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Morphological Filters Based on Motif Combination for Functional Surface Evaluation

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Abstract—Regarded as the complement of commonly used mean-line based filters, morphological filters are more function oriented. They are relevant to geometrical properties of surfaces and provide better results for functional evaluation of surfaces. The paper first gives a brief introduction to morphological filters. An algorithm to implement morphological filters is proposed, which is based on the motif combination. Experimental data are presented to illustrate the algorithm's superiority in performance. The end effect of morphological filters is corrected by the reflective padding. Either circular or horizontal structuring element is available using this method. Two examples of applying the morphological closing filter with the disk and the line-segment structuring element on a milled surface profile are illustrated. Finally, the morphological alternating sequential filter is employed to evaluate the roughness of functional stratified surfaces as a replacement to the two-stage Gaussian filter.

Keywords-morphological filters; motif combination; surface texture; functional analysis

I. INTRODUCTION

Surface finished has always been important in engineering as it plays two critical roles: on one hand it helps to control the manufacturing process; On the other hand it helps functional prediction. Over the years, more attentions were given to the former, while less work has been done for functional evaluation. This leads to the abundance of mean-line based evaluating techniques (Gaussian filter, spline filter etc.) and the propagation of characterizing parameters (Ra, Rz, Rq etc.) [1]. However mean-line based techniques and parameters are designed to describe the average statistical characteristics of surface textures. In contrast, the envelope filter, achieved by rolling a ball over the surface, is more related with geometrical properties of surfaces and offers better results for functional prediction of surfaces [2].

With the introduction of mathematical morphology, morphological filters emerged as the evolution of the traditional envelope method [3, 4]. Morphological filters are essentially the superset of the early envelope filter, offering more tools and capabilities. They are carried out by performing morphological operations on the input surface with circular or flat structuring elements. Over the last decade, morphological filters have found many applications in practice. The morphological closing filter was utilized to approximate the conformable interface of two mating surfaces [5]. The morphological alternating symmetrical filter was employed to decompose the surface topography of an internal combustion engine cylinder [6]. ISO 16610-49 [7] illustrated an example of detecting the defective milling mark from a milled surface using the morphological scale-space technique.

This paper proposes a morphological method based on the motif combination and illustrates its usage for the evaluation of stratified functional surfaces. Section 2 gives a brief introduction to morphological filters. An algorithm based on the motif combination is presented in Section 3. Section 4 illustrates two examples of applying morphological closing filters using the disk and the line-segment structuring element respectively. A discussion to the algorithm is given in Section 5. In section 6, we use morphological filters to evaluate stratified functional surfaces and demonstrate their superiorities over the two-stage Gaussian filter. Finally Section 7 reaches the conclusion.

II. MORPHOLOGICAL FILTERS

Morphological filters are based on four basic morphological operations, namely dilation, erosion, opening and closing. They form the foundation of mathematical morphology [8].

Dilation combines two sets using the vector addition of set elements. The dilation of A by B is:

$$D(A, B) = A \oplus \overset{\vee}{B}.$$

where $\overset{\vee}{B}$ is the reflection of B through the origin of B.

Erosion is the morphological dual to dilation. It combines two sets using the vector subtraction of set elements. The erosion of A by B is:

$$E(A, B) = A \ominus \overset{\vee}{B}.$$

Opening and closing are dilation and erosion combined pairs in sequence. The closing of A by B is given by applying the dilation followed by the erosion,

$$C(A, B) = E(D(A, B), \overset{\vee}{B}).$$

Fig. 1 demonstrates an example of the closing of an open profile by a disk. The closing envelope is the lower locus of the disk rolling over the measured profile from above.

Opening is the morphological dual to closing. The opening of A by B is given by applying the erosion followed by the dilation,

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$$O(A,B) = D(E(A,B), \check{B}).$$

In contrast to Fig. 1, Fig. 2 presents the opening envelope of the profile which is obtained by rolling the disk over the profile from below.

Morphological operations are nothing new in surface texture analysis. The scanning of the tactile stylus over the workpieces surfaces, as a common practice in roughness measurement, is a morphological dilation operation. The mechanical surface could be reconstructed by carrying out on the measurement data the erosion operation with a sphere of the same radius as the stylus [9].
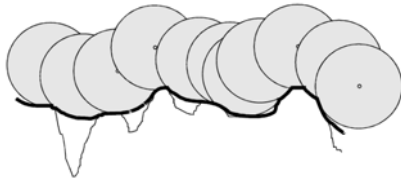
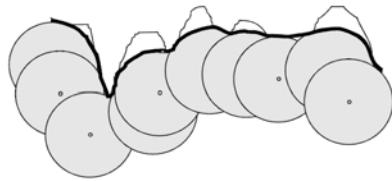

Figure 1. Closing of an open profile by a disk.

Figure 2. Opening of an open profile by a disk.

III. ALGORITHM BASED ON MOTIF COMBINATION

ISO 16610-41 [10] presents a basic method to compute discrete morphological filters. It puts the origin of the structuring element at every point of the input profile, as illustrated for a few positions of a circular structuring element for dilation in Fig. 3. Extreme value at each position is collected and they form the output envelope. The extreme heights for input points are the results of adding the ordinates of input profile points with the ordinates of sampled points on the disk, as marked by the top-most stars at vertical lines in the figure. Due to the duality of the dilation and the erosion, the erosion could be easily computed by first flipping the structuring element and later flipping the dilation results,
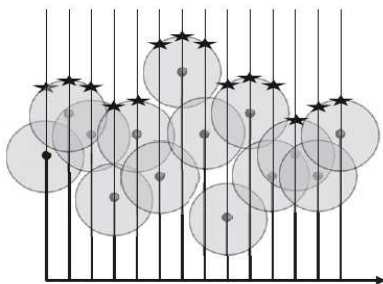
$$E(S,B) = -D(S, -B).$$

Figure 3. Dilation of discrete measured points with a disk.

This method follows the definition of morphological operations and therefore it is called as the naive algorithm. Scott [11] proposed an alternative way to calculate the profile envelope using the motif combination. A couple of definitions were given as the data type used in the motif combination algorithm.

Events: an event split the profile into a number of discrete sections. The events might be the highest points on all the local peaks or all the upcrossing of the profile through a reference line or even every sample point of the profile. They are numbered in order along the profile. The initial set of events is all the sample points on the profile.

Motif: a motif (i, j), where i < j, consists of that section of the profile between the ith and jth events.

Motif Combination Test: it is performed on two adjacent motifs (say, two motifs (i, j) and (j, k)) with the common event (say, j) to determine if the common event is significant or not. If the event is not significant, two adjacent motifs to that event are combined (say, motifs (i, j) and (j, k) are combined to form a new motif (i, k)) and thus the event is eliminated.

The motif combination procedure eliminates insignificant motifs and obtains significant ones. It is consistent with the functionality of morphological filter in that the features on the profile smaller than the structuring element in size are removed by the filters. This consistency provides an access to computing morphological filters by means of the motif combination. For rolling a disk on the profile, the functional motif combination test is to check if the disk is possible to contact the common event by placing the disk on two adjacent motifs, as illustrated in Fig. 4. For sliding a horizontal line-segment (the line-segment is not allowed to tilt), the test is to check whether the line-segment could contact the common event from above (See Fig. 5).
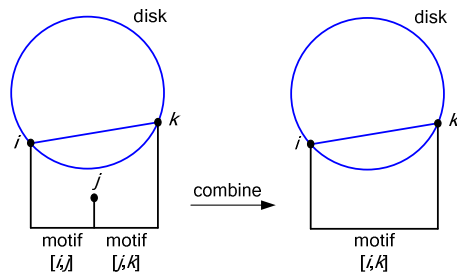

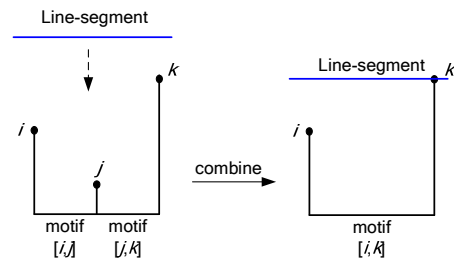
Figure 4. Motif combination by rolling a disk.

Figure 5. Motif combination by sliding a line-segment.

The motif combination procedure starts with the set of all events, namely all the sampled data on the profile,

and then it eliminates insignificant events by repeatedly applying the motif combination test on adjacent motifs until all the motifs could pass the test. The set of events on the motifs in the final solution are the discrete points that the disk could contact from above, namely the closing envelope. The pseudocode of the motif combination algorithm is presented in Fig. 6. The profile motif combination method results in a sequence of the points which may contact the structuring element when it is moving along the profile. With the final motifs, the closing envelope ordinates are computed by interpolating points on the arcs determined by the motifs at each sampling position for the circular structuring element, and finding the minimal height of two events on the motif for the line-segment structuring element, respectively.

Alogrithm *MotifCombination*(*S*, *r*)
{Given a data set *S* with *n* points and the chosen}
{disk radius *r*, compute the final motifs *motifs* }

Chain list *motifs*= {(p_1, p_2), (p_2, p_3), …, (p_{n-1}, p_n)};
while 1
    if *CombineMotifs*(*motifs*, *r*)
        break;
    end if;
end while;
return *motifs*;

Procedure *CombineMotifs*(*motifs*, *r*)
flag = false;
motif1 = *motifs*(1);
for *i* = 2 **to** *motifs.length*
    motif2 = *motifs*(*i*);
    if *CombineTest*(*motif1*, *motif2*, *r*)
        motif1 = {*motif1.Start*, *motif2.End*};
        motifs.Remove(*motif2*);
        flag = true;
    end if;
end for;
return *flag*;

Figure 6. Motif combination algorithm.

IV. ALGORITHM DISCUSSION

The motif combination algorithm sets out to eliminate insignificant motifs and obtain significant motifs. It is an iterative method that the motifs are merged repeatedly until no more combination occurs. The final motif events are the contact points. This algorithm is coincident with morphological filters due to the fact that the features on the profile smaller than the structuring element in size are removed by the motif combination.

To evaluate the performance of the algorithm, it is necessary to analysis the time complexity of the algorithm. For the naive algorithm, the worse case is that the size of the structuring element is larger or equal to twice of the profile length. The calculation of each envelope ordinate involves the whole profile data, thus for worst case the time complexity is O(n^2). For the motif

combination approach, the iterative process has the time complexity O(n).

In order to verify the actual performance, experiments are carried out on the profile data with the point amount varying from 1000 points to 80,000 points. The profile data were sampled from a metal sheet surface. The evaluation length is 80 mm with the sample interval 1 μm. The morphological closing filter with the 5 mm disk was performed on the profile data using the naive algorithm and the motif combination algorithm respectively. These algorithms were implemented by Visual Studio C++ and ran on a computer with 3.16GHz Intel Core Duo CPU and 3GB RAM. The performance data are listed in Table 1. It is obvious that the motif combination algorithm achieves much better performance than the naive method, especially in the case of large amount of sample points.

TABLE I.   ALGORITHM RUNNING TIMES ON VARIOUS AMOUNT OF PROFILE DATA

Algorithm	5,000	10,000	40,000	80,000
Naive	0.0010s	1.0294s	4.8391s	9.9274s
Motif Combination	0.0076s	0.0157s	0.0609s	0.1238s

End distortion is common for the filtration of open profiles. Morphological filters are of no exception. For mean-line filters, a common solution is to add sufficient zeros to two ends of the profile, referred as zero-padding. Zero-padding is not suitable for morphological filters because the padded part of the profile should not be geometrically viewed as a horizontal line with zero height. Instead it should reflect geometrical features of the profile ends. To achieve this, the padding of the profile data is conducted by reflecting the two ends of the profile in the range of half size of the structuring element. Fig. 7 demonstrates the reflective padding of the profile data.
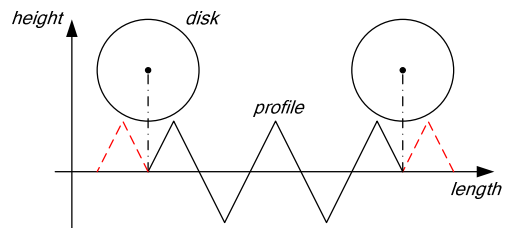

Figure 7. Reflective padding.

V. EXPERIMENTAL STUDIES

Fig. 8 and Fig. 9 illustrate two examples of applying the closing filter to a milled surface profile with the disk and the line-segment structuring element respectively. The experimental profile consists of 250 sample data, with length 1.25 mm and sampling interval 5 μm. In Fig. 8, the profile is filtered by a 0.5 mm disk. The figure presents the closing envelope on the top of the profile, along with the solution motif events marked by dots. Fig. 9 presents the results of the morphological closing filter with line-segment length 0.1 mm.
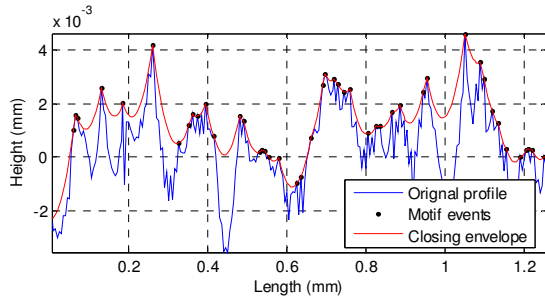
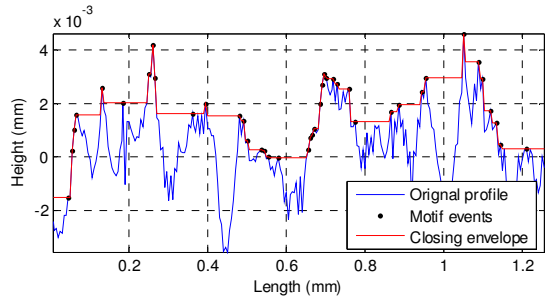Figure 8. Closing envelope with disk radius 0.5 mm and motif events.

Figure 9. Closing envelope with line-segment length 0.1 mm and motif events.

## VI. EVOLUTION OF STRATIFIED FUNCTIONAL SURFACES

In engineering, surfaces with stratified functional properties are very common, for instance, the inner surface of cylinder liners. These kinds of surfaces are composed of deep valleys superimposed by plateaux. The plateaux support force bearing and friction while the valleys serve as lubricant reservoirs and distribution circuits. The traditional method for the analysis of these surfaces is performed by applying the two-stage Gaussian filter, the so-called Rk filter. However there are several drawbacks of this method [12]. Firstly, it was derived from empirical foundation with a significant assumption: surface contains a relative small amount of waviness, which is ambiguous and confusing. Secondly, running-in and running-out sections are generated from the Gaussian filter. These sections truncate the profile and only 20%-60% of the measurement data are used in evaluation.

In contrast, by using morphological filters, the profile does not need to be pre-processed to remove the form. The roughness profile can be obtained over the complete measurement length, therefore the resulting roughness profile has no running-in and running-out sections being "removed". Fig. 10 presents such an example. The experimental profile was extracted from a plateau honed surface. It is obvious that the profile contains certain form component. Morphological alternating sequential filter, combination of first the closing filter and then the opening filter, with disk radius 5 mm, is employed to generate the reference line (See Fig. 10(a)). The closing filter suppresses all the valleys on the original profile that are smaller than the disk in size and the opening filter removes all the peaks on the resulting closing envelope which are smaller than the

disk. The roughness profile is obtained by subtracting the reference line from the original profile (See Fig. 10(b)).
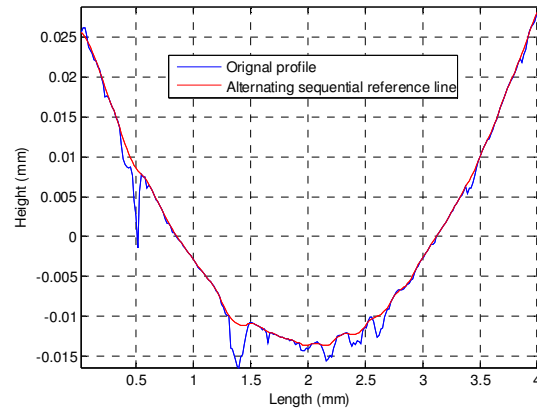
(a)   Original profile and reference line.
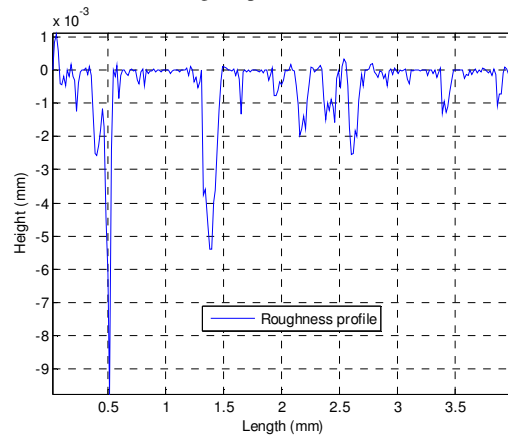
(b)   Roughness profile

Figure 10. Roughness profile from an alternating sequential filter with disk radius 5 mm. (a) Reference line; (b) Roughness profile.

VII. CONCLUSION

Regarded as the complement of mean-lined based filters, morphological filters provide better results for functional evaluation of surfaces. A practical algorithm is proposed to implement the morphological filters for profile data. The algorithm is based on the motif combination, which is an iterative process. The experimental data shows that it is superior to the naive algorithm in performance, with the time complexity $O(n)$. The end effect of morphological filters is corrected by the reflective padding. Both circular and horizontal structuring elements are available using this method. Two examples of applying the morphological closing filter with the disk and the line-segment structuring element on a milled surface profile are illustrated. Finally, the morphological alternating sequential filter is employed to evaluate the roughness of stratified functional surfaces. It has many merits over the tradition two-stage Gaussian filter. The profile does not need to be pre-processed to remove the form and the roughness profile can be obtained over the complete measurement length without truncated sections.

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