Efficient Soft Tissue Modelling Using Charged Particle Control Points

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Abstract

As the performance levels of personal computers increases so does the desire for more realistic and immersive software and simulation. An area where this is particularly the case is that of medical training simulation, where there is an increasing demand for high fidelity virtual environments. However, realistically modeling of soft tissue deformation still poses a considerable challenge especially when haptic feedback is required. This paper presents a new approach to soft tissue deformation using a novel 'Charged Particle' method to control the haptic rendering while also adding a further level of realism by incorporating independent high resolution visualization to the simulation.

I.3.5 [Computer Graphics]: Curve, Surface, Solid and Object Representations

1. Introduction

This paper describes how we are extending our work into fast methods for haptic interaction with tissue deformation [BJ08]. Our hypothesis is that haptics-based interaction with soft tissue models is now possible at a high enough fidelity for training surgical procedures. To verify this we are building a simulator for Central Venous Catheter Insertion guided by Ultrasound. This procedure involves using an ultrasound transducer to track a small needle or catheter as it is punctured into the target vein in the neck to deliver drugs. Note, however, that one of the main objectives of this work is to produce a method which is easily transferable to many other medical simulations as well.

Our previous work focused on producing a realistic haptic model for soft tissue deformation. Here, we extend this by using the concept of Charged Particles to act as control points for a higher resolution realisation of the soft tissue we are modelling, addressing both haptics response and visualization. The motivation is to provide a flexible soft tissue deformation model that can be used with commercial off the shelf (COTS) haptic devices such as a Phantom Omni. We aim to provide a simulation that is both visually and haptically realistic that will run in real time, which will enhance training simulation and act as a viable alternative to other more traditionally used methods such as ChainMail, Finite Element Modelling and Mass-Spring systems [NMK*06, BDK*04].

Section 2 provides a review of related work. Section 3 then covers the methods used in the Charged Particles approach, with focus on the haptic rendering and the overlaid visualization. We will then present our current results and conclusions based on our work, including the future plans for our model.

2. Related Work

A particle system is a computer graphics technique that is used to create certain fuzzy phenomena that are difficult to model using standard graphical techniques [Ree83]. Particle systems have been used to great effect in a wide variety of applications to model anything from fire and water to birds in flight. Blood, smoke [DMDU07] and other effects needed for medical simulators have all been modelled with particle systems [CK00, Bro02, AGG*03].

Particle systems can also be used for surface reconstruction and in a medical context have been applied to skeletal surfaces and organ interaction [ACS04]. Often implicit surfaces are fitted to the shape of the object defined by the particles [LGS06]. For the modelling of muscles, oriented particles were proposed by [ST92] to simulate elastic surfaces by using attraction-repulsion forces to model interactions between particles. [NT98] also used oriented particles but with a spring model connecting particles. A multi-layer particle system is described in [AS00] to simulate the motion and the form alteration of anatomical organs. However, the integration of realistic tissue properties into particle models isn't a trivial task [BDK*04]. Previous work with particles has not included support for a force model that can be used with haptic feedback devices.

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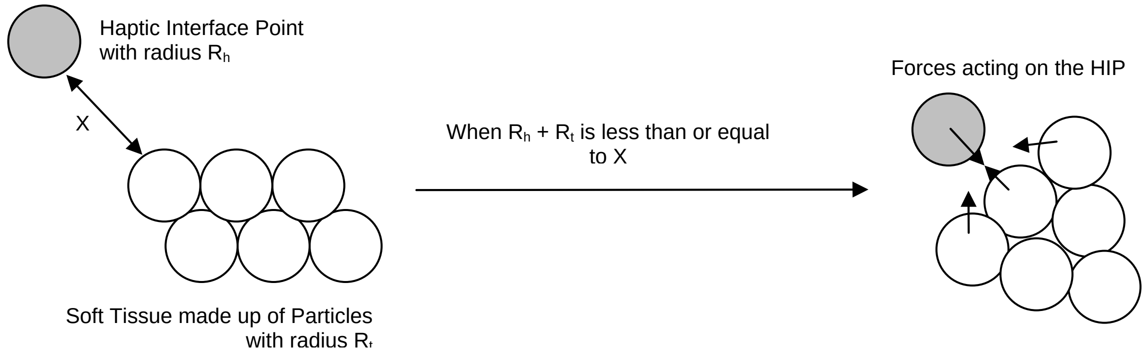

Figure 1: *As the HIP, the highlighted particle, moves closer to the particles which represent the soft tissue to be deformed then under the rules of electromagnetic interaction the particles are repelled accordingly.*

3. Methods

3.1. Haptic Rendering

Our model extends particle systems by implementing particles that have haptic properties. Traditionally a particle is thought of as having no mass or dimensions, which will ordinarily make it difficult to assign haptic properties to a particle. To allow the points in our system to be rendered haptically, we model each particle as having an electromagnetic charge (similar to orientated particle systems). It is this charge that will determine how the particles will interact with each other, and also with the haptic interaction point (HIP), which will ultimately produce the deformation of the object to be modelled. The particles are required to obey the basic laws of electromagnetic interaction. Particles of a similar charge will repel and those with opposing charges will attract.

A surface is modelled as a grid of particles, each of which has a number of attributes including its position, index number, origin, electromagnetic charge, and nearest neighbouring particles. The particle system as a whole has a number of attributes that describe properties of the material we are modelling. These global attributes are:

- Maximum displacement from the origin point. This allows different materials of differing rigidity to be modelled, so a very malleable object would have a larger maximum displacement than a stiff object.
- Elasticity of the material, that is how quickly an object will return to its original state once deformed, if it will indeed behave elastically.
- Sphere of influence. The proximity with which any other particles will need to be within for any interactions to occur.
- Maximum particle separation. This is the maximum allowable distance between a particle and any of its six nearest neighbours.

The soft tissue model is created from a two dimensional patch of particles, which is applied at the surface of an object. Given the nature of the tessellation of the particles this gives a maximum of six nearest neighbouring particles. When a particle is displaced from its origin point the nearest neighbours are queried to ensure that they satisfy the distance constraints of the system. If any of the neighbouring particles are in violation of these displacement rules they will be displaced so as to take up the strain/slack. This is then dissipated through the entire structure until all particles meet the displacement rules of the system. This is a similar to the approach used in the 3D Chainmail algorithm [Gib97] where deformation applied at a given point will result in the neighbouring links in the chain moving to take up the slack or disperse the tension.

The HIP is modelled with the same electromagnetic charge as the particles that go to make up the soft tissue. This means that when the cursor is within the sphere of influence of a particle that makes up the soft tissue, it will repel the soft tissue accordingly. The sphere of influence is calculated as the radius of the cursor added to the radius of the particles in our system. Individual collisions between the HIP and the object we are modelling will therefore never occur and so make the whole process efficient to implement.

Due to the way in which the interaction forces are calculated the HIP and the particles in our system will never actually come into contact. However, the visual realisation of the system will show them to be in contact. This is because the repulsive forces are calculated when the distance between the HIP and the soft tissue is equal to or less than the sphere of influence of the system as a whole (see Figure 1) .

The structure to be modelled has a maximum deformation value, which when reached and given a sufficient force, the tissue will no longer act elastically. Reaching the maximum deformation and applying a great enough force will cause the tissue to be ripped or punctured. Once the surface of an object is penetrated then the charge of the particles internal to the structure are reversed resulting in

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the HIP 'snapping' to the points. This represents a needle puncture model with the haptic properties of a needle through soft tissue [BJ07].

3.2. Graphical Realisation

Haptic rendering is a computationally expensive process, and so this places constraints on the number of charged particles that we can display while still maintaining real time execution. Our previous work suggested that using our charged particle model we can achieve a frame rate of approximately 25 to 30 frames per second with a resolution around 2500 charged particles and around 5000 particles running at around 20 frames per second [BJ08]. This resolution is sufficient to model a relatively small object or surface. As more complex or larger objects and surfaces are required, however, it becomes quickly apparent that this resolution does not give a particularly smooth or continuous surface.

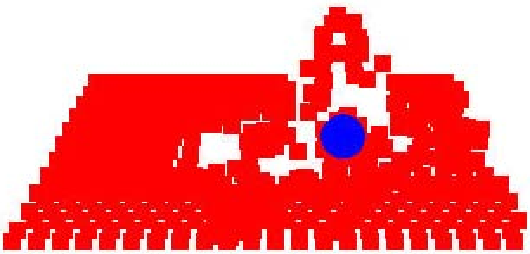

Figure 2: *Screenshot of deformation using approximately 1000 charged particles*

Given a set number of charged particles we can vary the size of the object or surface to be modelled by altering the sphere of influence of the particles that make up the object to be modelled. This allows a large surface to be modelled with only a limited number of particles. This approach is perfectly acceptable for haptic rendering because it is difficult for the user to discern between a system with a high sphere of influence and one with a low sphere of influence. It is very apparent to the user visually if the sphere of influence of the particles is spread too far, however. This will result in a jagged or uneven surface and even in a non-continuous surface, i.e. holes and spaces appear in the visualization - see Figure 2. This is obviously an unacceptable outcome. To resolve this problem we have modelled the graphical rendering and haptics rendering as two different interconnected systems.

The charged particles are used to act as control points for the visualization of the soft tissue we are modelling. This allows for a high resolution visualization to be overlaid on to the charged particle control points. We are using a Bezier Surface approach to generate the visualization of the soft tissue, although other surface generation algorithms could also be used.

We use the charged particles to generate a number of interconnected Bezier patches, each with 16 control points. Given the interconnected nature of the surface this means that different patches will share control points, this gives the surface a continuous appearance (see Figure 4).

4. Results and Conclusions

We are currently developing our algorithm using OpenHaptics [IHZ05] to handle the haptic rendering and OpenGL for the graphical realisation. We are implementing our model to run in real time on a standard desktop computer, a single AMD Athlon 3500+ with 1 Gb of RAM and a SensAble Technoloogies Phantom Omni Haptic Device.

We have easily achieved results in real time using between 2500 and 5000 charged particles. See Figure 3 for a summary of results achieved using the charged particle model only.

Number of Particles	Approximate Frames Per Second
1000	50
2500	30
5000	20
10000	10

Figure 3: *Table of results for the charged particle model*

When we apply our Bezier patch graphical realisation to the model we are typically using around 5000 charged particles which is then overlaid with 50 interconnected Bezier patches, each of which is made from approximately 400 points. This gives us a surface composed of 20,000 points. The effect of adding the high resolution visualization is negligible on the frame rate when we are using up to 5000 charged particles, it is only when we begin to exceed this number that there is noticeable implication to the frame rate we can achieve. See Figure 4 for an example of the results we are currently achieving.

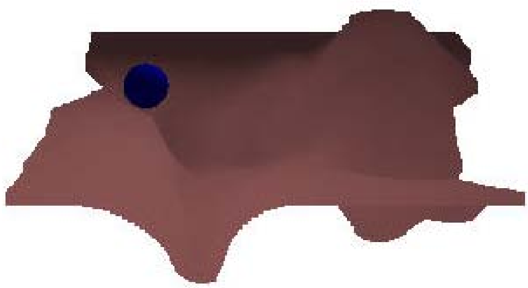

Figure 4: *Screenshot of deformation using Bezier surface of approximately 25,000 particles*

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5. Future Work

Results indicate that haptics-based interaction with soft tissue models is possible using our approach. To complete the proof of our hypothesis we still need to investigate whether a high enough fidelity for training surgical procedures has been achieved. We are currently undertaking a validity study to evaluate the face validity of the algorithm. This will use the Central Venous Catheter Insertion guided by Ultrasound simulator application that we are developing.

We believe that the number of charged particles used and consequently the number of visual particles, which constitute the Bezier patches, can still be increased, or indeed the system can be optimised to achieve a real time frame rate with around 10,000 charged particles.

We are currently looking at way to generalise the algorithm so that is may be applied to any standard model file and so be used to model almost any object required. We are also looking at ways to take the model further in terms of features and tools. Where at present the model only supports soft tissue deformation and some basic needle puncture we would like to extend this to refine the needle puncture model but also to include the addition of cutting and restructuring of the object being modelled.

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