Direct Model Generation for Subject-specific Non-segmented Medical Volume Data

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Abstract

Segmentation is an important prerequisite among many conventional modeling techniques in producing a surface or volume mesh. This poses as a major obstacle in the surgical simulation work flow due to the potential processing time and human intervention involved. The procedure's impracticability hinders subject-specific surgical applications from deploying in daily clinical environment. In this work, a direct, segmentation-free model generation method is proposed. The two-step method generates a volumetric model from a set of unprocessed, non-segmented medical volume data. With the use of "Volume Proxy Mesh" (VPM) as the foundation mesh structure, the entire volume data is converted into a tetrahedral mesh in the first phase. Specifically, vertices in the mesh are directly placed to sample the geometric details in the dataset based on each voxel's curvature information. Thus, segmentation is strategically lessened to trivial automated step. In the second phase, Particle Swarm Optimization (PSO), a global optimization algorithm, is employed to maximize the deformation quality of the initial resulting mesh. Through a designed cost function, the initial mesh quality is improved iteratively until criteria are reached. Visualization results of several sets of subject-specific kidney data illustrate the effectiveness of the proposed algorithm and the applicability of PSO in tetrahedral mesh refinement.

1. Introduction

Preprocessing operations on medical data are a big part of the standard workflow in surgical simulations [1]. Segmentation, a particular step quite complicated and technical, is considered as a crucial beginning in setting up the region of interest for the simulation. This is followed by other stages such as modeling and physical parameter settings. These procedures alone would take an immense amount of time, not to mention all the technicalities entailed to handle these operations. Although simulation is possible on prepared dataset, the inefficiency and tediousness dramatically suppress its wider application on patient-specific, unprocessed data [2]. It is necessary to develop an alternative method that simplifies the procedures and shortens the delays between inputting the preprocessed medical data and surgical simulation. With this in mind, the authors have proposed a direct model generation method that minimizes preprocessing procedures. Moreover, the method hides these procedures from the user's awareness such that it successfully bypasses any manual intervention during preparation, see Figure 1.

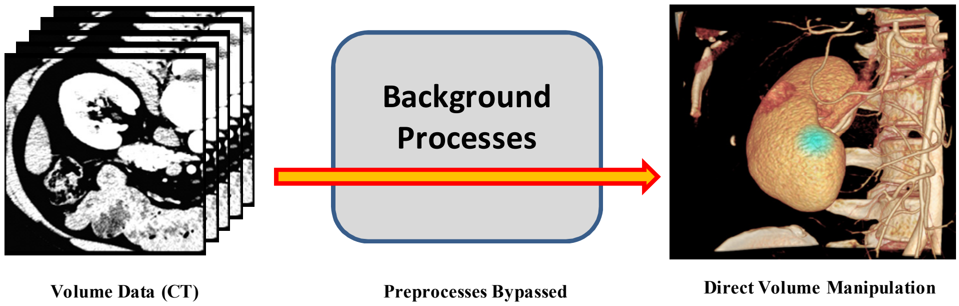


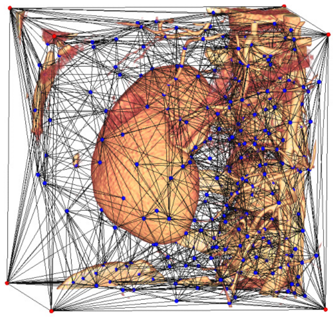
Figure 1. Preprocessing procedures bypassed

2. Method

The proposed method consists of two steps: 1) Curvature-based sampling and 2) Mesh quality improvement. It aims to take a set of unprocessed, non-segmented medical data as input, and then generate a volumetric model of the data directly for surgical simulation and manipulation. In other words, it automatically handles preprocessing procedures, without the user intervening with, or knowing of any. In developing this method, "Volume Proxy Mesh" (VPM) proposed by Nakao et. al [3] is employed. This continuous volume mesh structure can envelope and sample the entire volume dataset. Thus, it is capable of generating a comprehensive volume model with all the data contents at the same time (Figure 2). The special characteristic of the VPM helps bypassing a computationally heavy segmentation procedure, reducing it into a step of appropriately sampling the data. This inspired the first step of the proposed method: Curvature-based sampling.

The first step of the method, curvature-based sampling, focuses on sampling the data correctly to give a close representation of the dataset. This is done by placing vertices of the mesh at important features in the data. The features are represented by curvature values computed per voxel. The higher the curvature values, the more delicate the feature is. Based on the curvature values in the voxels, the method places vertices beginning from the finest to the broadest features in the data. During the process, two parameters "ε" (maximum distance in voxels) and "λ" (percentage of curvature sensitivity) are used to govern the complexity of the placements. Also based on the magnitude of the features, the parameters are in charged to separate vertices from each other. Figure 3a shows how vertices are placed on different features of a tooth, while 3b shows how vertices are separated by the distance created by the two parameters. With the resulting vertex placements, a tetrahedral mesh is generated.

Succeeding to the vertex placement step, the direct model generation method moves onto the second step: Mesh quality improvement. The quality of a mesh affects the quality of volume deformation. Since the first step of the proposed method focuses on sampling the data, the result is tailored to the data but it does not guarantee good mesh quality. Hence, a follow-up step is needed to compensate for the possible flaws in deformation that the vertex placement might have caused. This is achieved by implementing "Particle Swarm Optimization" (PSO), a global optimization algorithm [4]. In the context of mesh quality improvement, a cost function that evaluates the quality of the mesh is used for the optimization. As PSO moves the initial vertices to new locations, the cost function evaluates the general mesh quality in searching for a better mesh quality. As the mesh quality improves, the tetrahedrons in the mesh become more well-structured such that the deformation quality of the mesh would improve altogether.



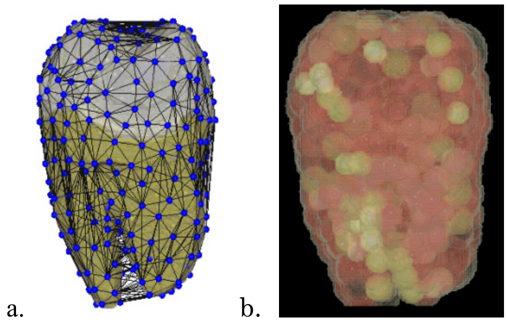


Figure 2. Volume Proxy Mesh sampling one dataset   Figure 3. Vertex placement step on tooth dataset

3. Result

Visualization results are obtained by applying the proposed method to two sets of patience-specific kidney volume data sized at 256^3. Figure 4a presents the vertex placement on Data A, while the meshing result is shown in 4b. Figure 4c provides another visualization on Data B, while 4d demonstrates another mesh in VPM. Figure 5, on the other hand, shows a trend line of how the initial mesh quality of Data B improves as iteration goes until 200.

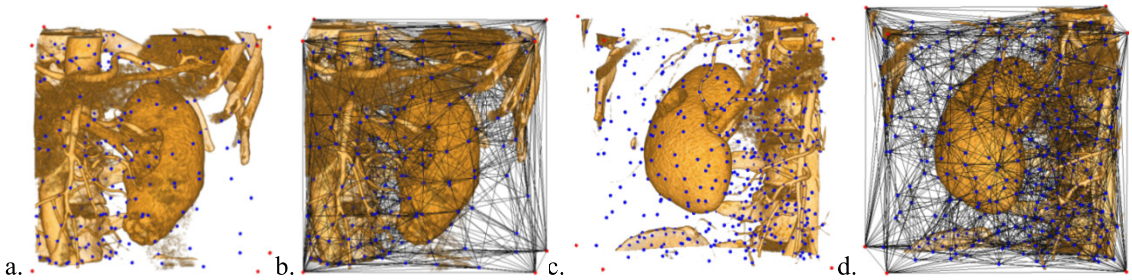


Figure 4. Vertex placement (4a) and VPM (4b) of Data A; vertex placement (4c) and VPM (4d) of Data B

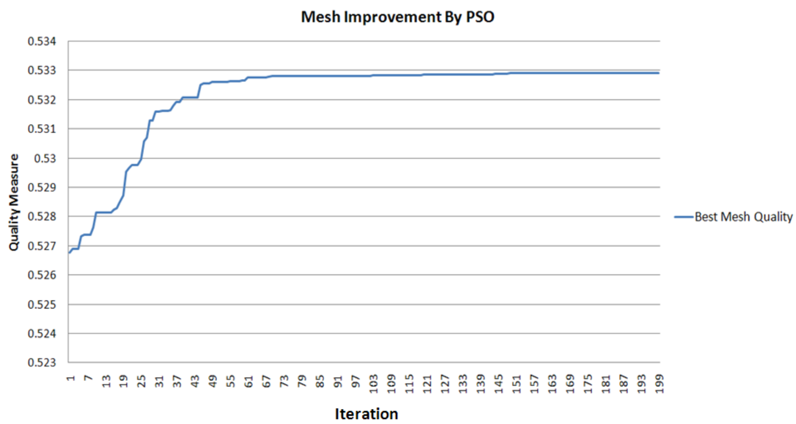


Figure 5. Mesh quality improvement by PSO on initial mesh of Data B

4. Discussion

The results presented showed its capability of generating well sampled volume models from an unprocessed dataset. From the visualization results, it can be seen that more vertices are placed along the fine features, while less vertices are placed on the broader structures in the data. This shows that the method can closely describe and represent an entire set of unprocessed volume data without performing tedious procedures. The second result also shows that the improvement of mesh quality is possible with the use of PSO. At the current stage, the mesh quality only improves slightly. However, further studies will be performed to maximize improvements, for the ultimate goal of ensuring deformation quality.

The proposed method achieves the concept of direct volume manipulation, which is similar to, yet one step further then direct volume rendering. Instead of just being able to view a set of medical data through direct rendering, the direct volumetric model generation approach can offer straight forward manipulation upon loading unprocessed volume data. In this way, surgical simulation would not only be viewable intuitively, it can also be deformable within a trivial, reasonably short period of processing time. Since preprocessing procedures is seemingly omitted from the perspective of the users, direct, patient-specific surgical simulation can be carried out easily. Therefore, this method is practical to be applied in the clinical setting for frequent, repetitive use.

5. Conclusion

This study proposed a method that directly generates volumetric model from unprocessed, patient-specific medical volume data. The method first samples the data by placing vertices at meaningful features, and then improves the mesh quality of the initial mesh generated from the vertex placements. Results showed that the method bypassed preprocessing procedures and has successfully created volumetric models from patient-specific data. Also, the method showed positive attempt in improving the mesh quality of the initial mesh, such that a well data-tailored and at the same time well structured mesh can be produced. This method is a straight forward approach that can be a solution to practical surgical simulation.

References

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