ISBN: 978-3-95450-231-8 ISSN: 2673-5490 doi: 10.18429/JACoW-IPAC2023-THPA042

HANDLING THE FUNCTIONAL FEATURES OF ACCELERATOR COMPONENTS USING ISO GPS SITUATION FEATURES

B. Nicquevert[†], CERN, Geneva, Switzerland
F. Rey, ESS, Lund, Sweden

Abstract

The building blocks of a scientific facility based on particle beams comprise magnets and electro-magnetic devices. The optical design usually imposes a demanding accuracy with respect to their theoretically exact position and orientation. It happens that the functional features are either not clearly defined – what is the « axis » of a magnet –, or not explicitly used along their lifecycle. Improving how to handle these functional features would contribute to meeting demanding challenges.

The European Spallation Source (ESS) is aiming at providing a powerful proton linear accelerator and a target system to produce pulsed neutrons. The challenging complex design and integration yielded to introducing a tool shared in common by all stakeholders along the lifecycle: the "situation features", as defined in ISO GPS (Geometrical Product Specifications) standards. They are here developed, and extended to beyond-mechanics use cases. Two examples of fiducialization and installation phases are presented for neutron beam guides (in the present paper) and quadrupole magnets (in the associated poster). Perspectives of generic use are also highlighted.

WHAT IS AN AXIS ALIGNMENT?

“Then, Socrates, we will “align the axis of the magnet with an accuracy of 50 microns”.

– This is a good thing, Timaios, and I congratulate you for this nice plan. Just tell me, what do you mean by axis of the magnet, the one that you wish to handle?

– It is a straight line, Socrates, that, as you see, just stands right in the middle of the magnet like in drawing.

– Ô Timaios, I do not see anything in the middle of the magnet. What are you looking at, for Zeus sake?

– Worshipful Socrates, this is the axis of the cylinder where later on will the beam pipe be installed, easy!

– Really? How do you define it? Are you sure it is unique? Then, with respect to what will you align this invisible middle-of-the-cylinder-deemed-straight-line?”

No doubt that the Pythagorician geometrist Timaios, from Plato’s famous work *Timaios*, was not working with magnets and beam pipes. Socrates’ questions are albeit more than relevant to question the operation meaning of the request stated by Timaios, formulated in the exact terms that can be found in almost every paper dealing with installation and alignment of modern scientific facilities based on particle beam physics.

How to define an axis

Take a real cylinder, represented in Fig. 1 by its “skin model” 1, a non-ideal surface model [1] including deviations (of form, orientation or position).

The axis can be defined either as the extracted derived “real” feature 8 (the set of points representing the centres 7 of the local associated circles 6 to real cross-sections 5) [2]; or as the ideal straight line 9 associated to it; or as the axis 3 of the associated (ideal) integral feature of type cylinder 2. Depending on the (often implicit) choices for the criteria (e.g. least squares or minimax) and for the material constraints (e.g. external or without constraint), the association operation [3] can end up with more than twenty different meanings, just for a cylinder. When the “axis” is established from larger and / or more complex set of integral features, this may be even more misleading.

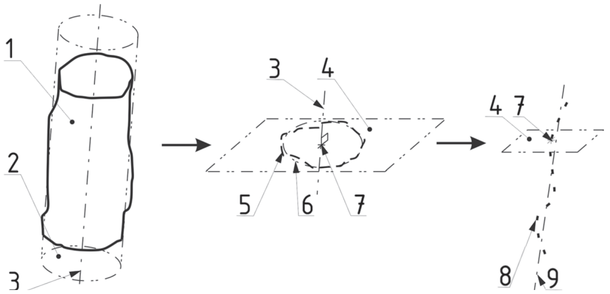

Figure 1: Defining various axis of one real cylinder [2].

These notions of axis, association, criteria, or accuracy are frequently not (re)defined in an explicit way. Some other ones may not even be mentioned, like the datum system or geodetic network with respect to which the device is supposedly aligned. In many occasions, this uncertainty on the definition does not impact the performance, because the actual functional accuracy is less strict than the required one, and can accommodate a larger budget. However, with much more demanding levels of accuracies for upcoming scientific projects (e.g. [4-8]), such uncertainties may impact the final result by introducing biases and misunderstandings between stakeholders.

This paper aims at clarifying the meaning of such requirements and providing practical tools for all stakeholders involved along the lifecycle of any device installed along the beam – ensuring a unique and common understanding of how the functional features are identified and how their *situation* (meant as the combination of both the *position* and the *orientation* of the device, defining the six degrees of freedom of its free rigid body motion) is handled [9].

Steps along the lifecycle

The first phase of the lifecycle of the facility is to set up its optical layout according to the scientific aim and the nature of the beams. This leads to defining the theoretical (nominal) situation of all devices according to their type, allocated to a functional slot along a lattice [10]. Then comes the phase of design and engineering of every device type as they appear along the beam, so that it delivers the expected optical function. That stage usually includes integration and interface management.

[†] bertrand.nicquevert@cern.ch

After the manufacturing phase of a given asset (serialised instance of a type), its characteristics are measured and situated with respect to external marks (fiducialization phase). After the asset is assigned to a determined functional slot, installation of a specific device finally occurs. The “alignment of the axis with a 50 µm accuracy” is then carried out, using fiducial marks as targets.

Some ESS Devices along the beams

The European Spallation Source (ESS) project [11] aims at running a bright powerful neutron source for imagery. A proton beam is thrown on a rotating tungsten target, triggering spallation reaction that produces neutron beams that are extracted and sent to experiments. This study aims to identify and handle the functional features.

The first device is a neutron guide made up of three pairs of parallel opposite, polished mirror, planes, as shown in Fig. 4 (photo), acting as *functional features* of mechanical type. The fiducial marks are conical surfaces on which retroreflective target mounted on a sphere are set up for surveying operations using a laser tracker. The axis of the neutron guide may be nominally defined as the intersection of the middle plane of the vertical planes with the middle plane of the horizontal planes. The orientation of the device is then defined with the “polarising” horizontal plane. The front and back planes serve defining the longitudinal centre along the beam.

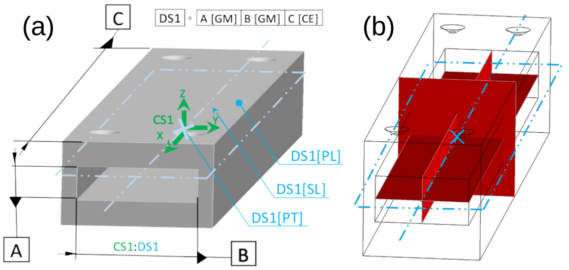

Figure 2: Neutron guide: (a) model with explicitly represented situation features; median features of associated features to functional features (b).

These three nominally defined features, axis (a straight line), centre (a point) and polarising plane (a plane) are the so-called “situation features” of the guide. During installation, they are not accessible, hence the need to measure their situation with respect to the fiducial marks. The same occurs for the second device, a quadrupole, with geometrical or magnetic situation features [12].

Nominally, geometrical and magnetic situation features are identical, and their ideal situation is defined by the layout. The challenge consists of ensuring that the reality reaches this ideal aim as close as possible. The sources of deviations are numerous, from uncertainties in design, manufacturing tolerances, fiducialization accuracies and operation fluctuations, to alignment precision and accuracy, or quality of the geodetic network. Making a clear distinction of the various features at stake is a must.

MANAGING MUTUAL SITUATIONS

Situation features of an integral feature are defined in ISO GPS system [1] as ideal features of types point [PT], straight line [SL] or plane [PL]. In such a set, a condition of mutual situation applies to ensure mathematical consistency: the Point is set to be on the Line, and the Line to be contained by the Plane. This minimum set of situation features is called a **ToLiP**, “*poinT On Line In Plane*” and can be explicitly represented [13], see Fig. 2a.

The relationship between an integral (single or compound) feature and its situation feature(s) is defined by intrinsic parameters depending on its nominal shape and invariance class [1]. For the neutron guide, the linear parameters are width, length, height and centre offset; the angular parameters are implicitly square. The more complex the feature, the larger the set of intrinsic parameters.

The situation features, as their name indicates, are used to define the situation (position *and* orientation) of their integral feature. Setting up their own situation gives therefore ways to handle all translational and rotational degrees of kinematical freedom of the integral feature seen as a rigid body, and ultimately to define the situation tolerances along the directions defined by its situation features [14].

Mutual situation of ToLiPs

A “full” ToLiP is a set made of three situation features. Partial ToLiPs made of one single or of only two situation features define other invariance classes where not all degrees of freedom are locked [1, 15]. Handling the situation of a device along its lifecycle means managing the mutual situation of the minimal set of its situation features (ToLiP) with respect to either the ToLiPs of other functional features of the device (internal use) or an external datum system, itself defined as a ToLiP (set of situation features of the resulting datum system [16, 17]). In order to manage in a systematic way this mutual situation, we have defined a new concept called **CoToLiP** (see Fig. 3), prefix *Co* standing for “***co***mposition of ToLiPs” [18].

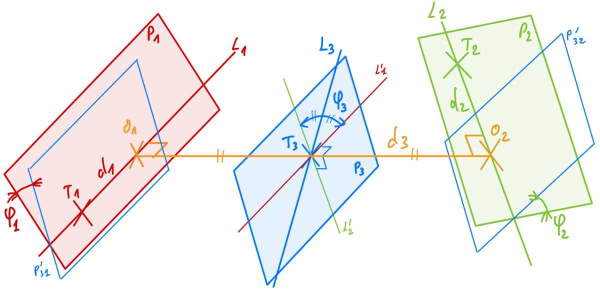

Figure 3: Definition of the CoToLiP (in blue) of two full ToLiPs, with the six parameters of their mutual situation (mutual position d_1, d_2, d_3; mutual orientation φ_1, φ_2, φ_3).

Overall process

The real integral functional features are measured, for instance by a laser tracker. Their situation features (ToLiP 1) are obtained through an association operation [3] (Fig. 4). The association parameters can be defined in the functional (FUN) specification [19], e.g. [GM] as in Fig. 2a. Once established, these situation features are used to build up a local “datum coordinate system” (indication CS1 [20] in Fig. 2b). The spheres are contacting features [21] to the fiducial marks. Their actual position is measured and recorded in CS1. This set of n spheres provides a collection of points that locks all degrees of freedom: it is represented by ToLiP 2.

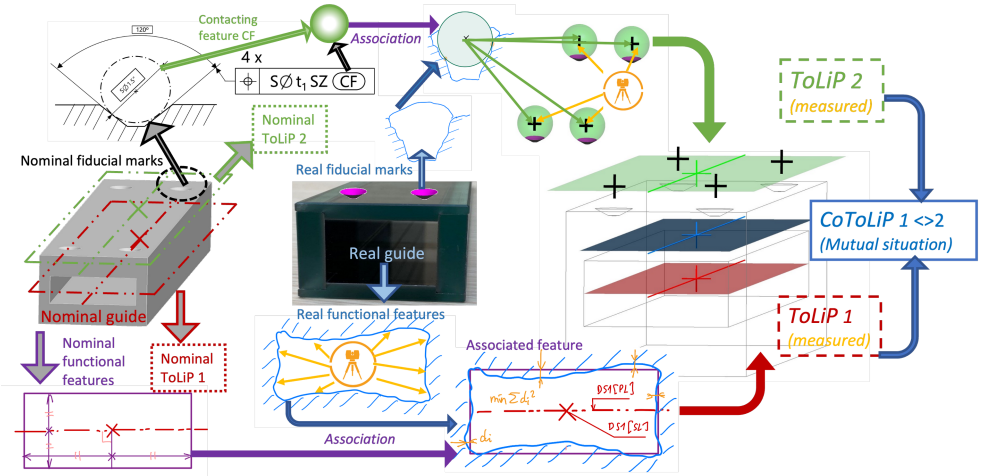

Figure 4. Fiducialization part of the overall process for handling of functional features using situation features along the neutron guide's lifecycle. Bottom: association of ideal integral features with real functional features; top: association of contacting features with real fiducial marks; right: fiducialization and establishment of the CoToLip of mutual situation.

The mutual situation of both ToLiPs is represented by their CoToLiP 1< >2 (Fig. 4 right). In the next phases (Fig. 5), it is used by replacing the measured ToLiP 1 and by applying it on the ToLiP 1 of the nominal functional features as defined in the layout, to determine the theoretical position of each sphere centre (ToLiP 2 "layout situated"). This operation sets the *target values* used by the survey team on the field: placing the collection of spheres at this position ensures, by inverse transformation, that the actual functional features (ToLiP 1 "survey situated") are situated where they were expected to be, modulo the uncertainties.

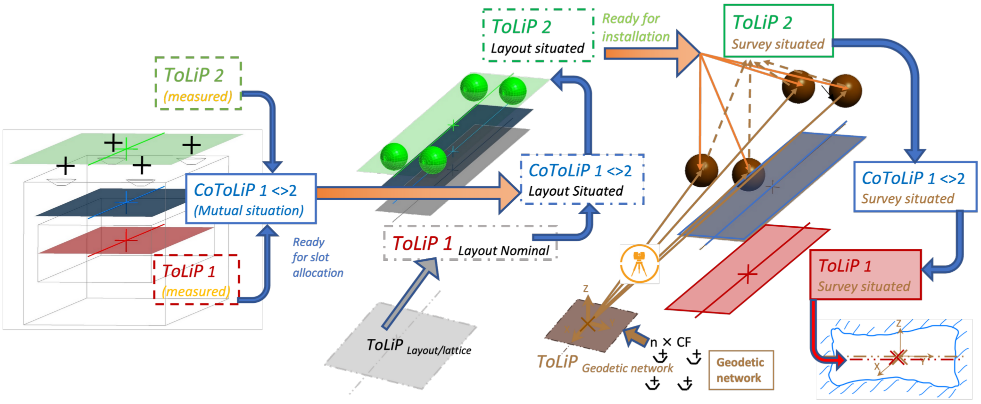

Figure 5. Installation part of the overall process for handling of functional features using situation features along the neutron guide's lifecycle. Middle: configuration and layout; right: installation and survey.

The CoToLiP 1< >2 of real mutual situation, set up by measurement, is used to define the nominal situation of the fiducial marks in the layout, then to fix the situation of the functional features in the geodetic network. It allows to consistently handle *in one go* the 6 degrees of freedom.

The poster [12] complementing this (too short) paper defines the slightly more the CoToLiP, and develops the case of a quadrupole, through an association operation with its non-geometrical (magnetic) functional features.

CONCLUSION AND NEXT STEPS

Using situation features provides a unique formalism all along the lifecycle, from engineering to alignment, that ensures a unique understanding by all stakeholders. The next steps of the work are to build up more ISO GPS tolerancing tools based on situation features [22] on the one hand, and on the other hand to develop a method for error evaluation and global accuracy estimation.

This paper sets up the motivation for a research and development program currently starting in association between CERN and the École Normale Supérieure of Paris-Saclay [23]. The aim is to address the highly demanding requirements of big science, and to provide more complete, consistent and robust conceptual tools to the ISO Technical Committee TC213 (GPS) for the elaboration of the next generation of standards and promotion of their use by high technology industry and other users.

– Worshipful Socrates, you open my eyes! Now I understand that defining the axis of the magnet deserves special attention if we aim at optimising our limited geometrical six dimensional stack-up integration budget.

REFERENCES

[1] ISO 17450-1:2011 “Geometrical product specifications (GPS) – General concepts — Part 1: Model for geometrical specification and verification”, ISO, Geneva, 2011.

[2] ISO 17450–3:2016 “Geometrical product specifications (GPS) – General concepts — Part 3: Toleranced features”, ISO, Geneva, 2016.

[3] ISO/DIS 4351:2022 “Geometrical product specifications (GPS) – Association”, ISO, Geneva, 2022.

[4] C. Collette et al., “Active quadrupole stabilization for future linear particle colliders”, Nucl. Instr. and Methods in Phys. Resesarch Section A: 621, 1–3, (2010), 71-78, doi:10.1016/j.nima.2010.05.020.

[5] K. Charles et al., “Alignment & stability challenges for FCC-ee”, EPJ Techniques and Instrumentation (2023) 10:8. doi: 10.1140/epjti/s40485-023-00096-3

[6] A. Khan et al. “Review of alignment and stability tolerances for advanced light sources” (2023), J. Phys.: Conf. Ser. 2420 012055

[7] S. M. Liuzzo et al., “Influence of Errors on the ESRF Upgrade Lattice”, 6th Int. Particle Accelerator Conf. (IPAC’15), Richmond, USA, May 2015. Paper TUPWA014.

[8] C. Steier et al., “Design Progress of ALS-U, the Soft X-Ray Diffraction Limited Upgrade of the Advanced Light Source”, 10th Int. Particle Accelerator Conf. (IPAC’19), Melbourne, Australia, May 2019, paper WEPGW110.

[9] V. Srinivasan, “A geometrical product specification language based on a classification of symmetry groups”, Computer-Aided Design 31 (1999) 659–668.

[10] P. Le Roux et al., LHC “Reference Database: Towards a Mechanical, Optical and Electrical Layout Database”, Eur. Particle Accelerator Conf. (EPAC’04), Lucerne, Switzerland, May 2004, paper WEPLT025.

[11] R. Garoby et al., “The European Spallation Source Design”, Physica Scripta, vol 93, p. 014001, 2018. doi:10.1088/1402-4896/aa9bff

[12] B. Nicquevert and F. Rey, “Handling the functional features of accelerator components using ISO GPS situation features”, Intl Particle Accelerator Conf. (IPAC’23), Venice, Italy, May 2023, associated poster THPA042 to this paper. https://edms.cern.ch/document/2872028

[13] B. Nicquevert, draft proposal for ISO/NW 20223, “Technical Product Documentation – Identification and representation of situation features”, internal ISO/TC213 document, Feb. 2023.

[14] F. Rey and B. Nicquevert. “From Engineering to Alignment: how functional geometrical requirements on equipment are handled and transferred into installation drawings”, Int. Workshop on Accelerators Alignment (IWAA), Ferney-Voltaire, Nov. 2022.

[15] A. Clément, A. Rivière, P. Serré, C. Valade. « The TTRS: 13 constraints for dimensioning and tolerancing ». In: Proceedings of the 5th CIRP International Seminar on Computer-Aided Tolerancing, 1997, 28–29.

[16] ISO 5459:2011 “Geometrical Product Specification – Geometrical tolerancing — Datums and datum systems”, ISO, Geneva, 2011.

[17] F. Rey and B. Nicquevert, B., Guideline « ESS Datums and How to Use Them », ESS, Lund, Sweden, ESS-3231594.

[18] B. Nicquevert, “Les éléments de situation. Sur quelques éléments fondamentaux de « tolipologie »” (in French), 2023, CERN, Geneva, Switzerland, EDMS 2817750, preprint HAL-03996426, March 2023.

[19] ISO/TS 20619:2018 “Geometrical product specifications (GPS) – Types of documents with GPS”, ISO, Geneva, 2018.

[20] ISO/DIS 5459:2011/AMD:2022, Draft Amendment to “Geometrical product specifications (GPS) – Datum and datum systems”, ISO, Geneva, 2022.

[21] B. Nicquevert, “Note on Fiducialisation and Geodetic survey”, CERN, Geneva Switzerland, EDMS 2817752, and ESS, Lund, Sweden, ESS-4961975, March 2023.

[22] ISO 1101:2017 “Geometrical product specifications (GPS) – Geometrical tolerancing — Tolerances of form, orientation, location and run-out”, ISO, Geneva, 2017.

[23] E. Morse et al., “Tolerancing: Managing uncertainty from conceptual design to final product”, CIRP Annals, 67, 2, (2018), 695-717, doi:10.1016/j.cirp.2018.05.009.

See also LURPA, Research topic “Numerical models for the specification and control of geometric variations of products”, https://lurpa.ens-paris-saclay.fr/en/topic-2-numerical-models-specification-and-control-geometric-variations-products.