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Tooth segmentation on dental meshes using morphologic skeleton

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ABSTRACT

Tooth segmentation has an important role in computer-aided orthodontics. However, fine segmentation results remain difficult to obtain because of various tooth shapes, complex tooth arrangements, and especially, tooth-crowding problems. Most published approaches or commercial solutions in this area are either interaction-intensive or inaccurate, and thus, we propose a novel tooth segmentation approach based on morphologic skeleton for scanned dental meshes. Strict single-vertex width boundaries are obtained through improved morphologic skeleton technique. The skeleton describes the topological relationship among different dental parts on meshes and is exploited by automatic adjacent teeth separation. The morphologic skeleton technique eliminates dependence on a complex, precise mesh feature estimation and is implemented efficiently. The characteristics of the skeleton also facilitate effective teeth separation. Our techniques significantly reduce user interactions and are robust to various levels of tooth-crowding problems. We have conducted experiments on clinical dental models, thus demonstrating the effectiveness of the proposed approach.

1. Introduction

Numerous dental clinics world-wide use orthodontic computer-aided-design (CAD) systems to prepare for treatments. These CAD systems exploit hardware-supported computer graphics technology to effectively and efficiently plan treatments traditionally done manually. These systems free clinical dentists from repeated work and facilitate accurate treatment planning. Orthodontic CAD systems have an important part in modern dentistry [1–3]. In computer-aided orthodontics, for example, after acquiring a dental model by scanning the teeth of the patient, the dentist often needs to extract all teeth separately from the model. After tooth segmentation, the dentist analyzes tooth positions and arrangements on a computer screen and runs simulations to work out an applicable treatment plan. During a treatment planning procedure, tooth segmentation is a critical part that produces segmented teeth with precision that significantly influences the accuracy of the following work. The efficiency of tooth segmentation is also critical because most dentists do not like spending hours just segmenting teeth.

However, tooth segmentation on dental meshes remains a difficult task. Dental meshes from patients often have teeth crowding problems when adjacent teeth crowd, thus making the interstices between them irregular and difficult to distinguish. Various tooth shapes make outlining tooth contours difficult. Artifacts resulting from scanning or model-making errors on commonly obtained clinical meshes make teeth segmentation more challenging. Normal mesh segmentation approaches are not directly suited for segmenting dental meshes because they lack adjustments to handle complex tooth shapes and teeth arrangements. Other segmentation approaches proposed to handle dental meshes have shortcomings, such as being either labor-intensive or not sufficiently accurate. Although several commercial products in this field are available, such as "3Shape", their user interactions are intensive and significantly influence the accuracy of results.

In this study, we propose a novel tooth segmentation approach based on morphologic skeleton techniques. Our approach requires less user interaction and manual parameter tuning. It is robust to various tooth shapes, complex tooth arrangements, and various levels of tooth-crowding problems. Furthermore, based on morphologic skeleton techniques, the proposed approach eliminates the need for a complex, precise estimation of mesh features, which is often critical in other works. The present approach only requires an efficient rough initial guess of mesh features.

Overall, our approach has three major benefits:

(1) User interactions are significantly reduced to obtain high-quality tooth segmentation results, with minimal parameter tuning.
(2) The morphologic skeleton based-techniques proposed in this study are both easy to implement and efficient.
(3) The techniques presented in this study are robust to various tooth shapes, irregular teeth arrangements, and common teeth crowding problems.

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2. Related work

In this section, we briefly review several related works on general mesh segmentation approaches in computer graphics as well as approaches specifically designed for dental meshes.

2.1. General mesh segmentation approaches

Numerous mesh segmentation approaches have been proposed in computer graphics. The most recent works include K-means [4], clustering or decomposition [5,6], fitting primitives [7], graph cut [8], normalized and randomized cut [9], watersheds [10], random walks [11], core extraction [12], shape diameter function [13], active contours or scissoring [14,15], fast marching [16]. Surveys have been conducted in [17,18]. These approaches can be briefly classified as region-classifying approaches [4–7,10,11,16] and boundary-outlining approaches [8,9,12–15]. Region-classifying approaches aim to find different regions based on similarity measures. These approaches regard segmentation by finding mesh regions or grouping different mesh regions. Boundary-outlining approaches attempt to find optimal curves that split two adjacent parts, often by maximizing differences among separated parts. These approaches regard segmentation as a task for finding cutting boundaries that clearly bound the segmented area. Non-supervised or semi-supervised machine learning approaches have also been proposed for mesh segmentation [19,20]. These approaches learn from databases that contain various mesh segmentation results to gain information that can guide them in segmenting meshes automatically.

However, when dealing with complex tooth shapes and segmentation arrangements, we need a more specific approach that fully exploits dental characteristics.

2.2. Dental mesh segmentation approaches

Both automatic and interactive approaches have been proposed for dental mesh segmentation.

Given that tooth boundaries are clear in projected 2D images, Yamany et al. [21] used a specifically designed mesh representation that maps 3D vertices onto 2D vertices and exploits 2D image segmentation techniques to segment teeth. Similarly, Kondo et al. [22] proposed an automatic approach by extracting interstice points on planar and panoramic range images, i.e., the projection of model vertices onto the occlusal plane and the side view along the dental arc, respectively. Their approach is highly automatic, with only an interaction of the occlusal plane specification. However, when the information provided by the two projected range maps is restricted, the aforementioned approach may not be able to extract several complex interstices. Using simple rectangular spokes along the dental arc to separate teeth may also miss some irregular interstices or lead to inaccurate cuttings. This problem is particularly critical when dealing with adjacent teeth with interstices with complex shapes. Another approach using range map images was presented in the work of Grzegorzek et al. [23]. These researchers used multiple parallel-range map images to obtain 2D contours and to cut adjacent teeth by connecting significant non-convex points on them. The contours are then refined with active contours and mapped back into 3D space. This approach produces precise 2D contours to use multiple range map images instead of single ones. However, restricting range map images from a single view leads to inaccurate tooth contours, and some of their critical non-convex points may be difficult to find on contours with complex shapes.

Given that image-based segmentation lacks information in 3D space, focusing on segmenting teeth directly on 3D meshes is reasonable. Zhao et al. [24] proposed an interactive approach based on user-specified separating points between adjacent teeth. The contour of each tooth is then selected by automatically connecting user-specified interstice points through tooth contours. However, the interactions of their approach are intensive for clicking at least two points for each tooth. The contours of their segmented teeth are also not guaranteed to be smooth enough. Kumar et al. [25] automatically identified interstices between teeth by connecting significant points on tooth boundaries that connect the lingual and labial sides and used them to cut adjacent teeth. Their approach works well on regular teeth but may not work on teeth with complex contours by misleading both sharp point extraction and cutting curve approximation. The commonly encountered crowding problem may also decrease the effectiveness of this approach.

Given that each tooth on a dental model can be supposed to have a closed contour around its bottom area, active contour techniques have also been exploited. Kronfeld et al. [26] proposed a snake-based approach that starts with an initial contour on the gingiva and evolves through a GVF-like feature attraction field. The cusps of each tooth are then selected to start a local tooth contour and to evolve until each tooth bottom is reached. Their approach is highly automatic but may not produce good results when the model has boundary noises that interrupt feature attraction fields.

Several commercial orthodontic CAD systems are also available, such as Insignia, Suresmile, and 3Shape. Among these products, only 3Shape provides teeth segmentation functionalities to end-users. However, the segmentation operation of 3Shape is interaction-intensive and may not produce good results if the required interactions are not sufficiently accurate.

In general, published approaches for teeth segmentation on dental meshes have at least one of the following problems:

(1) easily affected by boundary corruption,
(2) incapable of accurately finding interstices, and
(3) interaction-intensive.

We argue that a practical teeth segmentation approach should accomplish the following objectives:

(1) locate teeth on meshes automatically,
(2) separate adjacent teeth accurately with regard to various levels of crowding problems,
(3) acquire smoothed and well-fitted boundaries for teeth, and
(4) robust to mesh noises and less dependent on a complex and precise estimation of mesh features.

2.3. Mesh skeleton techniques

Mesh skeleton is used to represent the basic topological relations among different parts of a mesh. To put it simply, a mesh skeleton is a space curve to which the maximum distances of all vertices are the same. Skeletonization is a useful technique to obtain inherent geometric information within meshes and is used in various scenarios, such as in smoothing, simplification, segmentation, and animation. Typically, a mesh skeleton refers to the interior curve inside enclosed mesh surfaces; this skeleton is extracted by using either volumetric or geometric approaches [27]. Volumetric approaches use regularized volume representation to enclose all mesh vertices and faces to facilitate the process of peering outside parts iteratively [28–30], whereas geometric approaches directly work on mesh vertices and faces through techniques such as Voronoi graph [31], Reeb graph [32], deformable models [33], mesh decomposition [12], and mesh contraction [27].

In the present work, we aim to extract the skeleton on the surface for areas composed of connected triangulated faces; thus, the aforementioned approaches are unsuitable. We use a morphologic skeleton