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Study and Comparison of Surface Roughness Measurements

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Résumé
Cet état de l'art recense les travaux récents qui exploitent les caractéristiques surfaciques des maillages 3D (telles que la rugosité et la saillance), pour optimiser certains traitements. Le tatouage ou la compression avec pertes sont des applications qui pourraient tirer profit d'une caractérisation précise de la rugosité, de façon à mieux cacher les marques ou à quantifier plus grossièrement les zones rugueuses, sans trop altérer visuellement l'objet. Sachant que la notion de rugosité dépend de l'échelle à laquelle la géométrie est perçue, certains travaux se sont tournés vers des approches multi-échelles. Mais aucun, à notre connaissance, n'est capable de la caractériser avec précision, ce qui nous semble pourtant déterminant pour les applications citées. Le potentiel de l'analyse en ondelettes ou des modèles fractals nous semble encore peu exploité dans ce sens, alors que les informations apportées pourraient aider à cette caractérisation. Enfin, seules quelques méthodes sont actuellement capables de différencier rugosité et saillance, alors que cette dernière notion est essentielle pour des applications telles que la simplification ou le débruitage de maillages. Sachant que plusieurs domaines liés à la physique et la métrologie se servent de paramètres précis pour renseigner sur la nature et les propriétés des surfaces réelles considérées, nous les avons étudiés en vue de leur adaptation pour les maillages 3D.

This survey paper focus on recent researches whose goal is to optimize treatments on 3D meshes, thanks to a study of their surface features, and more precisely their roughness and saliency. Applications like watermarking or lossy compression can benefit from a precise roughness detection, to better hide the watermarks or quantize coarsely these areas, without altering visually the shape. Despite investigations on scale dependence leading to multi-scale approaches, an accurate roughness or pattern characterization is still lacking, but challenging for those treatments. We think there is still room for investigations that could benefit from the power of the wavelet analysis or the fractal models. Furthermore only few works are now able to differentiate roughness from saliency, though it is essential for faithfully simplifying or denoising a 3D mesh. Hence we have investigated roughness quantification methods for analog surfaces, in several domains of physics. Some roughness parameters used in these fields and the additionnal information they bring are finally studied, since we think an adaptation for 3D meshes could be beneficial.

Mots-clés : 3D mesh, compression, feature-preserving smoothing, multi-scale analysis, quality assessment, roughness, saliency, simplification, visual masking, visual perception, watermarking.

1. Introduction

Nowadays, digital graphic content is massively used by industries and begin to invade our daily life. 3D graphic representations can be found everywhere, in medical imaging, as much as in video games, architecture, or other various simulations. Different types of representations are available, but 3D meshes are widely - and mostly - considered. With the expansion of the Internet, and the actual tendancy to buy and transfer digital content with various devices, appeared a need to apply to 3D meshes operations like progressive compression, simplification and/or watermarking. Such applications usually "damage" the appearance of the initial data. Hence the actual tendancy is to consider a process called "visual masking", to visually hide as much as possible these degradations. But since their perception by a human observer depends on the surface features, most of the

researches first focus on defining accurate and objective 3D mesh visual quality assessments. For that purpose, notions like roughness, geometric texture (or noise) and saliency (defined in next paragraphs or sections) are considered. The goal is to design metrics that correlate well with subjective experiments (carried out by human observers, on specifically designed 3D mesh databases).

A difficulty when working with roughness is that it is quite difficult to make a clear definition of it. A rough profile can take a lot of different shapes. To our knowledge, only few works (based on the notion of fractal dimension) are able to precisely characterize this concept, though it could be beneficial for improving the "visual masking" of 3D data. Moreover, assessing the roughness depends on the scale at which we see the geometric object. While seing an object from a very far sight, an area might seem smooth, while it could seem rough once zooming a little. With a broader sight, it might even be possible to find salient features (singularities that catch the eye of the observer since they differ locally from their surround). Distinguishing rough areas from salient ones is quite a challenging task, not perfectly done in all studies on roughness, though it is essential for faithfully simplifying or smoothing a 3D mesh.

The next section reviews works that address roughness, saliency, and the link between these two concepts, for applications that visually alter 3D meshes. Such applications cannot be correctly carried out without defining an objective and automatic 3D mesh visual quality assessment. Hence we also survey recent works dedicated to this task, based on finding a correlation between the human visual perception and the concepts of roughness and saliency. However, these studies dedicated to 3D meshes hardly cover the whole concept of roughness, while big pieces of work have been achieved in some domains of physics (like tribology, metrology, rock mechanics and so on). Section 3 is dedicated to these specific applications, and studies how roughness is computed for analog curves or surfaces. We emphasize that each domain poses its own rules : flat surfaces, specific scales, 2D profile or 2.5D mesh analysis, ... These works consider roughness not just as a "visual artifact", but also characterize it with a lot of different parameters implied in other phenomena like friction between contact surfaces. A study of these parameters and the information they carry is finally proposed, since we think it might be useful for improving 3D mesh applications.

2. Saliency and roughness computations on 3D meshes

Until recently, concepts like textured areas or geometric noise/artifacts were used to refer to non-smooth features of a 3D mesh, but talking of "roughness" is quite new. Lots of feature-preserving smoothing or denoising techniques (also referred as "surface fairing") have existed for quite a long time [ZLMZ06]. They are known to remove this kind of high frequency features while preserving saliencies. What these methods take into account are mainly "geometric properties" of the mesh (like normals or curvatures), not necessarily sufficient to obtain perceptually correct results.

Some recent studies (we first review) have investigated ways to better preserve saliencies during mesh simplification or smoothing, so that it better fits the perception of the human visual system (HVS). Fitting the HVS perception is also a main concern for visually assessing the quality of operations like watermarking or lossy compression. Since it is intrinsically linked with notions like roughness, texture and visual masking, we also address the corresponding methods in this section.

The same attention was raised for assessing the quality of 2D images, for a longer time [WBSS04, CLL*13]. These 2D studies have been a source of inspiration for 3D treatments. Some image-based solutions, working on 2D views of a 3D object have first been designed and used to pilot applications like simplification [LT00, QM08], rendering [BM98] and watermarking [RACM05]. It was also intended for adapting the level of detail of a rendered scene to the supposed perceptibility of each feature [Red01]. However it is not as efficient as directly working on the mesh, since it is hard to define meaningful viewpoints and 2D image metrics have been proven not to well reflect the visual quality of 3D meshes [RR01].

2.1. Visual saliency computation and applications

2D saliencies (on images) have been studied for quite a long time, leading to two different kinds of algorithms : top-down methods, based on low level features (easier to apply), and bottom-up techniques which work on the semantic of high-level salient features (like faces and texts) [CLL*13]. In both cases, saliencies are defined as singularities or features which catch the eye of the observer. Since it deals with details which attract a subjective interest, semantic may have some importance : depending on what the observer is searching on a picture, he/she may not be looking at the same spots. However high-level salient features tend to be looked at in any matter, as seen in the study from Howlett *et al.* [HHO05].

One of the first geometric-based, multi-scale method designed to compute saliencies on a 3D mesh was performed by Lee *et al.* [LVJ05]. As for most of the roughness measurements (defined in next subsections), the mean curvature is used to evaluate the saliency of a model. For each vertex of the mesh, a Gaussian-weighted average of this parameter is first computed inside various spherical local

windows (obtained by varying the standard deviation of the Gaussian). The vertex saliency S_i (at a given scale i) corresponds to the absolute difference between two averages, the second computed on a twice larger neighborhood. The more salient and different from its neighborhood an area is, the bigger the difference between those combinations will be. The multi-scale saliency map is finally obtained thanks to a non-linear combination and normalization of the S_i. The goal is to promote remarquable and isolated singularities and lessen the importance of similar peaks found in the same (rough) area. Five scales are generally sufficient.

Being able to detect saliencies allows to identify rough areas with a substraction mechanism. But as shown in [LVJ05], finding saliencies also make it possible to optimize operations like simplification or denoising : if a priority is made of keeping salient features unchanged, then the simplification step impacts areas which are not as important as these singular parts, to preserve human comprehension of the salient details (see Figure 1).

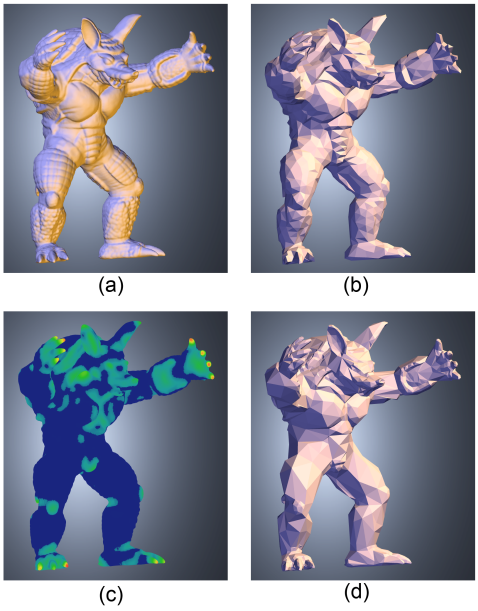

Figure 1: *Illustration of the saliency computation of Lee et al. [LVJ05] used for mesh simplification. (a) Original mesh. (b) 99% simplification. (c) Saliency map. (d) 99% simplificaton guided by saliency. Images from [LVJ05].*

Another application of this work is the one of Zhihong *et al.* [ZLMZ06]. It makes a direct use of the previous saliency computation, to optimize the result of a "discrete Laplacian smoothing" (which is not a feature-preserving process). A Laplacian smoothing (also known as "diffusion smoothing") consists in incrementally moving the vertices of a mesh in the direction of the Laplacian. The simpler approximation in the discrete setting (known as the "umbrella operator" or "Taubin's filter" [Tau95] when iterated) is obtained by moving every vertex of the mesh to the barycenter of its 1-ring neighbours. Here the computed saliency map is used to choose how much a vertex needs to be moved or kept at the same place. In order to preserve salient features, the original vertex and the barycenter are seen as the extremities of a linear interpolation. The maximum saliency will coincide with a parameter t=0 (original coordinates), while the minimum saliency value will be linked to t=1 (barycenter coordinates). Each vertex will then be placed regarding its own saliency value.

2.2. Roughness for visual quality assessment

In 3D mesh applications that introduce visual artifacts, distortion is most often evaluated with simple metrics like the Hausdorff distance or the (root) mean squared error : (R)MSE. All are based on Euclidean distance computations and poorly correlate with human judgement. In 2000, Karni and Gotsman were the first to introduce a "perception-inspired metric" that better assesses the degradations caused by the quantization implied in their spectral mesh compression [KG00]. Their model (later improved by Sorkine *et al.* [SCOT03]) both takes into account the geometric deformations (with the RMSE) and the object "smoothness" (linked to the surface normals and expressed with the vertex Laplacian coordinate error).

However the hypothesis that the "surface roughness" is implied in the visual perception of the distortion was not explicitly formulated before the work of Corsini *et al.* [CGE05]. They aimed to assess the degradations caused by watermarks, by checking on the roughness difference between the original and watermarked meshes. First, a methodology was defined to subjectively evaluate the differences between several examples, thanks to human observers. The result of these subjective tests were later used to normalize and adjust the objective computations, with a Gaussian psychometric function. Then their metric is defined as a "multi-scale per-vertex roughness" computation, which uses the per-face roughness definition of Wu *et al.* [WHTS01].

This latter measure consists, for a triangle face T (illustrated in Figure 2 (b)), in computing the dihedral angles between the faces of the 1-ring neighborhood of each of its vertices (P_1, P_2 and P_3). For the vertex P_1 (surrounded by five neighbour facets T, T_1, T_2, T_3 and T_4), the dihedral angles between TT_1, T_1T_2, T_2T_3, T_3T_4 and T_4T are computed together with the average G_1 and variance V_1 associated to P_1. As for the averages G_2 and G_3 and variances V_2 and V_3, associated to the vertices P_2 and P_3. Finally the roughness measure

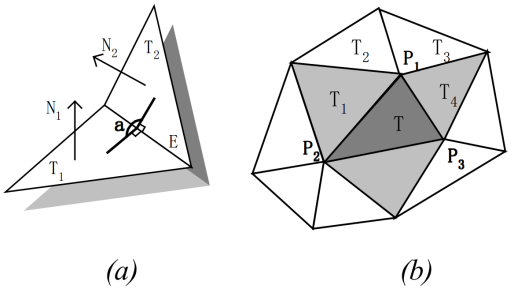

Figure 2: *(a) Illustration of the dihedral angle between the two triangles T_1 and T_2. (b) 1-ring faces implied in the computations associated to one of the vertices (P_1) of a triangle T that lead to the measure $R(T)$. Images from [WHTS01].*

of the face T is obtained by :

$$R(T) = \frac{G_1.V_1 + G_2.V_2 + G_3.V_3}{V_1 + V_2 + V_3} \quad (1)$$

Large dihedral angles characterize sharp edges (associated to the concept of saliency), while a high variance corresponds to a dispersion of the dihedral angle values around a vertex. This latter, which favor a high concentration of "bumps" of different sizes, typifies rough surfaces. However only those whose granularity (size/scale of the "bumps") is within a facet can be adequately detected (since only a 1-ring neighborhood is considered).

From the latter computation, the per-vertex roughness $R^N(v)$ of Corsini *et al.* [CGE05] is then deduced, with respect to a N-ring neighborhood around the vertex v (N corresponding to different roughness scales) :

$$R^N(v) = \frac{1}{|S_T^N|} \sum_{i \in S_T^N} R(T_i) A_{T_i} \quad (2)$$

where S_T^N is the set of faces inside the N-ring neighborhood of the vertex v, $|.|$ the cardinality operator, T_i a face inside this neighborhood, $R(T_i)$ the roughness of this face and $A(T_i)$ its area. Empirical observations have led to retain the 1, 2 and 4-rings. The final per-vertex roughness hence corresponds to the maximum $R^N(v)$ value among these three levels.

Drelie Gelasca *et al.* [GECB05] also designed a quality assessment technique for watermarking, based on the same subjective tests and correlations. The difference lies in the per-vertex roughness computation. It is based on a "height" difference between each vertex v and its equivalent v^S in a smoothed version (*i.e.* five times iterated Laplacian smoothing on the original mesh). This "height" difference corresponds to the projection of the vector $v - v^S$ on the vertex normal of the smoothed surface. Then the roughness of each vertex v is computed this way :

$$R(v) = \frac{V(S_h^2(v))}{A_{S^2}} \quad (3)$$

where S_h^2 is the set of the "heights" h associated to the 2-ring neighborhood of the vertex v, $V(S_h^2)$ the variance of this set and A_{S^2} the area of the faces in this neighborhood. The variance is very small on a smooth area since the heights are small. The previous works from [CGE05] and [GECB05] were compared (in [CGEB07]) for a watermark purpose and the second metric gave the best results.

Lavoué *et al.* [LGD*06] also developed a perceptual metric (called MSDM) for 3D mesh watermarking quality assessment, that seems to be quite efficient with other operations like simplification and compression. Their method relies on a transposition of a 2D local quality measure, defined between two images and called SSIM (for Structural SIMilarity) [WBSS04]. The SSIM metric leans on three comparison functions, deduced from the intensities of the images : the luminance L (based on the average of the intensities), the contrast C (based on the standard deviations) and the structural information S (based on the covariance). 3D geometric equivalents of these three functions were hence defined by replacing the image intensity value with the discrete mean curvature. Hence this latter has been shown to better reflect the geometric features of a 3D mesh [KKK02, LVJ05] than the vertex coordinates.

For each vertex v, a local spherical window (centered in v and having a predefined radius r) is first defined. The neighborhood of v is composed of all the vertices inside the sphere (shown in blue in Figure 3). The intersections of the sphere with the edges of the mesh (shown in green in Figure 3) are also added to this neighborhood. For each of these points, its curvature is linearly interpolated from the values obtained at its edge extremities. Then for each vertex v and its equi-

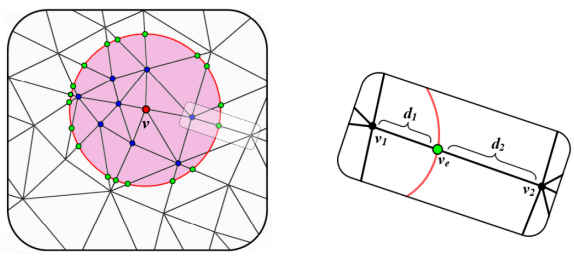

Figure 3: *Left : illustration of the local window defined for each vertex v and used to compute MSDM (the perceptual metric of Lavoué et al. [LGD*06]). Right : example of an intersection between an edge and the local window. Images from [LGD*06].*

valent in the modified mesh, L is found by computing the difference between the mean curvature averages in the two neighborhoods. C is found by doing the same with the standard deviations, and S with the covariance. The C parameter reflects actually the local roughness variation, as it computes (in windows x and y defined on both meshes) the dispersion of the mean curvatures around the curvature average.

$$C(x,y) = \frac{||\sigma_x - \sigma_y||}{max(\sigma_x, \sigma_y)} \tag{4}$$

$$\sigma_x = \sqrt{\frac{1}{n} \sum_{v_i \in x} (C(v_i) - \mu_x)^2} \tag{5}$$

where n is the number of vertices in the local window x, v_i the ith vertex of this window, $C(v_i)$ its mean curvature and μ_x the average of the vertex curvatures inside the window. A Minkowski metric is finally used to combine the three parameters into a single distance value. It was shown to better correlate to the same subjective tests than the previous studies [CGE05, GECB05], still in the context of watermarking quality assessment (though it was intended for a more general purpose).

In 2011, a new version of MSDM (called MSDM2) was designed by Lavoué [Lav11]. The parameters L, C and S were ponderated thanks to a Gaussian function. The computation of the curvature is now scale-dependent and the whole method was transformed to be multi-scale. A fast projection step was finally added to allow a comparison of two meshes with different connectivities. These modifications led to results which fit the subjective tests even better.

One year later, Wang *et al.* [WTM12] designed a simpler and faster to compute metric, called FMPD (for Fast Mesh Perceptual Distance). It was intended for watermarking, simplification and compression quality assessment. This metric is based on the Laplacian of the discrete Gaussian curvature computation. Like for the previous method, the metric can be computed on two meshes having different connectivities, but it is also invariant to mesh similarity transformations. It was demonstrated to slightly better correlate with the subjective assessments, since its surface roughness formulation appears more relevant to human perception. This is mostly due to the fact that the following two important phenomena (implied in the HVS) were considered : the visual masking and the psychometric saturation effects. The latter (not taken into account before) reflects the tendancy for a human to assign the same scores for assessing very small (or large) degradations of different intensities.

2.3. Visual masking for watermarking and compression

The visual masking property is a feature of our HVS that has been introduced for computer graphics applications with the work of [FSPG97]. It is stated that a geometric noise, artifact or pattern is not much perceptible in a textured area of the same frequency. Being able to separate rough areas from smooth and salient ones (which don't have the same masking properties) can hence help to improve operations on 3D meshes, like watermarking or compression.

In 2007, Lavoué's work [Lav07] aimed to compute a roughness measure especially adapted for being used in visual masking based applications. To do so, the proposed algorithm must separate rough parts from salient ones as much as possible. First, an adaptive smoothing (based on the five times iterated Laplacian smoothing) is intended to eliminate most of the rough regions. It also tends to transform salient regions so that their curvature is more important (they are thinner) on the smoothed mesh than on the original one (see Figure 4). Per-vertex mean curvature

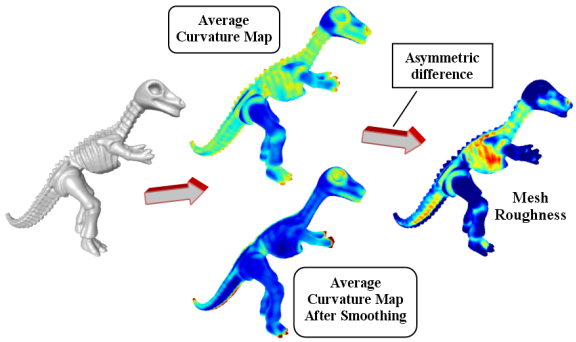

Figure 4: *Principle of the roughness computation of Lavoué [Lav07]. Images from [Lav07].*

averages are then computed on local windows, defined on the original and smoothed objects. The granularity of the roughness/noise that is aimed to be detected thanks to an asymetric difference of these averages can be chosen by varying the size of the local window.

The previous method was taken up and more detailed in [Lav09]. In this paper, a way to better the smoothing algorithm is considered : such a thing might be possible by using a feature-preserving smoothing. Moreover an application for compression optimization is introduced : by classifiying the vertices of a mesh in "smooth" and "rough" clusters, it becomes possible to associate a finer level of quantization to smooth and salient vertices than to rough ones (see Figure 5). This way, the compression can be more important while the visual quality of the mesh is preserved as much as possible, the bigger degradations being hidden in rough areas. Finally none of these works exploits the masking effect added by 2D textures, though they quote pieces of work on the subject.

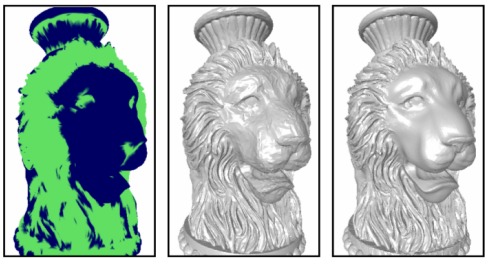

Figure 5: *Demonstration of the visual masking effect. Left : classification of the roughness into two clusters (rough vertices are in green, while smooth ones in blue). Middle : random noise added on smooth regions. Right : random noise added on rough regions, less perceptible. In a compression scenario : lowering the quantization level of the rough regions would be equivalent to adding noise into these areas. Images from [Lav09].*

2.4. Comparison of the roughness measurements

Though the presented roughness computations are different, they all have common points. A criterion/parameter (aiming at characterizing the geometric 3D shape) is first chosen to evaluate the roughness on each vertex. Then a reference value is found for a defined neighborhood. By making a comparison and combining all the local values from the neighborhood to this reference, a per-vertex roughness is computed. A computation of the mesh roughness can be achieved by combining again all the per-vertex roughnesses.

	Roughness criteria	Comparison	Neighborhood	Multi-scale	Roughness /saliency distinction
Corsini *et al.* 05	Dihedral angles	Averages ponderated with variances	N-ring	Yes	No
Drelie Gelasca *et al. 05*	Heights betw. meshes	Variance	2-ring	No	No
Lavoué *et al. 06*	Mean curv	Std deviation	Spherical window	No	No
Lavoué *et al. 11*	Scale-dependent mean curv	Gaussian-ponderated variance	Spherical window	Yes	No (?)
Lavoué 09	Mean curv	Asymetric diff. betw. original & smoothed meshes	Spherical window	Yes	Yes
Wang *et al. 12*	Gauss curv	Laplacian-ponderated diff. + modulation	1-ring	No	No

A first issue that seems to gather all methods, is that the defined metrics are all dependent on the facet sizes for their computation, even if the considered neighborhoods are slightly different. But the ones that seems to better correlate with the subjective experiments are those which consider a neighborhood inside a sphere, in order to delimit the same surface areas on both compared meshes. Moreover, multi-scale approaches seem to provide better results. This is not surprising since the concept of roughness itself is scale-dependent (remember that the same area could be defined as smooth at a large scale, but then rough or salient at a smaller scale). It hence depends on the neighborhood on which the computations are made, and on the geometric noise which is aimed to be detected. Finally an integration in the metric of phenomena implied in the HVS is also something that must be taken into account but require complex studies.

Most of the time, the criterion used for the roughness evaluation is the mean curvature, while the computation of a reference for the neighborhood and its combination with local values is performed by computing the variation of the previously quoted curvature. Hence most of these methods are based on a variance or standard deviation computation of such a criterion. Still, these measures are not sufficient when it comes to make a real difference between purely rough areas and salient features, or to differentiate various degrees of roughness. If the presented applications do not all seem to require this sensibility, to perform a good quality assessment work, being able to do so would allow one to use these concepts of roughness and saliency with a better accuracy, useful for numerous purposes.

3. Roughness computations in other fields

All the papers that deal with roughness on 3D meshes consider it as a geometric feature, important for visual perception in lossy operations like watermarking, simplification, smoothing, denoising or compression. All the proposed measurements are able to evaluate the global roughness of an area but do not provide enough information to distinguish between different rough profiles. Moreover saliencies are not necessarily differenciated from textured regions, and even with this work done, characteristics like patterns, anisotropy, regularity, size and quantity of the peaks and valleys, are not computed nor exploited. Finally, an even harder task (generally not mentioned nor discussed) is the detection of saliency among a rough area.

In some domains of physics, roughness measurements have been processed for a much longer time, getting interest in real analog object characteristics (like the influence of the shape of the surface on friction properties). Some standard parameters have been defined, and seem to be used in a lot of applications. A closer look at these studies might help to enlarge the idea of what makes a rough profile, and to enhance current methods on 3D meshes.

3.1. Roughness measurement methods in physics

Roughness is commonly defined as the very geometric non smoothness of a surface, independently from some other parameters like the characteristics of the used material. Consequently, whether it is computed on an analog object or a discrete one don't change its definition. Some applications actually use a 3D scanner to get a discrete version of real objects (like Mah *et al.*'s work [MSMT13], on which various roughness measurements are more easily computed than analogically. This latter paper (which deals with rock mechanics) presents a way to compute the roughness of rock joints, which contribute to its shear strength. Unlike those on 3D meshes, computations are eased by the assumption that the studied surface is quite flat. The 3D scanner is hence commonly used to produce 2.5D meshes of the joint surface. Then the obtained point cloud is used to compute the best fitting plane (shown on an example, in Figure 6), thanks to a principal component analysis.

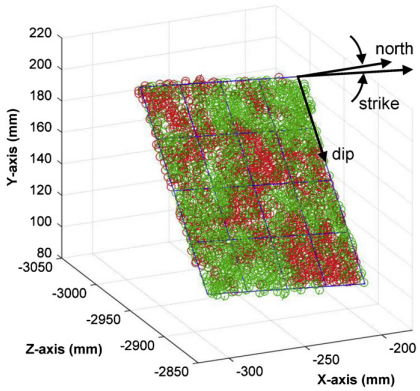

Figure 6: *Computation of the best fitting plane on a point cloud (used by Mah et al. [MSMT13] to compute roughness). The plane principal directions are called strike and dip. Red points are situated above the plane, while green ones below. Graph from [MSMT13].*

A rectangular area is then chosen along this plane and a 2D profile found by cutting it in bins on which an average offset is computed (with respect to the reference plane). Two parameters can hence be deduced (illustrated in Figure 7) : the "profile length" (line through the two local maxima) and the "maximum asperity amplitude" (obtained from the normal to the profile length). Empirical tables (called Barton's graphs) are then used to derive the "joint roughness coefficient" from the latter two parameters. Moreover this paper presents a way to measure the roughness anisotropy of the surface, by doing the previous computations on several rectangular subsets, rotated inside the supporting plane to get a circular anisotropic roughness map.

Roughness quantification methods for concrete surfaces

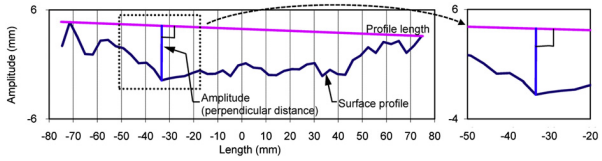

Figure 7: *Computation of the "profile length" and "maximum asperity amplitude" on a 2D rough profile. Images from [MSMT13].*

have been recently surveyed by Santos *et al.* [SJ13]. In this specific application area, the purpose for roughness computation is quite the same as previously : shear-stress prediction. Some techniques are purely analogical, while others convert the results to numerical data (with a 3D scanner or a mechanical stylus), to get a 2D profile. They can use contact or contactless processes, which can be totally, partially or non-destructive. Some of them can just identify macro-textures (waviness), like "the sand patch method" (described thereafter), while others are able to detect micro-textures. The principle of "the sand patch method" (which has particularly caught our attention because of its simplicity) consists in filling the "holes" of a bumpy surface with a calibrated sand, to see how much of the surface will be covered (Figure 9). Derivated techniques for "non-flat surfaces" like 3D meshes could be considered from this one. This is reminiscent of mathematical morphology techniques, also used in the work of MŁynarczuk [MŁ10].

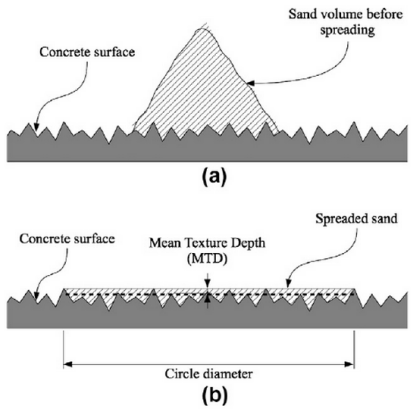

Figure 8: *Illustration of the "sand patch test" (described in the survey of Santos et al. [SJ13]) (a) before spreading and (b) after spreading. Images from [SJ13].*

3.2. Roughness parameters

Two main standard parameters are generally used to characterize the roughness of various surfaces, thanks to their

2D profile. The average roughness R_a is computed by :

$$R_a \approx \frac{1}{n}\sum_{i=1}^{n}|z_i| \tag{6}$$

while the root mean square roughness R_q can be found this way :

$$R_q \approx \sqrt{\frac{1}{n}\sum_{i=1}^{n}z_i^2} \tag{7}$$

where n is the number of discrete samples in the profile, and z_i the amplitude (offset) of each sample. The latter value is more sensitive to peaks and valleys. It can be seen as a standard deviation, close to the one used by the methods dedicated to 3D meshes (especially [GECB05]). However, these parameters are not sufficient to accurately define a rough profile, which can exhibit several different aspects, for the same values of R_a and R_q. [SJ13] gives the definition of several other parameters : Mean Peak Height, Mean Valley Depth, Mean Peak To Valley Depth, Ten Points Height, Maximum Peak Height and Maximum Valley Depth. Other interesting parameters and their measurement methods are also presented in the work of Siewczyńska [Sie12] and deserve to be more analysed.

Rough profiles are also studied in the field of tribology, whose interest lies in how surfaces in motion interact with each other. The work of Sedlaček *et al.* [SPV12] bears interest in the skewness and kurtosis of the rough profile, in their meaning and their correlated influence on friction. They found that the skewness R_{sk} is sensitive to important and occasional peaks and valleys, which is interesting as it seems to correspond to saliencies. Moreover depending on the sign of the skewness, it is possible to know if the profile predominantly contains low valleys and a lack of high peaks (negative skewness), or the contrary (positive skewness). The kurtosis R_{ku} gives an information about the probability density sharpness. A low kurtosis describes a profile with small peaks and valleys, while a high kurtosis corresponds to a profile with important ones. Being able to differenciate peaks and valleys may lead to new scopes. For example, we can think about deep and thin valleys in 3D meshes that can totally mask noise or visual defects in their deepest parts, since these parts are not or only partially perceived by most viewpoints.

4. Conclusion

The roughness of 3D meshes can be exploited in many ways, such as for the quality assessment of lossy operations like compression or watermarking. Other uses can be made of salient features detection for example to improve mesh simplification algorithms, feature-preserving smoothing, ... Being able to separate roughness and saliencies can lead to further improvements, by allowing a better use of the visual masking effect.

The most recent techniques use multi-scale approaches, as it is necessary to define a scale before being able to make a clear difference between smooth, rough and salient regions (depending on the size of the detected patterns). But what seems more challenging is the saliency detection among a rough area, nobody has (to our knowledge) ever adressed. It could be interesting to test if the actual methods are able to detect such a feature.

At the scale of the whole mesh, saliencies are seen as spatially-isolated and important peaks (of high amplitude), while roughness is characterized by several peaks with similar amplitudes spread over large spatial areas. Knowing this, the idea to study these characteristics in the frequency domain may comes to mind. Using techniques like the one of Zhang *et al.* [ZC01] to compute precisely and efficiently operations like Fourier transforms could lead to interesting results. Moreover the multiresolution analysis produced by wavelet transforms could even more accurately characterize a multi-scale notion like roughness. It is thus not surprising to find works based on the wavelet theory to analyze the road [WFZ05] or fabric [KKS*05] surface roughness. The latter method is particularly interesting since a wavelet-fractal technique is employed to calculate the fractal dimension used to objectively and quatitatively differentiate the degree of fabric surface roughness.

However, it is still difficult to get a precise measure of all the "properties" linked to a rough profile. To find more detailed information on the subject, some domains of physics have been investigated. A lot of interesting work has been done in this field, and deserves to be more researched. Some techniques, which quantify the roughness of rocks and concrete surfaces, have been quickly studied, along with a method to evaluate roughness anisotropy. Though the work is eased by some admitted properties of the studied objects (like flatness), new roughness computation methods for 3D meshes could be inspired from these works (for example, the sand patch and mathematical morphology). Finally, standard parameters (along with some others) have been listed, giving ways to define new properties of a rough profile. They (as much as roughness anisotropy) might be used to find new ways of enhancing 3D mesh treatments.

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