8 DESIGN OF HYBRID TISSUE MODEL IN VIRTUAL TISSUE CUTTING

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Haptic simulation of virtual tissue cutting is computationally intensive. The challenge is to simulate virtual cutting without simplifying assumptions. Unlike earlier works we achieve realism and real time performance by decoupling graphics and haptics. We propose a hybrid model of fuzzy and Kelvin model to achieve our goals. While the Kelvin model computes the collision response using position, time, and velocity representing transient effects, the Fuzzy model computes the force using depth and velocity, thereby including both transient and static properties of cutting in our simulation. Compared with conventional physical based modeling, the computation of force is independent of the geometry model of the cutting surface.

Categories and Subject Descriptors: D.2.2 **[Visual C++]**: OpenGL, OpenHaptics, MATLAB, Free Fuzzy Logic Library. I.2.3 **[LOGIC]**: Fuzzy Logic

General Terms: Algorithms, Measurement, Performance, Design, Experimentation, Human Factors.

Keywords: Transient Effects, Hybrid Approach for Tissue Cutting, Collision Response, Role of Haptics in Cutting.

1. INTRODUCTION

Virtual cutting of soft tissues has received little attention in the literature despite its potential importance for surgical simulators and other applications. Soft tissues exhibit complex material properties: they are non-linear, viscoelastic, layered, anisotropic, and nonhomogeneous.[1] Accurate modeling of the soft-tissue material properties is computationally intensive. Haptics requirement of 1000 Hz update rate makes the computation even more intensive. Assuming, however, that tissue is linear-elastic and that no changes occur in the discretization of a body, the linear superposition principle makes it simple to perform most computations in preprocessing as most literatures do. The challenge is to simulate virtual cutting without these simplifying assumptions. Aside from the issues of real-time computing, the simulation of cutting with a sharp edge is itself not easy because it appeals both to contact mechanics and to fracture mechanics.[2] To achieve realistic tissue cutting haptic feedback in real time, it is necessary to separate deformation accuracy with collision response. In this paper we propose to decouple graphical rendering from haptics rendering and to emphasis haptics rendering than graphical rendering for various reasons to achieve our goals.

1.1. Role of Haptics in Virtual Tissue Cutting

An integral part of virtual cutting is haptics — the sensation of touch and manipulation using motor system. Virtual tissue cutting with haptics feedback is important for many types of surgical manipulation, including separating tissues, testing the texture, strength, and the consistency of tissue and guiding movement in cutting or suturing. The interpretation of haptics permits the surgeon to apply appropriate tension to facilitate delicate dissection and exposure and avoid damage to surrounding structures. During open procedures the sense of touch is a primary source of information that guides the surgeon. Sensory information is processed rapidly and in a seemingly effortless fashion by the cerebral cortex to permit surgeons to manipulate tissue with great ease.

1.2. Challenges in Virtual Tissue Cutting

Most of the Virtual Tissue Cutting simulations compute the collision response from geometry based models and hardly provide realistic haptics feedback. Previous attempts made to address virtual tissue relate mostly to modifications made to the simulation of deformation of the geometry, and use similar computational approaches such as finite element methods (i.e. Refs. 2–5). With these techniques, cutting is assumed to take place when the force, or rather the stress, created by a tool during deformation reaches a threshold. The cutting process is typically simulated by eliminating one or several discrete elements from the virtual object, such as springs or tetrahedral regions. This makes it difficult to evaluate a force to be experienced by a subject holding a virtual cutting tool. Mathematical continuity of the computations related to deformation would be difficult to ensure, while the topology of the underlying mesh structure is changed. In geometry based approaches the simulation results do not generally depend on measurable parameters, but on arbitrary choices, for example mesh density. Numerical approaches such as finite element methods (FEM) and boundary element methods (BEM) break down as a result on their reliance on discretization of the geometry of a solid. They require far too many discrete elements to approximate a contact, compared to those needed to compute global deformation. Other possible approaches employ approximations of body geometries by standard cases such as half planes for contacts at uncut locations,[18] or infinite wedges for contacts where a cut is already initiated.[23] It is then possible to solve the problems of deformation and contact analytically, but even then, the cases of sharp contacts are still open problems.

Physically based approach, as opposed to geometry based approaches, depend on measurable parameters. Experimental data for cutting soft tissues are available in literature, for example, in Refs. 6–10. While Mahvash *et al.*,[6] used fracture based approach for modeling the experimental data, Song *et al.*,[7] used fuzzy based approach. Most literatures discuss force vs. displacement without considering velocity which is crucial parameter modeling the viscoelastic behavior of the soft tissue.[8] The term viscoelastic implies that the deformation of soft tissues depends not only on their instantaneous values but also on the history of the applied forces.

For haptic rendering, Mahevash *et al.*, considered three different stages of cutting process: contact, elastic deformation, and rupture; and they ignored the viscoelastic effect. Song *et al.*,[7] considered only the threshold force necessary for the rupture of the tissues, from experimental data at a constant velocity, ignored the rendering of contact and intermediate viscoelastic deformations.

In this paper, we developed a material model based on the experimental data of Ref. 7 which can also render contact forces and viscoelastic deformations along with the rupture forces at different depth of cutting and strain rate. A hybrid model of fuzzy based approaches and Kelvin model has been developed to achieve these goals.

2. FUZZY-KELVIN MODEL

As the mechanism of tissue cutting is so complex that not only the energy exchange occurred between the instrument and soft tissue, but also the heat loss and non-linear viscous loss happen, the transient parameters of the tissue cutting was difficulty to acquire and model.[6] Fuzzy characterization of tissue cutting may embody the complexities of cutting phenomena. When the system is non-linear and multivariable, fuzzy models offer some advantages over conventional mathematical models not only with robustness but also approximating the systems' real state and offering real-time computation of force values, given several state variables without a mathematical modeling. However, while Fuzzy system could capture the multivariate non-linear static properties of the system, it is very difficult to capture the transient properties of the system in a model such as Fuzzy system. Mathematical models could easily incorporate transient properties. Therefore for the simulation of tissue cutting where both transient and complex static properties are important for realistic haptics rendering. Fuzzy system of our simulator computes the realistic static properties of the cutting process which otherwise difficult to capture in a mathematical model in real-time. The schematic arrangement is shown in Figure 1.

We used Kelvin model[3] for transient properties and fuzzy model for static properties, both based on the experimental data borrowed from the Ref. 12 and work[7] respectively. The Kelvin model computes

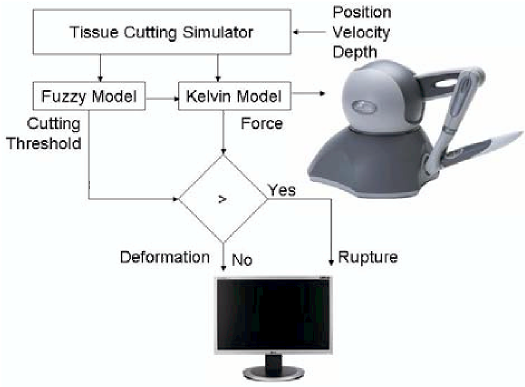

Figure 1. Schematic diagram of our tissue cutting simulator.

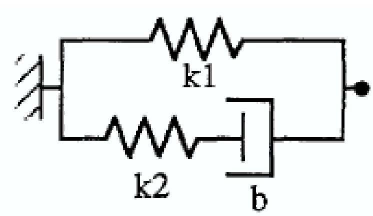

Figure 2. Kelvin model and the constants in the model.

the force given the time, velocity, and the displacement of the scalpel. The fuzzy model computes the force at which the tissue would rupture given the depth of penetration of the scalpel and the velocity. The rupturing force will not change with time; it depends only on the depth and the velocity of the scalpel.

2.1. Our Kelvin Model

Among several lumped parameter models, Kelvin model is widely accepted as close representation of transient properties of soft tissue.[11] Our Kelvin model is shown in Figure 2. The parameters k1, k2 and b have been estimated using the experimental results done on the liver and found to be 0.008 (N/mm), 0.007 (N/mm) and 0.130 respectively.[12]

2.2. Our Fuzzy Model

The force at which the soft tissue (liver tissue) will rupture with respect to velocity of scalpel and depth at which scalpel is cutting the soft tissue has been reported in Ref. 7 using fuzzy model. They used an identification method to determine all elements: variables, fuzzy sets, and consequent coefficients. This identification process results different models, as several inputs ranges partitions are considered. This approach is hybrid learning that combines two optimization methods. The only information specified by the user is the number and type of membership functions and the training sequence, and it can be combined with adaptive optimization methods easily. When given enough fuzzy rules, it can approximate any precision, so we chose it as the base of our model. The structure identification of the fuzzy system is to partition the input variable space equally and then estimate the precondition parameters. After choosing Gauss function as the Membership Function (MF) of the input variables, the post condition parameters were estimated and the parameters (mij, σij) of the input MF were optimized, and the procedure stops at a certain model when the performance is less than a desired value.

After the structure identification of the fuzzy system, the premises and number of rules were decided. Then the consequent parameters (pij) of the system should be estimated and the parameters (mij, σij) of the input variable MF are optimized. An adaptive neural fuzzy inference system (ANFIS) is a universal approximator that allows a fuzzy inference system to learn by using a backpropagation algorithm based on an input-output data set. Learning is performed in two stages, at first the antecedents parameters are kept fixed and the information is propagates to the fourth layer, where the consequent parameters are identified by using the minimum lease mean squares method, then the consequent parameters are fixed and the error is back-propagated, allowing the antecedent parameters modification by means of a gradient method.

3. IMPLEMENTATION

We used the same experimental data for liver cutting reported in Ref. 7 as input as shown in Figure 3 to the fuzzy training system. We used the ANFIS (Adaptive-Network-based Fuzzy Inference Systems) toolbox in MATLAB for building the fuzzy model. The output of the Matlab model is then fed to Free Fuzzy Logic Library (FFLL) an open source fuzzy logic class library for computing the cutting force on the fly.

We used PHANTOM from Sensable Technologies as our haptic device. The device has six DOF position sensing and three DOF force output. The velocity is calculated in the software by difference method. It has an update rate of 1000 Hz. The stylus is used as a cutting tool (scalpel) and the depth of the scalpel is calculated from a reference plane of the tissue.

We have used the same parameters of Kelvin model reported in Ref. 12 in all the three direction, though it could be different and make the model really non-homogeneous. First the Phantom stylus position, time, and velocity are given to the Kelvin model that computes the force. The depth of cut and velocity are given to the FFLL model to compute the threshold force for cutting. If the threshold force is greater than the force calculated from Kelvin model, then rupture is applied to the graphics display, otherwise only the deformation of the anatomy model is shown on the display.

4. RESULTS AND DISCUSSION

While the Kelvin model calculates the force using position, time, and velocity representing transient effects, the Fuzzy model calculates the force using depth and velocity. Therefore the tissue cutting simulation with the Fuzzy-Kelvin model would include the parameters position, time, velocity, and depth. We have used the modeling at various values of each of these parameters and the output of the Phantom has been recorded and the following plots are presented for comparison purpose.

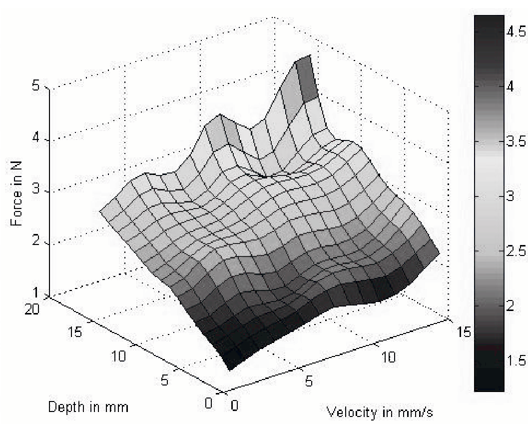

Figure 3. The relationship between input cutting variables depth, velocity, and force.

The relation between the force and the time at velocity 2 mm/sec and at depth 5 mm is shown in Figure 4. The sudden drop in the graph shows the rupturing force at which the fuzzy calculated force exceeds the Kelvin calculated force. At the rupturing point the force drops to nearly zero as no plastic deformation or tissue hardening occur. The rupturing force and the rupturing interval are same for every rupture as velocity and depth are kept constant.

When the depth of cut increases the force required to rupture and the time at which rupture occur also increase as shown in Figure 5. In Figure 6, the depth is kept constant and other parameters are

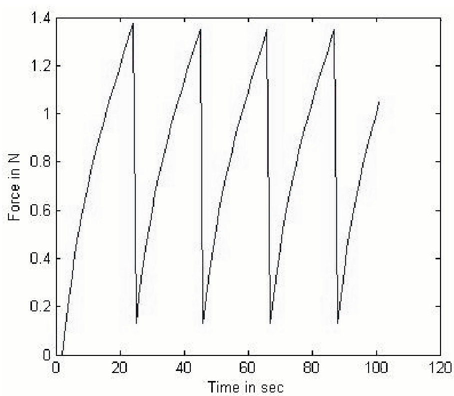

Figure 4. Relation between force and time at V = 2 mm/sec and depth 5 mm.

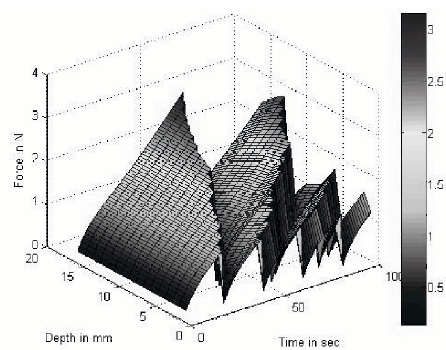

Figure 5. The relation between force, depth and time at velocity = 2 mm/sec.

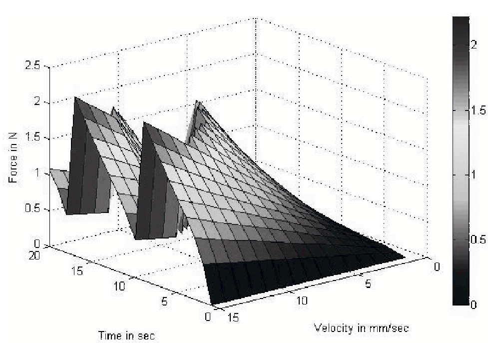

Figure 6. The relation between force, velocity, and time at constant depth = 5 mm.

varied. As velocity of cut increases, the rupturing force is also increasing non-linearly and the time taken for rupturing of the soft tissue decreases. In other words, with the lesser velocity, the soft tissue takes more time to rupture. The rupture curve seen here is the curve from the fuzzy model when the velocity is varied and the depth is kept constant.

As the cutting is advanced from one rupture to another rupture, we used the same Kelvin model parameters assuming it represents the lumped properties of the whole tissue and the boundary condition does not really change. However, if the boundary conditions change, Kelvin model parameters could be changed on the fly depending on the position, depth, or even time (tissue hardening). By incorporating different Kelvin parameters the geometry and the boundary conditions can be taken care.

5. CONCLUSION

A hybrid fuzzy and Kelvin model has been proposed to render haptics feedback both at real-time and more realistic. The model is more realistic compared to either Kelvin or fuzzy model alone. Compared with conventional physical based modeling, the calculation of reacting force was independent of the geometry model of the cutting surface. However our system provides framework incorporating geometry and boundary conditions of the soft tissue representing different Kelvin models. As the fuzzy model is limited by the number of samples and the interference from cutting acceleration and orientation, the precision of this hybrid model also affected and needs to be improved further. Although we only discussed the haptic model for liver cutting, it can be put into use for other tissue cutting phenomena and other haptic rendering device as well.

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