Real-time and Haptic Suture Simulation

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Abstract—**In this work, we propose a novel suture simulation method. Compared to the traditional approaches which just use rough Mass-spring Model to simulate the suture, we add the concept of control point and FTL into the Mass-spring Model, which will indicate the suture points in intersection with the soft tissue. Interaction forces during suture process are simulated on these control points, including friction force, surface tension, repelling force, etc. Moreover, to improve the update efficiency of the bounding-volume hierarchy(BVH) technique, a bottom-up strategy is proposed. Our method has its superiority in both visual and haptic realism, as well as in both suture and tying simulation.**

I. INTRODUCTION

As one of the most common operations, suture is a basic skill that every doctor must master. It may be divided into two categories: suture under non-endoscope and suture under endoscope. The former is that doctors directly sew the wound that exposes subcutaneous tissue, and the suture needle is big enough to be distinguished by the unaided eyes. The latter is that doctors operate the equipments, such as a clip, to control suture needle to sew the wound under the endoscope indirectly. And the needle is too fine to be distinguished, which greatly increases the difficulty to complete the suture operation. Due to the high magnification ability, the perception by touch doesn't match the feeling by vision very well, so tying a knot under the endoscope is even harder.

Suture simulation will simulate the whole suture process under the endoscope which can provide some training to help doctors improve theirs skills. The simulation involves using a suture to pierce through soft-tissue, pulling the lines to connect two separate surfaces, and tying knots. This paper carries on thoroughly studies about suture simulation, mainly including three problems: (1)knot-tying simulation; (2)a reasonable force feedback; (3) a real visual effect of suture.

The paper is organized as follows: Section 2 introduces the traditional suture modeling methods. In Section 3 and 4, approaches to suture simulation and collision detection are discussed in detail. Section 5 analyzes the force situation during the process of knot-tying. Section 6 analyzes the entire process of piercing and sewing. Finally, in Section 7, experiments are presented.

II. RELATED WORK

Prior work towards suture simulation proposes several suture modeling methods, which can be classified into two kinds: physics-based modeling and geometric-based modeling.

The physics-based method is to model the suture as mass springs, which is easy to model force along the suture. As mentioned in [1], mass-spring model is applied to simulate a suture, and finally yields a good result in a way. However, this method will cause a great distortion especially when dealing with deformation in a large area.

The geometric-based method uses the result of geometric computing to track the trajectory of the suture, but hasn't taken account of physical characteristics. In [2], the thread is modeled as splines with a few control points. These points under specific constraints can force the thread to slide through some specific piercing points, impose the direction of the spline at these points, and propose a proper friction model to allow the suture to remain fixed at the piercing point or slide through it. However, the knot-tying is out of the scope of the paper. Joel Brown et al [3] model the suture as a chain of short rigid links which are connected together. The trajectory of the suture is configured by a constraint-based technique called "follow-the-leader"(FTL).This method indeed yields to a good result showing realistic behavior and robust computation, but doesn't take the force model into account. Without force analysis, most physical characteristics are lost, such as the suture tension, the friction between the suture and the organ. Nonetheless, the concept of FTL is still worth learning.

In this paper, we keep some useful bits of other people's ideas. We use Mass-spring Model to simulate the suture [1], [4], and adopt FTL, "control points" and force model to configure the motion of the suture [5] and execute knot-tying simulation. In addition, a bottom up method is presented to shorten the time of updating the BVH.

III. SUTURE MODELING

Similar to [1], we model the suture as an articulated object with 80 short links sequentially connected at nodes acting as spherical joints. To keep the suture moving smoothly, the

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motion is calculated in a FTL manner [3]. Moreover, we introduces the concept of "control point" [2].In consideration of some inherent weaknesses of [2], we modify this method. In our paper, control points are used to interact with soft tissue rather than to track the motion of the thread. These constraints are mainly from tissue-suture collision or suture's attachment with the needle. Unlike the traditional geometric-based method, the force model will be imposed on the suture. More details will be given later.

IV. COLLISION DETECTION

Research on collision detection has increased dramatically in the past few years, so there are many quite mature methods which make considerable progresses in actual applications. In this paper, we adopt the BVH technique [6] which has been widely applied in the real-time collision detection between rigid objects.

A. The BVH Representation and Update

For these threadlike objects such as the suture thread, the structure of a BVH is quite simple (see Fig1). First, each line segment is enclosed by a bounding sphere which is specified with a radius as long as the line segment and a vector. These spheres are the leaf nodes of the BVH. Second, each pair of successive leaf spheres is enclosed by a minimal sphere as the father of leaf nodes. Keep doing this loop until a balanced binary tree is completely built up. The balanced binary tree is the BVH. The root of the BVH is a bounding sphere that encloses the whole thread. So, the hierarchical bounding representation of the suture has been completed.

For a deformable object, the processing method is similar to the threadlike object. So we will pass over the details.

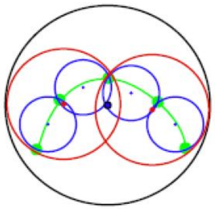

Fig1:the bounding sphere structure of a thread

B. The updating of the BVH

Unlike rigid object, the thread is always in a constant motion state. When the thread moves a little, the bounding spheres will be changed at once. So the BVH must adjust its structure with the change. If the BVH is rebuilt frequently, it will increase computation cost without a doubt. In fact, there is no need to reconstruction the BVH when the deformable object refreshes. During the movement of the suture thread, the shape and the position of minimal units might change but the hierarchy of BVH will not be altered. That is to say, to ensure the synchronization of the BVH and the thread, we just need to update the size and position of the bounding spheres, and simplify the calculation complexity.

In order to improve the update efficiency of BVH, a bottom-up strategy is adopted. At first, we use a mark bit called "Dirty" to identify whether the size or the position of each bounded line segment has changed. If Dirty is true, it means that the relevant bounding sphere needs to be updated. This will cause the adjustment of father nodes, and finally cause the updating of root. Thus, all nodes need to be updated are marked.

The usual practice to update the tree is based on recursion algorithm which may lead to multiple renewals of some nodes. The key to this question lies in making sure that child nodes are updated before parent nodes. So we apply a priority queue approach to store those nodes. The bottom-up updating method is shown in algorithm1.

ALGORITHM 1
THE BOTTOM-UP UPDATING METHOD OF THE BVH

```
1.      PriorityQueue<TreeNode>updateQueue;
2.      For each leaf L of T
2.1         If L is Dirty
                Update L
                Insert L'parent into updateQueue
3.      While updateQueue is not empty
3.1         Assign updateQueue head to TreeNode N
3.2         Update N
3.3         If N is not the root
                Insert N'parent into updateQueue
4.      Return
```

V. KNOT-TYING SIMULATION

By simulating suture tension and repelling force, we can get a good performance of knot-tying simulation. The calculation of tension is very easy by analyzing spring properties. So, there is no need to expand on this problem.

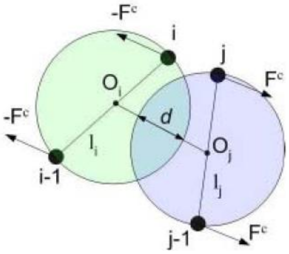

Fig2:The computation for repelling force

Repelling force, in other words, means to make the two objects tend to be separate, as shown in Fig2. The formula to calculate repelling force can be written as:

$$F_i^c = k^c e^{k^o(2d-O_{ij})} \tag{1}$$

Where k^c is repulsion factor, k^o is nonlinear-growing factor of repelling force, d is the width of suture, o^{ij} is the distance between line segments. The formula shows that as the distance o^{ij} shortening, repelling force will increase with exponent level.

VI. SUTURE SIMULATION

Except suture modeling and trajectory Tracking Control, in order to get a great visual effect, we still need to consider the interaction between suture and soft-tissue**.**

The needlepoint is not infinitesimal, so mass points on soft tissue surface will be dragged by pinhead when we thrust the needle into the soft tissue, as shown in Fig 3a.1. At the same time, the soft tissue will produce surface tension to resist the motion of needle. With the gradual penetration, the tension increases continuously and exceeds the threshold at last. Then, the tension is released and the needle will pierce through the surface. The first node of suture is set to be a control point, which drives the movement of the nearest point on surface. Fig3b.1 illustrates the process of frictional sliding. The "friction" caused by other mass points will certainly prevent sliding of the suture. When the friction exceeds a threshold, the suture slides. Simultaneity, the condition of the constraint node is transferred to the adjacent suture node that is pulled into the position of the penetrated soft tissue node.

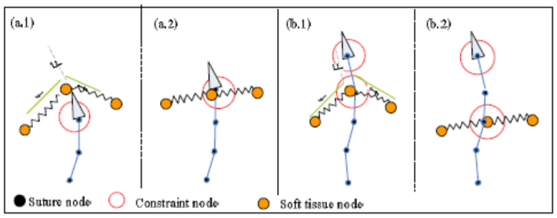

Fig3: Piercing and sliding control points[5]

A. *Calculation of the Friction during Sliding*

The relative slide between suture and soft tissue depends on whether the surface tension is greater than sliding friction. According to some properties on Mass-spring Model, the surface tension can be obtained readily. Consequently, the calculation of sliding friction is our immediate concern.

The movement of suture across soft tissue can be viewed as one of simple relative motion, as shown in Fig4. So the traditional friction formula can be adopted to calculate the sliding friction:

$$f = N\mu \tag{2}$$

μ is a static friction coefficient. N is the relative stress between suture and soft tissue, which is computed in the following way:

$$N = |\overline{F}_1 + \overline{F}_2 + \overline{F}_3 + \overline{F}_4| * \cos\theta_1 \tag{3}$$

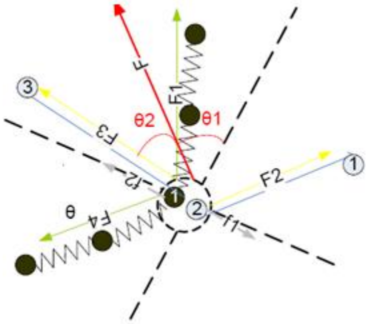

Fig4: The interaction force between the mass-spring model and the suture

B. *Interaction between Suture Tension and Spring Tension*

Fig5 shows the force situation when there is no slide. Suppose the suture tensions caused by the end points are F2 , F3, the tensions caused by other mass points are F1, F4 (The situation is much more complicated in fact, and the tension is influenced by more mass points. Then, we just calculate the sum of all spring tensions.) The external force imposed on tissue is computed as follows:

$$F = \overline{F}_1 + \overline{F}_2 + \overline{F}_3 + \overline{F}_4 \tag{4}$$

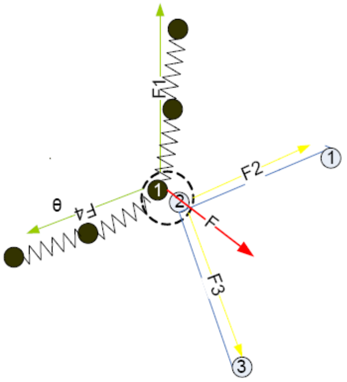

Fig5:The drag force from the suture to the tissue

VII. EMPERIMENTS

All results presented in this section are measured on a standard PC that is equipped with:

1) Intel Pentium M 1.7G Hz CPU
2) 1GB Bytes of DDR2 Memory
3) GeForce 6800 Graphics card

A. *The bounding sphere structure of the suture*

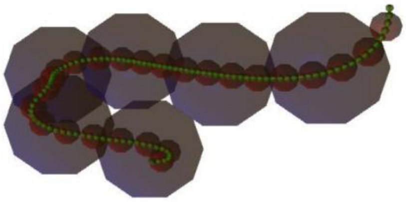

Fig6: the bounding sphere structure of the suture

Fig6 shows the level zero, the level two and the level four of the bounding tree. The smallest green spheres depict the leaf spheres used to cover the outline of the suture. The dull red spheres show level two and the biggest leaf spheres show the level four. It can be clearly seen that the leaf bounding spheres match the suture very closely. Based on the improved updating algorithm, the suture obtains a smooth motion which meets the requirement for a real-time computation

B. *Collision Detection*

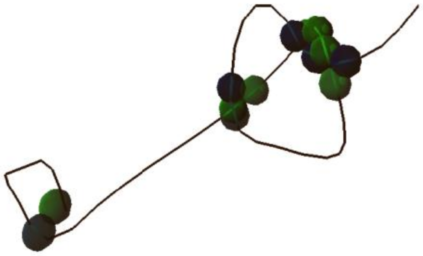

Fig7: the self-collision detection of the suture

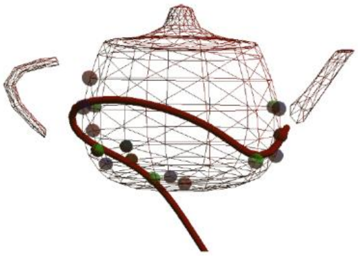

Fig8: the collision detection between the model and the thread

Fig7 illustrates the self-collision of suture, and those spheres mark the location of the contact points between suture segments. Fig8 depicts the collision between suture and polygon mesh, and the color spheres also mark the location of the contact points. Both of them show that the contact points can be detected extremely accurately.

C. *Repelling Force*

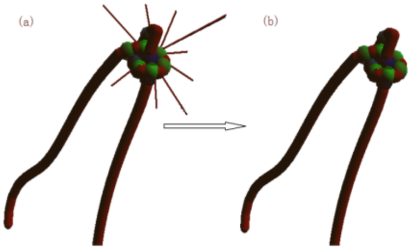

Fig8: The repelling force rendering

In this part, we want to verify that the suture model can tie a knot under the action of repelling force. At first, the knot is in a loose state. As one end of suture being pulled by Phantom, the knot binds tighter and tighter, which causes the repelling force, as shown in Fig8. With the help of control point and force model, the suture thread can be tied into knots in a natural way. Fig8(b) depicts the state of being in equilibrium after a short spell of tying. This is in accord with the fact: when the knot is in equilibrium, the repelling force will disappear**.**

D. *Simulation of suture with tying*

Some eventual effects are shown in Fig10. Fig10(a) is in an initial state. Fig10(b) depicts the control point when the sliding happens. Fig10(c) marks two control points. Fig10(d) shows that the suture finally seams two pieces of blood vessels together.Due to a rough model, the deformation of blood vessels looks a little distorted. However, the whole suture process is demonstrated clearly.

VIII. CONCLUSION

In this paper, we present a realistic and real-time suture simulation based on the combination of FTL and "control points" algorithm.Moreover, a bottom-up strategy is proposed to improve the update efficiency of the BVH.

According to the theory analysis and software simulation experimentation above, compared with the traditional FTL, our method has advantages as follows:

1) a reasonable force feedback;
2) realistic rendering.

Compared with mass-spring model, the superiority is demonstrated as follows:

1) knot tying simulation;
2) a reasonable force feedback;
3) a real visual effect of suture.

However, there are some drawbacks in our work. The process of suturing is somewhat simplistic. Those parameters involved greatly influence the visual effect**.** However, the correct way to obtain these data must go through a large number of surgical operations under the endoscope [7], [8]. The rendering progress is not good enough, including the rendering of soft tissue, the suture, the needle, etc.

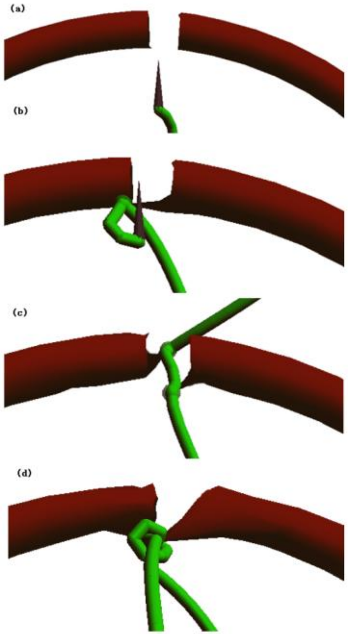

Fig10: Simulation of a complete vascular surgery

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