A Hybrid Surface-Voxel Approach for the Reconstruction of Surfaces from CT Projections of Non-Homogeneous Objects

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Introduction

The extraction of triangulated surfaces from Computed Tomography (CT) reconstructions is a crucial task in a variety of applications in medicine and industry [1]. The quality of the resulting meshes depends on the thresholds used to extract the surface prior to triangulation. If these thresholds are not calibrated thoroughly the resulting mesh will not represent the actual object thus rendering it insufficient for a desired task. We herein present a method to refine an initial surface mesh to the acquired rawdata. While we recently demonstrated that this is feasible for ideal homogeneous objects, i.e. ones with a constant linear attenuation coefficient, the contribution herein is a generalization of this method to multi–material objects and such with a non–constant linear attenuation coefficient (see figure 1) [2]. We propose a hybrid surface–voxel approach whereas internals of objects are modelled as voxel volumes obtained by an initial CT scan and the surface is modelled as a triangle mesh. The latter is iteratively optimized to increase the rawdata fidelity.

Materials and Methods

Given measured CT rawdata we reconstruct an initial volume using an algorithm appropriate for the used scan trajectory. This reconstruction is eroded to obtain the voxel model of the object internals. We further assume that a valid surface mesh of the initial volume is provided, e.g. by segmentation and triangulation. If we restrict ourselves to an ideal homogeneous object, the mesh can be forward projected by computing the intersection lengths of all rays with the triangles (see figure 2) and the vertices can be deformed to match the acquired rawdata. This optimization requires the computation of a multitude of ray-triangle intersections to obtain the required intersection lengths. As a typical object might contain up to several million triangles, we employ a spatial subdivision structure, an octree, to allow for a rapid computation of intersection lengths through the considered meshes which also enables a highly performant incorporation of regularizations. This approach is illustrated in figure 3 and the traversal of the octree in figure 4 [3]. However, if the desired object is non-homogeneous, e.g. castings after inhomogeneous solidification, a mere optimization of the vertices will not result in an accurate representation of the object. Hence, we propose a hybrid surface-voxel model. In particular, the internals of objects, i.e. all defects, are modelled as voxels while all rays between the initial, eroded volume and the surface mesh are considered ideal homogeneous and are extrapolated from the volume. This is illustrated in figures 5 and 6 with the corresponding cost function in figure 7. Given this approach allows for an accurate estimation of the surface without the assumption of an ideal homogeneous object.

Materials and Methods

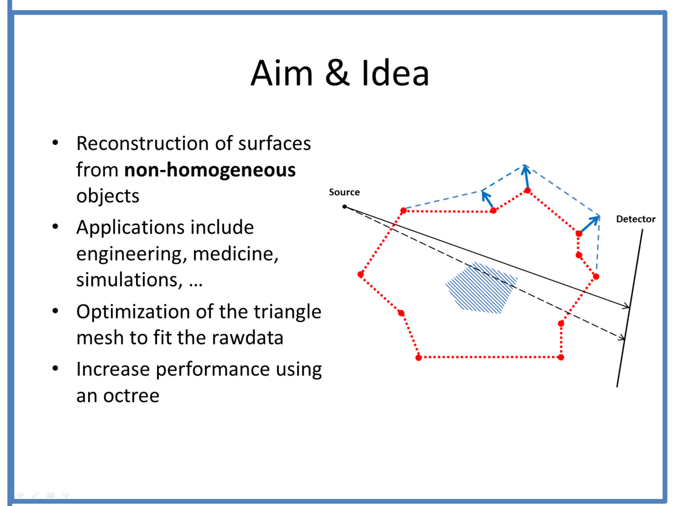

Figure 1: Optimization (blue arrows) of surface mesh vertices (red dots) to match the acquired rawdata requires the consideration of object defects and inhomogeneities (blue) to result in an accurate estimate to the real surface.

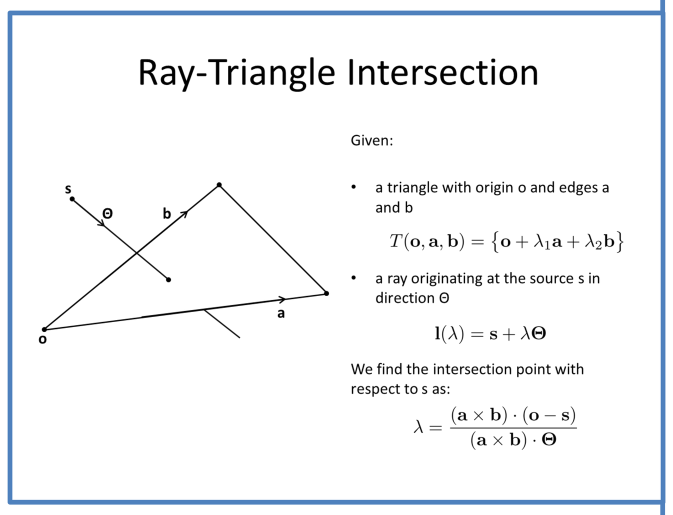

Figure 2: Algorithm for ray-triangle intersection. The forward projection of a surface mesh computes the intersections of all desired rays with the triangles of the mesh and estimates respective intersection lengths.

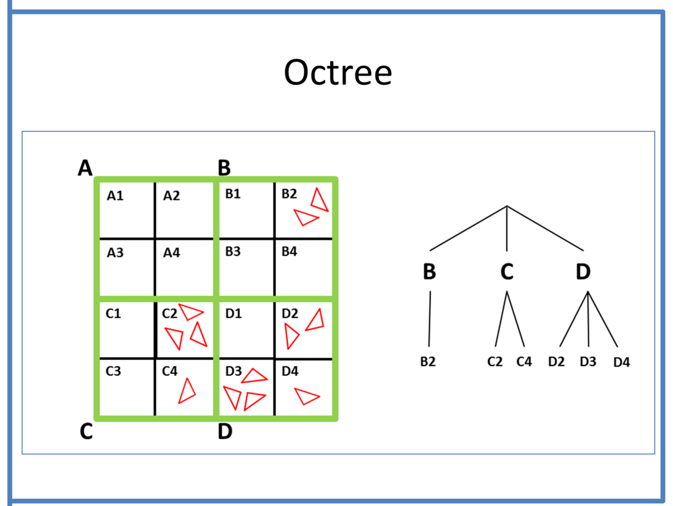

Figure 3: The employed spatial subdivision structure, i.e. an octree (green, left), for a set of exemplary triangles (red) and the corresponding tree structure (right).

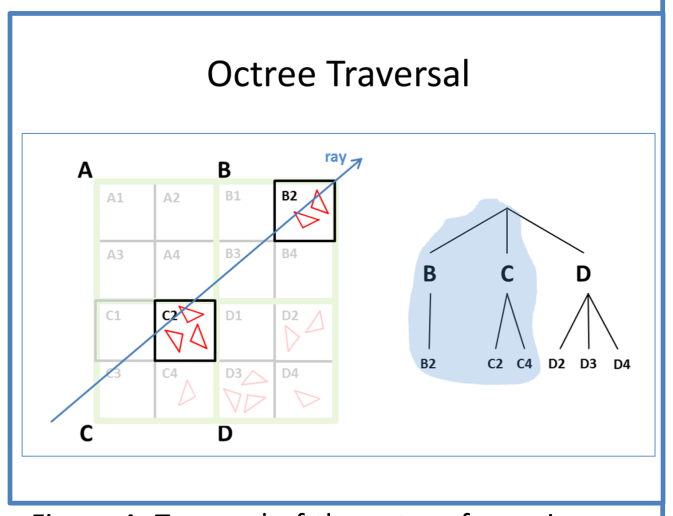

Figure 4: Traversal of the octree for a given ray only requires intersection tests with the highlighted triangles (left) and results in the consideration of only an octree branch (right) significantly improving the performance of all ray-triangle intersection tests.

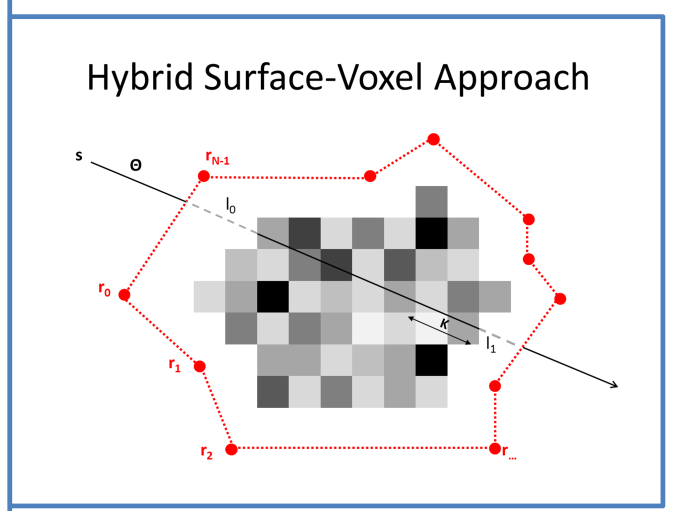

Figure 5: Proposed hybrid surface-voxel model. While object internals are modelled as voxels (grayscale) the surface is modelled as a triangle mesh (red). Rays between the surface and the voxel model, i.e. l_0 and l_1, are extrapolated from the volume over a distance κ.

Hybrid Surface-Voxel Approach

- Object internals are modelled as voxels originating from an initial reconstruction, i.e. including all object defects and cracks.
- The vertices of a sourrounding mesh are optimized to match the acquired rawdata while rays between the surface and the voxel mesh are extrapolated from the initial volume.
- See figure 5 for a graphical representation of this algorithm and figure 7 for the corresponding cost function.

Figure 6: Brief summary of the proposed hybrid surface-voxel approach. An illustration of the algorithm is shown in figure 5 and the corresponding cost function is shown in figure 7.

Cost Function

- Find vertices **r** matching the acquired rawdata **q** while considering object internals as voxels **f** originating from a standard reconstruction followed by erosion:

$$E^2(\mathbf{r}) = \|\mathbf{q} - (\mathrm{X}\mathbf{f} + \mathbf{L}(\mathbf{r}))\|_2^2$$

- Therein, X is a forward projection and **L(r)** models the intersection lengths between the voxel volume and the object surface.
- Note that **Xf** can be precomputed to speed up the optimization process.

Figure 7: Cost function for the proposed hybrid surface-voxel approach. The optimization is performed using a conjugated gradient (CG) descent.

Simulation Parameters

- Simulated scan:
  - Source-detector-distance: 947 mm
  - Flat detector with 1000×1000 pixels each of 388 µm
  - 360 projections over 360°
- Simulated objects:
  - The vertebra contains 70000 triangles
  - The algorithm was initialized with a version of the vertebra that was scaled by a factor of 0.9 around its center of mass
  - Hyperdense spheres were added to the vertebra to simulate a non-homogeneous object
- Test system:
  - 1 workstation with two Intel Xeon hexacore processor @ 3.46 GHz
  - 96 GB of RAM
  - Hyperthreading was disabled

Figure 8: Parameters for the conducted simulation. In particular, the used system geometry, the simulated object, i.e. a vertebra extended with hyperdense structures to obtain a non-homogeneous object, and details of the test system.

Results

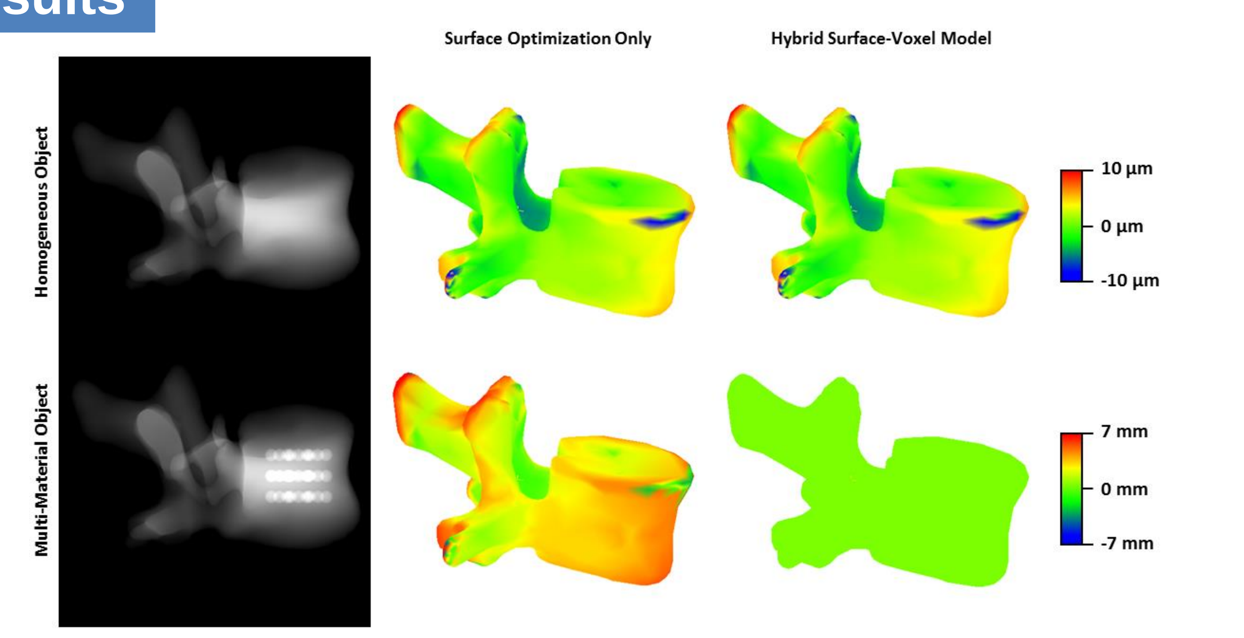

Figure 9: Simulated projections (left column) and results obtained by optimizing only the surface (middle column) and using the proposed hybrid surface–voxel model (right column) given an ideal homogeneous object (top row) and a multi–material object (bottom row). The color–coded figures show the signed distances between the obtained results and the ground truth mesh. Please note the different scaling between top and bottom row indicated by the colorbars.

Results

Figure 9 summarizes the results after 450 iterations of a mere optimization of the vertices and the proposed hybrid surface-voxel model using an ideal homogeneous object and the same object containing hyperdense structures mimicking defects (see figure 8). The left column shows the simulated projection images for the ideal homogeneous phantom (top left) and the multi–material phantom generated by adding hyperdense structures (bottom left) [4]. The middle and right columns show color–coded deviation maps of the results obtained with either a mere optimization of the surface (middle column) or the proposed hybrid surface–voxel approach (right column), respectively. These deviation maps show the signed deviation of the obtained mesh to the ideal vertebra. Given an ideal homogeneous object both an optimization of the surface and the hybrid surface–voxel approach are able to recover the vertebra from the given rawdata (top row) with errors in the order of a few micrometers illustrated by a green color. An optimization of the surface given rawdata of a multi–material object results in severe deviations in the order of millimeters if a homogeneous object is assumed (bottom middle). The proposed hybrid method is able to recover the vertebra given data of a multi–material object (bottom right).

Conclusion

We herein presented a method allowing for the refinement of surfaces and meshes from multi–material and inhomogeneous objects fit for real–world applications. We were able to illustrate that the proposed hybrid surface–voxel approach is superior to a mere optimization of the surface and results in deviations of not more than a few micrometers compared to a ground truth model. An interesting topic of future research could be the alternating optimization of the voxel data and the surface.

References

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[2] Sawall et al.. CT Reconstruction of Surfaces from Binary Objects. Proceedings of the Third *International Conference on Image Formation in X-Ray Computed Tomography*, June 2014.

[3] Sawall et al.. Fast computation of projections from triangulated surfaces. Proceedings of the *12th International Meeting on Fully 3D Image Reconstruction, June 2013.*

[4] BodyParts3D. http://lifesciencedb.jp/bp3d/

Acknowledgements

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