Virtual surgery system with realistic visual effects and haptic interaction

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Abstract

Currently, educational processes in medical surgery field involve not only theoretical in-class studies that are immediately followed by practical lessons in mortuaries and hospitals, but also involve simulations of various levels of reality. This paper describes our current progress in Virtual Surgery System development, which is targeted to support educational processes in medical surgery. With this system all surgery operations are performed using a virtual reality headset and haptic manipulators with force feedback. The main feature of our approach is applying a voxel data structure of a human body that provides an opportunity to simulate realistic behavior of the body. Thus, cutting, sewing, and welding of human tissues processes become realistic and, together with providing a realistic surgery scene, these will significantly speed up educational processes.

Keywords: Virtual surgery, virtual simulation, soft tissue mechanics

1. Use of VR in surgery simulations

As the presence of virtual reality in our daily lives increases, the educational system -- from the kindergarten and all the way to the college -- must respond to this new challenge. Naturally, medical surgical education is one of the top candidates for virtual reality technologies usage, as it can save many reagents and laboratory supplies, and overall reduce monetary spending[1]. This comes with a price of possible lack of proper experience with real-life operations and reduced realism of the simulation, which in surgery case can very well be downright lethal. We can, therefore, conclude that the field of virtual surgery has requirements much stricter than any other application of VR. What are those restrictions exactly?

- Highly-quality graphics, which can give the operating person a good idea of how the real thing looks;
- Realistic physics of human tissues and fluids, their proper response to various surgical procedures;
- Haptic and force feedback for user's hands according to situations in all processes;
- High level of user immersion.

As sad it might be to admit, none of currently existing virtual surgery solutions are capable of matching these criteria. This leads us to the point of this paper: we propose a complex of technological solutions for virtual surgery simulators. Among these technologies are:

- Implementation of soft tissue physics via triangulated mesh;
- Destruction and deformation of said mesh;
- Information collecting;
- Cloud storage of points necessary for rendering of multi-polygonal net;
- UV-less texturing;
- Manual interaction and haptic feedback using Glove One.

Following is description of how each of these technologies was implemented.

2. Soft tissue implementation with triangulated mesh

Proper simulation and rendering of physically realistic destructible soft tissue are costly both in resources needed to implement them and in computing power required for satisfactory performance. Hence, the choice of methods to use for this purpose is not to be taken lightly. After some deliberation of existing solutions with the functionality required for our project in mind, we settled on the triangulated mesh approach.

Following algorithms were used to implement functionality and physics of soft tissue with polygonal mesh.

2.1 *Tissue cutting*

To cut the mesh is to split the polygons located on the cutting line in half. This is accomplished by adding more edges and vertices.

Step 1. At the beginning of the process, we put a new vertex at the starting point of the cut line within the first triangle. From this vertex, we draw new edges to every other apex of this triangle, creating three new triangles as a result.

Step 2. Now, starting from this point, we start moving in the direction of the cutting tool, creating new vertices on every edge we cross. Old edges are replaced with a new one that are connected by the new apex, and extra edges are added to avoid creating quads.

Step 3. At the end of the cut, we repeat the process of the first step: splitting the last triangle into three parts.

We should note, that in this algorithm we limit the movement of the cutting tool to the straight line between two points on the triangle's edges. Because of this, the precision of the cut is in inverse relationship with the average size of triangle, and some of the more complex curves cannot be implemented into the cuts. One workaround for this is to add new vertices with predefined time intervals.

2.2 *Tissue tension*

We can implement the tissue tension by moving some vertices of the mesh, with movement gradually decreasing for vertices located further away from the initial point in which the force applies. The are several possible solutions for this.

The simplest one is to move all of the vertices within the given area. The amount of the movement would be inversely related to the distance between the moving vertex and the initial point to which force was applied. One critical flaw of this solution is, of course, the fact that it may end up moving the vertices not directly connected to the ones we were meaning to move.

The way the transformation affects an edge in the mesh depends on the angle between the edge and the direction of movement -- the acuter the angle, the greater would be the movement of the vertices adjacent to the edge. The spread of vertices movement further continues recursively, each one passing less movement to another one. This method allows us to simulate physics of tissue tension with satisfying accuracy. It is also advised to take the distance between vertices into account to reduce the number of visual artifacts.

2.3 *Tissue stitching*

To cut the mesh is to split the polygons located on the cutting line in half. This is accomplished by adding more edges and vertices.

There are two possible ways of implementing tissue stitching.

a. "Stapler-like" binding, in which specified vertices are bounded on the transformation level, passing each other information about their movement and acting in unison. In this case, we need to visibly mark the binding so it would be visible to player.

b. Stitching of the mesh. This method involves connecting two different meshes together with new edges and vertices, with triangles next to the seam being replaced to absorb the edges that are both adjacent and being stitched together.

3. Implementation of blood

Many mathematical blood flow models had been proposed by the researchers around the world, such as the ones described in Ref. 2, and we shall notice that the choice of the model is very strictly dependent on the purposes for which those model will be used. In the virtual surgery, the choice is affected by the specific operation, as blood may behave differently in different conditions. For now, we have settled on the general and all-purpose models for demonstration purposes.

While it is possible to implement blood as a system of particles each with its own form and textures, it is usually not recommended for most projects, as the computational complexity increases sharply. Physical interactions between each particle and surrounding tissue as well as surgery tools are very costly to compute and, as a result, lead to frame rate dropping. Visual artifacts in which particles "seep" through supposedly solid mesh are also not unheard of.

In our project, we used the Screen Space Fluids system. This system somewhat resembles the one we have described above but demands significantly less computational power. There is no need for a separate mesh or any other game objects in SSF implementation since all of the computing is done inside of the shaders. This greatly speeds up the whole process.

4. Digitalizing the human body

The soft tissue is merely one of the many building blocks of the human body, and of course, those blocks do not just float in the vacuum, separated from any other influences. In fact, the opposite is true -- human body is complex with so many systems of organs tightly intertwined it is almost impossible to seclude just a part of it for surgery processes least we want to sacrifice the realism of simulated operation. And yet, this is what we have to do. Our prime task, therefore, is to limit the consequences of separating the part of the body.

This is, however, not the only one issue we encounter. Recreation of even a separate part of the human body is a tedious process in itself. It's not only the physical properties of tissues and their biological purposes that are uneasy to properly implement -- the sheer size of the information we need to store is alarming by itself.

4.1 *Storing the information*

The data structure we choose directly affects the speed of information retrieval, recording and more. A good data structure can also spare us a lot of time and computational power, as we won't need to check every triangle sequentially to see if a collision has occurred. True, collision detection is one of the most essential things in any virtual simulation, and in a project where precision is literally a matter of life and death, extra effort should be put to ensure optimal performance.

A Bounding Volume Hierarchy may be used for this purpose -- a data structure which allows fast collision check, essentially a tree structure for sets of vertices[3, 4].

5. Conclusion

This concludes our report on the implementation of soft tissue physics. Naturally, this is the only beginning of the extensive research of the matter of virtual surgery and its possible applications for education. After the basics are properly implemented, we shall now focus on the creation of the realistic surgery simulation, which will consist of thoroughly recreated surgical operation -- appendix removal.

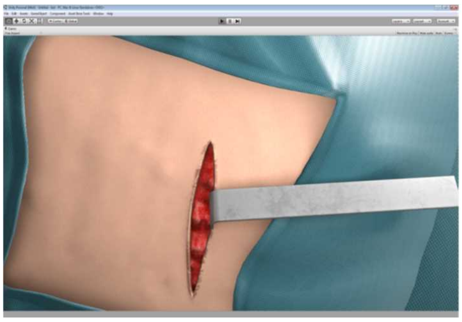

Fig. 1. Exampled of tissue cut rendered in real time

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