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To cite this article: F Marinello and A Pezzuolo 2019 *IOP Conf. Ser.: Earth Environ. Sci.* **275** 012011

IOP Conf. Series: Earth and Environmental Science **275** (2019) 012011 doi:10.1088/1755-1315/275/1/012011

Application of ISO 25178 standard for multiscale 3D parametric assessment of surface topographies

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Abstract. The objective of the present work is to discuss the potential of areal surface texture parameters as introduced and discussed by ISO standards 25178, as a widely recognized reference framework of indices and procedures, which can help and accelerate understanding of functional information. Such indices have been developed specifically for the micro-scale, however they can be successfully implemented also in the case of larger scales. Parameters extraction takes place in three main steps, independently from the scale: calibration, filtering and parameter extraction. The possibility of using the same approach and the same roughness parameters at different scales helps very much not only the post processing of surfaces data sets but also their interpretation, putting the basis for multiscale models.

1. Introduction

In the last couple of decades, the growing availability of sensors and instruments installed in laboratories or in the field (at ground level or on board of drones, airplanes or satellites) has greatly increased the amount of available data. In all of the cases, surface roughness is often addressed as a key parameter, useful to characterize processes (at the micro-scale), determine shapes (at the meso-scale) and identify landforms (at the macro-scale).

By way of example, roughness parameters have been used in order to delimit landslides [1], identify road networks [2], characterize animal body surface features [3, 4], analyse small devices functionality [5] or study nanostructured food packaging [6].

A number of different instruments has been developed in order to allow quantitative characterization of surface topographies at different scales. Such techniques are typically relying on optical non contact methods, which guarantee minimization of scanning times and of interaction forces with the measurand, and include LiDAR, diffraction, fringe projection, triangulation, interferometry, confocal etc [7-9]. In all of the cases, instrumentation collects local elevation on a vertical z-axis (as digital elevation models, DEM) producing an array of points regularly organized in the horizontal x-y plane. Despite a variety of terminology has been applied (ruggedness, rugosity, microrelief or microtopography), surface roughness is the generic term which identifies and characterizes topographies [10].

Data are very often structured in the form of maps with vertical elevation or some different functional information reproduced as pixels with constant resolution and spacing. Such maps are undoubtedly increasing the level of knowledge of different processes in agricultural or forestry fields, but, on the other hand, might cause growing difficulties and efforts, especially during data post processing. For this reason, parametrization is a fundamental step, which can help exploiting the content of information brought by revealed data. Through parametrization, big amounts of data can be summarized in a few numbers which accelerate understandability and in general decision making processes.

The main objective of the present work is to discuss the potential of areal surface texture parameters as introduced and discussed by ISO standards 25178 [11], as a widely recognized reference framework of indices and procedures which can help and accelerate understanding of functional information. ISO 25178 has been developed by the technical committee TC 213 (working group WG 16) for all areal surface topography measuring instruments regardless of their design or operation. Such indices have been developed specifically for the micro-scale, however they can be successfully implemented also in the case of larger scales. The possibility of using the same approach and the same roughness parameters at different scales helps very much not only the post processing of surfaces data sets but also their interpretation, putting the basis for multiscale models.

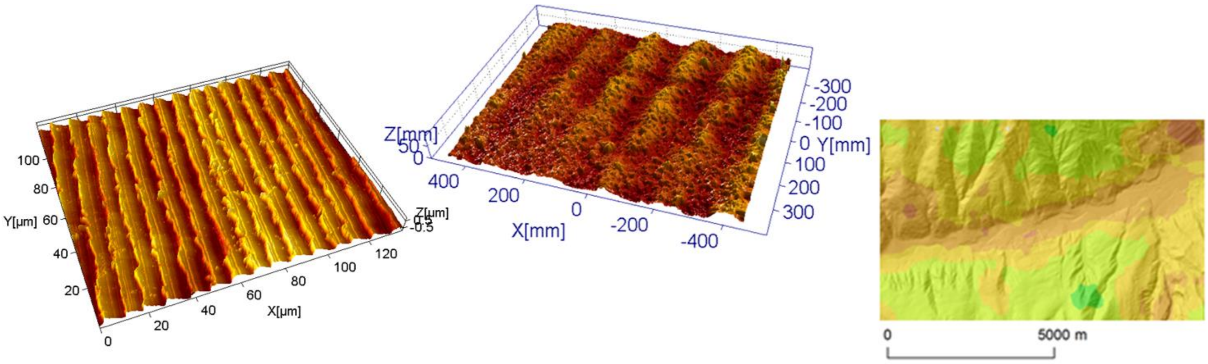

Figure 1. Three examples of topographies at three different scales: a micromilled surface in a 130×110µm range, a harrowed soil portion in a 900×700mm and a valley topography in a 9000×6000m.

2. Approach description

2.1. Data processing procedure

The extraction of quantitative parameters can take place according to the following three main steps, which are independent from the scale, and can be in general applied for post-processing of surface topographies:

1) calibration, to eliminate systematic distortions and give metrological traceability to measured data
2) three-dimensional filtering, as a needed set of operations allowing elimination of distortions (caused by the measurement process) and exploiting repeatability in the subsequent extraction of indices
3) extraction of different roughness parameters, including: height parameters (root mean square roughness, kurtosis, skewness,…), function related parameters (material ratio, volume,…), hybrid parameters (interfacial area ratio, root mean square gradient,…), spatial parameters (autocorrelation functions, texture direction,…).

A graphical representation of the three main operations following data acquisition is proposed in the following flow chart (Figure 2).

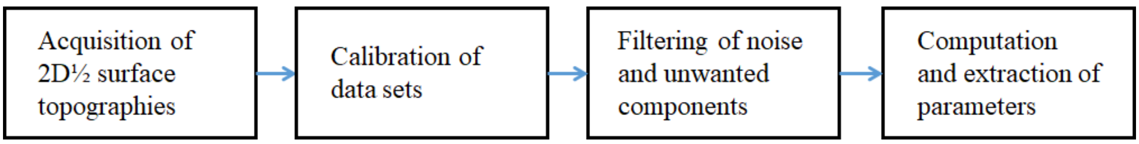

Figure 2. Flow chart of the proposed data processing approach

2.2. Calibration

In this paragraph a complete geometrical model for calibration of data sets is presented, adapted from [12]. In order to better clarify the model, basic assumptions are here briefly given. Let $i = 1, \dots, m$, and $j = 1, \dots, n$ be indices of the scanned pixels in a matricial representation, and x_i', y_j' and z' the corresponding lateral and vertical positions in a reference *x-y-z* space.
The apostrophe ' indicates that the measuring coordinate axes of the optical instrument are taken as reference coordinate system. Also it is assumed that the transfer function from the uncorrected z-coordinate $z'(x',y')$ to the actual coordinate $z(x',y')$ is single valued: as a consequence each measured position (x',y') corresponds to exactly one corrected value.
Under such condition, the following model based on the McLaurin series, evaluated in $(0,0,0)$ can be introduced to describe and calibrate surface topography data sets,:

$$x(x',y',z') = \sum_{n_{x'}=0}^{\infty}\sum_{n_{y'}=0}^{\infty}\sum_{n_{z'}=0}^{\infty} \frac{\partial^{n_{x'}} x}{\partial x'^{n_{x'}}}\frac{\partial^{n_{y'}} x}{\partial y'^{n_{y'}}}\frac{\partial^{n_{z'}} x}{\partial z'^{n_{z'}}}\frac{x'^{n_{x'}} y'^{n_{y'}} z'^{n_{z'}}}{n_{x'}!n_{y'}!n_{z'}!}$$

Approximating the series to the third order, and introducing the Peano residual term σ to include higher order infinitesimals, the following expression can be written:

$$x(x',y',z') = \frac{\partial x}{\partial x'}x' + \frac{\partial x}{\partial y'}y' + \frac{\partial x}{\partial z'}z' + \frac{\partial^2 x}{\partial x'^2}\frac{x'^2}{2} + \frac{\partial^2 x}{\partial y'^2}\frac{y'^2}{2} + \frac{\partial^2 x}{\partial z'^2}\frac{z'^2}{2} + \frac{\partial^2 x}{\partial x'\partial y'}\frac{x'y'}{2} + \frac{\partial^2 x}{\partial x'\partial z'}\frac{x'z'}{2} + \frac{\partial^2 x}{\partial y'\partial z'}\frac{y'z'}{2} + \frac{\partial^3 x}{\partial x'^3}\frac{x'^3}{6} + \frac{\partial^3 x}{\partial y'^3}\frac{y'^3}{6} + \frac{\partial^3 x}{\partial z'^3}\frac{z'^3}{6} +$$
$$\frac{\partial^3 x}{\partial x'^2\partial y'}\frac{x'^2y'}{6} + \frac{\partial^3 x}{\partial x'^2\partial z'}\frac{x'^2z'}{6} + \frac{\partial^3 x}{\partial y'^2\partial z'}\frac{y'^2z'}{6} + \frac{\partial^3 x}{\partial x'\partial y'^2}\frac{x'y'^2}{6} + \frac{\partial^3 x}{\partial x'\partial z'^2}\frac{x'z'^2}{6} + \frac{\partial^3 x}{\partial y'\partial z'^2}\frac{y'z'^2}{6} + \frac{\partial^3 x}{\partial x'\partial y'\partial z'}\frac{x'y'z'}{6} + \sigma\left((x,y,z)^3\right)$$

A similar model can be introduced for *y* and *z*:

$$y(x',y',z') = \sum_{n_{x'}=0}^{\infty}\sum_{n_{y'}=0}^{\infty}\sum_{n_{z'}=0}^{\infty} \frac{\partial^{n_{x'}} y}{\partial x'^{n_{x'}}}\frac{\partial^{n_{y'}} y}{\partial y'^{n_{y'}}}\frac{\partial^{n_{z'}} y}{\partial z'^{n_{z'}}}\frac{x'^{n_{x'}} y'^{n_{y'}} z'^{n_{z'}}}{n_{x'}!n_{y'}!n_{z'}!}$$

$$z(x',y',z') = \sum_{n_{x'}=0}^{\infty}\sum_{n_{y'}=0}^{\infty}\sum_{n_{z'}=0}^{\infty} \frac{\partial^{n_{x'}} z}{\partial x'^{n_{x'}}}\frac{\partial^{n_{y'}} z}{\partial y'^{n_{y'}}}\frac{\partial^{n_{z'}} z}{\partial z'^{n_{z'}}}\frac{x'^{n_{x'}} y'^{n_{y'}} z'^{n_{z'}}}{n_{x'}!n_{y'}!n_{z'}!}$$

Considering the measuring instrument to be in stationary conditions, partial derivatives can be considered to be couunstant:

$$\frac{\partial^{i+j+k} x}{\partial x'^i \partial y'^j \partial z'^k}\frac{1}{(i+j+k)!} = c_{xx'^iy'^jz'^k}\ ;\quad \frac{\partial^{i+j+k} y}{\partial x'^i \partial y'^j \partial z'^k}\frac{1}{(i+j+k)!} = c_{yx'^iy'^jz'^k}\ ;\quad \frac{\partial^{i+j+k} z}{\partial x'^i \partial y'^j \partial z'^k}\frac{1}{(i+j+k)!} = c_{zx'^iy'^jz'^k}$$

The following transfer function from instrument to metric coordinates can be consequently achieved:

$$\begin{bmatrix} x \\ y \\ z \end{bmatrix} = \begin{bmatrix} c_{xx'} & c_{xy'} & c_{xz'} \\ c_{yx'} & c_{yy'} & c_{yz'} \\ c_{zx'} & c_{zy'} & c_{zz'} \end{bmatrix} \cdot \begin{bmatrix} x' \\ y' \\ z' \end{bmatrix} + \begin{bmatrix} c_{xx'^2} & c_{xy'^2} & c_{xz'^2} & c_{xx'y'} & c_{xx'z'} & c_{xy'z'} \\ c_{yx'^2} & c_{yy'^2} & c_{yz'^2} & c_{yx'y'} & c_{yx'z'} & c_{yy'z'} \\ c_{zx'^2} & c_{zy'^2} & c_{zz'^2} & c_{zx'y'} & c_{zx'z'} & c_{zy'z'} \end{bmatrix} \cdot \begin{bmatrix} x'^2 \\ y'^2 \\ z'^2 \\ x'y' \\ x'z' \\ y'z' \end{bmatrix} +$$

$$+ \begin{bmatrix} c_{xx'^3} & c_{xy'^3} & c_{xz'^3} & c_{xx'^2y'} & c_{xx'^2z'} & c_{xx'y'^2} & c_{xx'z'^2} & c_{xy'^2z'} & c_{xy'z'^2} & c_{xx'y'z'} \\ c_{yx'^3} & c_{yy'^3} & c_{yz'^3} & c_{yx'^2y'} & c_{yx'^2z'} & c_{yx'y'^2} & c_{yx'z'^2} & c_{yy'^2z'} & c_{yy'z'^2} & c_{yx'y'z'} \\ c_{zx'^3} & c_{zy'^3} & c_{zz'^3} & c_{zx'^2y'} & c_{zx'^2z'} & c_{zx'y'^2} & c_{zx'z'^2} & c_{zy'^2z'} & c_{zy'z'^2} & c_{zx'y'z'} \end{bmatrix} \cdot \begin{bmatrix} x'^3 \\ y'^3 \\ z'^3 \\ x'^2y' \\ x'^2z' \\ x'y'^2 \\ x'z'^2 \\ y'^2z' \\ y'z'^2 \\ x'y'z' \end{bmatrix} + \sigma \begin{bmatrix} x'^3 \\ y'^3 \\ z'^3 \\ x'^2y' \\ x'^2z' \\ x'y'^2 \\ x'z'^2 \\ y'^2z' \\ y'z'^2 \\ x'y'z' \end{bmatrix}$$

The proposed transformation model can be implemented in order to describe 3D measuring instrument behaviour, with specific reference to systematic components. Conversely, stochastic contributes cannot be modelled through a mathematical function and are therefore comprised within σ Peano residual term.

Coefficients $c_{xx'}$, $c_{yy'}$ and $c_{zz'}$ are representative of linear calibration coefficients, while $c_{xy'}$, $c_{xz'}$ and $c_{yz'}$ quantify non orthogonality between instrument main coordinate directions. An ideally perfect scanner would exhibit values on the diagonal equal to 1, and null values out of the diagonal. Systematic non linearity along main axes are described by second and third order calibration coefficients: $c_{xx'^2}$, $c_{yy'^2}$, $c_{zz'^2}$, $c_{xx'^3}$, $c_{yy'^3}$ and $c_{zz'^3}$, while all of the other coefficients in the transformation matrix quantify second and third order coupled distortions. Estimation of different coefficients is not easy: however the aim of the model is not to provide a simple correction tool but, on the contrary, to introduce a general reference framework as a basis for instrument traceability.

2.3. Data filtering and extraction of parameters

The same TC 213 working on ISO 25178 created also an additional working group (namely WG 15) which actively contributed to the development of a toolbox containing different types of filters, eventually included within ISO 16610 [13]. The filtering operation is implemented for separation of surface components, such as roughness, waviness and form. Among the others, robust Gaussian, robust spline, morphological and wavelet filters can be applied. Robust filters are based on non-linear functions, which can generate mean surfaces not affected by local features or outliers such as high peaks or deep valleys. Morphological filters implement dilation and erosion operations, locally modifying features of the surface using a geometrical given shape called structuring element. Two operations are then defined: closing (a dilation followed by an erosion) or opening (dilation after erosion). Wavelet filters decompose surface into levels and allow extraction of components belonging to a specific scale level.

Filtered surface topographies can be eventually processed in order to allow computation and extraction of surface roughness parameters. ISO 25178 classifies 3D surface parameters into six main groups, as summarized in table 1.

Table 1. Main roughness parameters, as defined and classified by ISO 25178

Group	Abbreviated term	Notes	Applicative examples available at the		
			Micro-scale	Meso-scale	Macro-scale
height parameters	Sa, Sq, Ssk, Sku, Sp, Sv, Sz	Amplitude related methods, defined over the definition area	X	X	X
functional parameters (1)	Smr, Smc, Sk, Spk, Svk	Based on areal material ratio function of the scale-limited stratified functional surface	X	X	X
functional parameters (2)	Svq, Spq, Smq	Based on areal material probability curve, with the areal material area ratio expressed as a Gaussian probability	X		
volume functional parameters	Vm, Vv, Vmp, Vmc, Vvc, Vvv		X		
functional parameters	Svs, Srel, Svfc, Safc	Based on fractal cross-scale descriptive methods	X		
hybrid parameters	Sdq, Sdr	Defined on the basis of surface envelope and gradients	X	X	X
spatial parameters	Sal, Str	Based on autocorrelation functions.	X	X	X
miscellaneous parameter	Std	Based on texture direction of the scale-limited surface	X	X	X

The table shows also the present level of implementation of surface roughness parameters at a research or applicative level for the already cited different surface sizes: micro-, meso- and macro-scale (see e.g.

[14)]. The majority of applications are clearly found at the micro-scale, for millimetre and sub-millimetres surface analyses, but an increasing number of research studies is more recently implementing the same parameters at higher scales. Figure 3 reports the total number of published papers, as indexed by Scopus in the last decade and reporting roughness parameters in agreement with ISO 25178. The graph clearly shows how the number of documents is increasing at a rate higher than 30% per year. Such trend is mainly ascribable to the increasing recognition and understanding of the ISO 25178 parameters among both scientific community and private companies, and is reasonably expected to increase as an effect of the demand of simplified parameters for the analysis of surface data sets characterized by continuously growing resolutions.

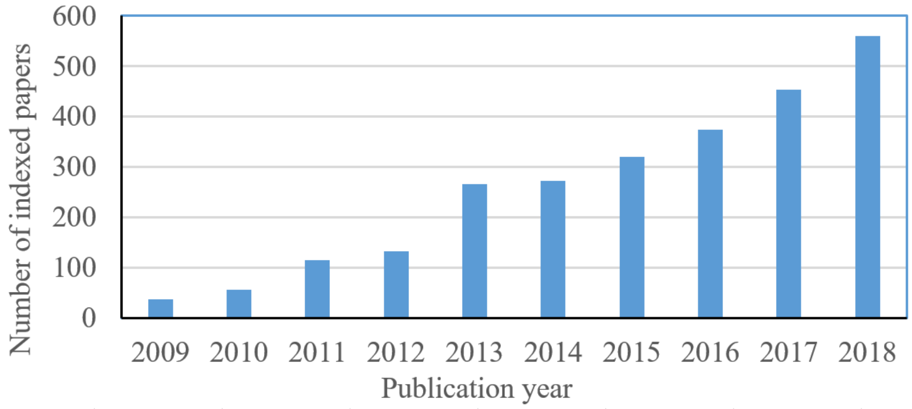

Figure 3. Number of published papers indexed by Scopus in the last ten years and implementing roughness parameters compliant with ISO 25178.

3. Conclusions

The present research is done with intention of producing an up-to-date understanding of the usage of surface roughness parameters at different scales.

Some conclusions can be drawn:

1. ISO 25178 provides an important reference for the definition of standard procedures and parameters for the characterization of surface topography data sets.
2. Specific filtering methods are also defined by the standard, allowing isolation of surface portions of interest, thus minimizing the uncertainty contributions related to noise, distortions or features not of interest for the specific applications
3. Specific calibration of data sets is needed in order to allow traceable computation of surface roughness parameters
4. In the point of view of the authors a growing number of research and applicative studies can benefit from extraction of parameters at different scales, from the micro- to the meso- to the macro-scale.

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