurement uncertainty is validated by traceable measurements.

3.2. Freeform, invariance class and surface classification

Many papers refer to ISO 17450-1 [4] when defining a freeform geometry (curve, surface), but the definitions of the terms freeform shape or freeform surface are not given in this standard. However, using the invariance class concept [4] as a useful approach to surface classification [5], it is clear that the common term "freeform surface" means complex surface.

According to [4], the *invariance class* concept expresses the set of objects that share the same invariant under some symmetry or transformation. It means that all ideal geometrical features belong to one of the seven invariance classes characterised by the number and type of degrees of freedom.

In the Glossary, the invariance classes are described as shown in Tab. 1.

Using the invariance class concept, each surface class is defined by the rigid motions (translations and rotations) that leave the geometrical surface unchanged (invariant), see the red arrows in the pictures in Tab. 1 (to keep the pictures clear, the rotation arrows are oriented in only one direction, rotation in the opposite direction is also possible). Thus, the following classes of surfaces can be distinguished: complex, prismatic, revolute, helical, cylindrical, planar or spherical.

Complex surfaces are often called freeform surfaces in industry. True *freeform* surface falls into the complex invariance class where the surface shape has no continuous translational or rotational symmetry around any axes. Example of true freeform surface is shown in the Complex (Freeform) row in Tab. 1. Many types of surfaces are also defined as freeform by industry, e.g. off-centred rotational optics and toroidal surfaces. These are mathematically not true freeform surfaces as they do have an axis, but this axis does not pass through the functional surface. In [5], these surfaces are called “quasi-freeform surfaces”.

Surface of revolute, helical and prismatic class can be generated by motion of generating curve g with respect to directing curve d. If at least one of these curves is freeform, the surface in the Glossary is classified as freeform and it is called a freeform revolute surface, freeform rail-revolute surface, freeform helical surface and freeform prismatic surface. Examples of these freeform surfaces together with the description of the generating principle are given in Tab. 2.

Table 1. Invariance classes

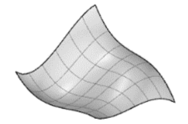
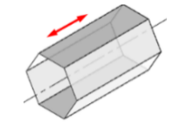
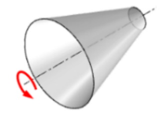
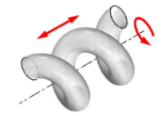
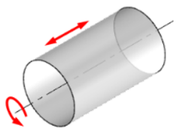
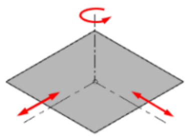
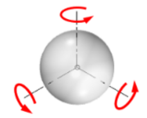
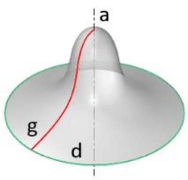
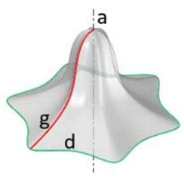
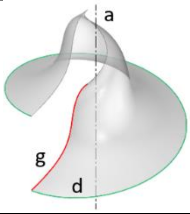
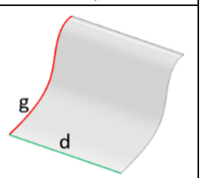
Invariance class	Unconstrained degrees of freedom	Example
Complex (Freeform)	none or none of the below	
Prismatic	1 translation along a straight line	
Revolute	1 rotation around a straight line	
Helical	1 translation along and 1 rotation combined around a straight line	
Cylindrical	1 translation along and 1 rotation around a straight line	
Planar	1 rotation around a straight line and 2 translation in a plane perpendicular to the straight line	
Spherical	3 rotations around a point	

Table 2. Freeform surfaces

Surface	Generating principle	Example
Freeform revolute	Revolution of freeform generating curve g along axis a of revolution. Directing curve d is a circle with centre on axis a lying in plane perpendicular to axis a.	
Freeform rail-revolute	Revolution of generating curve g that defines the surface shape around axis a of revolution with respect to the rail (directing) curve d that defines the surface edge.	
Freeform helical	Combination of revolution of generating curve g around axis a of helical motion and translation of generating curve g along axis a. The directing curve d is a helix.	
Freeform prismatic	Translation of generating curve g along directing straight line d.	

3.3. Nominal model, non-ideal surface model, freeform digital twin

A *nominal model* represents the ideal, theoretical shape of a surface or object intended by the designer [4], which does not take into account any physical deviations or deformations. Usually, the nominal model of freeform geometry is virtually represented by a CAD model. However, manufacturing technologies have their limitations in accuracy, and therefore the machined surface deviates from the nominal CAD model.

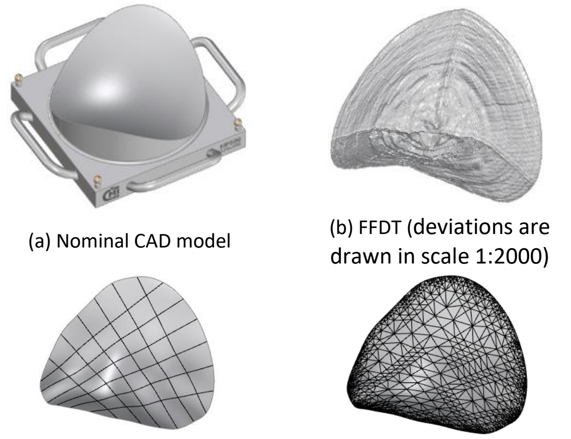
In order to include machined deviations in the virtual CAD representation of the workpiece, a *non-ideal surface model* (*skin model*) is defined in ISO 17450-1 [4] as a virtual model of the physical interface of the workpiece with its environment. The non-ideal surface model is developed based on numerical simulation of the physical interface of the workpiece by a smooth [4] or discrete [6] surface. The numerical simulations used to create a non-ideal surface model are supposed to cover geometric deviations that are expected, predicted or already observed in real manufacturing processes [6].

A novel approach to develop a non-ideal surface model called *Calibrated CAD model* (CCAD) was firstly introduced in [7] where the physical machined surface was mathematically modelled based on calibration data obtained by high precision tactile point-to-point measurement. In [8], this method has been updated and the shape information contained in the calibration data obtained by high-precision tactile scanning has been fully utilised. Thus, the non-ideal surface model called *FreeForm Digital Twin* (FFDT) was introduced based on calibration data as B-spline continuous surface that compensates for the residual manufacturing errors of the freeform functional surface with associated uncertainty. The novelty of the FFDT approach lies in the fact that measurement results with FFDT as a reference CAD model does not indicate the manufacturing errors of the machined surface (as is the case when using a reference nominal CAD model), but an error of the measuring system with a known uncertainty.

The definition of FFDT is included in the Glossary in the following way: FFDT is a mathematical (B-spline) or virtual (CAD) representation of the physical interface of the functional freeform surface with its environment throughout the life cycle of the material standard. Both mathematical (B-spline) and virtual (CAD) representations of the real surface are based on calibration data and indicate a continuous associated measurement uncertainty for the surface profile measurand, which is traceable to SI units. Continuous means that FFDT is represented by a smooth surface and not e.g. by a polygonal mesh or a set of points only. In the context of freeform metrology, the life cycle is a period of validity until the time of damage/wear or until the expiration date of the freeform standard calibration.

To compare the above-mentioned variants of CAD models, the functional freeform surface (hyperbolic paraboloid) of the CMI freeform standard Hyperbolic Paraboloid HP 300 [8] shown in Fig. 1 was chosen as an example. The nominal CAD model of the whole standard is depicted in Fig. 2(a), FFDT CAD model developed in [8] is shown in (b) and examples of smooth and discrete non-ideal surface models based on numerical simulations are drawn in (c) and (d).

It is clear from Fig. 2 that the shape information contained in the FFDT faithfully documents the actual shape of the physical functional surface. In the case of the HP 300, both the manufacturing and measurement strategies can even be revealed from the course of the continuous surface of FFDT. Non-ideal surface models obtained by numerical simulation cannot have such informative power.



(a) Nominal CAD model

(b) FFDT (deviations are drawn in scale 1:2000)

(c) Smooth non-ideal surface model (skin model)

(d) Discrete non-ideal surface model (skin model)

Figure 2. Comparison of nominal a non-ideal CAD models of HP 300

3.4. Line and surface profile measurand

In case of freeform surfaces inspection, the deviations (normal distances) of a set of measured points from the reference CAD model of the inspected surface are evaluated. Usually, the best fit transformation with respect to the nominal CAD model of the freeform surface is applied to minimise the surface profile deviation in the sense of ISO 1101 [9]. According to [9], the *surface profile* is defined by the condition that all measured points must lie between two equidistant surfaces surrounding a set of spheres of diameter T, the centers of which lie on the surface with theoretically accurate geometric shape, see the schematic representation in Fig. 3. Here, the theoretically accurate geometric surface is drawn in green, the measured points in black and the two equidistant surfaces in grey.

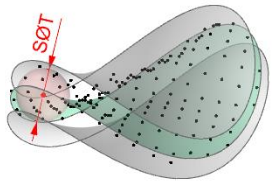
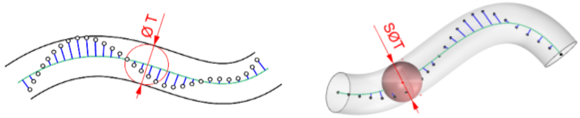


Figure 3. Definition of surface profile (example of HP 300 surface)

The *line profile* definition in ISO 1101 [9] used to assess curve measurement is defined similarly – in each cross-section parallel to the base plane the extracted profile line must lie between two equidistant curves enclosing a set of circles of diameter T whose centers lie on the curve with the theoretically exact geometric shape, see the schematic representation in Fig. 4(a). Here, the theoretically exact geometric shape is drawn in green, the black measured points lie on the extracted profile line and their normal deviations from the theoretical line are shown in blue. Surprisingly, this definition assumes only planar surface sections and therefore it would be possible to evaluate the line profile only when measuring 2D curves.

Therefore, in addition to the 2D line profile, the Glossary also includes an extension of the *3D line profile* recommended for measuring 3D curves in the following way: the 3D line profile is determined by the double value (in the case of oriented deviations by the double absolute value) T of maximum deviation of the measured point from the theoretically accurate 3D curve measured in the normal direction to the theoretical curve. The geometrical consequence of this definition is that the extracted 3D curve must lie in the canal surface surrounding the system of spheres of diameter T with the centers on the curve with theoretically accurate geometric shape, see Fig. 4(b).



(a) 2D curve

(b) 3D curve

Figure 4. Definition of line profile

4. Conclusion

The document "Glossary of terms and definitions of digital metrological twins for freeform metrology" compiled within the 23IND12 ADAM: Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing project 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 https://www.adam.ptb.de and an open access repository. This should support an increase in the use and understanding of digital metrological twins by calibration laboratories and less experienced users in the scientific community.

Introducing new terms into the Glossary can provide input to international and national standards bodies dealing with freeform coordinate metrology for future extensions of the ISO 10360 and ISO 1101 series and support more consistent terminology for digital twin concepts in advanced manufacturing.

Acknowledgement

The project "Application of Digital-Metrological Twins for emerging measurement technology in advanced manufacturing" (ADAM, grant number 23IND12) 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.

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