Eurographics Workshop on Visual Computing for Biology and Medicine (2010)
D. Bartz, C. P. Botha, J. Hornegger, R. Machiraju, A. Wiebel, and B. Preim (Editors)

Staircase-Aware Smoothing of Medical Surface Meshes

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Abstract

The evaluation of spatial relationships between anatomic structures is a major task in surgical planning. Surface models generated from medical image data (intensity, binary) are often used for visualization and 3D measurement of extents and distances between neighboring structures. In applications for intervention or radiation treatment planning, the surface models should exhibit a natural look (referring to smoothness of the surface), but also be accurate. Smoothing algorithms allow to reduce artifacts from mesh generation, but often degrade accuracy. In particular, relevant features may be removed and distances between adjacent structures get changed. Thus, we present a modification to common mesh smoothing algorithms, which allows to focus the smoothing effect directly to previously identified staircase artifacts. This allows to preserve non-artifact features. The approach has been applied to various data to demonstrate the suitability for different anatomical shapes. The results are compared to the ones of standard uniform mesh smoothing algorithms and are evaluated regarding smoothness and accuracy with respect to the application within surgical planning.

Categories and Subject Descriptors (according to ACM CCS): I.3.5 [Computer Graphics]: Computational Geometry and Object Modeling—Curve, surface, solid, and object representations

1. Introduction

The morphology of anatomic and pathologic structures and their spatial relations are examined for planning of surgical intervention or radiation treatment. Surface models of anatomical structures are usually derived from tomographic medical image data, e.g. from computed tomography (CT) or magnetic resonance imaging (MRI). Medical image data often suffers from a limited resolution and anisotropic voxels (slice thickness is considerably larger than the in-plane resolution). For generating surface meshes, the target structures need to be identified and delineated by user interaction, automatic or semi-automatic methods. 3D models, generated from such segmentation information, may contain several artifacts, such as staircases, terraces, holes, and noise. For a correct and convenient perception of shapes and spatial relations, the models should look naturally to resemble e.g. the intraoperative experience of surgeons. The natural appearance refers to smoothness of the surface, since anatomical structures usually do not exhibit sharp edges. Feature edges attract the observers' attention and might severely disturb perception of the overall shape and structure of the surface model. Artifacts can be reduced during mesh generation or by additional mesh postprocessing (smoothing). Unfortunately, this may alter the structures' volume, extent, relevant inter-structure distances and features, which are not caused by model generation, might get removed. Smoothing methods, in general, apply a uniform filter to the surface mesh. However, artifacts are often not uniformly spread over the surface (see Fig. 1(a)). As a result of uniform surface smoothing, artifacts get reduced, but as a side-effect non-artifact areas might get altered too much (see Fig. 1(b)). As a remedy, feature-sensitive smoothing was suggested [KBSS01]. These methods are successful in preserving sharp edges in CAD models. However, when applied to surface meshes derived from tomographic medical image data, they consider staircase artifacts as features to preserve. Context information, such as slice direction, slice distance and knowledge on the properties of artifacts are usually not considered for a locally adaptive artifact reduction.

To account for the described problems, we suggest an extension to common uniform mesh smoothing approaches,

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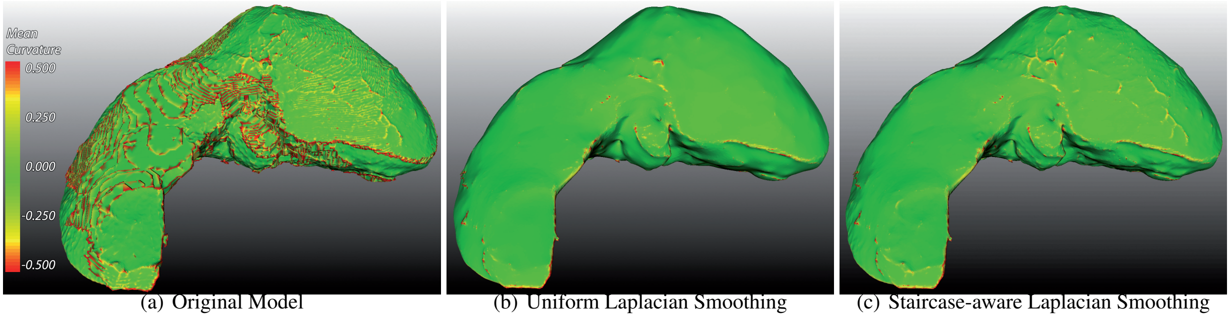


(a) Original Model (b) Uniform Laplacian Smoothing (c) Staircase-aware Laplacian Smoothing

Figure 1: *Staircase-aware smoothing applied to a surface model of the liver. Left: the initial model generated via MC; Middle: a Laplacian filtered model; Right: Laplacian filtering focused to the staircases with preserved surface details (right part of the model) and smoothed staircases (left part of the model); Coloring by mean curvature.*

that restricts the smoothing procedure to the staircase artifact areas. Our method can be applied to any available mesh smoothing method, whereas it adapts the displacement vector of each vertex according to the distance to staircase artifacts. Thus, it allows to smooth only specific parts of the model, while leaving areas without staircase artifacts unchanged (see Fig. 1(c)). This gives the opportunity to preserve model accuracy in non-artifact areas which is important in 3D diagnostic or surgical planning applications. We refer to this concept as *staircase-aware* smoothing.
Especially the anatomy of neck region is a good example, where several critical structures (e.g. arteria carotis, vena jugularis, sternocleidomastoid muscle, lymph nodes, salivary glands) are located very close and local distances and a natural appearance are relevant for the planning of surgical interventions or further treatment. Thus, we applied our modified smoothing approach to sample data acquired for surgery planning and investigated the influence on smoothness, distance and volume preservation.

2. Related Work

Medical surface models are generated from raw medical image data or binary masks, which are derived from volume data by preprocessing and segmenting the target structures (e.g. bones, vessels, liver, lymph nodes, ...). The image data are often composed of anisotropic voxels, which may introduce artifacts to the surface models (see Fig. 1(a) and 2). The anisotropy problem can be overcome, e.g. by shape-based interpolation [RU90]. However, interpolating intermediate slices results in much more data and computational effort. In clinical routine, this additional effort is often prohibitive, since data with lower resolution is usually acquired deliberately to save time and storage. The data can be transformed into a surface mesh using e.g. the Marching Cubes (MC) algorithm [LC87], or level-set methods [Whi00]. Several methods take care of artifacts during mesh generation, e.g. by additional trilinear interpolation and subdivision of the surface elements (Precise MC [ACMS98]) or iterative constrained relaxation of the surface (e.g. Dual MC [Nie04], Constrained Elastic Surface Nets [Gib98, BVP*00]). Some of these methods, however, such as Precise MC, achieve better visual quality at the expense of a significant loss of performance. However, the reduction of strong artifacts, such as staircases, goes along with a loss of smaller, potentially relevant details and large terraces may still remain.
Similarly, noise, staircase artifacts, or plateaus resulting from the limited resolution can be reduced after mesh generation by appropriate smoothing operations (e.g. Laplace filter, Mean Curvature Flow [DMSB99]). These methods allow to smooth surface models but cause volume shrinkage and loss of features. More specialized methods (Laplace+*HC* [VMM99], Taubin's $\lambda|\mu$ smoothing [Tau95]) try to prevent from shrinking volumes by an additional correction step. For models containing extreme staircase artifacts (e.g. Fig. 2 and 3), an appropriate parameter configuration is nearly impossible, if a natural appearance and accuracy are required simultaneously.
Several approaches are designed to reduce noise resulting e.g. from laser scanning [DMSB99, VMM99, TW03, BO03, JDD03, LMJZ09]. However, these methods focus on the preservation of sharp edges in non-medical data. Their direct application to medical surface models may give unsatisfying results, since anatomical structures typically have smoother shapes and the staircase artifacts would be interpreted as feature edges and thus be preserved. BADE ET AL. [BHP06] applied different mesh smoothing algorithms to surface models generated from binary image data and compared the results with respect to artifact reduction and volume preservation. They identified the Laplace+*HC* and Taubin's $\lambda|\mu$ smoothing as most appropriate for most anatomical structures with respect to volume and feature preservation. Additionally, they suggested a constraint for vertex placement during mesh filtering to preserve accuracy [BKP07]. Smoothing algorithms, such as Laplace+*HC* and Taubin's $\lambda|\mu$, are suitable for smoothing of small artifacts (staircases, noise) with si-

multaneous preservation of accuracy. Large staircase artifacts can still not be sufficiently reduced.
All of these widely used methods apply constant smoothing parameters to the target structure. In contrast, there are other methods available, that adjust smoothing according to classified features [HA08, OBS02], local mesh density [BX01], or even apply different filters [CC05] with the goal to preserve detected features. Thus, most feature-sensitive methods would preserve the artifacts in medical surface models. Furthermore, there is no mesh smoothing method available, which focuses smoothing to artifact areas and thus tries to split up the smoothing process for different problems.

3. Methods

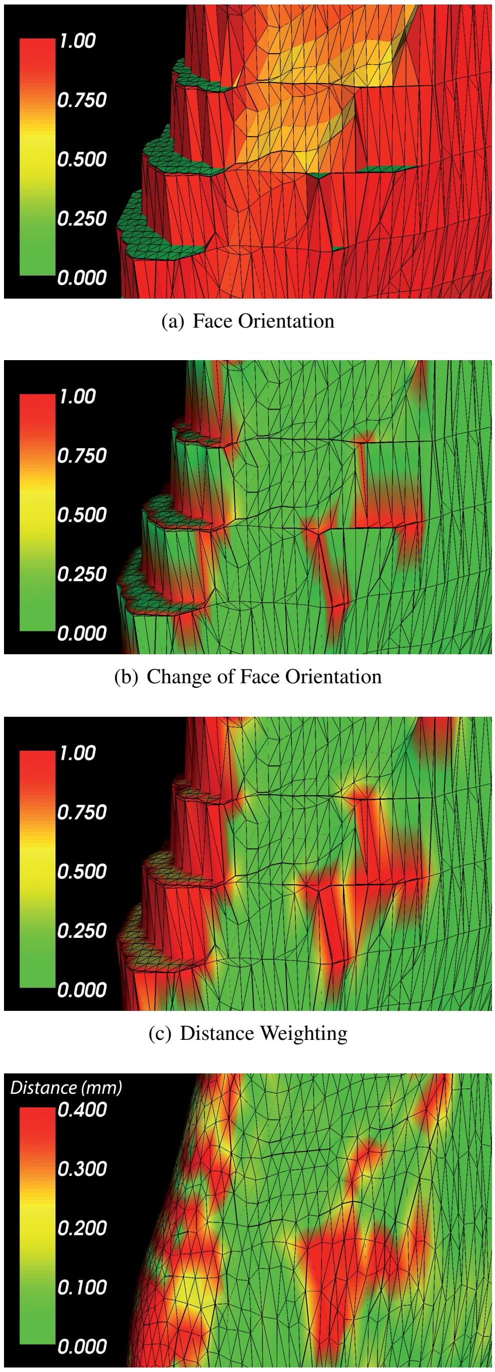
To enable staircase-aware smoothing, an initial identification and subsequent weighting of staircase areas is required. We assume that the surface normals have not been manipulated earlier in order to gain visual smoothness. Thus, each normal is oriented orthogonal to its face. All surface normals are consistently pointing towards the outside or the inside of the model and the normals of neighboring faces do not suddenly point to the opposite side. As a result, we can assume, that faces being orthogonal to slice orientation (typically along z-axis) have normals being parallel to it and vice versa.
Staircases can be characterized as parts of the model exhibiting feature edges of about 90 degree. However, this information is usually not sufficient to reliably detect staircase artifacts for two reasons:

- Other (relevant) features with similar feature angles might be contained in the model which should not receive a high weighting for the smoothing algorithm.
- Depending on the initially applied mesh generation algorithm, these staircase "borders" might already have been smoothed slightly. Thus, the corners within the staircases would exhibit similar curvature values as other "natural" features.

As a result, we employ knowledge on the slice orientation, slice thickness and on relative changes between faces in and orthogonal to the slice direction. Especially for data with very anisotropic voxel dimensions, staircases exhibit feature edges with almost 90 degree angles (between the face normals). However, for nearly isotropic voxels, these angles might get smaller. Thus, our approach allows to interactively adjust its sensitivity for different sizes of staircase artifacts. After computing the initial orientation rating, the vertices belonging to staircase artifacts are weighted to allow for subsequent usage during mesh smoothing. This is described in detail in the following subsections.

3.1. Identification of Staircase Artifacts

First, we determine the relative orientation θ_{f_i} of each single face f_i (see Fig. 2(a)) with respect to slice orientation. For that, we compute the angle α_i between the face normal and



(a) Face Orientation

(b) Change of Face Orientation

(c) Distance Weighting

(d) Final Smoothing Result

Figure 2: *The images show the single steps of the staircase-aware smoothing procedure for a part of the geometric model of a sternocleidomastoid muscle. (a) Colored by orientation of the faces in relation to the slice direction (z-axis). (b) Coloring of the vertices where the orientation of incident faces changes. (c) Vertex weighting according to distance to staircase edges. (d) Final smoothing result colored by local distance to the initial model.*

the slice orientation vector. These angles are then scaled to the range of [0,1] according to Eq. 1. Thus, for faces with normals being orthogonal to the slice direction the relative orientation θ_{f_i} equals 1, whereas for faces with normals being parallel to slice direction it equals 0.

$$\forall f_i \in F: \quad \theta_{f_i} = 1 - \|(\alpha_i - 90)/90\| \tag{1}$$

$$\forall v_j \in V: \quad \theta'_{v_j} = \max(\theta_{f_k}) - \min(\theta_{f_k}) \tag{2}$$

α_i - angle between normal of face f_i
and slice orientation vector
$v_j \in V; V$ - set of vertices of mesh M
$f_i \in F; F$ - set of faces of mesh M
$f_k \in F_{v_j}; F_{v_j} \in F; F_{v_j}$ - incident faces at v_j
$\theta, \theta' \in [0,1]; \theta_{f_i}$ - orientation of face f_i
θ'_{v_j} - orientation gradient of incident faces at vertex v_j

Subsequently, the orientation θ'_{v_j} at each vertex v_j is computed as the difference between the maximum and the minimum face orientation of all incident faces F_{v_j} at that vertex (see Eq. 2). As a result, θ'_{v_j} will be 1, if there is at least one incident face oriented orthogonal to slice direction and another face is oriented in slice direction. In contrast, θ'_{v_j} equals 0, if all incident face have the same orientation. However, the computation of θ_{f_i} and θ'_{v_j} described by Eq. 1 and 2 is sensitive to the global orientation, specifically to slice direction (see Fig. 2(b)). Fig. 3 illustrates the orientation rating for a model with staircases which are oriented along slice direction (z-axis) and for a second model which has been rotated out of slice direction by 45 degree. For the latter, the staircase vertices receive a lower rating, since the staircases do not exhibit faces in slice direction and orthogonal to slice direction. However, this is only an artifical example to demonstrate the weighting sensitivity. Staircase artifacts in medical surface models will always be related to slice direction.

3.2. Artifact Weighting

During the identification step, all vertices have been assigned a rating with values in [0,1], whereas the vertices at the staircase edges have received high values. For later smoothing, not only the vertices at the staircase edges are required. It is necessary, to define smoothing values within the flat areas of each staircase, which can be solved by computing the distance to the staircase edges.

To apply a weighting function to all mesh vertices, we apply a threshold $\tau_{\theta'}$ to the values of θ'_{v_j} and extract only the vertices with $\theta'_{v_j} > \tau_{\theta'}$. By default, we have set $\tau_{\theta'}$ to 0.7, which has given good results for different data. A decrease of $\tau_{\theta'}$ will include smoother staircases, whereas a high value of $\tau_{\theta'}$ extracts only staircases with 90 degree feature edges. Since the type of staircases should be almost homogeneous within

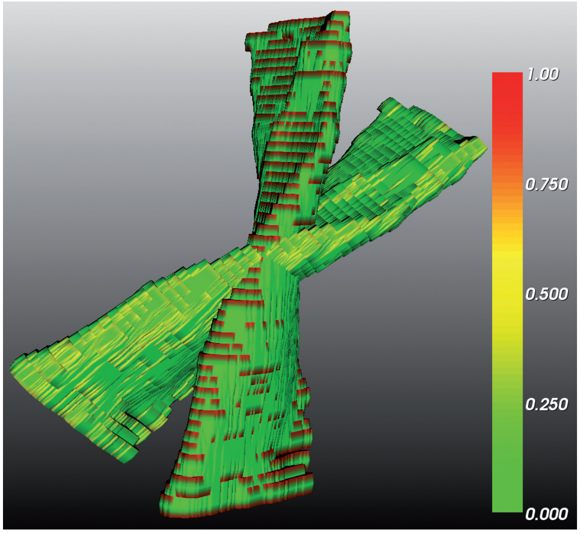


Figure 3: *Example of relative orientation change weighting. Two models of the sternocleidomastoid muscle are shown: one in original orientation along slice direction and one rotated by 45 degree. Note that the staircases of the rotated model receive a lower weighting.*

one surface model, the user can adjust the threshold $\tau_{\theta'}$ easily and fast. For all vertices v_j of the original surface mesh, we compute the minimum Euclidean distance d_{v_j} to the extracted staircase vertices. The distance values are scaled according to Eq. 3. A maximum threshold $\tau_{\max}$ can additionally be applied to account for the size of staircases, which is the slice thickness respectively. This allows to control the influence of detected artifacts to surrounding vertices within a given distance. However, the final weights w_{v_j} of the vertices, which are regarded as staircase edge vertices, are set to 1 and with increasing distance to staircase edge vertices, w_{v_j} decreases to 0 (see Fig. 2(c)).

$$\forall v_j \in V: \quad w_{v_j} = \begin{cases} \left(1 - \frac{d_{v_j}}{\max(D)}\right) & \text{if } d_{v_j} \leq \tau_{\max}, \\ 0 & \text{if } d_{v_j} > \tau_{\max}. \end{cases} \tag{3}$$

$$w'_{v_j} = w_{v_j} \cdot (1 - \beta_{\min}) + \beta_{\min} \tag{4}$$

$\tau_{\max}$ - max. distance threshold
$\beta_{\min}$ - min. weighting offset
$d_{v_j} \in D; D$ - min. Euclid. dist. of the vertices V to V'
$V' \in V; V'$ - the extracted staircase vertices
w_{v_j}, w'_{v_j} - distance-related weights for each vertex v_j

Besides the maximum distance used for scaling ($\tau_{\max}$), we also define a minimum value for the final weighting. Otherwise, unnatural edges might appear when using high values for the smoothing parameters or the number of iterations. A minimum smoothing value (e.g. $\beta_{min} = 0.1$) to be applied to non-artifact areas could prevent such additional artifacts. Thus, the previously computed weights are readjusted to the range above the applied minimum value (see Eq. 4). The parameter β_{min} allows to slightly smooth non-artifact areas to remove surface noise. As a result, there will not be a visually disturbing border between smoothed staircase areas and non-artifact areas without smoothing.

3.3. Application to Smoothing

The result of the previous steps is a weighting value for each vertex in the given surface mesh. This allows to modify the displacement vector determined from uniform smoothing for each vertex. For example, a standard Laplacian mesh smoothing filter is defined by Eq. 5:

$$\forall v_j \in V: \; v'_j = v_j + \frac{\lambda}{m} \sum_{k=1}^{m} (u_k - v_j) \tag{5}$$

$v_j, u_k \in V, \forall u_k \in U^1_{v_j}, m = \left|U^1_{v_j}\right|$

$U^1_{v_j}$ - 1st order neighbors of vertex v_j

λ - uniform smoothing factor

To make the smoothing process adaptive with respect to specific artifacts, we simply need to replace the weighting factor λ by $\lambda' = \lambda \cdot w'_{v_j}$ (see Fig. 2(d) for a sample result). The modification of the smoothing factor, shown above for the Laplace filter, equals to the application of d'_{v_j} to the final displacement vector. For a general application to other smoothing methods, the length of the displacement vector, computed by the smoothing method for each vertex, simply needs to be multiplied by the weight obtained from our method. Thus, our suggested modification can be applied to any smoothing algorithm. More specific algorithms, such as Laplace+*HC* or Taubin's $\lambda|\mu$, can be employed with their default parameters for smoothing and back correction as usual. The staircase weighting will be applied to the final displacement vector, that is determined by the specific smoothing method with its individual parameters and weightings.

4. Data and Evaluation

To evaluate staircase-aware smoothing, we employed four different clinical CT datasets (two of the neck and two of the liver) and applied our algorithm to differently shaped structures. All selected structures contain parts suffering from staircase artifacts and parts without such artifacts. However, the surface models represent typical results of the mesh generation process without artificially introducing artifact or non-artifact parts.

As sample structures from neck surgery, we selected the arteria carotis and the sternocleidomastiod muscle of two CT datasets, each with a voxel size of $0.453 \times 0.453 \times 3$ mm. All structures have been segmented manually by medical experts. The resulting binary masks have been dilated ($3 \times 3 \times 3$) and used to mask the intensity data. This allows the subsequently applied MC algorithm to generate partially smooth surfaces and restricts mesh generation to the boundaries of the applied mask, where the image data is inhomogeneous or neighboring structures have very similar intensity values. Thus, staircase artifacts may remain in those regions and as a consequence of the strongly anisotropic voxel dimensions, they tend to be very large. Furthermore, we employed two CT datasets of the liver with almost isotropic voxel dimensions ($0.797 \times 0.797 \times 0.8$ mm). The initial surface models have again been generated via MC from the intensity data which has been masked by a dilated binary data. Several staircase artifacts remained after model generation. Due to the roughly isotropic voxels, the artifacts are visually less disturbing.

For each of the three structure categories, the results have been averaged. We compared staircase-aware smoothing to standard uniform smoothing approaches: Laplacian smoothing (with and without node position constraint), Laplace+*HC*, and Taubin's $\lambda|\mu$. For Laplacian smoothing with node position constraint, we defined cubical voxel cells with the original voxel dimensions for each vertex, whereas the displacement of the vertices during smoothing is restricted to these cells. Staircase-aware smoothing has been applied to all of these uniform smoothing methods to allow for a direct comparison. For the surface models of the liver and of the arteria carotis, we used 20 iterations with λ=0.5 for all involved methods, since the staircase artifacts are relatively small for the liver data and the vessels are very sensitive to mesh smoothing due to their elongated, thin shape. For the models of the muscle, λ has been set to 1, to account for the large staircases. The parameters allow for a sufficient reduction of staircase artifacts for all methods. According to BADE ET AL. [BHP06], the additional parameters of the Laplace+HC filter have been set to $\alpha = 0$ and $\beta = 0.5$. For Taubin's $\lambda|\mu$ filter, μ equals 0.52 for the liver and vessel data 1.02 for the muscle data.

The resulting surface models have been compared regarding smoothness, shape and volume preservation. For smoothness, we employed the maximum angle between the vertex normal and the normals of all incident faces, which is similar to the faces' dihedral angles and partially comparable to the normal curvature described by GOLDFEATHER ET AL. [GI03]. This modified curvature measure has shown to be less sensitive for degenerated parts of the model (where the radius of the fitted sphere would be very close to 0 and the resulting default curvature value would thus get extremely high). Volume preservation is used to demonstrate the global error introduced by each mesh smoothing method. The preservation of shape is evaluated with two measures: the Hausdorff distance, which is determined between the smoothed and the initial surface (to show changes within the model) and the average minimum Euclidean distance between the smoothed and the reference model.

Table 1: *Averaged results for the comparison of the smoothing methods for the liver data. Each smoothing method has been combined with our staircase-aware smoothing (SA). NPC stands for "node position constraint".*

Smoothing method	Hausdorff distance to original model (mm)	Ømin. Euclidean distance to original model (mm)	volume (%)	avg. normal curvature (degree)
No Smoothing	0	0	100	22.46
Laplace	3.91	0.26	97.13	4.27
SA Laplace	3.73	0.17	97.71	5.87
Laplace+*HC*	2.80	0.09	99.32	8.54
SA Laplace+*HC*	2.58	0.07	99.37	10.29
Laplace with NPC	1.33	0.15	98.83	10.14
SA Laplace with NPC	1.34	0.11	99.07	10.54
Taubin's $\lambda\|\mu$	2.18	0.08	99.52	9.99
SA Taubin's $\lambda\|\mu$	1.90	0.05	99.66	13.65

5. Results

The comparison of the employed smoothing methods in combination with our suggested extension showed, that our method is able to restrict the smoothing process to the artifact areas and thus enable selective smoothing.

5.1. Models of the Liver

As expected, standard Laplacian smoothing yields strongest volume shrinkage compared to the original surface model (97.13%). However, the models of the liver are very large in relation to the size of the surface elements, which makes them relatively robust against volume loss (Tab. 1). For smaller structures, stronger volume shrinkage occurs. Our results confirm those of BADE ET AL. [BHP06] in terms of smoothness, volume and shape preservation. Additionally involving staircase-aware smoothing yielded at least the same values for Hausdorff distance and volume preservation or could slightly improve them. The Hausdorff distance decreased slightly for Laplacian, Laplace with node position constraint and Taubin's $\lambda|\mu$ filtering, whereas the average minimum Euclidean distance has slightly been reduced for all involved methods. Looking at smoothness, only marginally worse values are reached. However, those values are still a sufficient gain compared to the original model. The slightly higher values for average normal curvature are explained by those parts of the surface models, which were not subject for staircase-aware smoothing.

5.2. Models of the Sternocleidomastoid Muscle

Due to their size in relation to the slice thickness of the neck CT data, the models of the muscle exhibit more severe staircase artifacts than the liver models. However, the results are quite similar to the ones of the liver (Tab. 2). Standard uniform Laplacian smoothing yielded strongest volume shrinkage and curvature reduction, whereas the other employed methods provided relatively high accuracy for the applied smoothing parameters. Again, staircase-aware smoothing could keep and even slightly improve all results. For Laplace+*HC* and Taubin's $\lambda|\mu$ filter, the Hausdorff distance could be decreased by about 20-30%, whereas the curvature values are kept nearly constant.

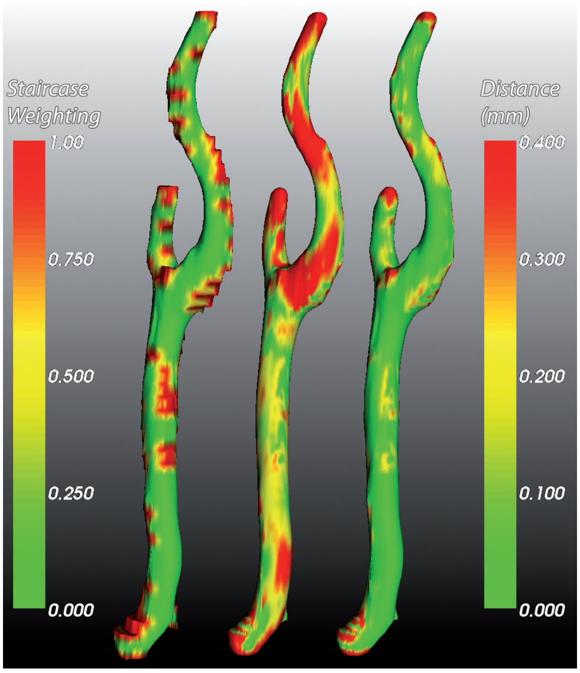


Figure 4: *Sample models of the arteria carotis. Left: original model, colored by computed staircase weighting (left colorbar); Middle: after uniform Laplacian smoothing; Right: after staircase-aware Laplacian smoothing. Middle and right models are colored by minimum Euclidean distance to the original model (right colorbar).*

Table 2: *Averaged results for the comparison of the smoothing methods for the data of the sternocleidomastoid muscle. Each smoothing method has been combined with our staircase-aware smoothing (SA). NPC stands for "node position constraint".*

Smoothing method	Hausdorff distance to original model (mm)	Ømin. Euclidean distance to original model (mm)	volume (%)	avg. normal curvature (degree)
No Smoothing	0	0	100	16.35
Laplace	3.54	0.30	95.84	4.23
SA Laplace	3.2	0.18	97.48	6.02
Laplace+*HC*	2.23	0.08	100.89	8.50
SA Laplace+*HC*	1.81	0.06	100.84	10.09
Laplace with NPC	1.54	0.19	98.69	8.18
SA Laplace with NPC	1.53	0.13	99.03	8.38
Taubin's $\lambda\|\mu$	2.28	0.09	101.01	8.18
SA Taubin's $\lambda\|\mu$	1.55	0.06	100.59	10.63

5.3. Models of the Arteria Carotis

Smoothing of surface models of vascular structures is usually critical, since such thin and elongated models tend to shrink strongly. Laplace+*HC* and Taubin's $\lambda|\mu$ filter yielded best results for volume and shape preservation. However, the larger artifacts did still remain to the models and smoothness could only be improved slightly (Tab. 3). As expected, standard Laplacian filtering (with and without node position constraint) resulted in strong volume shrinkage (volume preservation: 88.78% and 91.67%) and relatively large values for Hausdorff distance. In contrast, combining both methods with staircase-aware smoothing could preserve up to 96.34% and 97.30% of the original volume, whereas nearly the same smoothing effect could be achieved (see Fig. 4). Furthermore, a comparison of the distribution of distance changes shows that staircase-aware smoothing decreases the overall error (see Fig. 5).

6. Conclusion

Surface models from tomographic medical image data may suffer from artifacts, such as staircases and terraces. A reduction of these artifacts can be achieved e.g. via mesh smoothing. However, the properties of the available methods often do not meet the requirements in medical visualization or lead to a tradeoff between accuracy and visual quality. Staircases are the most dominant artifacts introduced by image segmentation and subseqent model generation. We have presented a modification to standard uniform mesh smoothing algorithms, that allows to focus the smoothing procedure on the areas containing staircase artifacts. Targeting the applied smoothing algorithm to these critical areas allows to preserve accuracy and features within other parts of the surface model. This is especially relevant for surgical planning, where pathological structures need to be evaluated and quantified.

Our method is suitable to be used in combination with standard smoothing algorithms for a large variety of structures. It is able to detect and smooth staircase artifacts resulting from isotropic and anisotropic data and can be used to extend any available mesh smoothing algorithm. Staircase-aware smoothing achieved results that are equal to standard uniform mesh smoothing algorithms or even slightly improved them. Especially for elongated surface models, which are very sensitive to volume shrinkage, staircase-aware smoothing preserves accuracy and still removes staircase artifacts reliably. The presented approach can be adjusted to different sizes of staircases and thus handle surface meshes from different meshing algorithms. Nevertheless, our method should be adjusted to allow for a special perservation of the end caps in vascular structures (see Fig. 4).

However, the quantification of volume and average distance can not completely characterize the value of staircase-aware smoothing. The size of the artifacts to be removed is related to the specific voxel size. Thus, the gain of accuracy preserving smoothing lies within the submillimeter/subvoxel range. However, the visual results of our method showed, that those parts of the model, which do not suffer from staircase artifacts, could be preserved. The subjective visual effect is stronger than usual quantification methods reveal. The

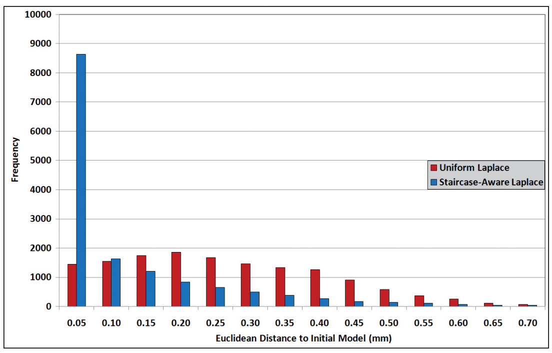


Figure 5: *Comparison of the distance histograms of uniform and staircase-aware Laplacian smoothing for the models of the arteria carotis.*

Table 3: *Averaged results for the comparison of the smoothing methods for the data of the arteria carotis. Each smoothing method has been combined with our staircase-aware smoothing (SA). NPC stands for "node position constraint".*

Smoothing method	Hausdorff distance to original model (mm)	Ømin. Euclidean distance to original model (mm)	volume (%)	avg. normal curvature (degree)
No Smoothing	0	0	100	16.50
Laplace	2.17	0.23	88.78	7.71
SA Laplace	1.97	0.09	96.34	9.07
Laplace+*HC*	0.76	0.04	100.46	10.60
SA Laplace+*HC*	0.71	0.03	100.56	11.74
Laplace with NPC	1.52	0.19	91.67	9.58
SA Laplace with NPC	1.46	0.07	97.30	9.96
Taubin's $\lambda\|\mu$	0.70	0.04	100.91	11.63
SA Taubin's $\lambda\|\mu$	0.64	0.02	100.52	13.46

strongest visual and quantitative gain is achieved for surface models, where only parts of the model suffer from staircase artifacts. Using uniform smoothing might alter the whole surface model, whereas staircase-aware smoothing preserves the non-artifact parts.

Acknowledgments: Tobias Moench and Simon Adler are funded by the German Ministry of Education and Science (BMBF) within the ViERforES project (http://vierfores.de, no. 01IM08003C).

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