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Combining volumetric dental CT and optical scan data for teeth modeling[☆]

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HIGHLIGHTS

- A novel teeth modeling framework by combining optical scan data and dental CT images is introduced.
- Co-segmentation between optical scan data and dental CT images is performed by the graph-cut method simultaneously.
- The proposed algorithm is automatic and time efficient, and shows high fidelity.
- Teeth data with defects such as metal artifacts can be completed successfully.

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ABSTRACT

Dental computer-aided design (CAD) systems have been intensively introduced to digital dentistry in recent years. As basic digital models, volumetric computed tomography (CT) images or optical surface scan data are used in most dental fields. In many fields, including orthodontics, complete teeth models are required for the diagnosis, planning and treatment purposes. In this research, we introduce a novel modeling approach combining dental CT images and an optically scanned surface to create complete individual teeth models. First, to classify crown and root regions for each set of data, corresponding pairs between two different data are determined based on their spatial relationship. The pairs are used to define the co-segmentation energy by introducing similarity and dissimilarity terms for each corresponding pair. Efficient global optimization can be performed by formulating a graph-cut problem to find the segmentation result that minimizes the energy. After classifying crown and root regions for each data set, complete individual teeth are obtained by merging the two different data sets. The advancing front method was successfully applied for merging purposes by considering the signed distance from the crown boundary of the surface mesh to the root surface of the CT. The teeth models which have detailed geometries obtained from the optically scanned surface and interstice regions recovered from volumetric data can be obtained using the proposed method. In addition, the suggested merging approach makes it possible to obtain complete teeth models from incomplete CT data with metal artifacts.

1. Introduction

Detailed digital models of individual teeth are required for many dental applications including orthodontic planning and simulation, dental implants, and jaw surgery. In the case of orthodontics, individual teeth models should be repositioned for diagnosis and planning purposes as well as simple visualization. Digital teeth models can be typically obtained by optical scanning or computed tomography (CT) scanning. One tooth is mainly composed of an exposed crown region and a root covered by gum or a jawbone. For the purpose of observing the morphology of each tooth, dental CT images are the best solution among current imaging modalities.

The importance of individual teeth segmentation has been raised and various approaches have been explored through various works. Gao et al. [1] extracted individual tooth contours explicitly from dental CT images using 2D level sets for each slice. They divided their algorithm into two stages: a single level set and coupled level sets for roots and crown segmentation, respectively. They also suggested a visualization framework of individual teeth

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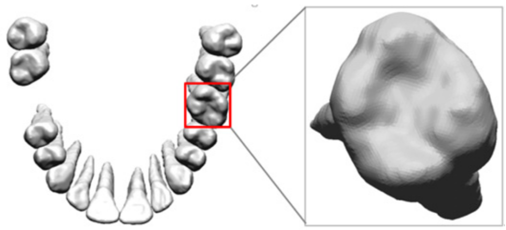
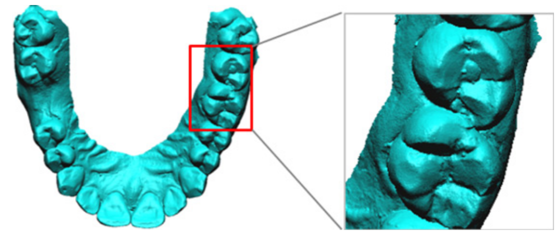
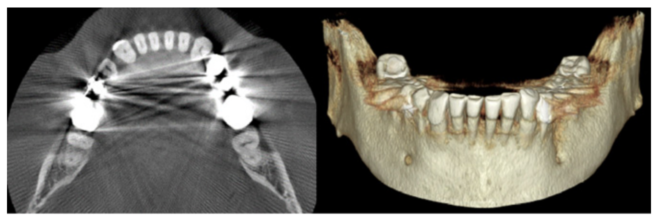


(a) Iso-surface extraction from dental CT.



(b) Optical scan data obtained from an intraoral scanner.



(c) Metal artifacts of CT images (left) and volume rendering (right).

Fig. 1. Comparison of spatial resolutions between CT and scan data (a–b); CT metal artifacts (c).

for orthodontics [2]. Hosntalab et al. [3] applied variational level sets to the 3D volume directly after generating panoramic images in the coronal view. In addition, there are several modeling services used by practitioners in commercial packages. One of the available commercial packages is *Anatomodel* of Anatomage Dental (Anatomage Inc., San Jose, CA, USA). However, these tools in dental services require many manual segmentation operations, and they require much time and human resources. In addition, the previous studies listed above, as well as commercial packages, are based only on dental CT images.

From a modeling point of view, using only CT images has several drawbacks. Dental CT images are, in general, obtained from cone-beam CT (CBCT) scanners with a low dose exposure and a small field-of-view (FOV) compared to general medical CT scanners. The image quality of CBCT scans has many artifacts and defects for various reasons. These artifacts make CBCT images insufficient in representing the detailed geometries, as shown in Fig. 1(a), which are important for dental implants and prostheses. Another critical problem of automatic teeth modeling with CT images is metal artifacts, as shown in Fig. 1(c).

Another major branch of teeth segmentation and modeling has been performed with optical scan data. These data have much higher accuracy (about 0.01 mm) than dental CT images, in general, but only include the exposed area in the mouth without distinction between the teeth and gingival regions, as shown in Fig. 1(b). To classify teeth from the data, several approaches use curvature values as a preprocessing step [4–7]. Because it is not a trivial task to separate teeth using only geometric information, one group used a training set to extract gingival contours by applying 3D statistical models [8]. However, it is not enough to extract only gingival contours in many dental applications because there are missing regions such as the geometries of interstices by occlusion. To resolve this problem, another group attempted to recover the geometries of interstices after removing valley-shaped regions [6]. Recently, Fan et al. [9] introduced an approach to segment individual teeth in the surface mesh using two phases segmentation. The input surface mesh is divided into small patches by low-level segmentation first, and similar neighboring patches are clustered by comparing the shape compactness. Nevertheless, there are still limitations in recovering unscanned areas because the geometries are basically missing.

To resolve this problem, we introduce a novel approach to construct digital teeth models by combining an optically scanned surface and dental CT images. In this approach, we extract crown regions from scanned surfaces with higher accuracy and root parts from dental CT images simultaneously by applying a co-segmentation concept using a graph-cut. The two segmented results are then combined seamlessly by considering the boundary shapes and adjusting different resolutions.

Our main contributions can be summarized as the follows:

– As we know, this is the first work for teeth modeling by combining dental CT images and an optically scanned surface data for the purpose of teeth modeling.
– We developed a co-segmentation method using dental CT images and an optically scanned surface data together for better segmentation results.
– The seamless merging of segmented regions from two different data types was developed to obtain each tooth model.

Co-segmentation schemes have been applied to general bitmap images obtained from digital cameras [10,11] or medical images [12,13]. There has been little study on different data types. Our technical approach for co-segmentation is similar to [10], but spatial irregularities of the surface mesh have led to a quite different formulation. In addition, we applied the classified results to merge them because our final goal was to obtain complete teeth models.

2. Overall procedure

Before describing the technical details of our approach, we will explain the overall procedure first. Fig. 2 shows a conceptual diagram of the overall procedure. From the volumetric CT images $\Omega \subset \mathbb{R}^3$, we extract separate individual teeth $V = V_1 + \cdots + V_n \subset \Omega$ where V_i is a segmented tooth region, $V_i \cap V_j = \phi$ and n is the number of teeth. This procedure is performed in 2 steps: first, the initial teeth region is extracted via optimal global thresholding and region growing with local thresholding. For optimal global thresholding, the Otsu's thresholding method is used to segment hard bone regions, including jaw bones and teeth. In the initial segmentation result, some of the teeth's surfaces are adjacent to jaw bones. To separate the teeth region only, the seed points for each tooth are marked manually and extracted by region growing with local thresholding. Our local thresholding finds connected voxels that are statistically similar to voxels surrounding the user defined seed points (voxels). The neighboring voxels of the boundary of the current active region are selected if their intensity is within [mean $\pm$ SD] of the active region, where SD is the standard