LUNG AUTOMATIC RECONSTRUCTION ALGORITHM FOR CFD SIMULATIONS

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Abstract. In this paper, the outline of a program generating almost fully automatically the surface mesh of a bronchial tree based on medical CT image data is presented. For the whole process, required user input is reduced to a minimum. Particularly of importance is the implementation of a skeleton algorithm in order to determine the generation of each bronchial branch and to cut the branches to obtain the outlet markers. No repetitive pixel painting or triangle picking tasks are needed during the surface mesh generation process.

1 INTRODUCTION

Most of the patients admitted in the intensive care unit need artificial ventilation. A better comprehension of the processes involved in air transport within the lungs is necessary in order to optimize the artificial ventilation techniques. Nowadays, computational fluid dynamics (CFD) allows for efficient and robust simulation of flows in highly complex geometries like the human upper or the central airways. However, as an input for CFD software, a spatially discretised computational domain representing the physical domain of interest, i.e. human respiratory system, a numerical volume mesh, has to be generated. The mesh generation process is normally long and cumbersome and need many manual interventions. In this paper, a program for automatised geometric segmentation and surface mesh generation based on medical computer tomography (CT) image data is presented. The main objective was to reduce the required interactive user input to a minimum.

The program consists of two major modules. One image processing module which allows geometry segmentation out of a staple of 2D medical CT images and a second module, a surface mesh generation module, for generating a triangle based surface mesh of the
segmented geometry. In this case, the algorithm has been applied to a CT dataset of an isolated pork lung for reconstruction of the central airways.

2 SEGMENTATION AND SURFACE MESH GENERATION

The image processing is performed on all images simultaneously using the standards segmentation techniques such as cropping, blurring, sharpening, thresholding and edge detection. Then, a region growing advancing front method is used to obtain a single set of connected voxels. It allows for capturing the entire bronchial tree and to differentiate the latter from the pulmonary blood vessels. Statistical filters as well as expanding and shrinking techniques are applied in order to remove undesired small details and concavities within the geometry. User input is only required to determine some global values such as the grey level used during the thresholding algorithm, to select the region of interest, and finally to define the desired number of generations which are going to be reconstructed. By superposition of the segmented geometric bodies with the original image the level of detail resolution as well as the quality of the overall segmentation process can be checked by optical means (Figure 1).

Figure 1: Superposition of the segmented lung with the original image. All small branches are captured by the segmentation algorithm (cyan patches), while the blood vessels are excluded from the computational domain.

The user input for the second module, the surface mesh generation, is limited to the definition of the inlet location. The initial surface mesh is generated using a marching cube method. A non shrinking smoothing algorithm, is used on the initial mesh to obtain a smooth surface and finally a polygon reduction algorithm allows to reduce significantly the number of triangles while keeping the form of the surface mesh. The triangles at the inlet plane (trachea) are flagged during the mesh generation process. All other branches finish with a dead end. They need to be cut perpendicularly to their axis in order to apply a pressure outlet condition at each end for the CFD simulation. This is done with the help of the compact line-like 1-D representation of the segmented 3D bronchial tree, the so-called skeleton.

Figure 2: Initial Surface meshes
3 SKELETIZATION AND BRANCH CUTS

For each branch, the CFD simulation needs to have an identified set of outlet triangles. These triangles should be coplanar. Therefore all branches need to be cut perpendicularly to its axis and the triangles resulting from the cut need to be flagged as outlet. This is done with the help of a skeleton algorithm.

The voxels of the skeleton of the bronchial tree (Figure 3) are extracted from the stack of images using an algorithm based on two discrete distance fields. A boundary seeded distance field is computed to determine the distance between a voxel and the closest boundary. This distance field is used to center the skeleton line along a branch. A point seeded distance field determines the distance between a voxel and the seed point (here at the beginning of the trachea) following a path fully inside the segmented lung. The local maxima of the point seeded distance field are branch ends and are used as starting points for the acquisition of the skeleton. The size of the neighbourhood for the local maxima search is chosen in order to capture all physical branches while reducing the number of phantom branches (created by noise on the boundary of the segmented lung). The skeleton is then stored using a hierarchic branch structure. The position, direction and path as well as the length and children of each branch are stored in this data structure. The generation of each branch can be also derived using this structure.

Figure 3: Skeleton of the bronchial tree. All branches are described by a thin line, the generation of the branch is colour coded.
Figure 4: Final surface mesh with 4 generations. The branch cuts are performed automatically and perpendicularly to each branch.
The branch ends are then cut using the information delivered by the skeleton. The user can choose how many generations of branches the lung model should have (Figure 4). The cuts can be performed either at the end of each branch thus keeping the full network of branches resolved through the underlying CT images or they can be performed further up in the lung model in order to reduce the model to a specified number of generations. The position and the normal vector of the plan used for cutting the branches is delivered primarily by the skeleton, but these values are iteratively optimized in order to cut each branch as perpendicularly to the branch axis as possible. Triangles located behind or being directly cut by the cut planes are erased and the corner points of the resulting triangle front are projected onto the cutting plane. Outlet markers are set at the branches ends. The volume meshes can then be created with standard unstructured or pseudo-structured grid generators such as e.g. NETGEN or CENTAUR™.

4 CONCLUSION

The presented process chain allows for an almost automised reconstruction of a complex surface mesh from high resolution medical CT image data. Geometry reconstruction of bronchial trees with four to eight generations of branches can be quickly generated from standard 1024x1024 pixel CT scans with slice spacing of 0.6mm and 50% overlap. During the whole mesh generation process, only little user input is necessary. User input is needed in order to define global constants such as the thresholding and sharpening values. It is also needed in order to select a seeding point for the region growing algorithm as well as the point seeded distance field. The surface mesh generation, the smoothing, and the triangle reduction algorithm are fully automised. Finally, the geometry of the bronchial tree is reduced to the desired level of central airway generations by fully automatic branch cutting and additionally the outflow planes are flagged as outflow markers.

The applied algorithms allow to reduce the time used for geometry reconstruction and mesh generation. The skeleton technique is efficient for the upper and central airways which are organised in a tree structure, but it can also be easily applied to other bio-medical applications such as blood vessels or rhino pharyngeal flow investigations after only minor adaptations.

REFERENCES