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Geometrical product specification (GPS) — Filtration —

Part 60:
Linear areal filters — Basic concepts

Spécification géométrique des produits (GPS) — Filtrage —

Partie 60: Filtres surfaciques linéaires — Concepts de base

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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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For an explanation on the meaning of ISO specific terms and expressions related to conformity assessment, as well as information about ISO's adherence to the WTO principles in the Technical Barriers to Trade (TBT) see the following URL: Foreword - Supplementary information

The committee responsible for this document is ISO/TC 213, *Dimensional and geometrical product specifications and verification*.

ISO 16610 consists of the following parts, under the general title *Geometrical product specifications (GPS) — Filtration*:

— *Part 1: Overview and basic concepts*

— *Part 20: Linear profile filters: Basic concepts*

— *Part 21: Linear profile filters: Gaussian filters*

— *Part 22: Linear profile filters: Spline filters*

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— *Part 41: Morphological profile filters: Disk and horizontal line-segment filters*

— *Part 49: Morphological profile filters: Scale space techniques*

— *Part 60: Linear areal filters: Basic concepts*

— *Part 61: Linear areal filters: Gaussian filters*

— *Part 71: Robust areal filters: Gaussian regression filters*

— *Part 85: Morphological areal filters: Segmentation*

The following parts are planned:

— *Part 26: Linear profile filters: Filtration on nominally orthogonal grid planar data sets*

— *Part 27: Linear profile filters: Filtration on nominally orthogonal grid cylindrical data sets*

— *Part 45: Morphological profile filters: Segmentation*

— *Part 62: Linear areal filters: Spline filters*

— *Part 69: Linear areal filters: Spline wavelets*

— *Part 70: Robust areal filters: Basic concepts*

— *Part 72: Robust areal filters: Spline filters*

— *Part 80: Morphological areal filters: Basic concepts*

— *Part 81: Morphological areal filters: Sphere and horizontal planar segment filters*

— *Part 89: Morphological areal filters: Scale space techniques*

Introduction

This part of ISO 16610 is a geometrical product specification (GPS) standard and is to be regarded as a general GPS standard (see ISO 14638). It influences chain links C and F of all chains of standards.

The ISO/GPS Matrix model given in ISO 14638 gives an overview of the ISO/GPS system of which this part of ISO 16610 is a part. The fundamental rules of ISO/GPS given in ISO 8015 apply to this part of ISO 16610 and the default decision rules given in ISO 14253-1 apply to specifications made in accordance with this part of ISO 16610, unless otherwise indicated.

For more detailed information about the relation of this part of ISO 16610 to the GPS matrix model, see Annex C.

This part of ISO 16610 develops the basic concepts of linear areal filters, which include Gaussian filter, Spline filters, and Wavelet filters.

Geometrical product specification (GPS) — Filtration —

Part 60:
Linear areal filters — Basic concepts

1 Scope

This part of ISO 16610 sets out the basic concepts of linear areal filters.

2 Normative references

The following documents, in whole or in part, are normatively referenced in this document and are indispensable for its application. 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 16610-20, *Geometrical product specifications (GPS) — Filtration — Part 20: Linear profile filters: Basic concepts*

ISO 16610-21:2011, *Geometrical product specifications (GPS) — Filtration — Part 21: Linear profile filters: Gaussian filters*

ISO/IEC Guide 99:2007, *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 16610-20, ISO 16610-21, ISO/IEC Guide 99, and the following apply.

3.1
linear areal filter
areal filter which separates surfaces into long wave and short wave components and is also a linear function

Note 1 to entry: If F is a function and X and Y are surfaces then F is a linear function implies F(aX + bY) = aF(X) + bF(Y).

Note 2 to entry: A linear areal filter is for surfaces in a specified coordinate system, for example, planar and cylindrical.

Note 3 to entry: Linear areal filter examples include Gaussian, spline, spline wavelet, and complex wavelet.

3.1.1
linear planar filter
linear areal filter (3.1) which separates planar surfaces into long wave and short wave components, which applies to nominal planar surfaces

Note 1 to entry: A planar surface is open in all directions.

3.1.2
linear cylindrical filter
linear areal filter (3.1) which separates cylindrical surfaces into long wave and short wave components, which applies to nominal cylindrical surface

Note 1 to entry: A cylindrical surface is open in the axial direction and closed in the circumferential direction.

3.2
phase correct areal filter
linear areal filter (3.1) which does not cause phase shifts leading to asymmetrical surface distortions

Note 1 to entry: Phase correct filters are a particular kind of linear phase filters because any linear phase filter can be transformed (simply by shifting its weighting function) to a zero phase filter, which is a phase correct filter.

3.3
mean surface
long wave surface component determined from the surface by application of an areal filter

3.4
weighting function
function for calculating the mean surface, which indicates for each point the weight attached by the surface in the vicinity of that point

3.5
filter equation
equation for the mathematical description of the filter

Note 1 to entry: Filter equations do not necessarily specify an algorithm for the numerical realization of the filter.

[SOURCE: ISO 16610-1:2015, 3.10]

3.6
transmission characteristic of an areal filter
characteristic that indicates the amount by which the amplitude of a sinusoidal surface is attenuated as a function of its wavelengths

Note 1 to entry: The transmission characteristic is the Fourier transformation of the weighting function.

3.7
cut-off wavelength (nesting index)
wavelength of a sinusoidal surface of which 50 % of the amplitude is transmitted by the *linear areal filter* (3.1)

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 linear areal filter is an example of a nesting index.

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

3.8
filter bank
set of high-pass and low-pass filters, arranged in a specified structure

[SOURCE: ISO 16610-20:2015, 3.6]

3.9
multiresolution analysis
decomposition of a surface by a *filter bank* (3.8) into portions of different scales

Note 1 to entry: The portions at different scales are also referred to as resolutions.

[SOURCE: ISO 16610-20:2015, 3.7]

4 Basic concepts

4.1 General

A filter claiming to comply with this part of ISO 16610 shall exhibit the characteristics described in 4.1, 4.2, 4.3, and 4.4.

NOTE A concept diagram for linear areal filters is given in Annex A. The relationship to the filtration matrix model is given in Annex B.

The most general linear areal filter is defined by Formula (1):

$$w(x,y)=\iint K(x,y;\mu,\upsilon)z(\mu,\upsilon)d\mu d\upsilon \tag{1}$$

where

$z\ (\mu,\upsilon)$ is the unfiltered surface;

$w\ (x,y)$ is the filtered surface;

$K\ (x, y{:}\ \mu, \upsilon)$ is the kernel of the filter, which is real, symmetric, and spatial invariant.

If $K(x,y;\mu,\upsilon)=K(x-\mu,y-\upsilon)$, the filtering is a convolution,

$$w(x,y)=\iint K(x-\mu,y-\upsilon)z(\mu,\upsilon)d\mu d\upsilon \tag{2}$$

and the kernel is also called the weighting function of the filter.

However, extracted data are always discrete. Therefore, the filters described here are also discrete. In cases that the weighting function is not discrete, the discrete nature of the extracted data shall be taken into account (see 4.3).

NOTE An alternative approach is to use a unique interpolation scheme on the discrete extracted data to create a continuous signal (with finite degrees of freedom) and use this as input to subsequent filtration operations.

4.2 Separable weighting functions

If the weighting function is separable, i.e. it can be written as a tensor product of profile filter weighting functions

$$K(x,y)=u(x)v(y) \tag{3}$$

the convolution is also a tensor product:

$$w(x,y)=\int u(x-\mu)\left[\int v(y-\upsilon)z(\mu,\upsilon)d\upsilon\right]d\mu \tag{4}$$

i.e. the convolution is separable, too. Thus, the convolution can be calculated in a two-step process, using profile filters instead of areal filters:

$$g(x,y)=\int v(y-\upsilon)z(x,\upsilon)d\upsilon \tag{5}$$

and

$$w(x,y)=\int u(x-\mu)g(\mu,y)d\mu \tag{6}$$

4.3 Discrete representation of data

A sampled surface can be represented by an $n \times m$ matrix of heights, Z. The length n of the row vectors and the length m of the column vectors are equal to the number of data points in x and y directions respectively. The sampling is assumed to be uniform in x and y direction, i.e. the sampling interval Δ is constant in x and y direction. Thus the matrix element of the row i and the column j is given by $z_{ij} = z(x_i, y_j)$, with $x_i = i\Delta$ $(i = 1 \ldots n)$ and $y_j = j\Delta$ $(j = 1 \ldots m)$.

4.4 Discrete representation of the linear areal filter

A discrete linear areal filter is represented by an array *H*, which is the tensor product of two matrices *U* and *V*, provided the filter has a separable kernel, i.e.

$$H = U \otimes V \qquad h_{irjs} = u_{ir} v_{js} \tag{7}$$

is valid. The matrices *U* and *V* are both square matrices, with the dimension being equal to the number of data points to be filtered along the respective direction, i.e. if the input data are given by an $n \times m$ matrix, *U* is an $n \times n$ matrix and *V* is an $m \times m$ matrix.

Three types of areal filters are possible, depending on the periodicity of the filter in both directions. If the filter is periodic in both directions, the areal filter is called a periodic areal filter; if it is non-periodic in both directions, the surface filter is called a non-periodic areal filter; if it is periodic in only one direction, the areal filter is called a semi-periodic areal filter.

NOTE Non-periodic areal filters are used for open surfaces, for example, planar surfaces, periodic areal filters are used for closed surfaces, for nominal example, toroidal surfaces, and semi-periodic areal filters are used for semi-closed surfaces, for example, cylindrical surfaces.

If the filter is non-periodic along the respective direction, the corresponding matrix is a constant diagonal (Toeplitz) matrix

$$\begin{pmatrix} \ddots & \ddots & \ddots & \ddots & \ddots & & & & \\ & c' & b' & a & b & c & & & \\ & & c' & b' & a & b & c & & \\ & & & c' & b' & a & b & c & \\ & & & & \ddots & \ddots & \ddots & \ddots & \ddots \end{pmatrix} \tag{8}$$

otherwise, if the filter is periodic along the respective direction, the corresponding matrix is a circulant matrix

$$\begin{pmatrix} a & b & c & \cdots & \cdots & c' & b' \\ b' & a & b & c & \cdots & \cdots & c' \\ c' & b' & a & b & c & \cdots & \cdots \\ & \ddots & \ddots & \ddots & \ddots & \ddots & \\ & \cdots & c' & b' & a & b & c \\ c & \cdots & \cdots & c' & b' & a & b \\ b & c & \cdots & \cdots & c' & b' & a \end{pmatrix} \tag{9}$$

If the filter is phase correct, the matrices representing the filter are both symmetrical, i.e. $b = b'$, $c = c'$,... (generally $a_{ij} = a_{ji}$) is valid.

The sum of the matrix elements a_{ij} of each row *i* is constant and for low-pass filters equals unity, i.e.

$$\sum_j a_{ij} = 1 \tag{10}$$

NOTE In case of a symmetrical matrix, the sum of the matrix elements a_{ij} of each column *j* is also constant and equals unity, i.e. $\sum_i a_{ij} = 1$ is also valid.

4.5 Discrete representation of the weighting function

As each row of the matrices used in the tensor product representation of the filter is identical after being shifted accordingly, the matrix elements can be represented by only one row. Thus one has

$$u_{ir} = f_k \text{ with } k = i - r \tag{11}$$

and

$$v_{js} = g_l \text{ with } l = j - s \tag{12}$$

yielding the tensor product

$$h_{irjs} = u_{ir} v_{js} = f_k g_l = h_{kl} \text{ with } k = i - r \text{ and } l = j - s \tag{13}$$

The values h_{kl} form a matrix h of a dimension equal to the dimension of the input or output data matrix, respectively. This matrix is the discrete representation of the weighting function of the filter.

NOTE 1 Normally, the definition area of the weighting function is much smaller than the area of the data sets. Then h contains zeros outside the definition area of the weighting function.

EXAMPLE 1 The moving average areal filter is frequently used for easy smoothing of a data set (not necessarily an optimal method and used here as an illustration only). This is an example of a filter with a discrete weighting function. This weighting function (a length of 3 has been taken in each direction) is given by

$$\frac{1}{9}\begin{pmatrix} \ddots & \vdots & \vdots & \vdots & \vdots & \vdots & \\ \cdots & 0 & 0 & 0 & 0 & 0 & \cdots \\ \cdots & 0 & 1 & 1 & 1 & 0 & \cdots \\ \cdots & 0 & 1 & 1 & 1 & 0 & \cdots \\ \cdots & 0 & 1 & 1 & 1 & 0 & \cdots \\ \cdots & 0 & 0 & 0 & 0 & 0 & \cdots \\ & \vdots & \vdots & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \tag{14}$$

NOTE 2 The weighting function is often also called the impulse response function because it is the output data set of the filter if the input data set is only a single unity impulse.

$$\begin{pmatrix} \ddots & \vdots & \vdots & \vdots & \\ \cdots & 0 & 0 & 0 & \cdots \\ \cdots & 0 & 1 & 0 & \cdots \\ \cdots & 0 & 0 & 0 & \cdots \\ & \vdots & \vdots & \vdots & \ddots \end{pmatrix} \tag{15}$$

If the weighting function is given as a continuous function, it should be sampled, in order to get a discrete data set. The sampling intervals used shall be equal to the sampling interval of the measured data. Subsequently, it is mandatory to re-normalize the sampled data of the weighting function in order to fulfil the condition that they shall sum to unity, thus avoiding bias effects (for details concerning bias effects, see Reference [3]).

EXAMPLE 2 The Gaussian filter according to ISO 16610-21 is an example of a continuous weighting function $s(x)$ defined by Formula (16):