TEETH SEGMENTATION IN 3D DENTITION MODELS FOR THE VIRTUAL ARTICULATOR

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ABSTRACT

A virtual articulator is a system currently being developed for dentistry. It is supposed to virtually determine teeth antagonists and the occlusion surfaces between them. In contrast to state-of-the-art mechanical articulators, it should use 3D dentition models acquired with highly precise 3D scanners for this. These models, however, describe not only teeth surfaces. Neighbouring surfaces such as teethridge are also included in them. Thus, the first and unavoidable step in designing a virtual articulator is the segmentation of teeth from 3D dentition models. In this paper, we present a robust solution to this problem. First, 2D sectional images of the 3D models are generated and binarised. Second, 2D teeth outlines are estimated using active contours and summarised to 3D segmentation results. The algorithm has provided excellent experimental results and will be used in the industrial realisation of the virtual articulator.

***Index Terms*—** Teeth Segmentation, Active Contours, 3D Dentition Models, Virtual Articulator

1. INTRODUCTION

Dental treatments often require a functional analysis of movements of the mandible and of the various tooth-to-tooth relationships that accompany those movements. For the time being, this is practically done by a device called *mechanical articulator*. Mechanical articulators simulate the temporomandibular joints and jaws to which maxillary and mandibular casts are attached (see Figure 1, left). They are used in the fabrication and testing of removable prosthodontic appliances (dentures), fixed prosthodontic restorations (crowns, bridges, inlays and onlays), and orthodontic appliances. Mechanical articulators, however, feature some limitations. They have a small number of degrees of freedom, and their spatial accuracy is rather moderate - at least in comparison to the precision of state-of-the-art 3D scanners nowadays available in the medical industry.

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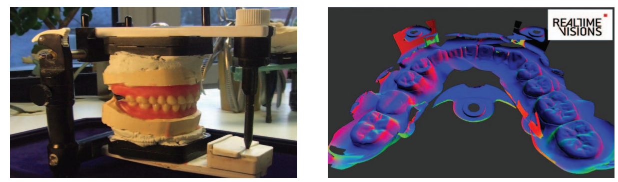

Fig. 1. Left: typical mechanical articulator. Right: 3D dentition model for the virtual articulator.

For these reasons, a cooperation project funded by the German Federal Ministry of Economics and Technology aiming at conceptualising and developing a *virtual articulator* has been initialised. The virtual articulator is a system with the same practical application as the mechanical one, however, it is working in a much more precise and convenient way. The system uses 3D dentition models in order to simulate, visualise, and log the motion of the maxillary and mandibular teeth relatively to each other. Moreover, it determines the teeth antagonists and the occlusion surfaces between them. It is not limited in the number of degrees of freedom and its high spatial accuracy is secured by precise 3D scanners applied for the acquisition of the dentition models. However, apart from the teeth areas, neighbouring surfaces such as teethridge are also included in the models (see Figure 1, right). Therefore, the first and unavoidable step in designing a virtual articulator is the segmentation of teeth from the 3D dentition models.

The list of requirements for the teeth segmentation approach has been created by dental doctors and technicians involved in the project. The segmentation algorithm must: (i) work with a high geometrical accuracy, (ii) require little user interaction, and (iii) provide segmentation results for a jaw with 16 teeth within few seconds. These requirements have significantly influenced the selection of our segmentation strategy and serve as a basis for its evaluation. Our approach starts with generating 2D slices from the 3D dentition models given as range images. Thus, the problem is reduced to the 2D segmentation task. One can distinguish between four main categories of 2D image segmentation algorithms, namely the pixel-based, the region-based, the contour-based, and the model-based methods. The pixel-based and the region-based approaches work very fast and do not require any user interaction, however, due to their simplicity they are unable to overcome the problem of artefacts in the data (e. g., wholes in the 3D dentition models). The contour-based strategy, still fast and fully automatic, is suitable for segmenting structures with clear boundaries. Unfortunately, neighbouring tissues visualised in dentition models are very similar to each other and there are no clear borders between them. Model-based methods are able to integrate a priori knowledge into the segmentation process and this is their huge advantage, if the application domain is so clearly defined as in our case. Therefore, we use active contours, a model-based approach, for segmentation in all the 2D images. Active contours use results of the contour-based and the region-based methods and integrate the object-based model knowledge into the segmentation process [1]. Finally, we summarise the 2D image segmentation results back to the 3D space which provides the 3D teeth models.

The paper is structured as follows. Section 2 overviews most relevant approaches for 3D segmentation. In Section 3, our own segmentation method is described. Section 4 comprehensively evaluates the approach using a manually created ground truth. Section 5 concludes the paper and states shortly our future work in the context of the virtual articulator.

2. RELATED WORK

Automatic teeth segmentation algorithms can be used for several purposes and there is some related work in this area. However, none of the published approaches has been applied for the virtual articulator, since its idea is new and has been initialised in our project. This makes the requirements our proposed method has to fulfil and, therefore, the segmentation algorithm itself original and novel.

The most related work has been published by Kondo et al. in [2]. This paper presents an automated method for tooth segmentation from 3D digitised image captures by a laser scanner. Similar to our approach, the authors avoid the complexity of directly processing 3D mesh data and process range images. They use two range images. They first obtain the dental arch from the plan-view range image and then compute a panoramic range image of the dental model. The interstices between the teeth are detected separately in the two range images, and results from both views are combined for a determination of interstice locations and orientations. Finally, the teeth are separated from the gums by delineating the gum margin. The authors tested their algorithm on 34 dental models, however, no gold standard has been used for evaluation.

There are further scientific contributions in this area. In [3] an automatic tooth segmentation method using active contours without edges is presented. Here, the authors concentrate on identification of deceased individuals based on dental characteristics. However, in contrast to our approach, side views of the teeth are segmented in this work. In [4] a method

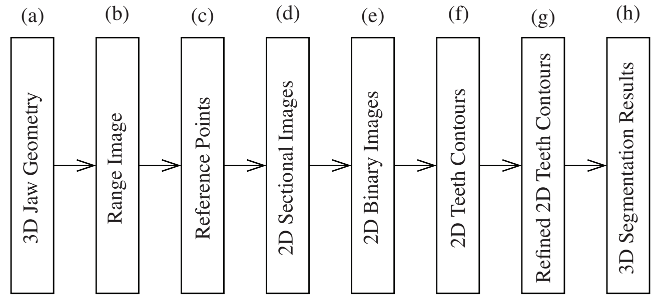

Fig. 2. Processing chain of our segmentation algorithm serving as a road map for Section 3.

for segmentation of teeth in volumetric computed tomography (CT) data using panoramic re-sampling of the dataset in the coronal view and variational level set is proposed. Another related work has been published in [5]. Here, the authors present a multi-step approach based on geometric types of active contours. Finally, Zhao et al. introduce in [6] an interactive method for teeth segmentation. Based on curvature values of the triangle mesh, feature points are connected to feature regions and feature contour is obtained with the help of user supplied information.

3. SEGMENTATION APPROACH

In this section, we describe our teeth segmentation algorithm. Its processing chain is depicted in Figure 2, whereas steps from (a) to (e) can be considered as preprocessing (Subsection 3.1) and steps from (f) to (h) contain the computation of teeth contours in 2D and their summary to 3D segmentation results (Subsection 3.2).

3.1. Preprocessing

First, a 3D dentition model is loaded to the system in form of a 3D jaw geometry (STL format) and a range image is created from it. Second, the user sets reference pixels in the middle of all teeth seen in the range image. Third, slices of the denture surface represented by the range image are cut on multiple planes which produces 2D sectional images. Finally, the sectional images are binarised by a simple thresholding so that white pixels represent available geometry and black pixels depict the background.

3.2. 2D Teeth Contours and 3D Segmentation Results

2D contours are estimated separately for all binary images resulting from the preprocessing and all teeth in them. For a single tooth in a single image a quadratic region around the reference pixel with a fixed size is taken into consideration. An iterative algorithm is applied for this region row by row. If it discovers a pixel that belongs to a new contour, it follows

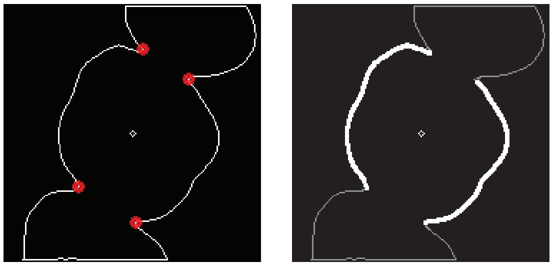

Fig. 3. Left: split points of the main contour. Right: contour segments after splitting.

the contour storing its pixels in form of a chain code. Depending on the kind of the contour (white to black passage, or black to white passage), it is denoted either as internal or external. Obviously, internal contours (white to black) represent artefacts (wholes) in the binary images (black pixels in a white region) and are disregarded from further investigations. Since the external contours nest inside each other, they can be stored into a data structure called the *contour tree*. The contour tree can be determined by drawing a diagram that represents the way the contours nest. One way to do this is to draw a set of paths that cross every contour exactly once. One of the contours from the tree with some minimum length is chosen to be the *main contour* for the following steps of the algorithm.

However, since the quadratic regions considered above are sized to enclose more than a single tooth, the main contour looks as depicted in Figure 3. In order to close the tooth contour, split points between the teeth (marked in red in Figure 3) must be determined. For this, the so called *dominant points* are detected first. Candidates $\boldsymbol{p}$ for the dominant points are identified by inscribing triangles in the contour as in Figure 4, whereas the following criteria must be fulfilled

$$\begin{aligned} d_{\min} \leq \|\boldsymbol{p} - \boldsymbol{p}^{+}\| \leq d_{\max} \\ d_{\min} \leq \|\boldsymbol{p} - \boldsymbol{p}^{-}\| \leq d_{\max} \quad . \\ \alpha \leq \alpha_{\max} \end{aligned} \tag{1}$$

$\|\boldsymbol{p} - \boldsymbol{p}^{+}\| = a$ and $\|\boldsymbol{p} - \boldsymbol{p}^{-}\| = b$ are Euclidean distances between the points. $\alpha \in [-\pi, \pi]$ is the opening angle at the point $\boldsymbol{p}$ and can be easily computed with

$$\alpha = \arccos \frac{a^2 + b^2 - c^2}{2ab} \quad . \tag{2}$$

Details about the selection of points $\boldsymbol{p}^{-}$ and $\boldsymbol{p}^{+}$ can be found in [7]. A particular candidate point $\boldsymbol{p}$ may be associated with multiple valid triangles with respect to the criteria (1). In this case, the triangle with the smallest opening angle $\alpha(\boldsymbol{p})$ is preferred and the value $(\pi - |\alpha(\boldsymbol{p})|)$ is assigned to the candidate $\boldsymbol{p}$ in order to express its *angularity*. Further, the algorithm makes sure that only one of candidates lying within

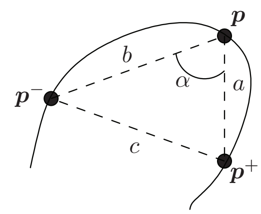

Fig. 4. Finding candidates for dominant points.

a valid neighbourhood is considered as the dominant point. Two candidates $\boldsymbol{p}$ and $\boldsymbol{p}_v$ are defined to be valid neighbours, if $\|\boldsymbol{p} - \boldsymbol{p}_v\| \leq d_{\max}$. The candidate with the highest grade of angularity is selected as the dominant point for a particular neighbourhood. In addition to the dominant points, points on which the convexity property of the main contour is not fulfilled are also calculated. They are quantitatively expressed by a measure of nonconvexity. Those with a high value of this measure (greater than a particular threshold) are called *convexity artefacts*. The split points between the teeth are identified by the intersection between the set of dominant points and the set of convexity artefacts. Finally, the resulting contour segments (see Figure 3, right) are connected to each other based on the the Bresenham line algorithm [8].

The contour found by the algorithm described above encloses usually only a subarea of the tooth. Therefore, it is refined with the snakes algorithm. A snake is an energy-minimising spline guided by external constraint forces and influenced by image forces that pull it toward features such as lines and edges [9]. Snakes are active contour models, they lock onto nearby edges, localising them accurately. In the final step of our method, the 2D refined contours computed for a particular tooth in different sectional images are summarised to a complete 3D tooth segmentation result.

4. EXPERIMENTS AND RESULTS

We used altogether 28 pairs of 3D dentition models given in the STL format for experiments. We divided them into three categories. The first one (dataset I) consists of 8 pairs acquired from artificial sets of teeth created by an experienced dental technician. It represents almost perfect teeth. The second one (dataset II) includes 17 pairs of 3D dental models which were acquired from real patients with healthy teeth. Although the contours of the teeth are very smooth, the malposition of teeth occurs often in these models. The third category (dataset III) consists of 4 pairs of 3D dentition models. Here, the malposition of teeth is significant which makes the segmentation task very difficult. All dentition models have been manually segmented by an experienced dental technician which provided a gold standard for evaluation.

In our experiments we distinguished between the four different kinds of human teeth, namely incisors, canine teeth,

Dataset	Mean Value $\times 100$								Standard Deviation $\times 100$							
	Incisors		Caninus		Premolars		Molars		Incisors		Caninus		Premolars		Molars	
	Se	Sp	Se	Sp	Se	Sp	Se	Sp	Se	Sp	Se	Sp	Se	Sp	Se	Sp
I	82	100	83	100	99	99	97	98	17	1	12	1	2	1	5	1
II	86	99	90	99	99	98	95	96	13	2	11	1	2	1	14	4
III	54	80	76	99	96	98	94	95	33	38	19	1	10	2	12	6

Table 1. Mean values and standard deviations of the sensitivity (Se) and specificity (Sp) of our algorithm for teeth contour estimation calculated for four different types of teeth and three different datasets.

premolars and molars.[1] It is obvious that the difficulty of the segmentation task differs significantly from one teeth category to another. Therefore, it would have not made any sense to evaluate them together. We evaluated the accuracy in the determination of the 2D tooth contour using two well-known measures, the sensitivity and the specificity. The results can be found in Table 1. As one can see, remarkable high performance has been achieved in all three datasets for premolars and molars. Incisors make problems to our algorithm, especially those from the dataset III.

5. CONCLUSIONS

In this work, we presented a new algorithm for segmentation of teeth in 3D dentition models. The approach will be used in the practical realisation of the so called virtual articulator. The requirements for our method defined by a dental technician include a high geometrical accuracy, limited user interaction, and execution time efficiency. In the development and evaluation phase of our algorithm we focused on the 2D tooth contour determination which finally served as a basis for the full 3D tooth segmentation

In the only interactive step of our approach, the user is required to manually set reference points for all teeth in a range image. Usually, there are 14 to 16 teeth in a dentition model. Thus, the manual effort has been significantly reduced in comparison to a previous method, where the teeth contours had been segmented completely manually. The execution time of 8 seconds from setting the reference points until achieving the segmentation result for one dentition model also fulfils the requirements of the virtual articulator. The geometrical accuracy of our segmentation approach has been evaluated for more than 800 teeth against a gold standard created by an experienced dental technician. The high sensitivity and specificity achieved in our experiments, especially for premolars and molars, prove the applicability of our method in the practical realisation of the virtual articulator.

In the future, we will analyse range images taken from frontal views of the teeth in order to increase the segmentation accuracy for incisors.

[1] Incisors – 1st and 2nd in the quadrant, canine tooth – 3rd, premolars - 4th and 5th, molars – 6th, 7th and 8th.

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