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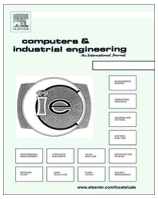

Optimized normal and distance matching for heterogeneous object modeling

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ABSTRACT

This paper presents a new optimization methodology of material blending for heterogeneous object modeling by matching the material-governing features. The proposed method establishes point-to-point correspondence represented by a set of connecting lines between two material directrices. To blend the material features between the directrices, a heuristic optimization method is developed to maximize the sum of the inner products of the unit normals at the end points of the connecting lines and minimize the sum of the lengths of the connecting lines. The geometric features with material information are matched to generate non-self-intersecting and non-twisted connecting surfaces. By subdividing the connecting lines into an equal number of segments, a series of intermediate piecewise curves is generated to represent the material metamorphosis between the governing material-features. A dynamic programming approach developed in our earlier work is presented for comparison purposes, and the computational efficiency of the proposed heuristic method is also compared with earlier techniques in the literature. Computer interface implementation and illustrative examples are also presented in this paper.

1. Introduction

Heterogeneous objects are made of different materials where each material contributes to a certain property. By properly controlling the constituent material compositions, a heterogeneous object can be designed to exhibit different properties in different areas of the object. If designed properly, these objects can perform better than their homogeneous counterparts in many different engineering applications because of their ability to satisfy multiple property requirements spatially (Samanta & Koc, 2005). In our earlier work (Samanta & Koc, 2005), we presented a feature-based heterogeneous object modeling method. Object features that control material composition are identified as material-governing features because they dictate the material variation inside the object. A lofting-based method (Samanta & Koc, 2005) was used to blend the material features. To generalize material blending between any material-governing features, a new method of material blending between the material governing features is presented in this paper. As shown in Fig. 1, a smooth transition between two given material-governing features is provided to blend the material properties for heterogeneous object modeling. This can be also used as shape blending, morphing, or metamorphosis, which is represented by a series of "in-between" curves generated as a linear combination of the input curves. In other words, a ruled surface is generated using the inputs as directrices (Choi, 1991; Peternell, Pottmann, & Ravani, 1999), and each isoparametric curve on the surface constitutes a stage of the metamorphosis.

In our previous work (Samanta & Koc, 2005), we found that the property requirement at each material-governing feature followed the normal direction. The outcome of the lofting process represents a smooth blending among its generators. In the case of surface lofting from generator curves, the resulting surface passes smoothly through each of the curves. In the same way, lofting can be used to get a smooth transition from one governing feature to another. As shown in Fig. 1, the property requirements at each of the generators are blended along the normal direction from the generators. It is assumed that each isoparametric entity in the blend direction will represent constant property requirements. Fig. 1 shows how two different material property requirements are blended using a lofting process. Two material governing features (curves) $MF_i\ (u)$ and $MF_j\ (u)$ are exposed to high and low temperatures, respectively, and therefore exhibit different property requirements. It is a known fact that, from a heated body, heat flows in the normal direction from every point of the body. Therefore, the isoparametric curves on the loft surface will represent iso-conditions (iso-temperatures). In the figure, the thicknesses of the curves show the temperature intensity and therefore different property

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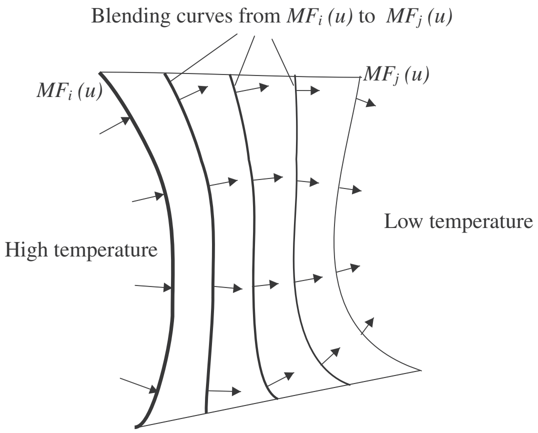

Fig. 1. Material (property) blending between two material-governing features MF_i (u) and MF_j (u).

requirements. To be able to blend the material between two or more generators along their normal directions, the normal vectors of the material-governing features must match. While matching the normal vectors, the following conditions must be met for smooth transition:

(a) The connecting lines must not intersect (there should not be any intersections of two or more ruling lines).
(b) The generated surface must not be twisted, i.e., the length of the ruling lines must be as short as possible.
(c) The end points of each ruling line must be *matching*, i.e., they must have some common or similar properties.

This problem can be generalized by generating a ruling surface between two directrices. A naïve way of constructing the ruling lines is by parametrically connecting the points on the two directrices. The rationale here is that both end points of each ruling line have the same parameter values. This does not guarantee a non-twisted ruled surface, particularly in the case of directrices given as closed curves. The surface may also become self-intersecting and therefore unsuitable for the material blending of metamorphosis, as also pointed out by Elber (1995) and Surazhsky and Elber (2002). Therefore, other sophisticated methods are required to find the "best" set of ruled lines that satisfy all the conditions mentioned above.

In the literature, several methods have been proposed, mostly catering to specific applications. For shape blending, attention is focused on establishing matching between the input curves based on common local properties such as position, edge/arc length, angle, parameter, tangent and curvature. Sederberg and Greenwood (1992) established vertex-to-vertex matching based on locations and angles at the vertices of 2D polygonal curves. The intermediate shapes are obtained by linear interpolation of the matched vertices. The method also tries to avoid local self-intersections. The same authors have used a similar method (Sederberg & Greenwood, 1995) in which the inputs are given as piecewise polynomial curves. Meek and Walton (2009) developed a blending formula for two open curve segments to generate accurate blending with better approximation.

When combinations of some of the common characteristics are found over a range of the input curves, they are referred to as "features." Although the exact definitions of "features" vary by methods, the common goal is to establish matching between the features and to ensure that they are maintained during the blending process. Hui and Li (1998) used 2D shapes composed of curve segments and defined rules in order to identify features. They developed algorithms to match the features based on their positions and shapes.

The approach of Cohen, Elber, and Bar-Yehuda (1997) is to establish matching between two given C^1 continuous parametric curves based on tangent maps. To construct a set of non-self-intersecting ruling lines, one curve is reparameterized with respect to the other by means of formulating an optimization problem. The objective is to maximize the sum of the dot products between the unit tangents to the curves at the matched points. Constraints are specified to avoid local self-intersection. An approximate solution to the problem is obtained by first discretizing the curves into piecewise polygonal curves and is subsequently solved using dynamic programming. However, the method is explained in detail only for matching open curves, where matching of the end points of the curves is constrained. For matching closed curves, the authors suggest using a k-shift of tangents approach.

Johan, Koiso, and Nishita (2000) also used optimization to match equally spaced sampled points from two given input curves. The objective here is to minimize the sum of a cost function, which is composed of a weighted sum of the difference of angles and difference of parameters at the matched vertices. Dynamic programming is used to solve the problem. The overall approach, as the authors mentioned, is an extension of earlier work (Cohen et al., 1997; Sederberg & Greenwood, 1992).

It is argued that feature identification and matching is important so that the matched features transform into each other smoothly while ensuring no deformation or distortion of the in-between curves. In most cases of shape blending, feature identification is easy because the input shapes already contain some similarities between themselves. Although this helps in achieving visually pleasing animations, the resulting ruled surface may not always be twist- or stretch-free. Moreover, in cases of input curves that exhibit very little or no similarity, it may be very difficult to identify common features. Therefore, in such applications, other local properties are used for establishing the matching.

In another work Wang and Tang (2005), the authors presented optimal boundary triangulations of interpolating ruled surfaces. This paper presented an algorithm for constructing an optimal triangulated ruled surface that interpolates two discrete directrices. The developed algorithm, called the multilayer directed graph, was used to establish an equivalence between the optimal triangulation and the single-source shortest path problem on the graph.

In the use of ruled surfaces in Computer-Aided Design and Manufacturing (CAD/CAM) applications, such as the adaptive ruled layers approximation for multi-axis machining in rapid prototyping, the directrices are given as two consecutive piecewise linear curves (or polygonal contours). In work by Koc and Lee (2002), the directrices were obtained by slicing a stereolithography (STL) file. The authors found the matching points so as to minimize the twisting of the resulting ruled surface by minimizing the total ruling line length. Both curves were reparameterized by means of inserting points so that one-to-one matching could be achieved.

For multi-axis machining of ruled surfaces (Bedi, Mann, & Menzel, 2003; Bohez et al., 1997; Chiou, 2004; Gong, Cao, & Liu, 2005; Koc & Lee, 2002; Marciniak, 1992; Monies et al., 2004; Senatore et al., 2005; Tsay & Her, 2001; Yang, Leu, & Zhou, 1998), the cylindrical or conical cutter contacts the surface along a ruling line. In the case of developable ruled surfaces, the axis of the cutter is parallel to the ruling line by a constant offset. Therefore there is no deviation between the machined surface and the designed surface. However, this is not the situation in the case of machining undevelopable ruled surfaces where it is impossible to avoid machining errors such as gouging and interference. Bohez et al. (1997), Yang et al. (1998), Tsay and Her (2001) and Senatore et al. (2005) showed that, for a cutter used for side milling of a ruled surface, the machining error is a function of the angle between the normal