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Geometrical product specifications (GPS) — Filtration —

Part 62:
Linear areal filters: spline filters

Spécification géométrique des produits (GPS) — Filtrage —

Partie 62: Filtres surfaciques linéaires: filtres spline

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Foreword

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The procedures used to develop this document and those intended for its further maintenance are described in the ISO/IEC Directives, Part 1. In particular, the different approval criteria needed for the different types of ISO documents should be noted. This document was drafted in accordance with the editorial rules of the ISO/IEC Directives, Part 2 (see www.iso.org/directives).

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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 16610 series can be found on the ISO website.

Any feedback or questions on this document should be directed to the user's national standards body. A complete listing of these bodies can be found at www.iso.org/members.html.

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 link C on feature properties 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 information on the relationship of this document to the filtration matrix model, see Annex A.

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

This document specifies the terminology and concepts for linear areal spline filters. It specifies how to separate long- and short-wave components of a surface with a global shape retainment.

Geometrical product specifications (GPS) — Filtration —

Part 62:
Linear areal filters: spline filters

1 Scope

This document specifies the characteristics of a linear areal spline filter with a global shape retainment.

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 16610-1, *Geometrical product specifications (GPS) — Filtration — Part 1: Overview and basic concepts*

ISO 16610-21, *Geometrical product specifications (GPS) — Filtration — Part 21: Linear profile filters: Gaussian filters*

ISO 16610-22:2015, *Geometrical product specifications (GPS) — Filtration — Part 22: Linear profile filters: Spline filters*

ISO 16610-60:2015, *Geometrical product specification (GPS) — Filtration — Part 60: Linear areal filters — Basic concepts*

ISO 16610-61, *Geometrical product specification (GPS) — Filtration — Part 61: Linear areal filters — Gaussian filters*

ISO/IEC Guide 99, *International vocabulary of metrology — Basic and general concepts and associated terms (VIM)*

3 Terms and definitions

For the purposes of this document, the terms and definitions given in ISO 16610-1, ISO 16610-21, ISO 16610-22, ISO 16610-60, ISO 16610-61 and ISO/IEC Guide 99 and the following 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/

3.1
spline
linear combination of piecewise polynomials, with a smooth fit between the pieces

[SOURCE: ISO 16610-22:2015, 3.1, modified — Note 1 to entry removed.]

3.2
spline filter
linear filter based on splines

3.3
linear areal filter
areal filter which separates surfaces into long-wave and short-wave components and is also a linear function

[SOURCE: ISO 16610-60:2015, 3.1, modified — Notes to entry removed.]

3.3.1
linear planar filter
linear areal filter (3.3) which separates planar surfaces into long-wave and short-wave components, which applies to nominal planar surfaces

[SOURCE: ISO 16610-60:2015, 3.1.1, modified — Note 1 to entry removed.]

3.3.2
linear cylindrical filter
linear areal filter (3.3) which separates cylindrical surfaces into long-wave and short-wave components, which applies to nominal cylindrical surfaces

[SOURCE: ISO 16610-60:2015, 3.1.2, modified — Note 1 to entry removed.]

3.4
cut-off wavelength
wavelength of a sinusoidal surface of which 50 % of the amplitude is transmitted by the *linear areal filter* (3.3)

Note 1 to entry: Linear areal filters are identified by the filter type and the cut-off wavelength.

Note 2 to entry: The cut-off value for the spline filter is an example of a nesting index.

Note 3 to entry: The cut-off 50 % value is by convention.

[SOURCE: ISO 16610-60:2015, 3.7, modified — Note 2 to entry revised.]

4 Spline areal filter

4.1 General

The following low-pass filter formula for spline profile filters is based on cubic splines with a regularization parameter depending on the cut-off wavelength for the smoothness of the resultant waviness profile (low-passed signal) and a tension parameter influencing the slope of the transfer function. It is the areal extension of the linear profile spline filter as specified in ISO 16610-22. Two versions of the areal spline filter are specified, one as linear planar filter for open surface areas and another as linear cylindrical filter for closed surface areas, i.e. cylindrical surfaces with periodic continuation.

4.2 Filter formula for cubic spline filter for topography maps on uniformly sampled grids

4.2.1 General

The filter formula is shown in Formula (1):

$$\boldsymbol{w} = \boldsymbol{A}_y \boldsymbol{z} \, \boldsymbol{A}_x^{\mathrm{T}} \tag{1}$$

where

- $\boldsymbol{z}$ is the $n \times m$ -dimensional matrix representing the height map of input data, for example the primary surface of $n \times m$ sampling points;
- $\boldsymbol{w}$ is the $n \times m$ -dimensional matrix representing the height map of output data.

The transformation matrices $\boldsymbol{A}_x$ and $\boldsymbol{A}_y$ are defined by Formula (2) and Formula (3), respectively:

$$\boldsymbol{A}_x = \left(\boldsymbol{E} + \beta\, \alpha_x^2\, \boldsymbol{P} + (1-\beta)\, \alpha_x^4\, \boldsymbol{Q} \right)^{-1} \tag{2}$$

$$\boldsymbol{A}_y = \left(\boldsymbol{E} + \beta\, \alpha_y^2\, \boldsymbol{P} + (1-\beta)\, \alpha_y^4\, \boldsymbol{Q} \right)^{-1} \tag{3}$$

where

- $\boldsymbol{E}$ is the unity matrix;
- $\boldsymbol{P}$ and $\boldsymbol{Q}$ are the matrices for the discretized differentiation;
- β is the tension parameter (4.2.3);
- α_x and α_y are parameters (4.2.2), depending on the smoothness, of the cut-off wavelength of the spline.

For $\boldsymbol{A}_x$, the matrices are all of dimension $m \times m$ according to m sampling points along x-direction; for $\boldsymbol{A}_y$, the dimension of the matrices is $n \times n$ according to n sampling points along y-direction.

4.2.2 Regularization parameter

The parameter μ specifies the regularization, i.e. the degree of smoothing. The regularization parameter is therefore related to the cut-off wavelength, λ_c, for minimum tension by Formula (4) and Formula (5):

$$\mu = \alpha_r^4 \tag{4}$$

$$\alpha_r = \frac{1}{2\sin\left(\dfrac{\pi\, \Delta r}{\lambda_c}\right)} \tag{5}$$

where either $r = x$ or $r = y$, for each of the lateral axes, respectively, i.e with sampling interval $\Delta r = \Delta x$ along the x-direction in the case of $\boldsymbol{A}_x$ and the sampling interval $\Delta r = \Delta y$ along the y-direction in the case of $\boldsymbol{A}_y$, respectively. See Reference [4].

For non-minimum tension of the spline, i.e. for $\beta > 0$, the regularization depends on both tension and cut-off wavelength, as shown in Formula (6):

$$\mu = (1-\beta)\, \alpha_r^4 \tag{6}$$

See Reference [5].

NOTE For sampling intervals $\Delta r \ll \lambda_c$, the regularization parameter tends to infinity, i.e. $\alpha^4 \rightarrow \infty$.

4.2.3 Tension parameter

The product $\beta\alpha^2$ is the tension factor with parameter β lying between 0 and 1. The parameter β controls the degree of following topography curvatures, where with curvature a local property of a curve or a surface is meant, which is defined at every point quantifying second order deviations of a curve from a straight line or a surface from a plane. Following curvatures closely means optimal shape retainment of the low-pass result, the output data $\boldsymbol{w}$. For β = 0, the characteristics of the transfer function conform with ISO 16610-22:2015, Formula (1), a minimum tension which is equivalent to the steepest slope of the transfer function and therefore a better shape retainment than for β > 0. For β = 0,625 242, the characteristics of the transfer function are similar to the Gaussian filter[5] as specified in ISO 16610-21 and ISO 16610-61.

NOTE The shape retainment by the spline filter for β = 0 is global, while the shape retainment by the Gaussian regression with a parabolic regression (p = 2) is local.

4.2.4 Matrices of differentiation *P* and *Q*

4.2.4.1 General

The matrix $\boldsymbol{P}=\left(P_{i,j}\right)$ represents the discretized first derivations, the gradient operations to evaluate slopes. The matrix $\boldsymbol{Q}=\left(Q_{i,j}\right)$ represents the discretized second derivations to evaluate curvatures. The indices $j=1,\ldots,K$ denote the column indices and $i=1,\ldots,K$ the row indices using $K=m$ if used for $\boldsymbol{A}_x$ (filtering in x-direction) and using $K=n$ if used for $\boldsymbol{A}_y$ (filtering in y-direction). The following matrix elements are non-zero and the others are zero.

4.2.4.2 The main diagonals

The main diagonal of matrices $\boldsymbol{P}$ and $\boldsymbol{Q}$ have the following elements:

$P_{i,i}=2$ for $i=2,\ldots,K-1$ and $Q_{i,i}=6$ for $i=3,\ldots,K-2$.

In the case of cylindrical surfaces, these values apply also for $i=1,2,K-1,K$ for $\boldsymbol{A}_x$ if the x-direction lies on a circle being the intersection of the cylinder surface and a plane orthogonal to the cylinder axis and for $\boldsymbol{A}_y$ if the y-direction lies on such a circle.

The main diagonal holds $P_{i,i}=1$ for $i=1,K$, $Q_{i,i}=1$ for $i=1,K$ and $Q_{i,i}=5$ for $i=2,K-1$ in the case of plane surfaces as well as for $\boldsymbol{A}_x$ in the case of a cylindrical surface, if the x-direction lies parallel to the cylinder axis, and for $\boldsymbol{A}_y$ if the y-direction lies parallel to the cylinder axis.

4.2.4.3 The two first-off diagonals

$P_{i,i+1}=P_{i+1,i}=-1$ for $i=1,\ldots,K-1$ and $Q_{i,i+1}=Q_{i+1,i}=-4$ for $i=2,\ldots,K-1$.

In the case of cylindrical surfaces and for $\boldsymbol{A}_x$, if the x-direction lies on a circle being the intersection of the cylinder surface and a plane orthogonal to the cylinder axis and for $\boldsymbol{A}_y$, if the y-direction lies on such a circle, these values are as well filling the matrix elements of all four corners of the matrix:

$P_{1,K}=P_{K,1}=-1$ and $Q_{1,2}=Q_{2,1}=Q_{1,K}=Q_{K,1}=Q_{K,K-1}=Q_{K-1,K}=-4$.

In the case of planar surfaces and of the direction parallel to the cylinder axis, matrix $\boldsymbol{P}$ is tri-diagonal with

$P_{1,K}=P_{K,1}=0$ and $Q_{1,2}=Q_{2,1}=-2$ and $Q_{1,K}=Q_{K,1}=0$ and $Q_{K,K-1}=Q_{K-1,K}=-2$.