Virtual Open Heart Surgery: Obtaining Models Suitable for Surgical Simulation

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Abstract. We present a pre-processing strategy including imaging, segmentation, and model reconstruction that is well suited for previously published GPU-accelerated techniques for surgical simulation. In particular we describe these modeling steps as a prerequisite for our virtual open heart surgery simulator. A short description including relevant references is presented for each of the steps.

Keywords. Segmentation, surgical simulation, congenital heart disease

Introduction

The modern graphics processing unit (GPU) has provided a new computational platform suitable for surgical simulation [1]. Using the GPU for both simulation and visualization, the deformation of complex morphology can now be simulated interactively [2-4]. While [1-4] introduce the technical aspects behind a GPU-based surgical simulator, this paper presents a method to obtain simulation suitable, high resolution morphological volumes and surfaces – a prerequisite for realistic simulation of e.g. open heart surgery [5].

1. Materials, Methods and Results

Our aim is to obtain a volumetric segmentation of the heart muscle (the myocardium) and vessel walls. A spring-mass based physical simulation is then used to interactively deform this volume [2]. Visualization of the deformed heart is fully decoupled from the underlying simulation [3], and surfaces are thus reconstructed independently of the resolution of the spring-mass system.

1.1. Imaging and segmentation

All models are reconstructed from isotropic 3D MRI covering the whole heart (Figure 1, left). An operator-independent acquisition lasting from six to twelve minutes results in 50 to 120 slices. The voxel resolution ranges from 1.5^3 mm^3 to 2.0^3 mm^3 depending on the heart rate, size, and general cooperation of the patient [6-7]. A watershed-based segmentation algorithm was used to segment the blood pool and myocardial volume semi-automatically (Figure 1, middle left) using the Cardiac3D software (Systematic Software Engineering, Denmark). The user interactively inserts colored markers in the MRI and the resulting segmentation is presented instantly (transparent red/green colors) [8-10]. Some manual adjustments are always necessary, and a "drawing stencil" is provided to support this operation. The tissue bordering major blood vessels (i.e. the

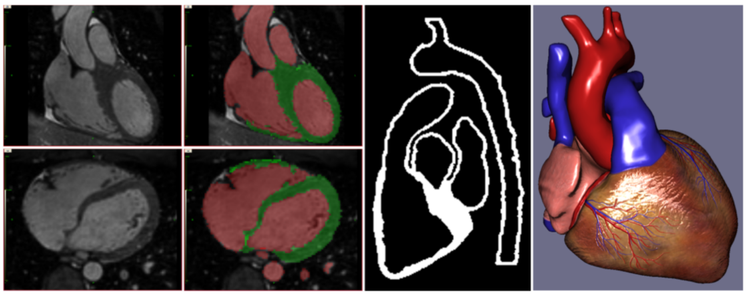

Figure 1. MR image acquisition (left), segmentation (middle left), smoothing and vessel wall growing (middle right), and surface reconstruction (right).

aorta, the pulmonary arteries and veins, and the caval veins), the atria, and parts of the right ventricle is too thin to be clearly visible on the MRI. To overcome this problem, (vessel) walls are automatically grown to constitute the blood pool borders in areas where the segmented blood pool is not bordered by segmented tissue (Figure 1, middle right). We tend to smooth the epicardium (the outmost myocardial border) more than the endocardium (the innermost myocardial border) as we extract the segmentation. This is achieved by restoring the segmented blood pool and hereby the endocardium some user-defined fraction through the smoothing process. The endocardium is consequently only affected in the remaining smoothing iterations.

1.2. Obtaining the volumetric simulation grid

A typical 3D MRI dataset contains 256 x 256 x 100 voxels [6-7]. The number of voxels classified as tissue by the segmentation process is in the order of 250.000. Ideally, each of these tissue voxels should be treated as one particle in the spring-mass simulation. The simulation and convergence rates for such large systems are too slow however, even with for GPU-accelerated implementations. We consequently downsample by a factor of 2^3 to obtain approximately 30.000 simulation nodes in a regular three-dimensional grid [2]. The binary image in Figure 1 (middle right) shows one slice from such a simulation grid.

1.3. Surface visualization processing

A highly detailed surface is extracted from the segmented endocardium-, epicardium-, and vessel borders at full resolution by the marching cubes algorithm [11]. The resulting model easily contains 1.000.000 triangles. We represent each vertex by an offset from the nearest simulation grid node [3]. It is necessary to express each offset in a vector basis local to the simulation node to have the offset vector deform according to the spring-mass system's deformation. This requires some per vertex processing in each frame. As this is a relatively costly operation we reduce the triangle count in the high-resolution surface model to avoid a visualization bottleneck. Normal maps are used to conserve the details of the high-resolution mesh in the simplified model of 50.000-100.000 faces (Figure 1, right).

Our implementation of force feedback is realized by a GPU based picking and force calculation technique [4]. It requires off-screen rendering of a low-resolution model with a vertex for each "surface mass point" in the simulation grid. This model is again obtained from the marching cubes algorithm [11].

2. Discussion

We see two potential scenarios for the current simulator prototype; patient-specific preoperative planning, and surgical education [5]. In the first scenario we can segment the blood pool, the left sided myocardium and grow vessel walls in one to two hours in good quality datasets. The right sided epicardium remains a challenge to segment rapidly, but could be “grown” to a certain thickness surrounding the blood pool by a dedicated volume paint application instead. Generally, any thin borders are invisible on the MRI due to partial volume effects, which makes the “tissue growing mechanism” a necessity. While some manual corrections are needed at the segmentation stage, the remaining pre-processing steps can be fully automated. We are currently evaluating the required segmentation time on a larger number of patients.

When working in the educational scenario, we have no time constraints creating each model. In Figure 1, right 2 we consequently normal mapped the myocardial surface with the coronary arteries – drawn manually by a graphics artist. We could also have encoded information on e.g. the electrical induction system in such texture maps. These need not be visible to the user but can be used instead to detect and report the likelihood of each incision damaging in this case the induction system.

3. Acknowledgments

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