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Geometrical product specifications (GPS) — Partition —

Part 3:
Methods used for specification and verification

Spécification géométrique des produits (GPS) — Partition —

Partie 3: Méthodes utilisées pour la spécification et la vérification

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Foreword

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This document was prepared by Technical Committee ISO/TC 213, *Dimensional and geometrical product specifications and verification*, in collaboration with the European Committee for Standardization (CEN) Technical Committee CEN/TC 290, *Dimensional and geometrical product specification and verification*, in accordance with the Agreement on technical cooperation between ISO and CEN (Vienna Agreement).

A list of all parts in the ISO 18183 series can be found on the ISO website.

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Introduction

This document is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO 14638). It influences chain links B, C and E of the chains of standards on size, distance, form, orientation, location and run-out in the GPS matrix model.

The ISO GPS matrix model given in ISO 14638 gives an overview of the ISO GPS system, of which this document is a part. The fundamental rules of ISO GPS given in ISO 8015 apply to this document and the default decision rules given in ISO 14253-1 apply to specifications made in accordance with this document, unless otherwise indicated.

For more detailed information on the relation of this document to other standards and the GPS matrix model, see Annex C.

This document develops the concepts and methods for default partition of the skin model (in specification) and the sampled surface model (in verification) along with ISO 18183-1[1)] and ISO 18183-2.

1) Under preparation. Stage at the time of publication: ISO/FDIS 18183-1:2023.

Geometrical product specifications (GPS) — Partition —

Part 3: Methods used for specification and verification

1 Scope

This document specifies the procedure for the partition operation of geometrical product specification and verification.

This document does not apply to profile and areal surface texture.

2 Normative references

The following documents are referred to in the text in such a way that some or all of their content constitutes requirements of this document. For dated references, only the edition cited applies. For undated references, the latest edition of the referenced document (including any amendments) applies.

ISO 18183-1[2)], *Geometrical product specifications (GPS) — Partition — Part 1: Vocabulary and basic concepts*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 18183-1 apply.

ISO and IEC maintain terminology databases for use in standardization at the following addresses:

— ISO Online browsing platform: available at https://www.iso.org/obp

— IEC Electropedia: available at https://www.electropedia.org/

4 Default partition

4.1 General

If not otherwise indicated, the default partition shall be that which partitions the skin model (in specification), the nominal model and the sampled surface model (in verification) into single features (single surfaces or single lines). See Figure 1.

For the purposes of this document, a single feature is taken to be of maximum extent. The maximum extent is derived from any combination of length, area, curvature, invariance degree and point set characteristics.

2) Under preparation. Stage at the time of publication: ISO/FDIS 18183-1:2023.

a) Default partition of the nominal model **b) Default partition of the skin model (in specification)** **c) Default partition of the sampled surface model (in verification)**

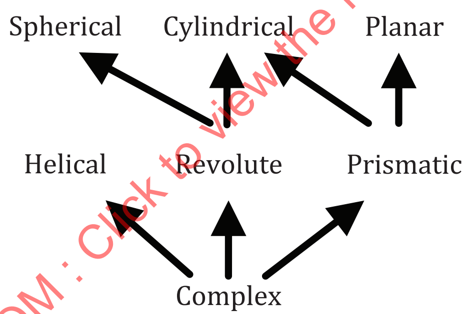
Figure 1 — Default partition

4.2 Default partition for surfaces

If not otherwise indicated, the default partition for surfaces shall be that which partitions the surface into single surfaces. For the purposes of this document, a single surface is taken to be the maximum area possible.

A single surface is a connected surface (a continuous region where any two points can be connected by a path that remains entirely within the surface's boundaries) where no subset of the considered geometric entity exists with an invariance class not respecting the partial ordering of invariance classes (see Figure 2) and, in the case of a surface of revolute invariance class, where its generatrix is a single line.

A single surface is finite (limited in extent).



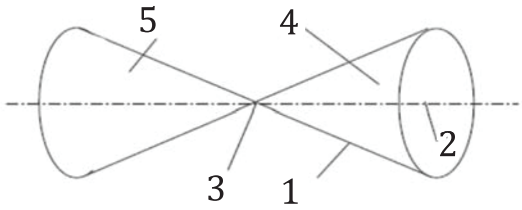
NOTE An upward arrow indicates an increasing freedom in the degree of invariance.

Figure 2 — Partial ordering of the seven invariance classes based on degree of invariance

Where the generatrix intersects the axis of revolution:

— once, each side of the generatrix intersection is considered as a separate single surface (see Figure 3);

— twice or more, the surface between adjacent intersections is considered as a single surface (see Figure 4).

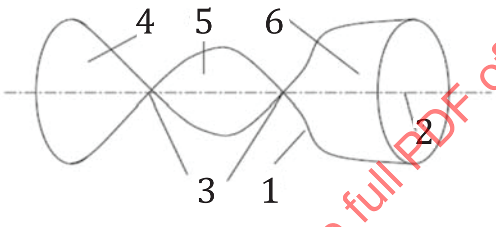


Key

1 generatrix
2 axis of revolution
3 intersection point
4 single cone surface, right side
5 single cone surface, left side

NOTE The generatrix intersects the axis twice; in this case there are three single surfaces.

Figure 3 — Example of a surface of type cone



Key

1 generatrix
2 axis of revolution
3 intersection point
4 single revolute surface, left side
5 single revolute surface, middle
6 single revolute surface, right side

NOTE The generatrix intersects the axis twice or more; in this case there are three single surfaces.

Figure 4 — Example of a surface of type revolute

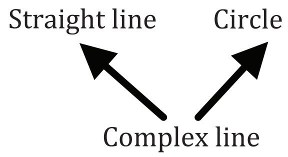
For real surfaces, curvature and slippable motion should be used to determine single surfaces. References to this and other methods can be found in Annexes A and B.

4.3 Default partition for lines

If not otherwise indicated, the default partition for lines shall be that which partitions the line into single lines. For the purposes of this document, a single line is taken to be the longest line possible.

A single line is a connected line where no subset of the considered geometric entity exists with an invariance class not respecting the partial ordering of invariance classes (see Figure 5).

A single line is finite (limited in extent).



NOTE An upwards arrow indicates an increasing freedom in the degree of invariance.

Figure 5 — Partial ordering based on degree of invariance

For real lines, the concept of curvature and slippable motion should be used to determine invariant lines and, hence, single lines. In practice, the straight line is a special case of a circle with zero curvature. Figures 6 to 9 illustrate the partition of a line into single lines through curvature calculation.

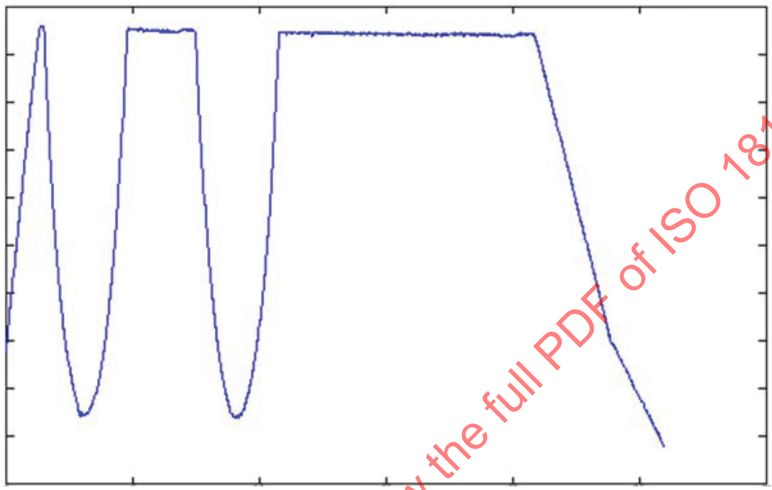


Figure 6 — Original line

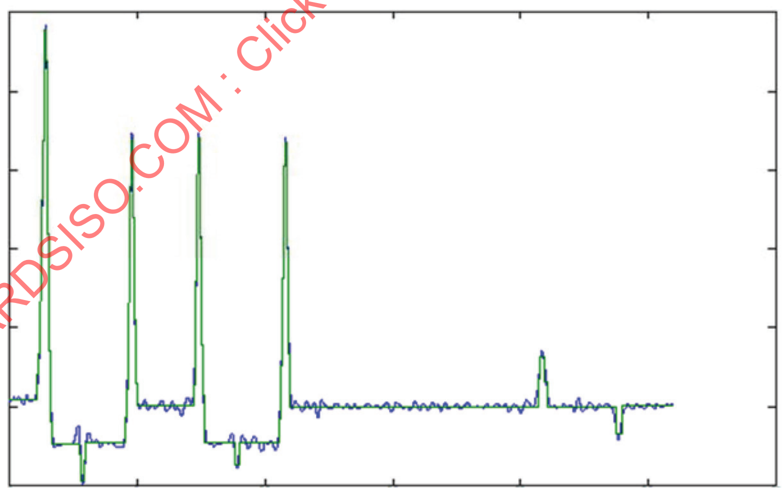


Figure 7 — Calculated curvature from Figure 6 partitioned into single lines

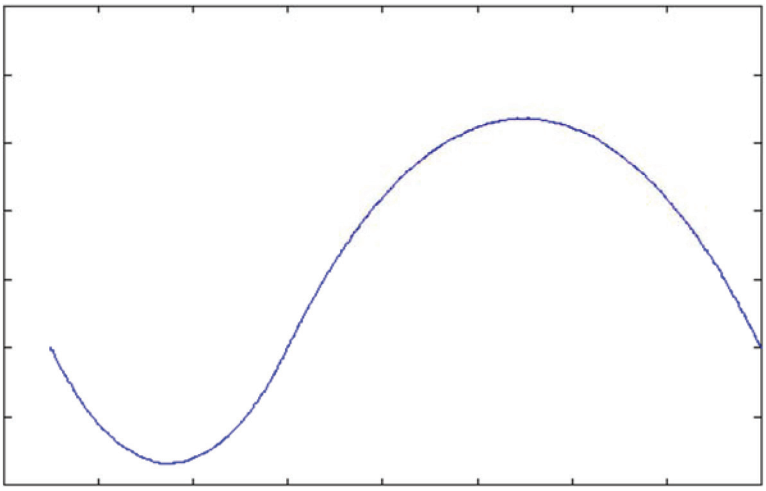


Figure 8 — Original line

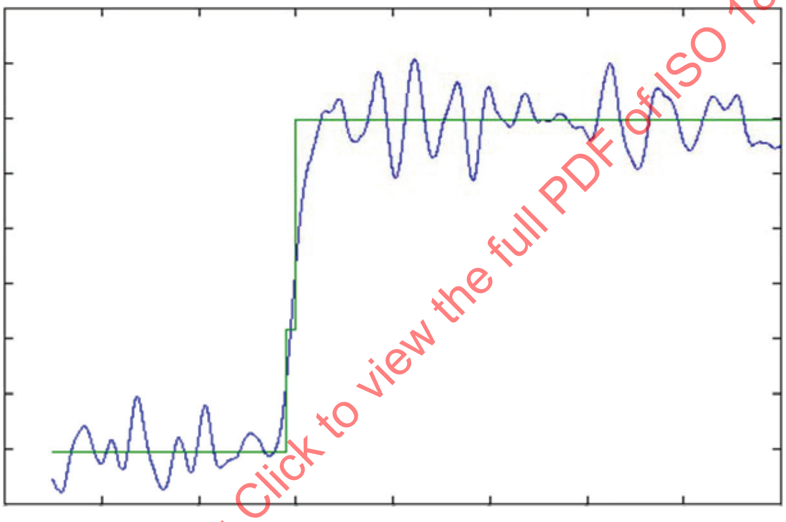
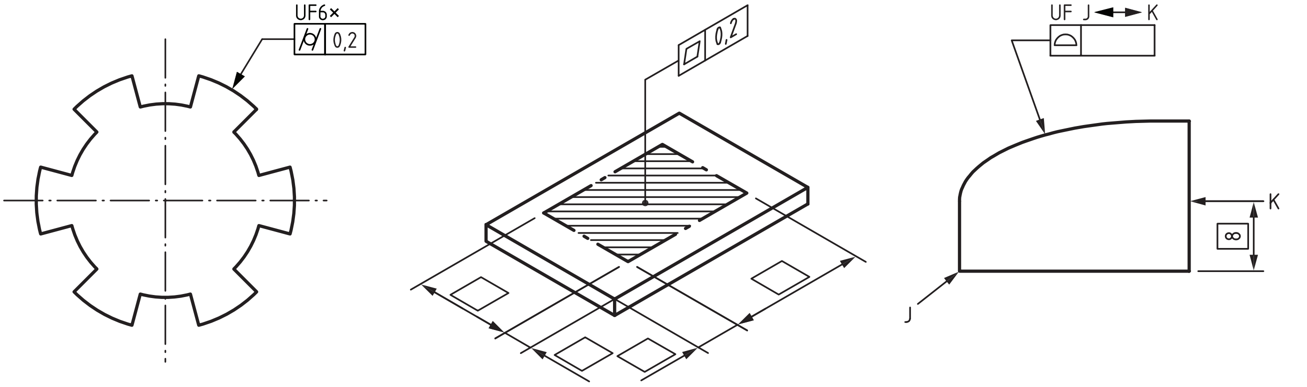


Figure 9 — Calculated curvature from Figure 8 partitioned into single lines

5 Explicit partition

Explicit partition applies in the case of united features, restricted single features and restricted compound features. See Figure 10.

All explicit partitions start with the default partition.



a) United feature b) Restricted single feature c) Restricted compound feature

NOTE Source: ISO 1101:2017, Figures 48, 57 and 60.

Figure 10 — Example of explicit partition

Annex A
(informative)

Additional information about curvature

A.1 Discrete curvature

A.1.1 General

The classic theory of curvature concerns smooth curves and surfaces. Discrete curvature occurs on discrete curves and surfaces, i.e. an ordered or unordered set of points sampling a curve or a surface. The study of discrete curvature is developed within the field of discrete differential geometry (DDG) that studies discrete analogues of smooth geometric objects and aims to develop discrete equivalents to the geometrical notions of normal and curvature.

The following is an incomplete list of major methods that can be used to compute discrete curvatures. Inclusion in this annex does not mean that the method is endorsed, nor does non-inclusion mean that it is not endorsed. They are included for information purposes only, to show that methods to compute discrete curvatures exist.

Two major approaches have been developed: fitting (reconstruction) methods and discrete methods. Fitting methods require the local reconstruction of a smooth curve or a surface in the vicinity of the considered point and the evaluation of the differential parameters at the surface point. Discrete methods use mesh-based representation to define a neighbourhood at the considered point and proceed by discretization of continuous operators or by development of discrete analogues to these operators.

A.1.2 Discrete normal vector

In the neighbourhood of a vertex, the unit vertex normal is computed as the weighted sum of the normal vectors to the triangle facets, as in Formula (A.1):

$$n(x)=\frac{\sum_{j=1}^{k}\alpha_j n_j}{\left\|\sum_{j=1}^{k}\alpha_j n_j\right\|} \tag{A.1}$$

where

- $n(x)$ is the unit normal vector of the vertex;
- α_j is the weight (e.g. the area of the triangle facet);
- n_j is the unit normal vector of all adjacent triangle facets;
- k is the number of neighbour triangle facets of the vertex (one-ring neighbours), see Figure A.1.

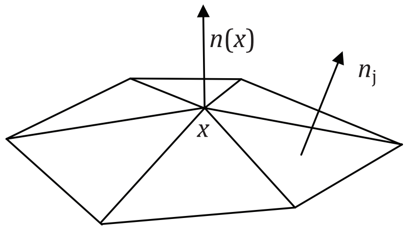


Figure A.1 — Discrete normal vector of vertex *x*

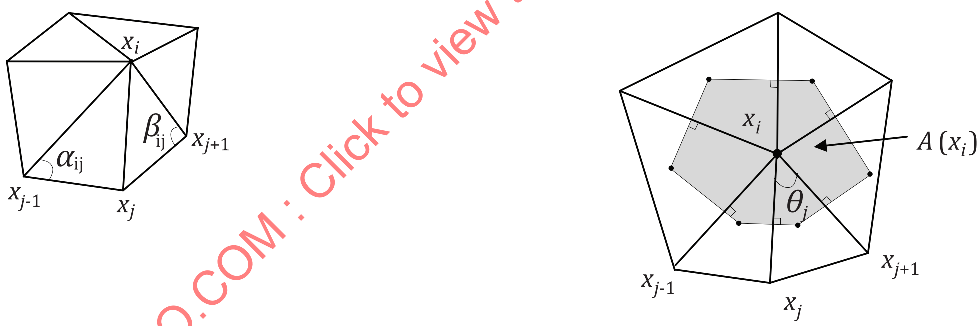
A.1.3 Discrete curvatures using discrete Laplace-Beltrami operator

Considering the triangular surface, the discretization of Laplace-Beltrami operator Δ is defined according to Formula (A.2):

$$\Delta(x_i) = \frac{1}{2A(x_i)} \sum_{j=1}^{k} \left(\cot \alpha_{ij} + \cot \beta_{ij}\right)\left(x_i - x_j\right) \tag{A.2}$$

where

$A(x_i)$	is a finite-area region on a triangulated surface based on Voronoi cells;
α_{ij} and β_{ij}	are the two angles opposite to the edge in the two triangles sharing the edge (x_i, x_j);
k	is the number of the neighbour triangle facets of the vertex, as depicted in Figure A.2.



a) One-ring neighbours of vertex **b) Area of vertex**

Figure A.2 — Angles and edges on a discrete surface

The mean curvature and Gaussian curvature, $H(x_i)$ and $K(x_i)$, are defined according to Formulae (A.3) and (A.4), respectively:

$$H(x_i) = \frac{1}{2}\left\|\Delta(x_i)\right\| \tag{A.3}$$

$$K(x_i) = \left(2\pi - \sum_{j=1}^{k} \theta_j\right) / A(x_i) \tag{A.4}$$

where θ_j is the interior angle of the neighbour triangle facet.

The principal curvatures of the vertex, k_{max} and k_{min}, are defined according to Formulae (A.5) and (A.6):

$$k_{max}(x_i) = H(x_i) + \sqrt{H^2(x_i) - K(x_i)} \tag{A.5}$$

$$k_{min}(x_i) = H(x_i) - \sqrt{H^2(x_i) - K(x_i)} \tag{A.6}$$

A.2 Classification of points based on curvature

Curvature indicators enable the local discrimination of the shape. Indeed, their values and signs allow a consistent classification of point on surfaces which are invariant to rigid transformations. Points can be classified, for example, based on the signs of the Gaussian curvature and the mean curvature (*K-H* classification) or the values of the shape index and the curvedness (*s-c* classification). See Figures A.3 and A.4.

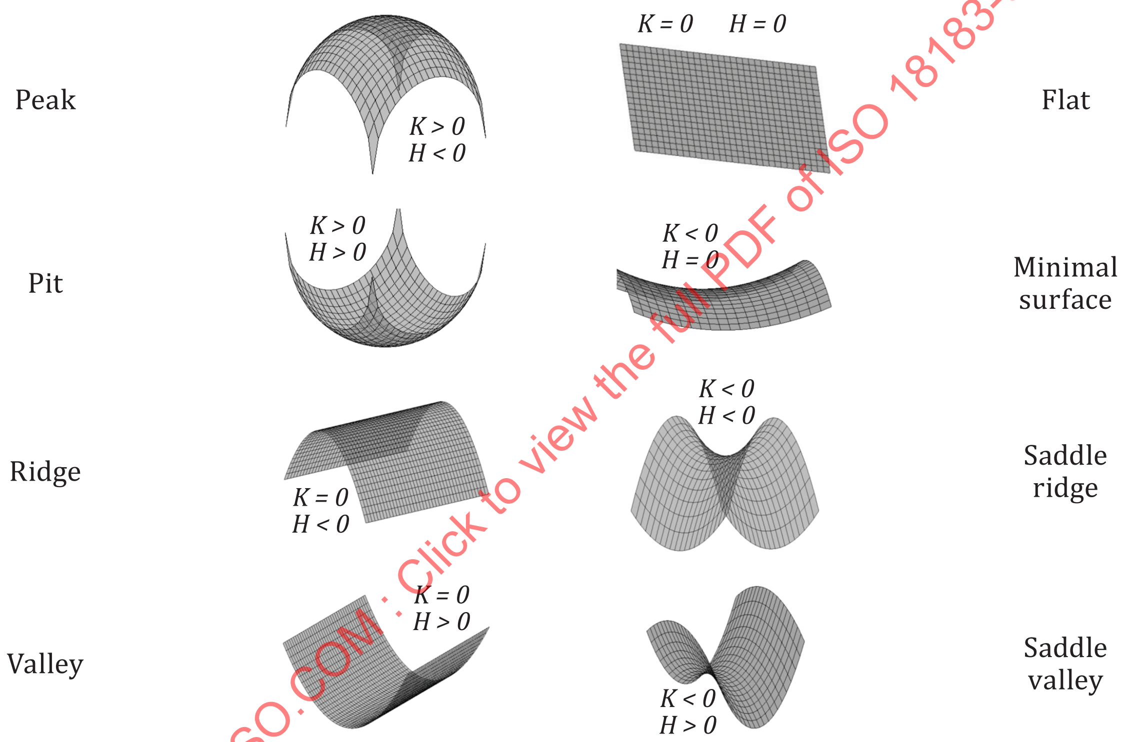


Figure A.3 — Example of *K-H* classification

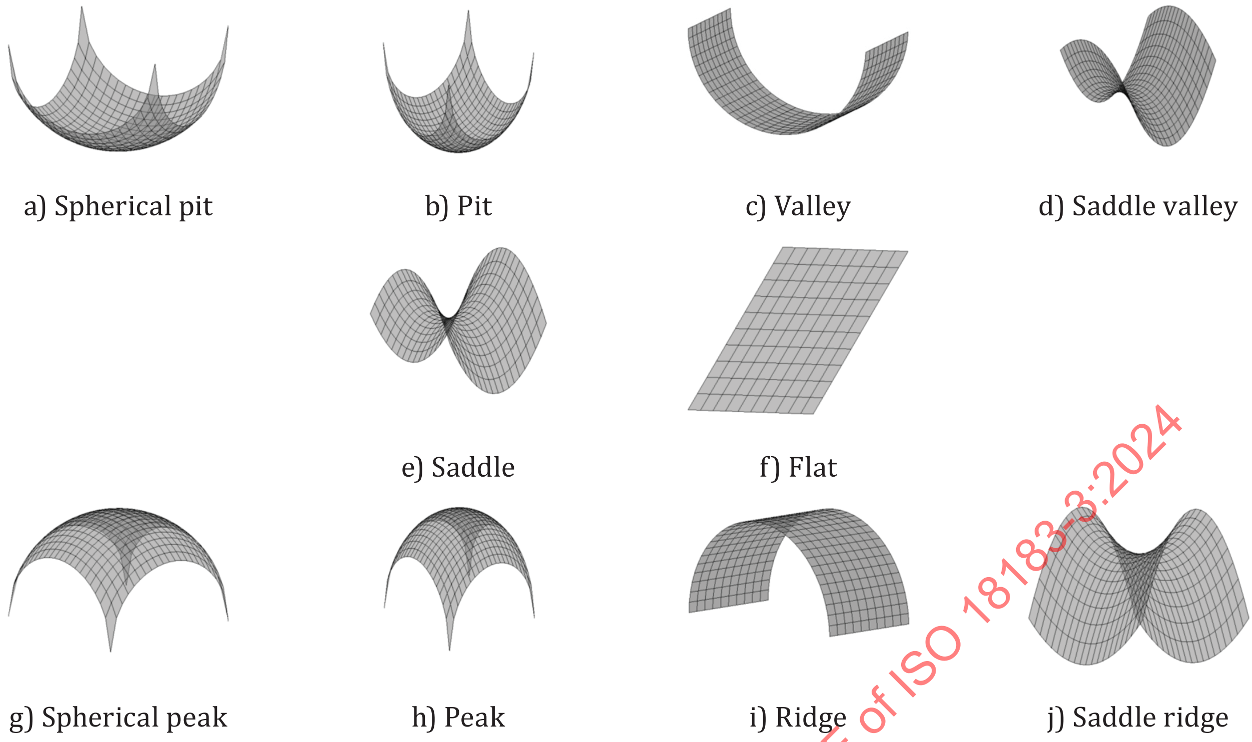


Figure A.4 — Example of *s-c* classification

Annex B
(informative)

Implementations for the default partition

B.1 General

The following is an incomplete list of methods that can be used to implement the default partition on discrete surfaces (obtained from the skin model by an extraction) or sampled surfaces (obtained from the real workpiece model by a physical extraction). Both surface models are described by an ordered or unordered set of points. In many situations, a reconstruction phase is needed to create the underlying topology based on triangular meshes.

Inclusion in this annex does not mean that the method is endorsed, nor does non-inclusion mean that it is not endorsed. They are included for information purposes only, to show that methods claiming to implement the default partition exist. Implementation for the default partition applies to both discrete surfaces and sampled surfaces.

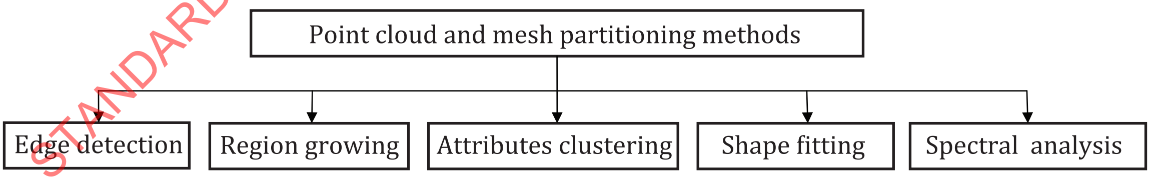
B.2 Classification of partitioning methods

B.2.1 General

Several methodological frameworks have been developed to address the underlying problem of partitioning point clouds and meshes into homogeneous regions based on different criteria.[6][7][8] Existing partitioning methods can be classified into five main categories, as shown in Figure B.1.

All the following methods operate on points from discrete features and real points from real surfaces. There are bottom-up methods, where small surface portions are merged into successively larger surface portions, and top-down methods, where the surface is divided into successively smaller surface portions that can be used to partition a workpiece into single surfaces.

The invariance class-based methods (Stanford and Vienna methods) could provide an initial default partition enhanced by curvature-based methods (Cachan method) and a deterministic evaluation of intrinsic and relational parameters, for the Turin method. The latter provides a probabilistic description of all the features, which is important in the verification phase. Hence, a hybrid partitioning method is more suitable for default partition.



NOTE Source: Reference [20].

Figure B.1 — Classification of point cloud and mesh partitioning methods

B.2.2 Edge detection

Edges are usually defined by points where the curvature changes rapidly to exceed a given threshold. The partition is then realized by detecting the edges to mark the boundaries of different regions and then grouping points inside the boundaries. Partitioning methods by edge detection[9] are known to get inaccurate results in the case of noise and irregular density of point clouds.

B.2.3 Region growing

Partition by region growing is achieved by decomposing a point cloud or a mesh into regions that share similar properties, such as normal and curvature.[10] The growing process is repeated until a set of termination or growing criteria is satisfied, and then different regions characterized by dissimilarity are obtained. There are two major categories of region growing methods: a) seeded-region (or bottom-up) methods and b) unseeded-region (or top-down) methods.

The performance of seeded-region methods is highly dependent on the selection of seed points. Inaccurate selection of seed points will cause under- or over- partition. Moreover, the partition results can be sensitive to the selected threshold. The main difficulty of unseeded-region methods lies in deciding where and when to subdivide the regions. This requires a lot of previous knowledge, such as object models and the number of regions.

B.2.4 Attribute clustering

The core of attribute-clustering methods[11] is to address the attributes for each point based on the geometric characteristics and then calculate the distance of each node to the specific region. The attributes commonly used in point cloud and mesh processing include curvature, convexity, normal and slippage.

Thereafter, the points are clustered into segmented regions by comparing their attributes. The points belonging to each cluster have similar attributes and are labelled as a unique region. The most important factor that determines the segmentation results is the criterion function used for clustering. The attribute-clustering method can be further divided into iterative clustering and hierarchical clustering according to the clustering process.

Since attributes of individual points are usually described using points in a local neighbourhood, this partitioning method is also sensitive to the noise and the definition of the neighbourhood.

B.2.5 Shape fitting

Shape-fitting methods fit primitive shapes, such as planes, spheres, cylinders, cones and tori, to point clouds. Points belonging to the same primitive shape are labelled as one partitioned region. Shape-fitting methods can partition points into primitive shapes,[12] which belong to the invariance classes. However, it is difficult to determine the initial minimal point sets, and sometimes the computational task is intense if no further optimization is applied. In addition, these methods cannot deal with surfaces which are not primitive shapes.

B.2.6 Spectral analysis

Spectral graph theory can be used to state the relationship between the combinational characteristics of a graph and the algebraic properties of its Laplacian. Spectral analysis methods[13] try to use the eigenvalues and eigenvectors of a properly structured square matrix, which is informative of local geometric attributes of a mesh. The spectral analysis method shows its ability to segment objects regarding deformation. However, three issues should be considered: the selection of the type of Laplacian or the Laplacian-Beltrami operator, the weighting scheme and the clustering technique.

B.3 Invariance class-based partitioning methods

B.3.1 Stanford method

The Stanford approach[14] uses the concept of slippable motion to partition a real surface. Local slippage motion signatures (local set of possible invariant displacements) are calculated at each small portion of the surface and iteratively combining portions (bottom-up approach) with matching slippable signatures (if below a predefined threshold). When no combination is possible (to within the predefined threshold), the resulting surface patches are the real surface partition.

B.3.2 Turin method

The Turin method[15] formulates a semi-parametric probabilistic model for each of the seven invariance classes. Given a set of points sampled from a real surface, the Turin method reconstructs all the seven different probability density functions (PDFs, one for each model) and then compares these PDFs on the basis of their likelihood value to identify the most probable class of symmetry for the set of points considered.

The Turin method can be used as a bottom-up or a top-down approach to calculate a partition of the real workpiece:[16]

— In the bottom-up approach, small surface portions, identified as belonging to the same invariance class, are merged into successively larger surface portions.

— In the top-down approach, the real surface is divided into successively smaller surface portions based on a table of possible composition of two surface portions belonging to the seven invariance classes.

All of these algorithms use a threshold value to decide whether the selected set of points belong to one symmetry class or another; currently, there is a lack of enough industrial experience to recommend (a) standardized value(s) for this threshold.

The Turin Group claims that the method requires very few points (and no surface normals) to recognize the classes of symmetry and both intrinsic and relational surface parameters providing a probabilistic description for them. Therefore, the Turin method can have a powerful application for measurements which have a relatively low density of points, for example those obtained by coordinate measuring machines (CMMs).

B.3.3 Vienna method

There exists another method developed by the Vienna Group which is a generalization of the Stanford method.[17] Here, line geometry, calculated from points and surface normals, creates a seven-dimensional space in which, for example, spheres, cylinders, cones, rotational surfaces and helical surfaces are linear subspaces. Hence, surface portions can be classified and segmented from the linear subspace they span in the special seven-dimensional space to create real surface partition.

Like the Stanford method, the Vienna Group claims that the method seems to be very robust only if the sampling density is sufficiently high and the surface normals can be estimated with great precision. Therefore, the Vienna method can have a powerful application for measurements which have a relatively high density of points, for example those obtained by 3D laser scanners.

Invariance class-based methods could provide an initial default partition and a deterministic evaluation of intrinsic and relational parameters for the Turin method. The latter provides a probabilistic description of all the features, which is important in the verification phase.

B.4 Curvature-based partitioning methods

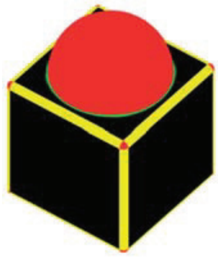
B.4.1 General

The classical discrete curvature estimation methods can be classified into three categories: the discrete differential geometry operators method, the tensor-based method and the surface-fitting method. Curvature-based partition is achieved by identifying and clustering all the points into edges and shape types according to their shape index and curvedness values. Since curvature measures for individual points are usually estimated using vertices in a local neighbourhood, this method is sensitive to measurement noise and neighbourhood selection.

In practice, the curvedness of a vertex at the sharp edge is usually much larger than other vertices. Therefore, it can be identified when the curvedness is larger than a given threshold.

According to the interval of the shape index, the local shape types of the vertices can be classified into nine categories: spherical pit, pit, valley, saddle valley, saddle, spherical peak, peak ridge and saddle ridge. See Figure A.4.

Planar shapes cannot be identified using the shape index. However, curvedness helps to identify planar shapes since the curvedness is equal to zero. In practice, the curvedness cannot be exactly equal to zero, but close to zero. Therefore, the local shape of a vertex can be identified as plane if its curvedness is smaller than a given threshold that is sufficiently small. See Figure B.2.



NOTE Source: Reference [19].

Figure B.2 — Shape type visualization

B.4.2 Cachan method

The Cachan method[18] is based on shape segmentation and comprises four main steps: discrete curvature estimation, boundary identification, vertex clustering and connected region generation (Figures B.3 and B.4).

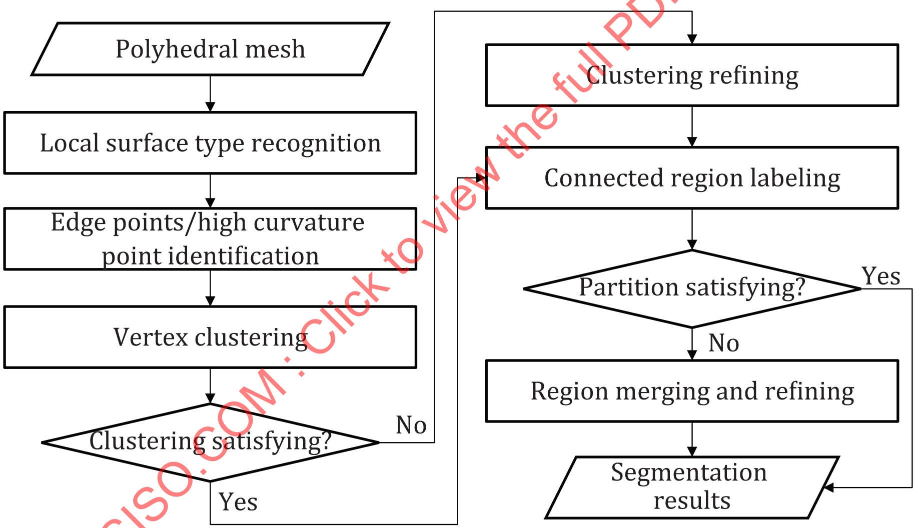
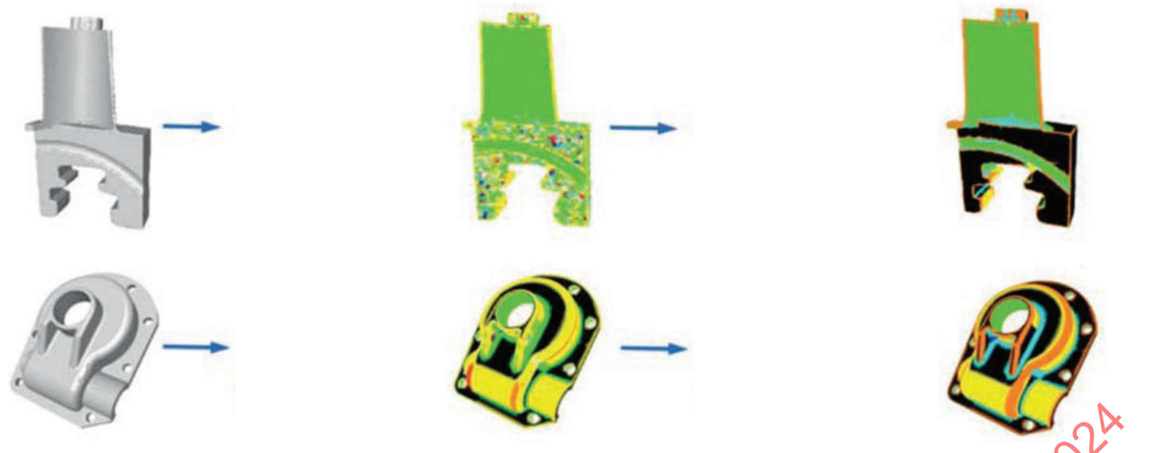


Figure B.3 — Framework of the Cachan partitioning method



a) Point cloud b) Initial clustering c) Cluster refining

NOTE Source: Reference [19].

Figure B.4 — Curvature-based segmentation (Cachan method)

B.5 Hybrid partitioning method

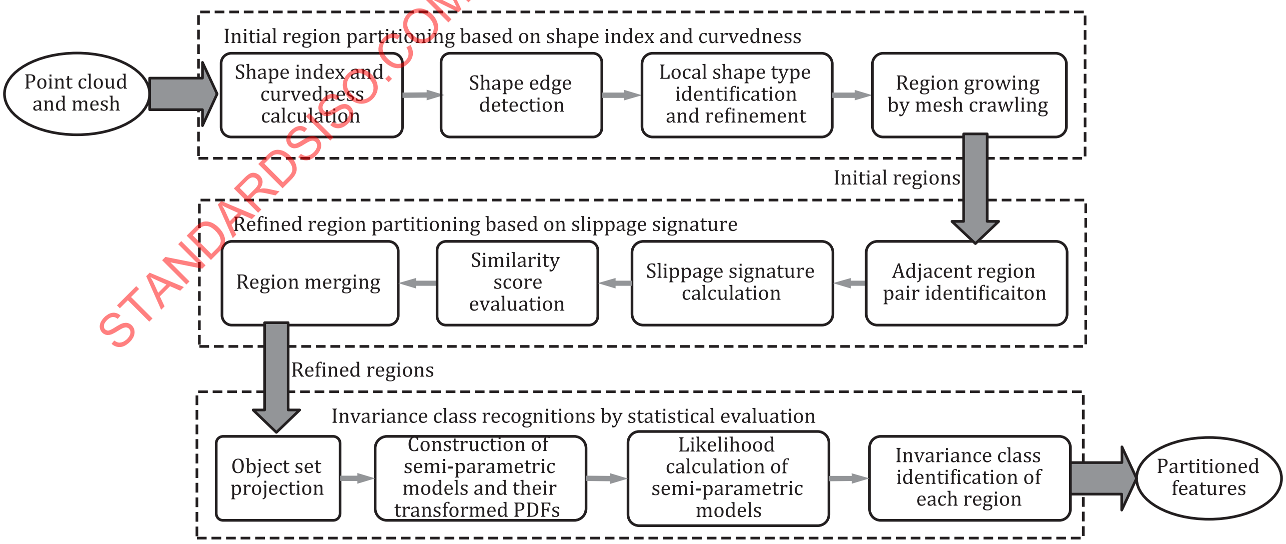
Combining the advantages of the three previous partitioning methods, a hybrid partitioning method[19] is illustrated in Figures B.5, B.6 and B.7. It comprises three main steps:

a) initial region partitioning based on shape index and curvedness;

b) refined region partitioning based on slippage signature;

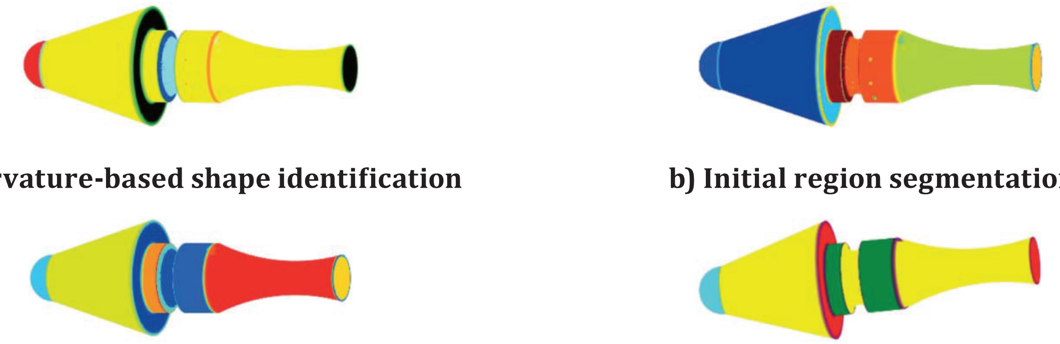
c) invariance class recognition by statistical evaluation.

The initial regions obtained by curvature-based partitioning belong to the defined sharp edge and the 10 local shape types, see Figure A.4. However, the 10 local shape types are mainly for visualization purposes. Therefore, the initial obtained regions will be classified into the invariant classes based on slippage analysis.



NOTE Source: Reference [19].

Figure B.5 — Framework of the hybrid partitioning method



a) Curvature-based shape identification

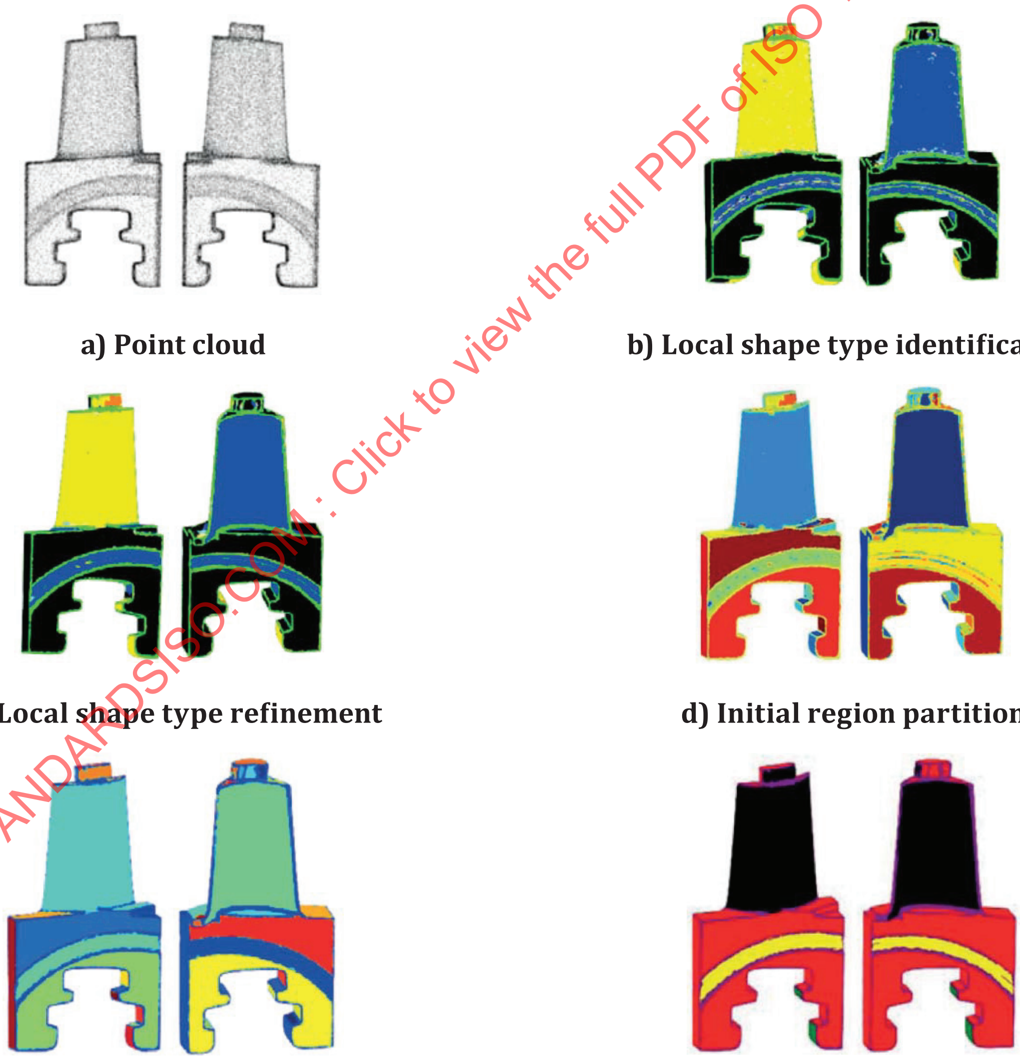
b) Initial region segmentation

c) Slippage signature-based region partition

d) Invariance class partition and recognition

NOTE Source: Reference [19].

Figure B.6 — Partition results for a tessellated (discretized) CAD part



a) Point cloud

b) Local shape type identification

c) Local shape type refinement

d) Initial region partition

e) Slippage signature-based region partition

f) Invariance class recognition

NOTE Source: Reference [19].

Figure B.7 — Partition results for a measured part