LR-Spring Mass model for Cardiac Surgical Simulation

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Abstract. The purpose of the research conducted was to develop a real-time surgical simulator for preoperative planning of surgery in congenital heart disease. The main problem simulating procedures on cardiac morphology is the need for a large degree of detail and simulation speed. In combination with a demand for physically realistic real-time behaviour this gives us tradeoffs not easily balanced. The LR-Spring Mass model handles these constraints by the use of domain specific knowledge.

1. Introduction

The purpose of the research conducted was to develop a surgical simulator [1-2]. The surgical simulator should be used for pre-operative planning of congenital cardiac disease. The problem definition and preliminary evaluation was done in cooperation with paediatric cardiac surgeons from Aarhus University Hospital. The basic requirements for a surgical simulator were defined to include real-time calculations of deformation and interaction as well as real-time changes in the morphology of the tissue in response to incisions.

Standard elastic models such as Spring Mass and FEM have slow convergence to equilibrium because of the large degree of detail in the geometry.

2. Related Work

Other surgical simulators are based on Spring Mass algorithms [1-2]. The LR Spring Mass model combines techniques such as local interaction [3] and iterative relaxation [4] to achieve a fast convergence with real-time response.

3. Geometry

The surgical simulator was envisioned as a pre-operative planning tool for the surgeons. It was therefore important to derive the geometry from actual patient specific data, accessible prior to the surgical procedure.

The MR-data reconstruction by Sørensen et. al. [5] was used to construct the geometrical data for the surgical simulator. The basic cardiac model consisted of 35.000 nodes to recreate a heart in sufficient detail.
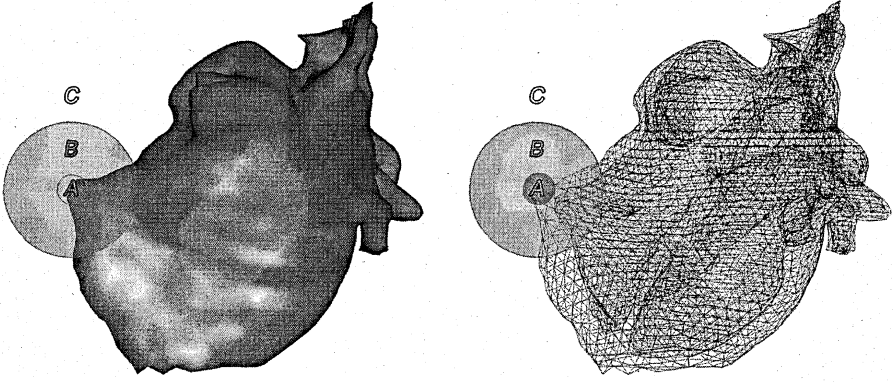
Figure 1: Dividing the deformation into three areas (A, B, C). Area A: The position is set absolute. Area B: The position is calculated with Spring Mass and relaxation. Area C: The position is calculated with relaxation only.

An inner surface and an outer surface were constructed based on cardiac MRI. These surfaces define the volume of tissue. The surface consists of nodes connected with springs. In between the surfaces additional springs were inserted to simulate forces between the surfaces.

4. Problem Definitions

We ended up defining an LR-Spring mass elastic model based on the following observations: The surgeons were only interested in the precise behaviour of a small area around the tool interaction at a given time. Throughout a surgical procedure the position of this area will change. Furthermore, the surgeons do not need the information offered by a time dynamic simulation; a static equilibrium is sufficient.

5. LR-Spring Mass Model

The LR-Spring Mass model is based on a static formulation of the Spring Mass problem. We seek the configuration of nodes such that for internal forces g and external forces f for nodes j and i:

$$\sum_j g_{ij} - f_i = 0 \text{, for all } i$$

That is, when the external and internal forces are in equilibrium for all nodes.
The internal forces are calculated as linear springs (default length l and spring stiffness k):

$$g_{ij} = k_{ij} (l_{ij} - \|x_i - x_j\|) \frac{x_i - x_j}{\|x_i - x_j\|}$$

The system is solved with a local, iterative method as proposed in [3].
To speed up the convergence we will use a technique known as relaxation. Relaxation has been used in [4] to constrain the deformations of a dynamic Spring Mass model. Relaxation iteratively moves nodes of a spring such that the original length is retained:

$$diff = \frac{(\|x_2 - x_1\| - l_{rest})}{\|x_2 - x_1\|}$$

$$x_2 = x_2 + \tfrac{1}{2} \cdot \|x_2 - x_1\| \cdot diff$$

$$x_1 = x_1 - \tfrac{1}{2} \cdot \|x_2 - x_1\| \cdot diff$$

In the area of interest we will use both the static spring mass calculation and relaxation, but outside this area we will only use relaxation to create *some* response - though not as realistic as the spring mass based, see figure 1.

6. Results

The LR-Spring Mass model clearly gives a faster convergence than basic Spring Mass or FEM based algorithms inside the area of interest. The entire organ reacts much faster than basic Spring Mass or FEM based algorithms but only in an approximate physical manner.

7. Conclusions and Future Work

The LR-Spring Mass model is specifically suited for congenital cardiac diseases - or simulation of other organs with a complex morphology that requires a large degree of detail. The model uses levels of interests, static equilibrium and accelerated convergence through relaxation.

The basic elastic model for the simulator for Congenital Cardiac Diseases is ready. The next step in the research is to support a complete surgical procedure, specifically with added support for the re-modelling of the cardiac morphology.

The process of developing the LR-Spring Mass model was based on discussions with surgeons and the surgeons could see potential in the elastic model for pre-operative planning of congenital cardiac diseases. A more formal clinical evaluation is a natural next step in the research.

References

[1] Cover, S.A, et. al. Interactively Deformable Models for Surgery Simulation Proceedings of ICRA, 1993, pp. 68-75

[2] Provot, X. Deformation Constraints in a Mass-Spring Model to Describe Rigid Cloth Behavior. Graphics Interface '95, 1995, pp.147-154

[3] Brown, J., et. Al. Real-Time simulation of Deformable Objects: Tools and Application. In Proceedings of Computer Animation 2001, 2001, pp. 228-236

[4] Casson, F.B. de and Laugier, C. Modelling the dynamics of a human liver for a minimally invasive surgery simulator. Medical Image Computing and Computer Assisted Intervention 1999 (MICCAI'99), ,vol. 1679 of Lecture Notes inComputer Science, 1999, pp. 1156-1165

[5] Sørensen, T.S et. al. MRI Based Preoperative Reconstruction and Surgical Planning in Congenital Heart Disease. 11th Annual Medicine Meets Virtual Reality Conference, 2003