From planar surfaces based on lattices to freeform surfaces based on triangular meshes: an advanced extension of the areal motif method

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Abstract. Surfaces are shifting from traditional planar surfaces to freeform surfaces with significantly reduced volume and weight and highly improved performance. The areal motif method is used to analyse the topographical features on planar surfaces which are important to surface function. However the areal motif analysis cannot be directly applied to freeform surfaces, usually described by the triangular mesh data structure. To overcome this obstacle, a feasible strategy is proposed to extend the motif method. Morphological operations are employed to separate the "texture" and "form" surface. The watershed segmentation is then applied to the "texture" height surface in which the connection of each vertex is defined by the triangular mesh. The tiny motif due to the over-segmentation is combined by pruning the peaks and pits in the Pfaltz graph.

1. Introduction

Surface is the interface that limits the body of an object and separates it from the surrounding medium. It is functionally important as it governs mechanical, tribology, biological, chemical properties and so force, all of which impact the way that the object is interacting with others [1]. Prime examples exist both in nature and man-made products. It is well known that the lotus leaf is hydrophobic because the epidermis of its surface is overlapped by many tiny bumps covered by epicuticular wax and thus this special double surface structure is water repellent, resulting a self-cleaning effect, also known as the lotus effect. Based on this mechanism, many products were developed to achieve the lotus effect, such as the self-clean roof tiles, the so-called water proof nano-material coats and so on [2]. Another example is the shark skin surface, which is presented with many miniature teeth-like ridges. These ridges or denticles can improve swimming efficiency and enable silent movement by reducing water drag. This principle is applied in diving suits and wet suits [3].

The importance of surface to the component functional behaviours gives rise to the study of surface geometrical structures including surface shape and surface topographical features. Surface analysis techniques are available to extract and evaluate the topographical features in micro scale. The analysis tool-box comprises the Gaussian filter, the spline filter, the wavelet analysis, the morphological operations and the motif methods [4]. The motif method was originally proposed to identify the significant peaks on surface profile and later extended to areal surface. The areal motif method was proved to be a very useful tool for the characterisation of engineering surfaces, usually followed by

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computing feature parameters. However a limitation of the exiting areal motif method is that it is restricted to planar surfaces. Nonetheless, as the modern manufacturing technology enables the production of surface with complicate structure, for instance freeform surfaces, patterned surfaces, or even their combination. The traditional motif method cannot be directly applied to these surfaces. In this paper, we post our initial work to extend the areal motif method to freeform surfaces.

2. Review of motif methods

The motif method appeared as a purely graphic method, originally developed by French automotive industry in 1970's. A motif is defined as a portion of the primary profile between the highest points of two local peaks which are not necessary adjacent. The initial motifs are the identified portions between adjacent local peaks. The four rules, i.e. the envelope condition, the length condition, the enlargement condition and the similar condition, are then applied on the initial motifs to remove insignificant ones and generate significant ones. In contrast to the mean line based filtration techniques, e.g. the Gaussian filter, the motif method is well suited for dealing with multi-processes surfaces and related to the envelope of the surface which is functionally important especially in contact phenomenon.

The profile motif method first became the French industry standard CNOMO (comite de Normalisation des MOyens de production) [5] and later accepted by ISO 12085 [6]. Even though the motif combination rules are standardized, the tweaking of the rules has continued because of its instability [7]. In 1992 a formal mathematical theory was proposed by Scott to stabilize motif combination rules and a couple of properties were found that the rules have to satisfy in order to achieve certain desirable metrological properties [8].

In 1990s the characterisation of surfaces was shifting from profiles to area surfaces both for instruments, analysis tools and parameters [9]. The profile motif was extended to the areal version. The initial idea is to view the surface as a landscape comprised by hills, dales and saddles, which is also known as the Maxwell theory [10]. A Maxwell hill is an area that all of its maximal uphill paths leading to one particular peak. Likewise a Maxwell dale is an area that all of its downhill paths leading to a particular pit. More importantly, the ridge lines are the natural boundaries of the dales, connecting saddles and pits and following the steepest downhill paths from saddles to pits; the course lines are the boundaries of the hills, connecting saddles and peaks and following the steepest uphill paths from saddles to peaks. Thus the areal motif method is essentially a special segmentation technique called as the watershed segmentation. Scott extended the Maxwell's definition of hill and dale. The areal motif is equivalent to a dale consisting of a single dominant pit surrounded by a ring of ridge lines connecting peaks and saddle points. A whole set of areal motif method was constructed on the basis of the Maxwell's theory and Pfaltz graphs [11]. Another variation of areal motif extension was proposed by Barré and Lopez, which is based on the Vincent's recursive watershed algorithm [12].

Nowadays, the state-of-the-art product technologies trigger a superior shift of engineering surfaces: freeform surfaces are replacing traditional planar surfaces and have significantly reduced volume and weight and highly improved performance. The characterisation of freeform surface is proved to be difficult. On one hand freeform surfaces cannot transform to planes that retain both orthogonality and scale and current surface characterisation techniques defined on the Euclidean geometries are distorted when they are applied to freeform surfaces. On the other hand, freeform surfaces might be specified by irregular polygon meshes (especially triangular mesh) rather than regular lattice heights. Therefore the areal motif method cannot be directly used on freeform surfaces due to these two restrictions. It is intended in this paper to extend the areal motif method to triangular mesh surfaces.

3. Areal motif analysis on triangular mesh surfaces

The basic strategy to extend the motif analysis to the triangular mesh freeform surface is to apply the watershed segmentation to the topographical features which are residing on the underlying "form" surface. In case of the traditional surfaces, the "form" surface is basically planar. The areal motif analysis can be extended to freeform surfaces by applying to the topographical features defined on the basis of the "form" surface. For mesh data, the exact positions of mesh vertices are not directly related to the computation. It is the topological connection of the vertices and the values of the chosen height function that determines the watershed segmentation.

3.1. Form removal

It is straightforward that the initial process will be the extraction of the "form" surface. It would be ideal to fit a normal surface to the mesh data. However the surface nominal equation is not usually available in practice. It is proposed to use morphological operations to extract the surface form component.

In brief, the rolling ball is employed as the structuring element and the surface under inspection is the input object. It is a nonlinear operation in that as the ball is rolling over the surface, it follows the general shape of the surface but the fine textures of the surface will be skipped. To be more precise, the fine textures having the curvatures larger than that of the ball will be suppressed. If the ball is rolling above the surface (morphological closing operation), the fine dale features are suppressed; and if scanning below the surface (morphological opening operation), the fine hill features are removed. These two operations can even be combined to yield an overlapping effect that the fine hill and dale features are both suppressed.

The traditional morphological methods are applicable to lattice data. Recently we developed a more general algorithm which can both work for the lattice data and mesh data [13]. The algorithm is based on the link that in discrete case the morphological envelope is equivalent to the alpha hull of a point set. By computing the boundary of the alpha shape facets, the morphological envelope can be derived and regarded as the "form" surface. The topographical features can then be extracted by comparing the original surface with the "form" surface. The vertex heights are given by the closest distances between two surfaces.

3.2. Construction of the Pfaltz graph

The Pfaltz graph is a topology network that can be used to describe the general structure of a surface [14]. The vertices of the Pfaltz graph are the peaks, pits and saddles of the surface topography. The lines linking the vertices indicate their interrelations, which are actually the ridge lines and the course lines. See Figure 1 as an example of the Pfaltz graph. Discrete algorithms are available to compute these critical points and lines [15, 16]. A peak point is a local maximum and a pit a local minimum. A hill is an area containing a peak and has all closed paths within the neighbourhood lower than this peak. A dale is an area containing a pit and has all closed paths within the neighbourhood higher than this pit. The saddle point has at least two portions of the closed path that are lower in height and two portions higher in height. To track the ridge line, it can start from the saddle point following the upward steepest path to a peak. Likewise tracking from the saddle point by following the downward steepest path can locate the course line. The boundaries formed by the ridge lines and the course lines produce the initial segmentation to the dales and hills features respectively.

3.3. Over-segmentation combination

The initial watershed segmentation tends to produce many tiny segments (motifs) due to local extremes or the measurement noise. It is requested to combine these tiny motifs because they are insignificant from the aspect of the surface functionality. This is done by pruning those peaks and pits from the Pfaltz graph which have the height lower than the pre-defined threshold. For example, a threshold of 5% can be set such that all those peaks or pits have their height lower that the 5% of the maximum height will be removed. See Figure 2 for an example of removing the peak "Pk4".

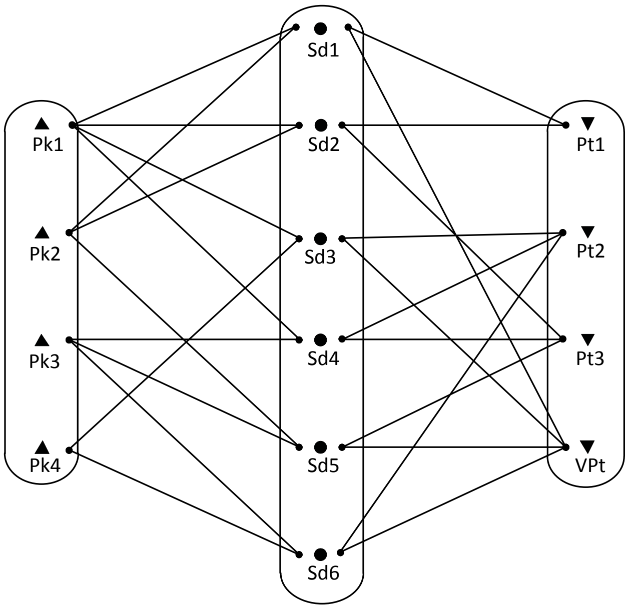


Figure 1. The Pfaltz graph.

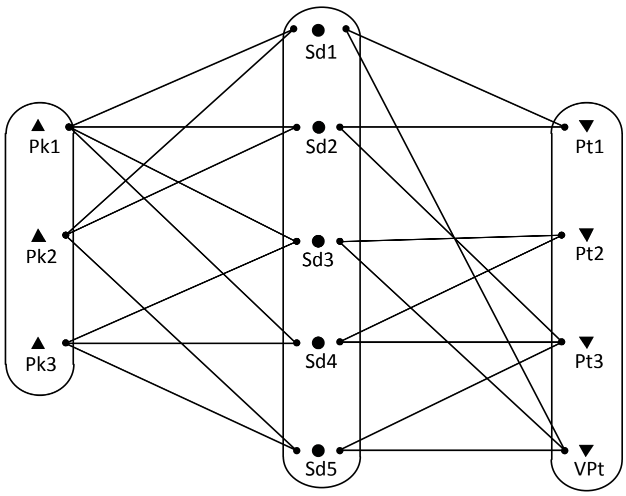
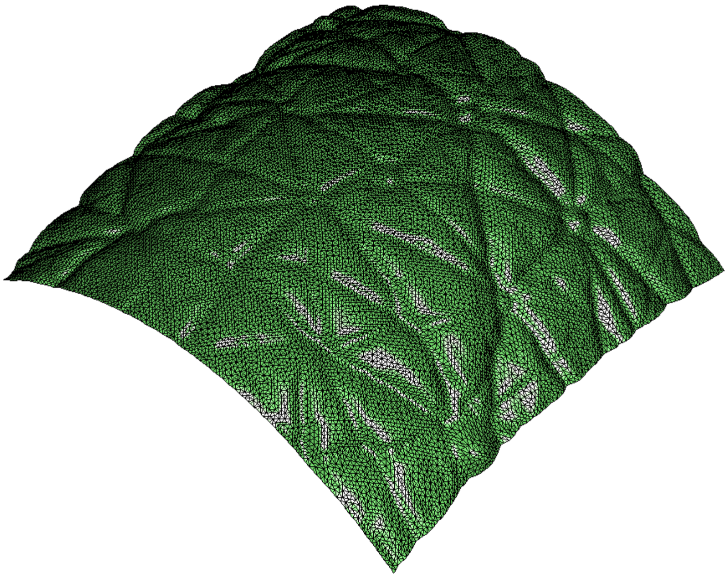


Figure 2. Prune a peak on the Pfaltz graph.

4. Example

A human skin surface illustrated in Figure 3a is employed as the object for the proposed areal motif method. Figure 3b shows the resulted course lines without merging tiny motifs. It apparently indicate the skin line network, however these lines also includes some others which are obviously not part of the network. Figure 4 presents the result with 5% pruning threshold. Much better result is observed that the segmented regions basically reveal the skin texture cells.



(a)

(b)

(c)

Figure 3. Motif analysis of an example skin surface: (a) Measured surface; (b) Segmentation without combination; (c) Segmentation with 5% pruning threshold.

5. Conclusion

Surface characterisation techniques are progressing with the shifting of surfaces. The motif method was updated from the profile version to its areal counterpart, which was proved to be a big step forward. The modern freeform surfaces impose obstacles to the areal motif analysis since these surfaces comprise significant form and are usually specified by the triangular mesh. A strategy is proposed to extend the motif method in this situation. The morphological rolling ball approach is adopted to extract the heights on the basis of the “form” surface. Then the watershed segmentation is applied to the heights whose connections are defined by the mesh. The over-segmentation problem is overcome by pruning the Pfaltz graph of the surface. An example is illustrated to show the result of the proposed method.

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