Technical Aspects of the GPU Accelerated Surgical Simulator

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1 Introduction

When a child is born with a malformed heart, an accurate understanding of the complex morphology and related surgical strategies is important to paediatric cardiac surgeons. Through our interdisciplinary research with paediatric cardiac surgeons we have developed a surgical simulator for this purpose (See Figure 1).

The complex morphology of a heart model requires highly detailed geometry, both for visualisation and tissue-deformation. To achieve this goal, combined with real-time interaction, our primary strategy has been to utilise modern consumer graphics processing units (GPUs) since they have a larger number of floating point operations per second than a comparable CPU.

2 Technical solutions

Tissue deformation is represented by a particle-spring system solved on the GPU [Mosegaard and Sørensen 2005a]. The shape of the heart is approximated by a set of particles moving according to the equation of motion and constrained by springs-forces connecting pair of particles. The computation involved with each particle has been mapped to the programmable GPU where it can be executed in parallel. Spring forces depend on the position of neighbouring particles, which can be deduced directly from the memory-address of the particle itself (through fixed offsets to neighbours) or indirectly through a list of memory-addresses (pointers). The direct approach requires an initial layout of particles in a grid. This wastes memory when the simulated shape is not a cube, but halves the amount of memory-lookups compared to the indirect method. Since the performance of the GPU-based particle-spring system is memory-access bound, the direct method is about twice as fast as the indirect method - while the indirect is already about 15 times faster than a CPU implementation.

When the particles are arranged in a regular grid in the direct approach, the visual quality suffers under a jagged look. In [Mosegaard and Sørensen 2005b] we presented a GPU-based method to decouple visualisation and simulation by mapping a detailed and smooth surface onto a more coarse simulation. This can be regarded as a displacement mapping from the set of dynamic particles to the required visual surface.

Surgeons interact with the simulator through two 6DOF force feedback devices (PHANToM Omni, SensAble). We have devised a strategy for both manipulating tissue and retrieving force-feedback, while avoiding the potential bottleneck of a per-frame read-back of all particles to the CPU [Sørensen and Mosegaard 2006]. Our strategy is to calculate and read back only the necessary particle-forces. In the case of a fixed grab on a set of particles, references to manipulated nodes are available from the CPU. These are transferred to the GPU and only the involved forces are read back. In the case of an instrument sliding along the heart, the involved particles change depending on the location of the instruments and the current deformation of the particle-system - information which is only available on the GPU. We handle this case by drawing the currently deformed geometry with surface-colour representing memory-addresses to relevant particles to an off-screen buffer. By sampling this buffer from a GPU-program, we can find the involved particles and proceed as in the case of a fixed grab.

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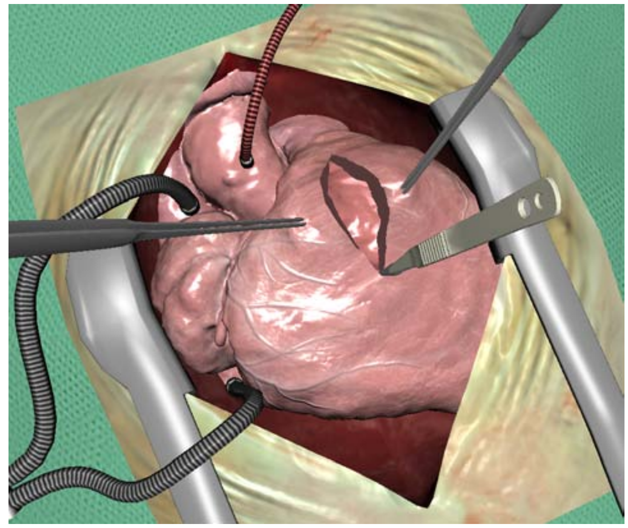

Figure 1: Screenshot from the simulator

In combination, the described techniques can be used to implement force-feedback handling of a simulation of deformable material. Specifically, we have implemented a surgical simulator for congenital cardiac defects. Using the newest consumer level GPU (GeForce7900GTX, Nvidia) we can interact with a patient-specific virtual heart consisting of 160,000 faces at 20 frames per second, while the underlying spring-particle system, consisting of 60,000 particles, runs at 300 hz.

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