ABSTRACT

Even though soft tissue deformation is one of the essential components of a real time surgical simulation, very little is known about the physical properties of general human tissues. Soft tissue deformations in computer graphics and surgical simulations are commonly modelled with Finite Element method (FEM) and Mass-spring Method (MSM) because they take the physics of deformation into consideration. Even though the FEM produces more physically realistic deformations, it is computationally costly and more vulnerable to surgical procedures. However, MSM is low computational complexity and simple implementation. These factors make the latter method highly attractive for virtual reality based surgical simulators. This paper discusses several methodologies for simulating soft-tissues in the reference frame of mass-spring models. In particular, the paper builds on the recent work on mass-spring model (MSM) and mass-tensor model (MTM).

Keywords – mass-spring model, surgical simulation, mass-tensor model, virtual reality, soft tissue deformations

1. INTRODUCTION

For years, surgical training is developed on animals, cadavers and patients. Many serious challenges arise from these training methods such as animals do not always reflect human anatomy; cadavers have different properties from living tissues; training on patients is highly risky. With the development of minimally invasive surgical procedures (MIS), surgeons have to fulfill higher requirement due to poor depth perception, limited field of view, and improper hand-eye coordination. It takes many years for surgeons to gain enough exposure to become specialist. Therefore, a major goal of all virtual surgical simulation systems is to assist the novices in speeding up the learning curve by providing a platform where medical procedures, diagnosis or planning can be performed in cyberspace as if in reality (Choi et al., 2004).

Realistic behaviour and real-time capability are two main features required for effective surgical simulation. Real-time interaction requires that all action exhibit physically correct behaviours and instantaneous response from the simulated soft tissue or organ corresponding to the behaviours of real human organs and tissues. Unfortunately, human tissue is very complex (Qin et al., 2010). While high accuracy is needed to achieve realism, highly complex models usually lead to increased computation times. In practice, the desired realism of the physical models must be balanced against the need for speed.

Primarily two most common methods are used for modelling of soft tissues in surgical simulation which are Mass-spring model (MSM) and Finite-element model (FEM). Finite Element Method (FEM) based on
continuum mechanics, provides high degree of accuracy but computationally intensive. So, it is undesirable for applications that demand real-time interactions (Liu et al., 2003). Meanwhile, Mass Spring Model (MSM) has a very easy architecture, low memory usage and is fast, which make it very attractive for real-time and fast surgical simulators (Mollemans et al. 2005).

In this paper we will present some variants of Mass-Spring Model (MSM) in determining its system parameters (masses, spring constants, mesh topology) such as Mass-tensor model and modified mass tensor model.

2. CONVENTIONAL MASS-SPRING MODEL (MSM)

In mass-spring models, object is modelled as a collection of point masses connected by springs in a lattice structure (as shown in figure 2.1). Representation of MSM is discrete, contrarily to continuum based approaches. MSM represent a body by a single or multiple masses that have no extension and hold the complete mass of the body by following the idea of classical mechanics. External forces applied to the body are concentrated in the point masses as well. Thus, every continuous body can be transformed into a system of distributed point masses through this way (Kenwright et al., 2011).

Figure 2.1: A schematic representation of a regular 2D MSM

These models include a mesh of springs that interconnect those point masses representing the elastic behaviour of the bodies. The spring mesh can have many different configurations depending on the geometry of the object and the topology selected to represent the elasticity properties. There are mainly 2 types of meshes: polyhedral meshes and nearest neighbour meshes. The polyhedral meshes fill the volume of the body with polyhedrons that can be regular or not. In some applications, regular meshes are preferable since they allow controlling better the elastic response of the body. Irregular meshes, on the contrary, have the advantage of allowing mesh refinement in those
areas where the required solution is higher. On the other hand, nearest neighbour meshes (refer Figure 2.2) make the elastic connections with a fixed number of nearest neighbours or with all the neighbours that are closer than a certain distance (Wang et al., 2009).

Figure 2.2: A schematic representation of 2D MSM where the connectivity is governed by an influence distance.

Regardless of the mesh type, when the model interacts with the environment new boundary conditions appear on the surface of the body. Generally, depending on the interaction type, the new surface conditions can be expressed in 2 ways: a set of forces exerted over some point masses or a collection of displacements imposed on the length of the springs including forces that act over each point mass of the MSM (Wang et al., 2009).

2.1 Related Work

In this advance technology era, there is an increased demand for real-time surgical simulation. This is because of the features that present in the virtual simulator can give the realistic behaviours of organs and tissues, haptic feedback as well as realistic visualization. Behaviour of the object can be defined by using the mathematical equations and the law of physics.

Due to the simplicity of the motion equations, various applications have already used nodal systems to simulate soft tissues, for instance (Brown et al., 2002) simulates the cutting operation of deformable tissue based on MSMs and (Keeve et al., 1996) models fat tissue in a craniofacial surgery simulator. Liu et al. (2003) described MSM based on the network of point masses connected by spring-dampers that present in MSM. A spring-damper is represented by an idealized spring function and a velocity dependent damping function. If a point x has mass m, then \( m \ddot{x} = k(x_0 - x) - \gamma \dot{x} \) where \( x_0 \) is the rest position of the mass, \( k \) and \( \gamma \) are the stiffness and damping coefficients respectively. For a set of N points in 3D space, let \( X \) be a \( 3N \times 1 \) column of vectors representing the
position of all points. Then the mass-spring system can be expressed as \( M \ddot{X} = K \dot{X} - Y \dot{X} \), where \( M \) and \( Y \) are \( 3N \times 3N \) diagonal mass and damping matrices respectively, and \( K \) is a \( 3N \times 3N \) banded matrix of stiffness coefficients. The equation can be rewritten as a set of first order differential equations and solved using standard method.

3. MASS-SPRING MODEL VARIANT

3.1 MASS TENSOR MODEL (MTM)

The original Mass Tensor Model (MTM) was introduced by Cotin (Cotin et al. 2000). In the MTM the modelled object is discretized into a tetrahedral mesh. Inside every tetrahedron \( T_i \), the displacement field is defined by a linear interpolation of the displacement vectors of the four vertices of \( T_i \), as defined by the finite element theory. The linear elastic energy of tetrahedron \( T_i \) can then be expressed as a function of the displacements of the four vertices and of the two Lamé coefficients \( \gamma \) and \( \mu \) which are biomechanical elastic constants. The force applied at vertex \( j \) of the tetrahedron \( T_i \) is defined as the derivative of this elastic energy:

\[
F_{jT_i} = - \frac{\partial W_{elastic}(T_i)}{\partial P_j} = \sum_{k=1}^{3} [K_{jk}^{T_i}] u_{T_i}(k)
\]

where \( u_{T_i}(k) \) is the displacement of vertex \( k \) of the tetrahedron \( T_i \) and \( K_{jk}^{T_i} \) are the stiffness tensors for this tetrahedron. These tensors are completely determined by the initial position of each vertex of the tetrahedron and the two Lamé coefficients, which are material specific. For the whole mesh, the total force is simply the sum of the contributions by all adjacent tetrahedral of the vertex \( j \).

3.2 PICINBONO'S TENSOR-MASS MODEL (PMTM)

A variant of a mass-spring system known as mass-tensor model (Choi et al., 2009) governed by the Voigt's model of visco-elasticity was improved by Picinbono et al. (2003) where every link between two nodes consists of a spring and a damper connected in parallel. The dynamics of each node in the system can be obtained by integrating the Newton's law numerically using finite difference method. This model is known as dynamic linear model or Picinbono's tensor-mass model. Picinbono's tensor-mass extended model were used by Xu et al. (2010) to
incorporate visco-elasticity into the model, which is then used as a reference for the system to obtain the parameters for the MSM model in order to reproduce the actual physical behaviours of soft tissue.

Picinbono's tensor-mass model was developed by incorporating visco-elasticity into the model, which is used as a reference for the system to obtain the parameters for the MSM model in order to reproduce the actual physical behaviours of soft tissue. Several heuristic techniques such as simulated annealing and genetic algorithm were employed to extract the system parameters of this model automatically. Although there are a number of viscoelastic constitutive models, it has been found that the direct incorporation of viscoelastic models into the tensor-mass model of soft tissue will lead to a significant increase of computational cost, because the information must be saved at every previous time step (Xu et al., 2011). In addition, an improved realistic mass-spring model in which the internal forces among mass nodes are derived within the framework of nonlinear continuum mechanics.

By replacing the potential (strain energy) function of a classical mass-spring model with the new proposed one in accordance with three-dimensional finite strain nonlinear anisotropic elasticity theory, the new model are made used to describe typical behaviours of living tissue such as incompressibility, nonlinearity and anisotropy (Xu et al. 2010).

4. FUTURE WORK

The MSM is an interesting alternative to the FEM especially for real-time interactive surgical application. This work can be further exploited by using a new approach to automatically define the parameters of a MSM based on a comparison to a linear elastic FEM for small deformations and another method based on the constitutive law of a material working under large deformations.

The following are the possible future directions of research related to this discussion:

a. Extend the method with the aim of considering the behavior of a cubical element under additional types of loads. This could improve in the accuracy of the MSM designed using this method, especially when stretching is not the dominant load.

b. Design of MSM with additional types of springs, such as nonlinear, torsion and angular springs which may improve the quality of the approximation.
5. CONCLUSION

This paper presents the framework of Mass-Spring Model in surgical simulation. Mass-Spring Model is the method often used for real-time surgery simulation due to their fast response and fairly realistic deformation replication. Moreover by refining dynamic parameters in Mass Spring Model, more efficient variants of MSM will be generated. Thus, mass-spring model will improve the prediction result and to ensure a certain prediction accuracy for typical surgical procedures.

REFERENCES


