A feasible way to analysis microstructures on a surface based on the extraction and construction of geometrical features

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Surface texture is well-known as an important factor in determining the satisfactory performance of a workpiece. Surface parameters, which have been defined in ISO standards, can characterise the surface texture well in many applications. However, roughness analysis may be ineffective in evaluating non-stochastic surfaces such as structured surfaces, as their function is highly dependent on the geometrical features of the structures rather than the surface roughness. Therefore, it is very important to be able to extract these geometrical features from measured surface data. This paper introduces a new procedure for the analysis of surface geometrical features. The aim is to inspect geometrical features and calculate their characteristics for further evaluation and verification. Firstly, a pattern analysis method which is described in ISO25178-2 is proposed to extract these geometrical boundaries. Secondly, curvature variation is selected as the criterion to find the joint points of straight lines and circular arcs which are approximated by using a least squares method. Finally, these extracted primitive segments can be reconstructed as geometrical features such as circles, slots and keyholes. Furthermore, their intrinsic characteristics (e.g. the centre point of a circle) and situation characteristics (e.g. centre distance between two circles) can also be characterised.

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1. Introduction

Surface roughness as a measure of surface texture plays an important role in determining how a real object interacts with its environment. A series of parameters which has been defined in ISO standards can be calculated to represent corresponding surface texture in a quantitative way. Although roughness analysis is accepted as an effective way to predict the performance of a surface, it is ineffective in evaluating a surface such as structured surfaces whose functions are highly dependent on the geometrical features of the structures rather than the surface roughness. Similarly, the deviations of these real geometrical features from their ideal form should be figured out for the quality evaluation.

At present, there are no appreciable instruments for the measurement of these tiny geometrical features on a surface directly. However, they can be measured indirectly by using surface instruments, and then be extracted with mathematic algorithms. In this paper, a pattern analysis method which is described in ISO25178-2[1] is proposed to extract boundaries of the geometrical features. As these boundaries are sets of discrete points, it is not convenient to represent the characteristics of geometrical features directly. A further segmentation based on these boundaries is imperative for the recognition, extraction and construction of geometrical features. The objective of segmentation is to use a minimum number of primitive pieces to approximate these boundaries with minimum distortion. During the last two decades, many techniques have been proposed for this purpose. Polygonal approximation is the simplest approach, but it is rarely used for further shape analysis. About 80-90% of the tested surface of the workpiece is a combination of simple geometrical features (such as line, circle)[2]. Hence, boundary segmentation using line segments and circular arcs is selected, and it is a better representation than polygonal approximation.

Realising the recognition and construction of predefined geometrical features based on those primitive segments is essential for the further characteristics analysis. For simplicity and commonly applications, circle, slot and keyhole are the primary geometrical features to be analysed. There are two types of characteristics defined in GPS standards, intrinsic and situation characteristics. The major work of this paper is to propose a method to calculate these characteristics of geometrical feature for the evaluation of structured surfaces.

2. Surface segmentation

Surface segmentation is an essential procedure for the geometrical features analysis. The edge information of the microstructures on a surface cannot be acquired by measurement due to their limited scales. Although there are many techniques have been implemented for edge detection, they are mainly used for image processing and analysis. In the field of surface metrology, a pattern analysis method [1, 3] based on morphological analysis has been developed for analysing microstructure featured surfaces. This segmentation method can be used to determine regions of a scale limited surface which define the scale limited features. Regions consisting of hills and dales on the scale limited surface are separated from each other. The boundaries between hills are course lines, while those between dales are ridge lines. It is demonstrated that ridge and course lines are maximum uphill and downhill paths emanating from saddle points and terminating at peaks and pits. Therefore, a scale limited surface can be organised by networks of critical points: peaks, pits and saddles points in addition to critical lines: ridge lines, course lines. Unfortunately the result of the segmentation is initially disappointing as the surface is separated into a large number of insignificant tiny segments. Thus it is necessary to merge these tiny segments to a few large significant segments. Height and area pruning method of the surface networks with appropriate thresholds can be implemented to obtain a more reasonable segmentation result.

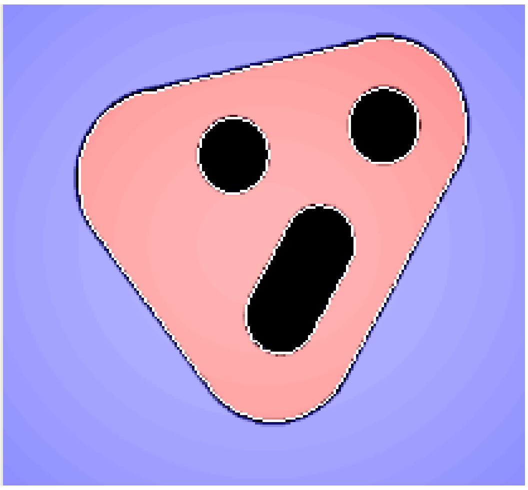

Fig. 1 Demonstration of surface segmentation

As the magnitude of altitude difference between regions of microstructures and other regions is usually much greater than that of roughness, the boundaries can be extracted out very effectively by further processing of the surface segmentation analysis. Figure 1 illustrates the result of surface segmentation of a surface data, and it shows that the boundary curves of geometrical features have been extracted out. In fact, the reliability and accuracy of boundaries are not only determined by the threshold used for segmentation, but also the clarity of microstructures. If the microstructures on a surface suffer ambiguity that may be caused by manufacture or measurement, it is impossible to obtain the intended boundaries by surface segmentation.

3. Boundary curve approximation

The boundaries of geometrical features usually cannot be represented by only one segment, so the segmentation of boundary curves is necessary before the features recognition and shape analysis. Many techniques of planar curve segmentation have been proposed in the literature. For instance, Biswajit Sarkar et al.(2003) use genetic algorithms to realise the approximation of planar curves[4]. Wu Chih Hu (2005) has developed a methodology for planar curve segmentation with line segments and conic arcs based on the types of breakpoints[5]. In this paper, boundary curves are segmented into lines and circular arcs based on curvature variation, and then least square methods are applied for the fitting of them. Figure 2 is a boundary curve which is the result from the surface segmentation of last section.

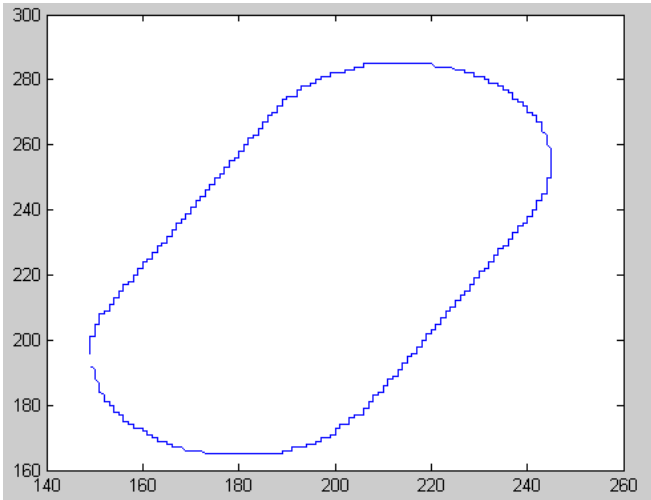

Fig. 2 One boundary curve of a geometrical feature

Curvature as a significant difference between lines and circular arcs is selected to find out the joint points which separate the whole boundary curve into primitive segments. To do this, each curvature of each point on the boundary needs to be calculated. Practically, curvature calculation in accordance with its formula cannot be applied here directly, as the boundary curves are mostly not smooth curves and the noise has a great impact on the result. A better way to get curvature is to calculate the radius of curvature which is the reciprocal of curvature.

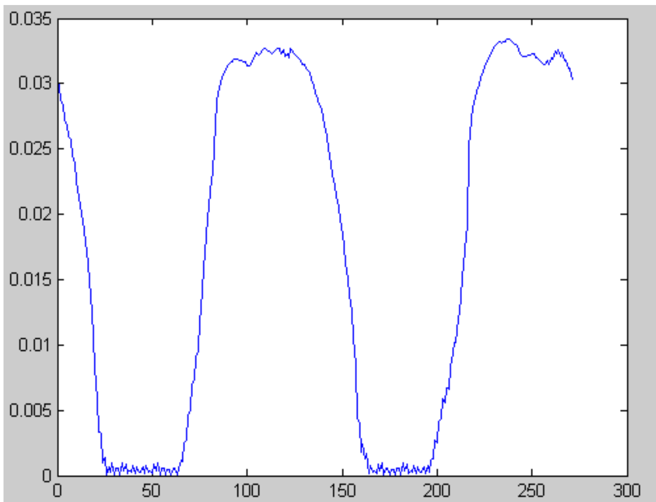

Fig. 3 Curvature of each point on the boundary curve

The calculation procedure of radius of curvature is very easy and described as follows. A boundary curve can be defined using the parameterisation (x(i), y(i)) ($0 \le i < N$), where x(i) and y(i) are two functions of the index variable *i*, and N is the number of points. To calculate the radius of curvature of point P(x(*i*), y(*i*)), sufficient adjacent points should be taken out. A possible choice is to taking k points from each side of P respectively and point P, so the total number of points used for circle fitting is 2k+1. If the boundary curve is not closed, this number is less than 2k+1 for those points at the end sides of the curve. The parameter k determines the magnitude of the variation of curvature among adjacent points. Figure 3 illustrates the curvature of all points on the selected boundary curve. After the curvature calculation, the joint points can be found out by taking the derivative of the curvature along the curve and locating the high spikes on the derivative as shown in figure 4.

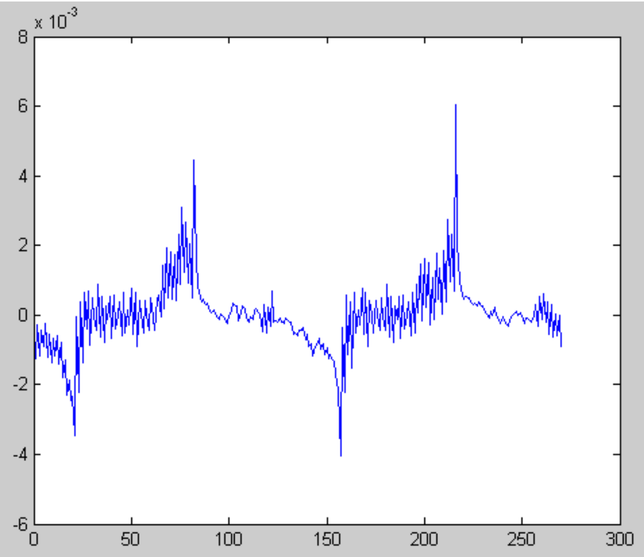

Fig.4 Derivative of curvature along the boundary curve

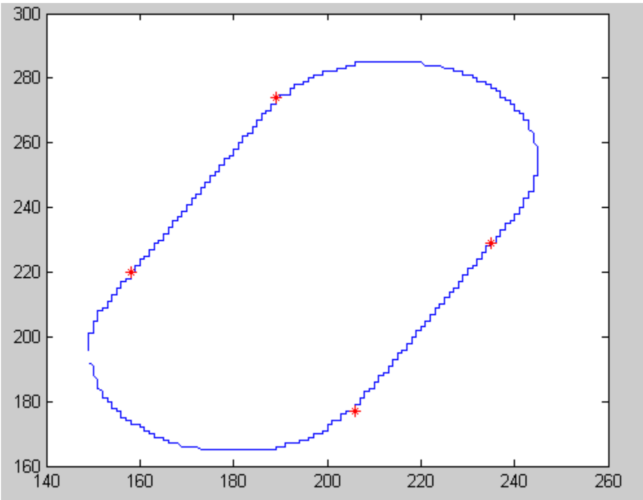

Fig.5 Extracted joint points of the boundary curve

According to the calculated joint points as shown in figure 5, a boundary curve can be separated to many short curve segments. A segment contains all the points between two adjacent joint points. However, before the approximation of a segment, its objective function of it is required. In other words, whether the segment is a line or circular arc needs to be determined in advance. The curvature of a point on a line, which is zero theoretically, should be very close to zero. A threshold can be chosen to simplify this determination. If the curvature is over this threshold, the segment is a circular arc; otherwise, it is a line. Thus, all segments that can be divided by joint points can be fitted by using least-squares method, and they can be used for the recognition and characteristics analysis of geometrical features.

4. Geometrical features construction

Various geometrical features can be constructed by combining lines and circular arcs with different quantities and sequences. For simplicity, circles, triangles, quadrilaterals, slots and keyholes are considered in this section. Suppose that C indicates a circular arc and L a line. These geometrical features could be expressed by a sequence of circular arcs and lines.

Geometrical features	expression
Circle	C
Triangle	LLL
Quadrilateral	LLLL
Slot	CLCL(LCLC)
Keyhole	CLLL(LCLL,LLCL,LLLC)

Table 1 Combination patterns for common geometrical features

Generally, each boundary curve is a combination of line segments and circular arcs after the processing of the boundary approximation. A boundary curve can be identified as a kind of geometrical feature by comparing their segment expressions. The boundary curve of figure 5 is recognised as a slot whose expression is 'CLCL'. Nevertheless, some boundary curves cannot be recognised as they are either ambiguous or beyond the scope of this paper. The interested geometrical features which have be predefined in Table 1 can be constructed from boundary curves, furthermore, the characteristics of these geometrical features can be quantified for the surface evaluation and verification.

Characteristic analysis of geometrical features includes their intrinsic characteristics as well as the situation characteristics between two features. For instance, centre point and radius are intrinsic characteristics of a circle feature. However, the distance between two centre points can be thought as a situation characteristic which reflects the relationship of two geometrical features. In ISO/TS17450-1 situation characteristics, which are length and angle, can be separated into location characteristics and orientation characteristics[6]. In this paper, both the intrinsic characteristics and situation characteristics are calculated and listed according to its feature type in table 2.

ParaName	Type	Value	Valid	Nominal	Lower	Upper	Unit
S2_A1|Radius	Radius	67.8600...	F	67	-0.5	0.5	um
C4_C0|Radius	Radius	69.0999...	P	69	-0.5	0.5	um
C3_C0|Radius	Radius	69.0999...	P	69	-0.5	0.5	um
S2_L0|Length	Length	139.240...	F	130	-5	5	um
S2_A1|Angle	Angle	-183.77...	F	-190	-5	5	deg
S2_L2|Length	Length	144.119...	P	140	-5	5	um
S2_A3|Radius	Radius	67.7300...	F	67	-0.5	0.5	um

Table 2 Characteristics list of geometrical features

5. Conclusions

This paper presents a new method for surface analysis based on geometrical features. It may be applied for analysing structured surface whose geometrical features are crucial factors instead of roughness. In this method, surface segmentation is implemented by using a pattern analysis method as defined in ISO25178-2. Primitive geometrical segments can then be acquired by boundary curves segmentation based on curvature variation. Finally, geometrical features can be recognised automatically by comparing combinatorial patterns of their primitive segments with the predefined ones. The procedure ends with a characteristics analysis of these geometrical features. The demonstrations in this paper show that it is feasible, efficient and stable method for the extraction of geometrical features on structured surface.

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