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Algorithm for the boundary detection of dental crowns for 3D dental model segmentation

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Abstract. This paper presents the segmentation algorithm on the 3D digital dental model for separating individual dental crown using fuzzy multi criteria analysis and Visualization Toolkit (VTK). The aim is to apply the algorithm in the 3D aligner development software package. The digital dental model is produced by 3D scanner in STL format and dental crown contour is calculated based two control points defined by user. Fussy multi criteria analysis with pairwise comparison of the mesh points aims to select a points subset that define the boundary between the dental crown and the jawbone. VTK provides ease of use computer graphics algorithms and visualisation tools. The result has shown that the proposed approach can successfully separate dental crown on the 3D digital dental model.

1. Introduction

Misalignment or incorrect relation between the teeth (malocclusions) can have impacts on physical, psychological, and social aspects, leading to consequences that affect quality of life because oral health constitutes a fundamental part of the general health [1]. Nowadays, a significant emphasis is put on minimally invasive procedures of orthodontic treatment, whereby patients are expected to be satisfied their wishes and expectations. The modern technology of the malocclusions' treatment with the help of transparent cap "eligners" appeared in the USA in the late nineties due to the introduction of computer technologies in dental disciplines. Computerized algorithms for an orthodontic diagnostic and treatment require digital dental models. There are three commonly used ways to obtain these models:

- computed tomography (CT) images and cone beam CT (CBCT);
- direct intraoral scanning of the dentition;
- laser/optical scanning of the plaster models.

In the last few years, CBCT has gained popularity in dentistry for three-dimensional (3D) imaging of jawbone and teeth. Unlike conventional multi-slice CT scanners, CBCT is suited for use in clinical dental practice where cost and radiation dose are important limitation and scanning object is only the head. CBCT provides volumetric data sets through slicewise inspections of standard orthogonal views. The reconstruction of dental tissues involves the inspection of hundreds of slices to evidence tooth regions, which cannot be easily separated from surrounding anatomies by only considering pixel's grey-intensity values [2].

Intraoral scanners have been recently introduced as a replacement for the dental impression-taking procedure. An intraoral scanner is easy to use and generates stereolithographic (STL) files that can be used to make digital models. Special software for intraoral scanners can be used for digital model analysis and dental crown segmentation to make a digital dental setup for digital planning of orthodontic treatment [3].

However, many orthodontic clinics cannot afford to use expensive equipment or prefer not to rely on a full workflow proposed by scanner producers. Nevertheless, treatment planning could take advantage of a 3D reconstruction. In this case even if plaster models have no information of the teeth roots scanned plaster models is still widely used for orthodontic diagnosis and research. Laser surface scanning is common in industry and medicine as a noninvasive alternative for generating a 3D computerized image. Despite its ability to scan only visible surfaces, its advantages in ease of use, self-calibration, and auto image distortion correction make generating 3D computerized images very convenient [4]. In this work, we focus on the digital dental model which generated by 3D scanner from the plaster models or intraoral scanners in STL file format.

Correction of the shape of the dentition is carried out by changing the position of the teeth. So individual 3D models of tooth needed to be extracted from initial model. Tooth segmentation from original model is a fundamental step that allows to move and rearrange teeth.

1.1. Related works

In the last years there have been detailed studies of the segmentation methods in general and particular mesh segmentation methods [5]. Techniques for solving the problem of teeth segmentation also have been proposed. Both manual and automated techniques were developed for the digital dental model segmentation such as segmentation using landmarks and plane cutting [6], and fully automated algorithm also based on plane cutting [7].

These techniques first create the horizontal plane that parallel to the average occlusal landmarks planar. This horizontal plane can be moved up and down along vertical axis by user. Then each vertex is determined whether it lies in upper side or lower side of the horizontal plane. On the next step, the program calculates and generates the vertical planes to separate each tooth. Each vertex on teeth is determined if it lies in between two planes. The difference between these two approaches is in the mode of defining the cutting planes. In contrast to the algorithm [6] which uses landmarks and plane locations defined by user, the algorithm [7] is fully automated. The main drawback of this method is the fact that the exact contour of the tooth cannot be obtained by checking for an intersection with the plane.

There is some dental research work on computer-assisted 3D reconstruction of teeth for human identification which includes tooth segmentation algorithms. In 3D automatic teeth segmentation for dental biometrics [8] feature regions are estimated using geometric curvature information and principal component analysis. The results of the proposed image pre-processing seem to be quite encouraging. However, the complete implementation of an active contour model is a challenging task, since the choice of coefficients is arbitrary and need to be determined empirically.

The surface representation of dental structures in 3D mesh represents a challenge for the incorporated image segmentation algorithms. Related research in computer-aided dental surgery, treatment planning and human identification is helpful to develop algorithms for the required task i.e. robust and automated teeth segmentation.

1.2. Technologies used

We are given a STL file with the digital solid dental model. STL format is represented by coordinates of triangles and normal vector. The figure 1 shows an example of input model and figure 2 presents a part of a mesh. Several software packages are available for performing analysis and visualize STL files.

The following software tools and libraries were chosen to provide the ability to create cross-platform applications:

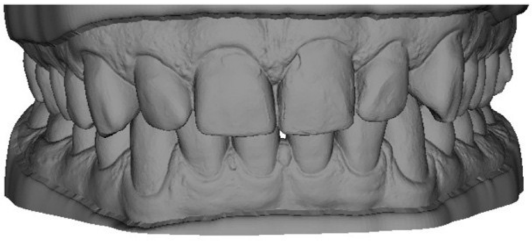

Figure 1. Digital solid dental model.

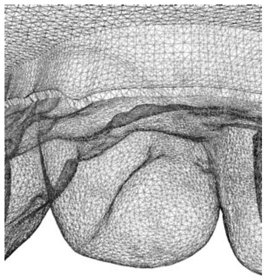

Figure 2. Mesh.

- Qt is a widely used cross-platform application framework for developing software which is intended to work on various combinations of software/hardware computing platforms.
- Visualization Toolkit (VTK) is an object-oriented based open-source software for computer graphics, image processing and visualization.

2. Detecting tooth contour

Our approach for extracting the teeth as separate objects from the original model is based on the detection of the tooth crown contour. The detection of the dental crown contour can be performed in two modes:

- manual selection based on a sequence of points;
- semi-automatic selection.

The second mode allows to determine the dental crown by only two points and consists in the following steps:

- Placement two points that defining the boundaries of the dental crown along the arch of the jawbone.
- Detecting the contour of the dental crown based on two points.
- Manual partial modification of the resulting contour by user.

To implement the first mode, *vtkContourWidget* was used. It allows users to place points on the mesh and connects them with a line automatically. The resulting contour lines rebuilt in case of changing the position of the points. It is also possible to use *vtkContourWidget* in the second mode. For this purpose, first we need to initialize it by predefined a subset of points corresponding to the contour between the dental crown and the jawbone. The figure 3 shows a general overview of the proposed approach. Next in this section specific aspects of the proposed approach will be described.

2.1. Problem Statement

The problem of the tooth contour detection can be briefly formulated as follows. We are given a set of points $P = \{x, y, z\}$ of a complete model mesh. We aim to select a subset $P_c \in P$, that defines the boundary between the dental crown and the jawbone.

For solving this problem, we propose to use a fuzzy multi-criteria analysis with pairwise comparison. The multi-criteria analysis is a decision-making tool developed for complex multi-criteria problems. It should be noted that it is more difficult to estimate the significance of some particular criteria than to determine the best of the two, that is, to carry out paired comparisons.

2.2. Fuzzy multi-criteria analysis with pairwise comparison of the mesh points

Pairwise comparison is used to avoid direct assignment of weights or scores of criteria to the available options. Let $P = \{p_0, p_1, \dots, p_n\}$ be a set of points that are subject to multicriteria analysis, points P_{start} and P_{end} control points defined by user (the figure 4 shows an example of the control points for the tooth 12), $C = \{c_0, c_1, c_2, c_3\}$ set of criteria to evaluate points.

- c_0 - distance to the control point P_{start} or P_{end};

- c_1 - y coordinate;
- c_2 - angle between vorticity and $\overrightarrow{P_{start}P_{end}}$;
- c_3 - gradient.

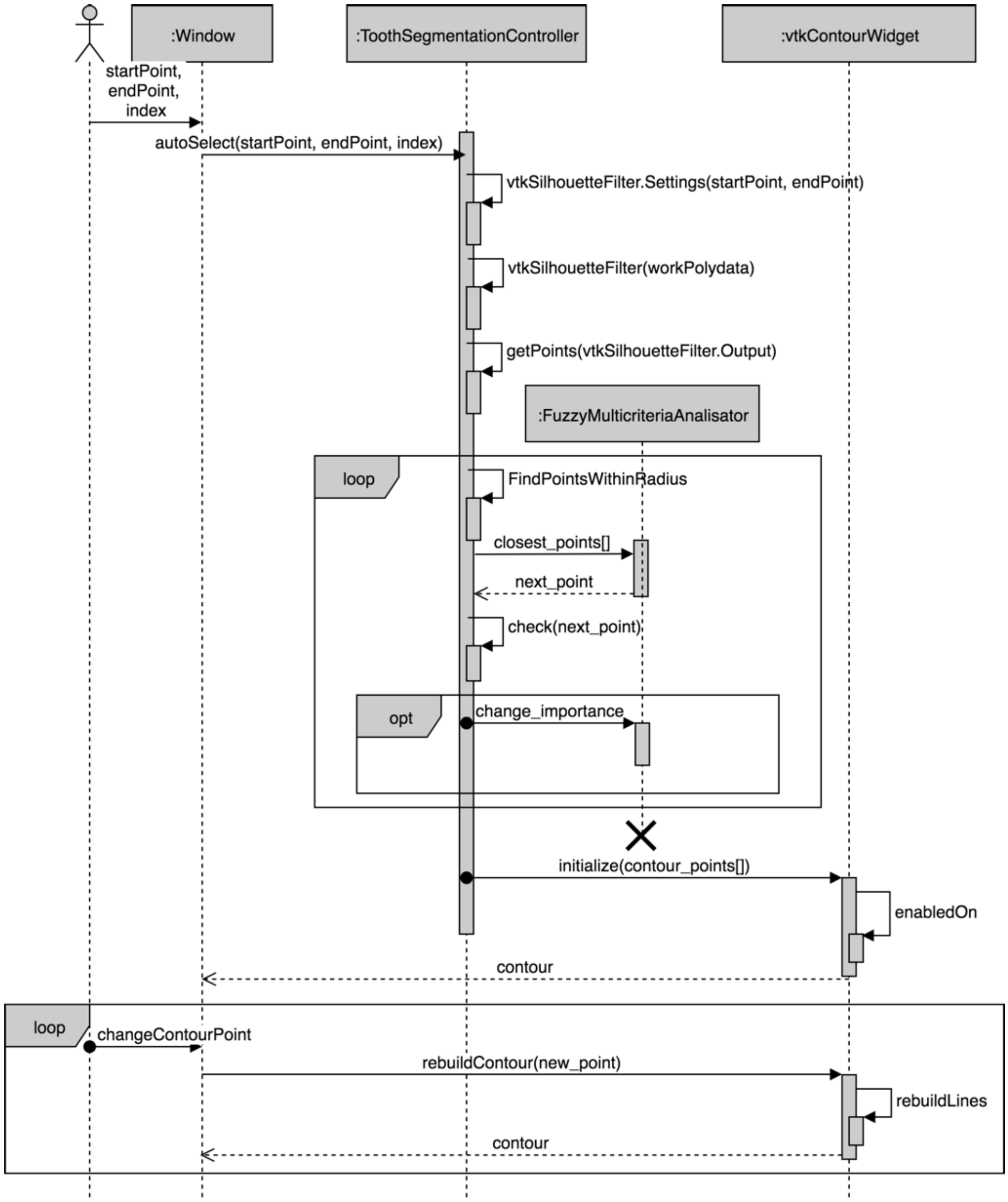

Figure 3. General overview of the teeth contours detection.

The direction of the vorticity for the previously mentioned tooth 12 is presented on figure 5. It can be noticed that the direction of the vorticity has a definite direction different from the surrounding at the border of the dental crown and the jawbone. The figure 6 shows the deviation of the angle between vorticity and $\overrightarrow{P_{start}P_{end}}$ from 90 degrees. The contours points are located in the places there the angle is changes and becomes close to 90 degrees. The gradient by coordinate Y as well as vorticity can show the location of the contour points. The figure 7 shows the gradient by coordinate Y. The contours points are located in the places there the gradient is changes from maximum value and becomes close to minimum. Both criteria give similar results, but at the same time they can be used together to specify points on the surfaces which are difficult for recognition such as areas near control points.

To order the elements from the set *P* by the criteria set *C* the following steps are taken:

- consider $\tilde{C}$ the fuzzy sets that are defined on the universal sets of P with the membership function $m^l(p_i)$ for each criterion in *C*;
- define the fuzzy set membership functions on the basis of pairwise comparisons of elements of *P*;

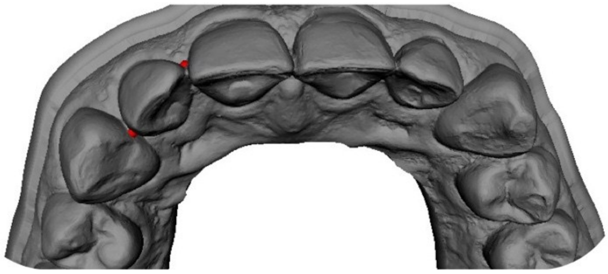

Figure 4. Control points.

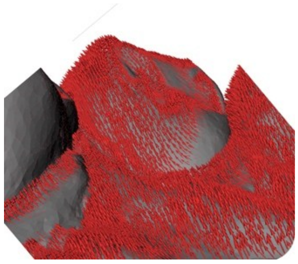

Figure 5. Vorticity.

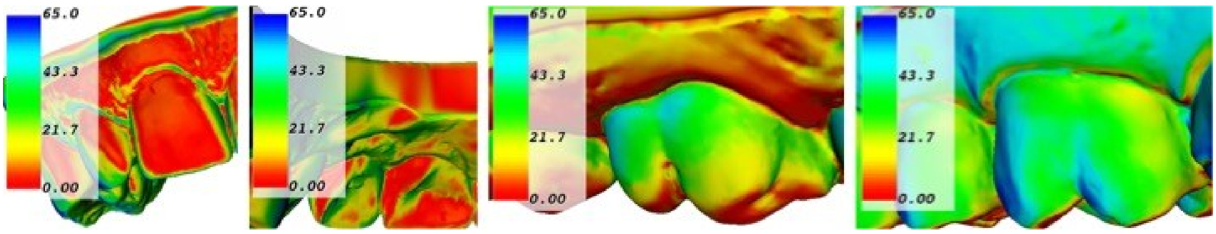

Figure 6. Deviation of the angle between vorticity and $\overrightarrow{P_{start}P_{end}}$ from 90 degrees.

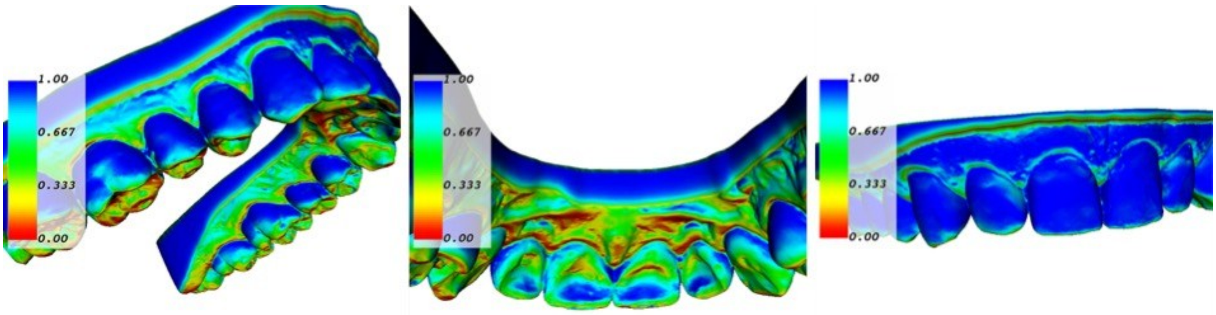

Figure 7. Gradient by Y coordinate.

- to take into account the different weight of the various criteria, we apply concentration or dilation $w_l, l = 1..m$ to the fuzzy sets;
- rank all elements of P on the basis of intersection of fuzzy set of criteria, according to the Bellman-Zadeh scheme [9].

To determine the degrees of membership, matrices of pairwise comparisons for each criterion could be formed. The total number of matrices coincides with the number of criteria. For the criterion c_l, the matrix of pairwise comparisons has the form:

$$A(c_l) = \begin{Bmatrix} a_{11}^l & a_{12}^l & \dots & a_{1n}^l \\ a_{21}^l & a_{22}^l & \dots & a_{2n}^l \\ \dots & \dots & \dots & \dots \\ a_{n1}^l & a_{n2}^l & \dots & a_{nn}^l \end{Bmatrix} \quad (1)$$

where $a_{ij}^l = 1$ if $i = j$, $a_{ij}^l = p_i^l/p_j^l$ for c_3 (to maximise the criterion) and $a_{ij}^l = p_j^l/p_i^l$ for other criteria (to minimise the criterion). The pairwise comparison matrix is diagonal, symmetric and transitive.

Thus, to define the degrees of membership, which are necessary for the formation of a fuzzy set, the following formula can be used [10]:

$$m^l(p_i) = 1/(a_{1i}^l + a_{1i}^l + \dots + a_{ni}^l) \quad (2)$$

Importance coefficients $w_l, l = 1..m$ are also based on evaluation of the degrees of membership (2) and respectively the matrices of pairwise comparison of criteria (1) could be formed. Since in our case there is no quantitative characterisation of criterion importance, we can adopt the 9-point Saaty scale [11], so the element a_{ij}^l of matrix *A* is defined as:

- 1 if there is no advantage of criterion c_1 over criterion c_2;
- 3 if there is a weak advantage of criterion c_1 over criterion c_2;
- 5 if there is a moderate advantage of criterion c_1 over criterion c_2;
- 7 if there is a very strong advantage of criterion c_1 over criterion c_2;
- 9 if there is an extreme advantage of criterion c_1 over criterion c_2.

The fuzzy set $\widetilde{D}$, which is necessary for rating analysis, is defined as the following intersection:

$$\widetilde{D} = \left\{ \frac{min_1^m[m^l(p_1)]^w}{p_1}, \frac{min_1^m[m^l(p_2)]^w}{p_2}, \dots, \frac{min_1^m[m^l(p_n)]^w}{p_n} \right\} \quad (3)$$

where $m^l(p_i)$ is the degree of membership of an element p_i to a criteria fuzzy set $\widetilde{c_l}$ The degree w indicates the concentration of the fuzzy set $\widetilde{c_l}$ in accordance with the measure of the importance of the criterion $\widetilde{c_l} \in C$. Analysing the resulting fuzzy set $\widetilde{D}$, the best option is to consider the one for which the degree of membership (numerator) is the largest.

2.3. Points reduction

Analysis of the full set of points is time and resource consuming. In order to reduce the number of points, the *vtkPolyDataSilhouette* will be used. *vtkPolyDataSilhouette* extracts a subset of a polygonal mesh edges to generate an outline (silhouette) of the corresponding 3D object. With the purpose to have a set of points suitable for detecting the tooth contour, *vtkPolyDataSilhouette* has to be initialized for each tooth independently. The specific parameters are a camera position and a camera focal point. The instances of *vtkPolyDataSilhouette* output for teeth 12 and 26 are presented in figure 8 and figure 9. The camera direction for each case is presented as an arrow. By using *vtkPolyDataSilhouette* we can significantly reduce the number of points for analysis. In the meantime, the main disadvantage of this approach is a dearth of points for the places where the boundary not clearly defined.

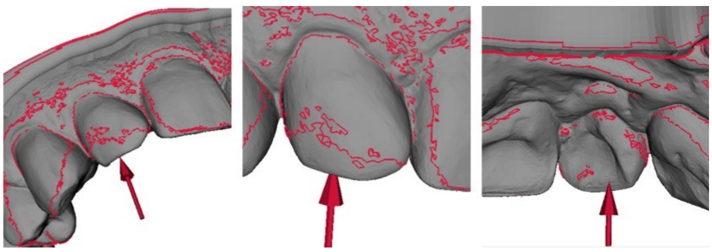

Figure 8. Output of the vtkPolyDataSilhouette for tooth 12.

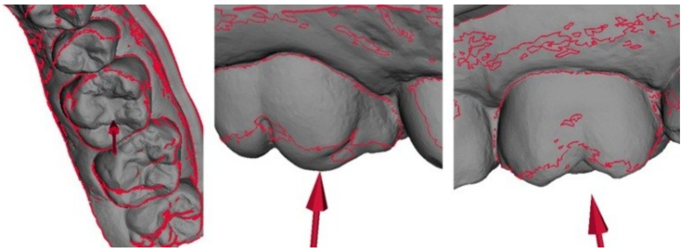

Figure 9. Output of the vtkPolyDataSilhouette for tooth 26.

3. Experiment

According to an investigation results of an implemented algorithm we decided to form two sets of the importance coefficients. One of them is for smooth descent from the control point P_{start}, the other is for a quick approach to the control point P_{end}.

In the first case we defined the following criteria comparison values:

- no advantage of criterion c_0 over criterion c_2;
- no advantage of criterion c_0 over criterion c_3;
- very strong advantage of criterion c_1 over criterion c_0.

In the second case we defined the following criteria comparison values:

- weak advantage of criterion c_0 over criterion c_2;
- moderate advantage of criterion c_0 over criterion c_3;
- very strong advantage of criterion c_0 over criterion c_1.

So, we obtain the following pairwise comparison matrices:

$$A(C_1) = \begin{Bmatrix} 1 & 0.14 & 1 & 1 \\ 7 & 1 & 7 & 7 \\ 1 & 0.14 & 1 & 1 \\ 1 & 0.14 & 1 & 1 \end{Bmatrix} \qquad A(C_2) = \begin{Bmatrix} 1 & 7 & 3 & 5 \\ 0.14 & 1 & 0.43 & 0.71 \\ 0.33 & 2.33 & 1 & 1.7 \\ 0.2 & 1.4 & 0.6 & 1 \end{Bmatrix}$$

According to the equation (2) and matrices $A(C_1)$ and $A(C_2)$ we have the following importance coefficients:

$$w_0 = 0.1, w_1 = 0.7, w_2 = 0.1, w_3 = 0.1$$
$$w_0 = 0.6, w_1 = 0.08, w_2 = 0.2, w_3 = 0.12$$

The resulting contours and extractions are presented in figure 10, figure 11 and figure 12.

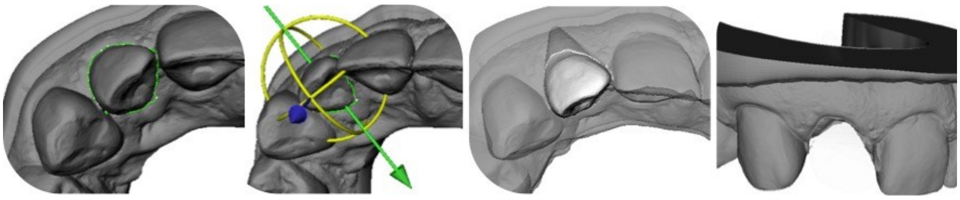

Figure 10. Contour and extraction for tooth 12.

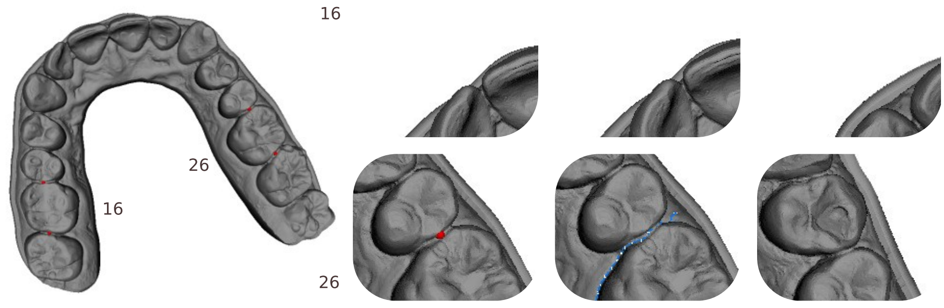

Figure 11. Contours and extractions for teeth 16 and 26.

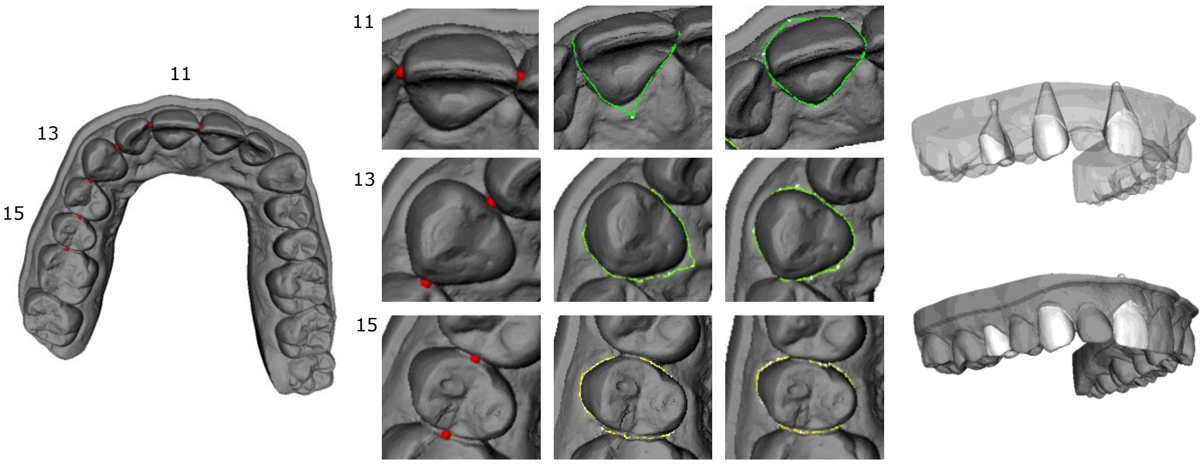

Figure 12. Contours and extractions for teeth 11, 13 and 15.

4. Conclusion and future work

We have presented a tooth segmentation method based on fuzzy multi-criteria analysis of the STL mesh points. Proposed algorithm was implemented with VTK which provides ease of use, experimentation and rapid prototyping of the algorithms. The method proposed here will be used as a part of software for automatic alignment of teeth models to the position of the ideal arch and generating a set of aligners. As a next step for improvement the proposed approach we should develop techniques for the control points accurate placement to avoid the contours intersections. It is also worth improving points reduction algorithms.

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