DEFORMATION MODELING USING GLOBAL MEDIAL REPRESENTATION STRUCTURES AND EVALUATION BY BISET MESH MATCHING

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ABSTRACT

In this paper, we present a novel hybrid deformation model using global mass-spring medial representation structures and local finite element model. We employ the hybrid models, by fully calculating the FEM deformation in the local operation part while only calculating the global deformation by medial representation method. To achieve the real-time requirement of realistic deformable modeling, it is necessary to use the GPU parallel computing for FEM on regional deformation details, so the major calculation work in the conjugate gradient solver for the solution matrix is moved from CPU to GPU to accelerate the effectiveness. Evaluation and experiments are also discussed.

Index Terms— Deformation Model, Mass-Spring, Medial Structure, Finite Element, Deformation Evaluation

1. INTRODUCTION

Although the simulation of human soft tissue has a long history in biomedical engineering and computer science, physically realistic modelling and computation of soft tissue's deformation has been the bottleneck of many applications, especially virtual surgery system. So far many simulations of deformation have been implemented using simple models: Mass-Spring [1], linear elastic FEM [3], [4], Centerline or Skeleton [11], Medial Representation Model [12] and so on. These methods work well for simulations of very small strains and local deformations, but have poor accuracy for large global deformation modelling. Global deformation [2] is commonly happened in medical domain and worth simulating for virtual surgery, such as large twisting or bending of an object, which involves the entire body. We could take the human intestine as a good example, for this case: while observing the patient's intestine, it is inevitable that the patient will move and so will his/her intestine move dynamically. In this situation, which is different from other soft tissue's minor deformations like needle insertion, scalpel cutting or forceps nipping, the intestine will move globally. Many problems in mechanics and physics lead to differential equations, and most of which are impossible to be solved in analytic way. Finite Element Models ([2]-[7]) is such a numerical method that subdivides the object to a finite set of primitives, such as tetrahedral mesh, with a physical equilibrium equation for each of them. With application of variational principle, it can transform to problems of solving large systems of linear equations. Conjugate Gradient algorithm [8] is a popular solution for large sparse symmetrical linear systems.

In this paper, first, we would focus on simulation for deformation of soft tissue in virtual surgery using nonlinear FEM in contrast with linear FEM. Then, we introduce the acceleration techniques of GPU Computing and Hybrid Deformable Model Structures. We also propose the evaluation method based on biset mesh matching. At last, we would conclude our experimental results based on 3D kidney model and blood vessel model.

3. LOCAL DEFORMATION OF FINITE LEMENTS

3.1 Dynamic Finite Elements Deformation

To model dynamical Finite Elements deformation of elastic objects, we should solve the following system of differential equations:

$$M\ddot{a} + D\dot{a} + R(a) = F \qquad (1)$$

where $\ddot{a}$, $\dot{a}$ are the respective acceleration and velocity vectors; M, the mass matrix, D, the damping matrix, R(a) is the stiff matrix, F is dynamical external force. Equation (1) becomes static equation if the acceleration and velocity vectors are neglected. We have to solve the system of differential equations (1) approximately by numerically integrating along time dimension. We solve the system of equations at a time step according to the previous time steps via Central Differences [5].

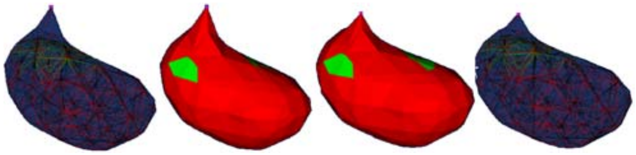

Fig.1. Linear/Nonlinear Deformations of Finite Elements

3.2 High Precision GPU Numerical Computation

The main computation for FEM in each round of the Conjugate Gradient algorithm is the matrix and vector multiplication, so the zero elements of the matrix would remain the same in the calculation process, which indicates it more suitable for its implementation onto the GPU. The kernel step is the multiplication of the sparse matrix and the vector. We move this part of calculation into the fragment processor of the GPU, to utilize GPU fragment processor in highly efficiently manipulation of the local texture memory on the mathematical calculation [6].

Fig.2 shows the main idea to employ GPU on matrix vector operation, which is the heavies load in deformation computation. However, the traditional GPU computing only has Single Float data type, while fast Conjugate Gradient solver requires high precision data type for each computational iteration. Thus, we employ Double Float Precision to achieve it [14].

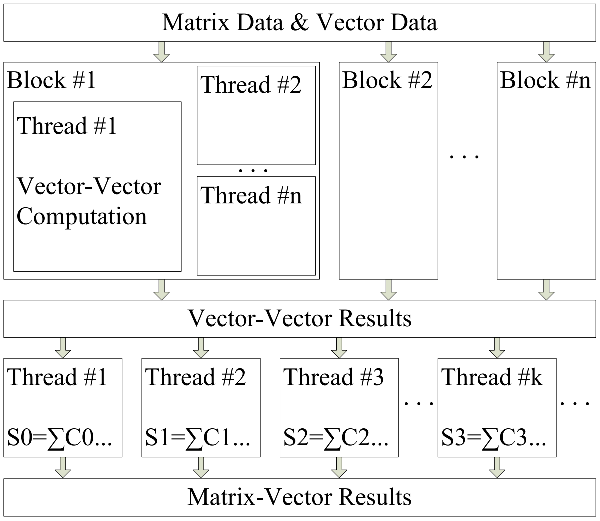

Fig.2. GPU Parallel Computing Architecture

4. HYBRID STRUCTURE OF MEDIAL LINE AND LOCAL DEFORMATION

4.1 Medial Centerline and Medial Representation

Medial Representation algorithm is a model based on Centerline. It records information of the centerline atoms only. When there is a deformation on the centerline, we can redraw the object's surface through the centerline information. So Medial Representation is quite appropriate to model soft tissue like blood vessel. Traditionally, on the basis of Blum's medial axes [15] and from Medial Representation, Prizer [16] proposed the M-Rep method, which is excellent to represent the internal structure and uses medial atoms and a particular tuple $\{x, r, F(\overline{b}, \overline{n}), \theta\}$ to indicate the boundary of the deformable object [11].

We implement the method of the M-Rep algorithm to simplify the global model. For atom i (i=2,3…n-1) on the centerline, the first boundary node B of this atom can be anyone(usually we choose the one that on the plane xOy of Cartesian coordinates) that satisfies the formula (2):

$$\begin{cases} \overrightarrow{C_{i-1}C_{i+1}} \bullet \overrightarrow{C_iB} = 0 \\ |C_iB| = r \end{cases} \qquad (2)$$

Where Ci means the ith atom on the centerline. That is, CiB must be vertical to vector Ci-1Ci+1, and with length of r. Then calculate every boundary node, use the following formula (3):

$$B' = x + R_{C_{i-1}C_{i+1}}(\theta)B/|r| \qquad (3)$$

where R denotes the operator to rotate its operand by the argument angle θ with the axis represented by the vector Ci-1Ci+1, B' and x are the coordinates of boundary and medial atom Ci respectively as shown in Fig.3.

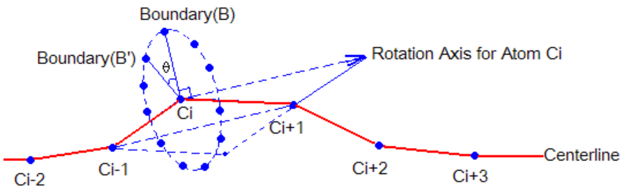

Fig. 3. Surface reconstruction method of simplified M-Rep

4.2 Local Region Deformation

Most surgery operations are performed in a small area on a soft-tissue, so we restrict the deformation in a local level if the external force is relatively small in order to reduce the calculation time.

In the pre-processing stage of the application, the Dijkstra algorithm is employed to calculate the shortest distance between mass points and a distance table, thus recording the distance between all points is generated.

The deformation procedure is the following: if a small force is applied on the white spots (Fig.4.) and the propagation of the force is limited in the second layer. The optimization will be skipped when the external force is larger than the threshold value.

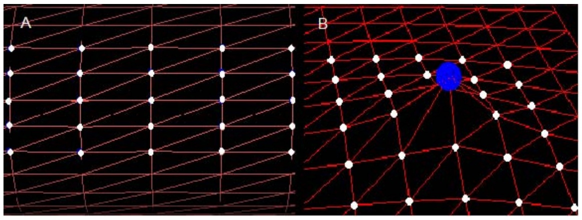

Fig.4. the local deformation result on the global surface

5. EVALUATION OF MESH BISET MATCHING

The mesh biset evaluation concept is deployed as the following steps: (1) to acquire the meshes from modelling result and from standard data; (2) to build the biset graph between the 2 set of meshes according to the segments connections between their corresponding points on the meshes; (3) to employ the statistics method on the lengths of the connective segments and then judge the errors and satisfaction levels of the models, as shown in Fig.5.

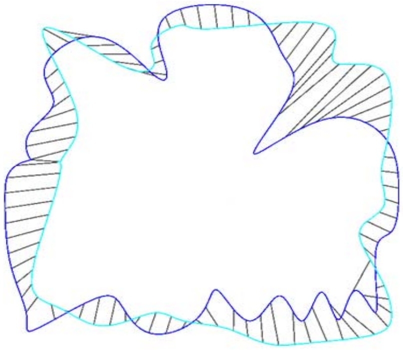

Fig.5. Evaluation based on Biset Mesh Points Connection

We have local error equation as,

$$LE_j = \frac{\sum_{i=1}^{N} LE_{ij}}{N} \qquad (4)$$

where $LE_{ij} = d_{ij}$, and d_{ij} standing for the line length.

And we have the global evaluation equation as

$$GA = \frac{M}{\sum_{i=1}^{M} \lambda^{P_i k}} \qquad (5)$$

where M is the total number of lines, $\lambda^{P_i k}$ is the punishment function which is various in different case, and $P_i = \left| \frac{LE_i}{L_i} \right|$.

6. EXPERIMENTS

We generate a human kidney mesh using the meshing technique discussed above and simulate its deformation under a boundary force. Fig.6. shows the results. Based on experimental statistics, if we set the meshing granularity to 15, we will have 1018 vertex and 3272 tetrahedron, and consequently, the computation iterations are 34 rounds costing 70ms and meeting real-time requrements. The validation results based on bi-set meshes matching are showed in Fig.7.

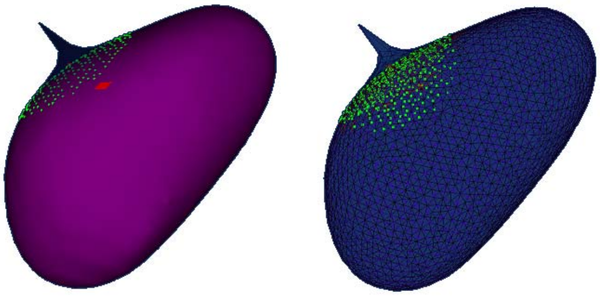

Fig.6. FEM Deformation with Local Region Constrain, comparison between surface rendering and meshing

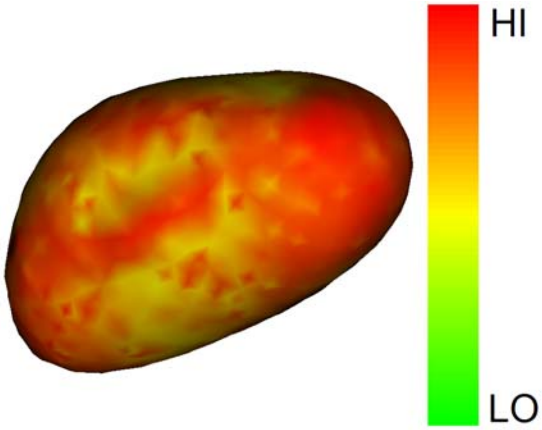

Fig.7. Validation Result of Different Color Mappings for Various Error Levels

Last but not least, we apply the hybrid structures of deformable models, by fully calculating the volumetric deformation in the local operation part while only calculating the global deformation by medial representation method, as shown in Fig.8.

The feasible and viable modelling application of suturing and cutting in virtual surgery is shown as Fig.9.

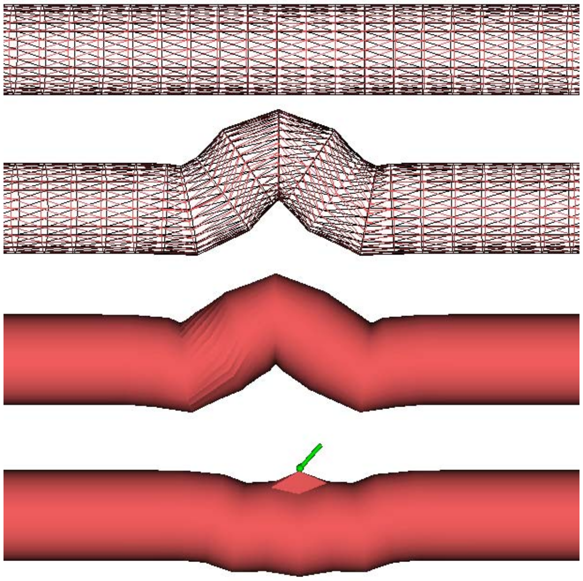

Fig.8. Medial Representation Global Deformation with Local Region Deformation (The first shows static meshes, second and third show Global Deformation, last shows Global Deformation with Local deformation)

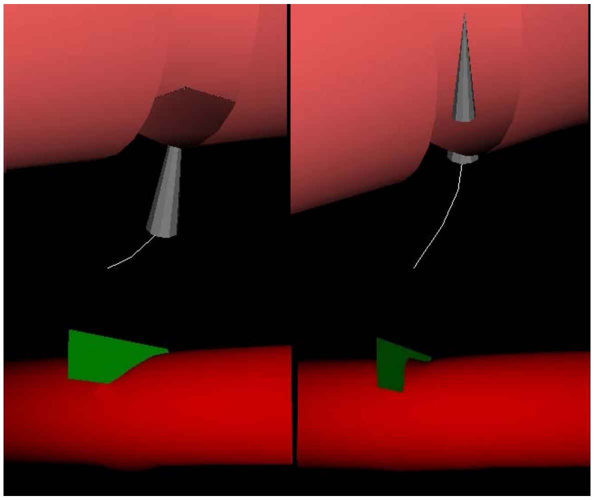

Fig.9. Suturing and Cutting Based on Deformable Models

7. CONCLUSION

In this paper we focus on the simulation for realistic deformation of soft tissue using nonlinear strain FEM, because it's important to simulate large global deformation in virtual surgery. And through experiments, we take the advantage of using nonlinear strain deformation to simulate soft tissue. To achieve real-time performance, we apply Revised Delaunay Meshing, GPU Computing and Hybrid Deformable Structures. Aiming at a more accurate and robust level of virtual surgery, some other technologies will be also implemented, such as condensation [6] for decreasing the size of system in FEM. The force feedback devices integration and deformation validation problems will also be considered and solved in the future.

8. ACKNOWLEDGEMENT

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