Robust harmonic field based tooth segmentation in real-life noisy scanned mesh

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ABSTRACT

Dental segmentation plays an important role in prosthetic dentistry such as crowns, implants and even orthodontics. Since people have different dental structures, it is hard to make a general dental segmentation model. Recently, there are only a few studies which try to tackle this problem. In this paper, we propose simple and intuitive algorithms for harmonic field based dental segmentation method to provide robustness for clinical dental mesh data. Our model includes additional grounds to gum, a pair of different Dirichlet boundary conditions, and convex segmentation for post-processing. Our data is generated for clinical usage and therefore has many noise, holes, and crowns. Moreover, some meshes have abraded teeth which deter the performance of harmonic field due to its dramatic gradient change. To the best of our knowledge, the proposed method and experiments are the first that deals with real clinical data containing noise and fragmented areas. We evaluate the results qualitatively and quantitatively to demonstrate the performance of the model. The model separates teeth from gum and other teeth very accurately. We use intersection over union (IoU) to calculate the overlap ratio between tooth. Moreover, human evaluation is used for measuring and comparing the performance of our segmentation model to other models. We compare the segmentation results of a baseline model and our model. Ablation study shows that our model improves the segmentation performance. Our model outperforms the baseline model at the expanse of some overlap which can be ignored.

Keywords: Dental 3D Segmentation, Harmonic Field, Human Evaluation, Clinical Noisy Dental Mesh

1. INTRODUCTION

Dental scanning has an important position in Dentistry. Due to the increasing number of people undergoing dental treatments, the demand for a more precise dental figure has grown. The traditional method using a plaster has many physical limitations in modification and usage. On the other hand, dental scans are free from those limitations and are available of having a physical form through 3D printings. This is a huge advantage on orthodontics. Dentists can move, extract, and align patient's tooth on CAD (Computer Aided Design) system. In other word, they can simulate orthodontic treatments without making additional plaster models. It can reduce mistakes of dentists and the time for making a new plaster model.

There are two main approaches for dental segmentation: curvature based method[1] and harmonic field based method.[2,3] Snake[4] (i.e., active contour model) based model is a kind of curvature based method that iteratively calculates curvatures for further feature extractions. The features go through several heuristic processes to extract boundaries between teeth and gum. Wu et al.[5] leverage Principal Component Analysis to pre-process the meshes and use curvature information to find a morphological skeleton for segmentation. Both methods are based on curvature but they perform poorly on data with gaps or noises.[2] To tackle the limitation, harmonic field based approach is introduced for dental segmentation.[2,3,6]

Zou et al.[6] improve cotangent weighing scheme by using concaveness for better results. However, it is still vulnerable to figures with complex geometrical shapes and irregular teeth arrangements. Li et al.[2] introduces alternative constraint values between adjacent teeth and suggests weights depending on concaveness with Gaussian curvature.

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Threshold values for segmentation were chosen by observing the harmonic field distribution. However, the presented algorithm has limited verification on other dental models with respect to global threshold. The study uses many hyperparameters, but on limited applications: full maxillary and mandibular models.

In our study, we propose a noise robust algorithm that can handle artifacts in real data. we perform dental mesh segmentation using harmonic fields and set vertex weights using the method introduced by Liao et al.[3] Since it does not work on noisy or fragmented data, we introduce several simple heuristic techniques. We qualitatively evaluate dental segmentation results generated by our algorithm with clinical experts. Moreover, we adopt human evaluation to show comparison with the baseline model and ablation study. Before our work, the only presented quantitative results of dental mesh segmentation are execution speed and comparison with ground truth. None of the presented methods compare their models with other proposed approaches quantitatively. It is hard to verify that the proposed method outperforms others without appropriate evaluation. Therefore, we use human evaluation to compare our model to other methods.

The remaining of the paper is organized as follows. In Section 2, we discuss how to make a harmonic field,and then, we propose several refinements to make a model robust. In Section 3, experimental results are presented by qualitative and quantitative analysis to show the superiority of our proposed method compared to the others. Moreover, ablation study is conducted for showing effectiveness of each component of our algorithms. This paper is concluded with brief discussions of the results in Section 4.

2. DENTAL SEGMENTATION USING HARMONIC FIELD

2.1 Data Description

We use four laser-scanned 3D dental mesh data from Osstem Implant Co.Ltd. Since they are made from casts in dental clinics, data contains a lot of noise. For example, there are holes, cracks, dental plates, and particles in the mesh data scanned from gypsum. Moreover, some parts of the data are removed or cutout for dental implant operation (i.e., sectional die).

2.2 Harmonic Field based model

Harmonic field is widely used for 3D mesh segmentation. It defines a field value Φ on each vertex of mesh with weight w on each edge, where

$$\Delta\Phi_i = \sum_{(i,j)\in E} w_{ij}(\Phi_i - \Phi_j) = 0. \tag{1}$$

There are various definitions of weights, such as a cotangent approach which considers concaveness,[3] and Gaussian curvature.[2] We apply the cotangent scheme defined in Liao et al.[3] Let a mesh, $M = (V, E)$, where V is a set of vertices and E is a set of edges of the mesh, and define the weighting scheme

$$w_{ij} = \frac{\gamma_{ij}(cot\alpha_{ij} + cot\beta_{ij})}{2}, \tag{2}$$

where α_{ij} and β_{ij} are opposite angles of E, and γ_{ij} is a binary coefficient which indicates concaveness.[6] The equation can be solved by least square linear system with given constraints:

$$A\Phi = b: \quad A = \begin{bmatrix} L \\ C \end{bmatrix}, \quad b = \begin{bmatrix} 0 \\ b' \end{bmatrix}. \tag{3}$$

L is a Laplacian matrix of mesh, defined as

$$L_{ij} = \begin{cases} \sum_{(i,k)\in E} w_{ik}, & \text{if } i = j, \\ -w_{ij}, & \text{if } (i,j) \in E, \\ 0, & \text{otherwise,} \end{cases} \tag{4}$$

the C is a constraint matrix, where

$$c_{ij} = \begin{cases} \omega, & \text{for } i = j \text{ and } i \in P, \\ 0, & \text{otherwise,} \end{cases} \tag{5}$$

and b' is a Dirichlet boundary condition vector, defined by Liao et al.[3] We assume that teeth are ordered sequentially by their placements. In other words, teeth can be numbered in integer, satisfying odd-numbered teeth is only adjacent to even-numbered teeth and vice versa. P is a set of all feature points. Each feature point on tooth belongs to a subset, P_{odd} or P_{even} depending on the teeth number where the point is placed. Feature points which are not on teeth are used as ground values. For flipping Dirichlet boundary condition in Section 2.3.2, two harmonic fields are generated by swapping the feature points between subsets P_{odd} and P_{even}. Formal definition of Dirichlet boundary condition vector b' is described in Section 2.3.2.

2.3 Algorithms

2.3.1 Additional Grounds (AG)

Since noisy data is used for evaluation, feature points described in Liao et al.[3] are not good enough to separate each tooth from the mesh. The presence of noises makes harmonic field irregular and thus hard to find a global threshold which successfully segments every tooth and gum using a calculated harmonic field. If the threshold value is changed for one tooth, segmentation results of other teeth can change. To prevent this issue, we introduce additional feature points and name them 'additional grounds (AG)'. The points are placed on the gum, near to the root of the teeth. These additional grounds can be considered as P_{ground} and used for calculating harmonic fields.

2.3.2 Flipping Dirichlet boundary condition (FD)

For a given harmonic field, even the best threshold for a segmentation could fail or miss some teeth. When boundary conditions are given as ω for P_{odd} and zero for P_{even}, which means boundary conditions of points on adjacent teeth differ, the distribution of harmonic field is not symmetric. Moreover, the contour of harmonic fields of tooth having P_{odd} is different from that having P_{even} and therefore is hard to find a threshold for both types of tooth. For these reasons, we suggest flipping Dirichlet boundary condition, i.e. swap the boundary condition values of P_{odd} and P_{even}. Two harmonic fields are used to differentiate each tooth from the mesh using two Dirichlet boundary condition, b'_1 and b'_2:

$$b'_{1i} = \begin{cases} \omega, & \text{for } i \in P_{even} \\ 0.5\omega, & \text{for } i \in P_{ground} \\ 0, & \text{for } i \in P_{odd} \end{cases}, \qquad b'_{2i} = \begin{cases} \omega, & \text{for } i \in P_{odd} \\ 0.5\omega, & \text{for } i \in P_{ground} \\ 0, & \text{for } i \in P_{even} \end{cases}, \tag{6}$$

where ω is a large constant (1,000 in our experiments).

2.3.3 Convex Segmentation (CS)

Since human teeth have rough surface, harmonic field values can change rapidly. The abrupt change of harmonic field values can result in incomplete segmentation (e.g., unsegmented areas surrounded by segmented regions). To fill these areas, we suggest convex segmentation which is performed on the horizontal slices of each tooth from bottom to the top. Since the cross-sections are almost convex, segmented boundary of each slice can be regarded as a convex. In that sense, we use the convex hull of each segmentation region Seg within a slice S_i (indexed from the bottom) as a method of convex segmentation. This convex segmentation can be generalized to an integration of series of the slices from bottom to top. Therefore, define proj() as a projection operator onto the horizontal plane, and the result of convex segmentation for a teeth mesh $M = (V, E)$ is

$$Seg \cup \left(\bigcup_i V_i \right), \tag{7}$$

where $V_i = \left\{ v \in V \mid \text{proj}(v) \in \textit{convexHull} \left(\text{proj} \left(Seg \cap \left(\bigcup_{j \leq i} S_j \right) \right) \right) \right\}$.

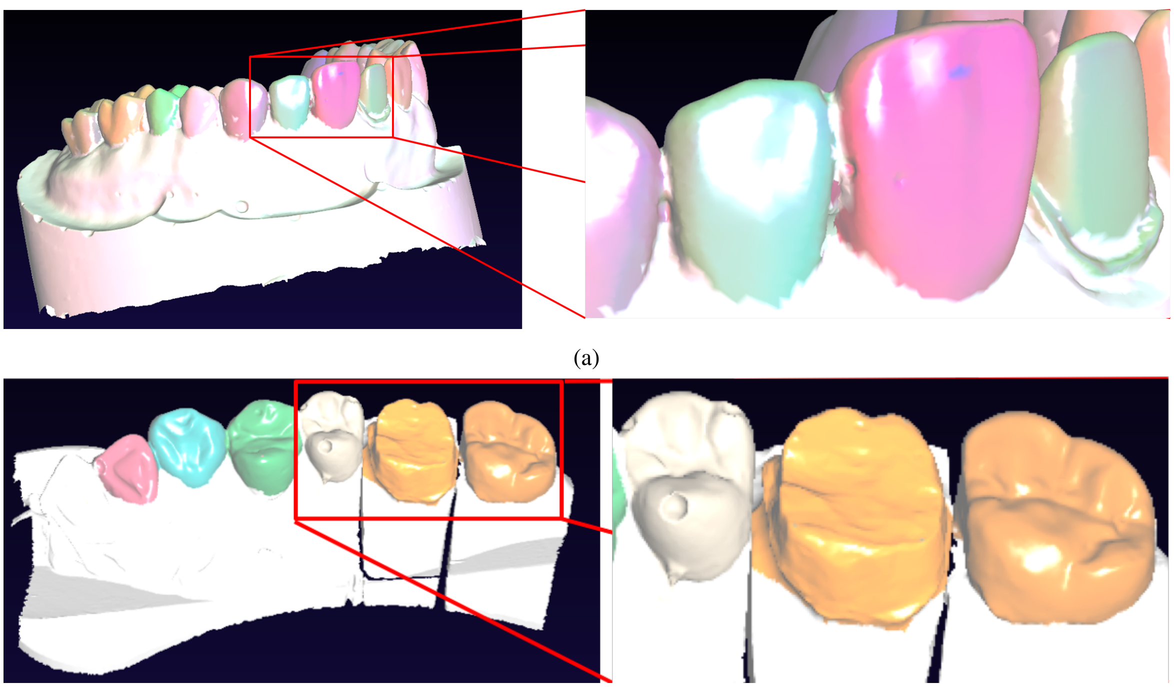
3. EXPERIMENTAL RESULT

Qualitative and quantitative evaluations are done to assess the performance of the segmentation model. The introduced segmentation model is evaluated on four clinical dental mesh data. The data is obtained from Osstem Implant Co.Ltd. Qualitative assessments are conducted through visual inspection of the segmentation results by clinical experts. For quantitative analysis, we have done three experiments. First, we calculated the overlap ratio between each teeth and compared it to that of the baseline model.[3] Second, human evaluation was performed in two groups (non-expert and expert group) to compare the performance of ours and other model and finally went through an ablation study.

3.1 Qualitative Result

Figure 1 shows qualitative results of our algorithms on mandibular teeth. Figure 1(a) presents the result of applying our segmentation model to a mandibular jaw with a crown (i.e., dental cap). The model performs well not only on fine-grained parts but also on handling flaws in data. The model successfully divides the pink tooth with the emerald tooth although there is a void region where mesh does not exist between them. In the Figure 1(a), our model can differentiate not only natural teeth but also a crown which has a different shape from a normal tooth. Also, every molar are segmented without any insufficient regions.

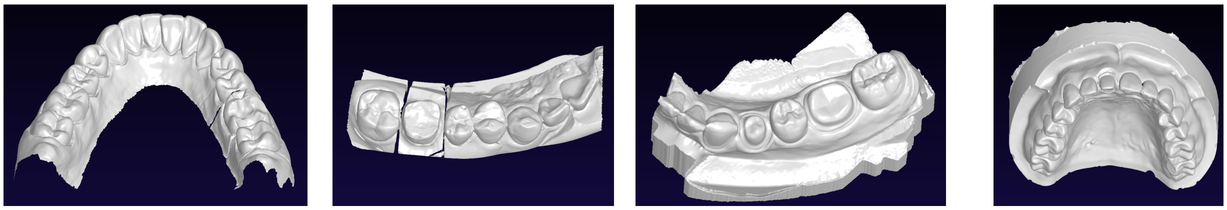
Figure 1(b) presents the result of applying our segmentation model to a part of mandible with a first molar prepared for crown. Although some part of the gum is included as the prepared tooth, our model generally succeeds on separating the tooth of which the upper part has been flattened for further dental treatment. Moreover, our model performs well on isolated second molar. On the grey-colored tooth, there are several craters which might have been formed while making or scanning the plaster model. However, our algorithm successfully fills these craters.



(a)

(b)

Figure 1: Qualitative results from our method on mandible teeth (a) with an abraded tooth and a crown, (b) with a first molar prepared for a crown.



(a) (b) (c) (d)

Figure 2: Mesh data used for human evaluation. (a) mandible with an abraded tooth, (b) mandible with a first molar prepared for a crown, (c) mandible with crowns, (d) maxillary teeth.

3.2 Overlap Ratio

Vertices of mesh being segmented to more than one tooth, i.e. overlapped, should be avoided. We measure how many vertices are allocated to more than one tooth by different segmentation methods and compare them. We use four different meshes as shown in Figure 2. The comparison is done between a baseline method and our segmentation method. The result of comparison is shown in Table 1, comparing overlap between two segmentation methods in four meshes. In this experiment, the degree of overlap is measured as Intersection over Union (IoU) and IoU of a mesh $M = (V, E)$ is defined as

$$\text{IoU} = \frac{|\{v \in V | v \text{ is labeled as more than one tooth}\}|}{|\{v \in V | v \text{ is segmented as teeth}\}|}. \tag{8}$$

All four meshes are not overlapped on the baseline model. On the other hand, our model makes overlapped regions on one mesh; mandible with an abraded tooth. This is because of Convex Segmentation (CS)which can make an overlap when convex hulls of two teeth are overlapped. However, the overlapped region is much less than one percent, and numerically, the number of overlapped points is 23 among 50,892 segmented points. It is ignorable if the increased performance caused by our model can compensate the overlap.

Table 1: Overlap ratio (IoU) of the baseline and our model on four different meshes.

Data	baseline	ours
mandible w/ an abraded tooth	0.0000	0.0005
mandible w/ a prepared tooth	0.0000	0.0000
mandible w/ crowns	0.0000	0.0000
maxillary teeth	0.0000	0.0000

3.3 Comparison with the baseline

We compare our algorithm with the most recent dental mesh segmentation algorithm that uses harmonic field. Human evaluation is conducted for this comparison. There are two rater groups; One group is composed of fifty non-experts and the other is composed of twenty-five experts. The raters are asked to give rates between 1 to 7 (higher the better) for each segmentation result of meshes in Figure 2.

Table 2 presents the result of human evaluation comparison. In all surveys, our model was given higher average scores than the baseline model. None of the segmentation results by the baseline model scored higher than 4. Since 4 is the median in the seven point scale, raters viewed the baseline model to have poor performance. On the other hand, the results of our algorithms got higher scores with less standard deviation. Although expert group generally gives lower score than non-expert group, they share similar tendencies among meshes. However, experts give higher scores on segmentation made by the baseline model for mandible with a tooth prepared for crown. For failures in segmentation, experts prefer several teeth being grouped as one tooth to omitting some teeth.

Table 2: Result of human evaluation which compares the baseline and our model using different mesh

Data	Non-experts				Experts			
	baseline[3]		ours		baseline		ours	
	Avg	Std	Avg	Std	Avg	Std	Avg	Std
mandible w/ an abraded tooth	3.32	1.27	**5.96**	1.01	3.16	1.40	5.72	0.94
mandible w/ a prepared tooth	3.7	1.41	**5.62**	1.09	3.96	1.43	5.44	1.29
mandible w/ crowns	3.74	1.37	**5.54**	1.20	3.60	0.91	5.00	1.15
maxillary teeth	3.38	1.40	**5.66**	1.21	3.40	1.26	5.40	1.12

3.4 Ablation Study

We conduct ablation study to analyze the contribution of each additional algorithm on dental segmentation by using human evaluation with same rater groups used in Section 3.3.

Table 3 shows the ratings of each segmentation model's performance on the same dental mesh (Figure 2 (a)). Although applying additional grounds does not make a significant change in ratings from non-experts, it increases the rating about one by experts. However, the scores from both rater groups are still below four which is the median of the seven point scale. Introducing Flipping Dirichlet boundary condition brings better performance on dental mesh segmentation. Two flipped Dirichlet boundary conditions trigger stabilization effect through using more information from harmonic fields. Further improvements are achieved by convex segmentation as a post-processing method. This is because, convex segmentation fills wholes on teeth, especially backward of incisors. From our experiments, each introduced algorithm makes an enhancement proving their effectiveness. Also, our final model achieves the best performance among four different algorithms.

Table 3: Result of human evaluation which compares the baseline and our three models. AG: Additional Grounds, FD: flipping Dirichlet boundary condition, CS: Convex Segmentation

Model	Non-experts		Experts	
	Avg	Std	Avg	Std
baseline	3.08	1.38	2.88	1.36
baseline + AG	3.3	1.37	3.84	1.11
baseline + AG + FD	4.86	1.07	4.68	0.90
baseline + AG + FD + CS	6.04	1.18	**6.20**	0.65

4. CONCLUSION

Although harmonic field based segmentation method is more robust than curvature based, it still has a limitation to real noisy data such as abraded teeth, sever region, artificial teeth (e.g., crown and implant). In this paper, we have proposed simple but effective algorithms for dental mesh segmentation based on the harmonic field to make a good segmentation on real noisy mesh data. The model is composed of additional grounds, flipping Dirichlet boundary condition, and convex segmentation. We demonstrate the effectiveness of the framework qualitatively and quantitatively. Although our model makes overlapped region between tooth on one mesh, the model makes much better performance according to human evaluation, and the region can be ignored due to its small size. We compare our model and the baseline on four different dental meshes by using human evaluation. Our Proposed model was evaluated by both experts and non-experts to outperform the traditional model in all meshes. Moreover, the ablation study shows that each algorithm, especially flipping Dirichlet boundary condition and convex segmentation improves the segmentation performance. There are many possibilities of further improvements such as applying our algorithms to segmentation field based model, but we leave them for future works.

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