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Simplified Blade–Tissue Interaction Model for Haptic Feedback

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Abstract

We present in this paper a novel approach for interactive cutting simulation through soft tissue. Instead of starting from the usual visco–elastic continuous model, we address a model which is focused on the haptic rendering of a simulated blade–and–tissue contact and a first partial implementation.

Keywords: haptic, cutting, interaction

1 Presentation and previous work

The field of surgery training and simulation has been explored for the last decade. Many simulators have been designed, and already offer acceptable visual feedback [1]. One of the main issue in surgery simulation is the cutting operation.

Many approaches are not designed to allow free form cutting operations: starting from a standard continuous material behavior, simulators like [1] are not intended to enable the user to cut through soft tissues. Though it is possible to provide tearing effects [2].

Using such approaches allow realistic haptic feedback for deformation–related operations, but not specifically for cutting operations, since the equation governing the behavior of the soft material supposes that this material remains continuous. Of course, this hypothesis is not respected when cutting through the tissue.

On the other side, some approaches focus on the cutting operation, *i.e.* the way to modify the topology of the material (and its mathematical representation) according to the path of the blade. The core of this issue is to minimise the number of geometrical elements required to represent the new topology, either by generating an optimal new structure (see [3] and [4]), or by simply removing the geometrical elements found in the path (see [2]).

Whenever the cutting problem is assessed, the shape of the blade is modeled as a segment ([4], [3], [5], and [6]), and the computation of resulting efforts limited to one point. This model is accurate enough when dealing with topology modification: a blade can easily be compared to a one–dimensional curve, as long as we consider the topology modification of the tissue. Using a segment is just another restriction which won't be discussed here any further.

Though, such a model does not fit our needs for the haptic feedback. Computing the resulting contact efforts at a single point can only lead to a 3 DOF behavior. When a wide blade is inserted into a soft material, a torque is necessary to make it rotate around its main axis (see figure 1), which at least depends on the physics of the material and on the geometry of the blade.

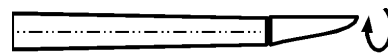


Figure 1: Main axis of a scalpel

We propose a novel approach which focuses on the interaction forces between a blade and a soft material. Our goal is not to propose a fully functional simulator yet, but to design a well suited haptic feedback dedicated to cutting simulations. The goal is different from other approaches, since we only expect to get a realistic haptic feedback. After presenting the expected system, we will expose the interaction model and its simplification.

The current results will be explained, allowing us to discuss the expected results in a near future.

2 Expected system

We expect to design a fully functional scalpel simulator, considering that we mainly focus on the quality of the haptic feedback. This implies some constraints for the design of the whole system, presented in figure 2.

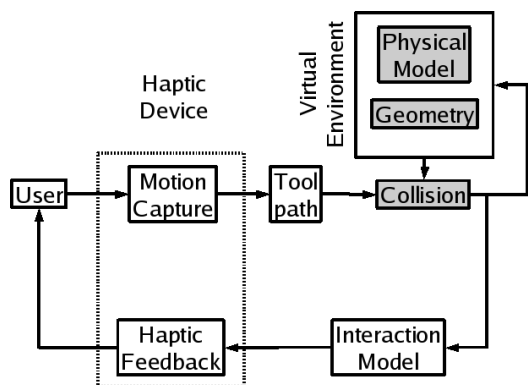


Figure 2: Functional description of the system

The first requirement is related to the human perception of haptic sensations. Previous researches proved that a haptic feedback needs a refresh rate of approximately 1 kHz. As a consequence, every choice in the design must take this constraint into account.

Secondly, cutting a tissue implies topological changes in the geometrical structure which represents the tissue. We have to take this into account, since many approaches rely on a precomputation which is not robust to topological changes (see [1]).

Then, we do not require the final system to provide a realistic global and visual behavior of the material. On the contrary, we only expect the material to behave in a believable way, *i.e.* a behavior expected by the final user.

Finally, we will study a haptic feedback which should be as realistic as possible. We will detail the model we propose for the contact between a scalpel and an organic soft tissue during a cutting operation.

3 Proposed model

The proposed model consists in a blade model and a soft tissue model. This soft tissue undergoes either a deformation or a cutting operation.

A simplified contact model will be proposed, as long as a state machine designed to manage the two aspects of contact efforts.

3.1 Blade model

The standard representation of a blade is a segment, and the forces are only computed at an arbitrary point of this segment. We propose here one model of a real blade, which will be simplified later on.

The blade is split as two main components. The first one is the cutting edge, which is the only part of the blade that can cause topological changes to the material under normal use conditions. The second one is the surface of the blade. Figure 3 illustrates these components.

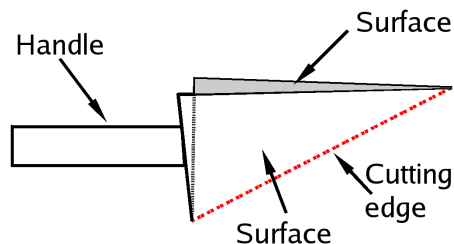


Figure 3: Blade model

We restrict the blade's shape under following assumptions: the cutting edge can be assimilated to a segment, and the surface can be decomposed into a set of planar surfaces.

3.2 Deformation

As long as there is no topological changes, the material is supposed to be elastic and computed both on the cutting edge and on the surface of the blade. The resulting contact force is:

$$F = K_e(x) \quad (1)$$

where x is the actual position of the contact point. F depends on the distance between the initial position x_m of a material point and its position x at time t (see figure 4). We introduce here a threshold position x_o between the tool and the material,

and we offer a feedback *before* the actual contact occurs. The resulting effort is:

$$F = \begin{cases} 0 & \text{if } x < x_0 \\ \frac{(x - x_0)^2}{(x_m - x_0)} \cdot K_{emax} & \text{if } x \in [x_0, x_m] \\ (x - x_0) \cdot K_{emax} & \text{if } x > x_m \end{cases} \quad (2)$$

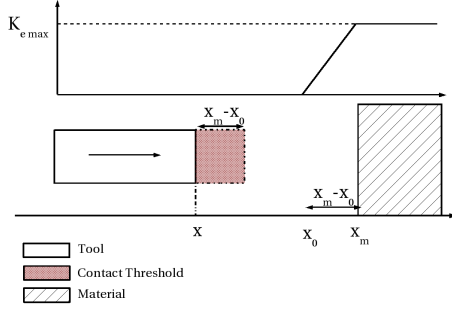


Figure 4: Elastic contact feedback

This model is one-dimensional and can be generalized to 3-dimensional space. Moreover, it ensures the continuity of the effort (and of its space derivative, depending on the parameters), increasing stability. In fact, any spatial discontinuity in the effort field has a negative impact on the haptic feedback.

3.3 Cutting and frictions

During a cutting operation, the contact between a blade and a soft material can be model by three different contact types presented in figure 5 (see figure 10 for an overview of a cutting operation).

In the following sections, the position of a point of the blade will be x , and its velocity \dot{x} .

Cutting effort: The first type is related to the cutting effort, and applies to the cutting edge. We note d the depth of the interpenetration, *i.e.* the length of the cutting blade which is in contact with the material. Soft materials are usually modeled as visco-elastic continuous materials. We do not consider any elastic effort along the cutting edge during a cutting operation. Hence an effort which can be expressed as:

$$F_{ve} = \int_0^d K_v(x) \dot{x}(t) dx \quad (3)$$

with \dot{x} the speed of a point of the edge and K_v a viscous coefficient depending on the materials the tissue and the edge are made of.

Friction effort: The second effort is due to viscous frictions between the surface of the blade and the material. It can be expressed as:

$$F_{vs} = \int_S K'_v(x, \dot{x}, t) \dot{x}(t) ds \quad (4)$$

where S is the part of the blade surface which is in contact with the material at time t , K'_v a viscous coefficient which depends on the materials the tissue and the blade are made of. This coefficient can also depend on the orientation of \dot{x} relative to the orientation of the surface.

Elastic efforts: Finally, the tissue can add elastic efforts along the blade during cutting operation. This elastic effort can appear with some materials that tend to keep their original shape when they are cut. This effort can be defined by the following equation:

$$F_e = \int_S K_e \delta(x, t) ds \quad (5)$$

where $\delta(x, t)$ is the displacement between the original position of the material point and its position at time t .

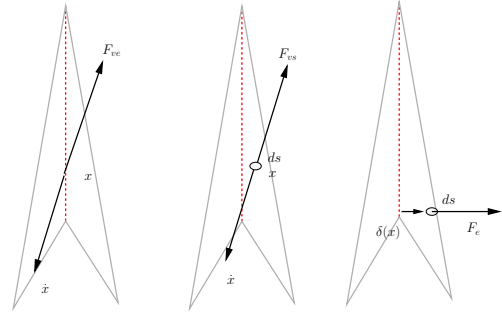


Figure 5: Cutting, friction and elastic efforts during cutting operation

3.4 Simplified contact model

Equations 3 and 4 compute the forces as a function of the speed of each point of the segment (respectively the surface). Haptic feedback is known to require an update rate of approximately 1 kHz. Computing the exact cutting and friction efforts requires the computation of the contact surface S and of the velocity \dot{x} of each point $x \in S$. We choose to simplify this first contact model in order to reduce the computation complexity.

We make two assumptions. First, the contact surface is supposed to be small. Secondly, the momentum is also supposed to be small. These approximations allow us to suppose that $\dot{x}(t)$ is almost constant for each $x \in S$.

Moreover, the respective viscous coefficients are supposed to be the same in each point of a given segment (resp. surface).

Under these assumptions, equations 3 and 4 become:

$$F_{ve} = d(t)K_v\hat{x}_e(t) \quad (6)$$

and

$$F_{vs} = S(t)K'_v\hat{x}_s(t) \quad (7)$$

However, equation 7 still requires the computation of the area of the contact surface $S(t)$. Such a computation can be very complex. We propose to approximate the surfaces by rectangular surfaces, as illustrated in figure 6. We can then consider any elementary surface as a segment with an associated width w and normal vector \vec{n} .

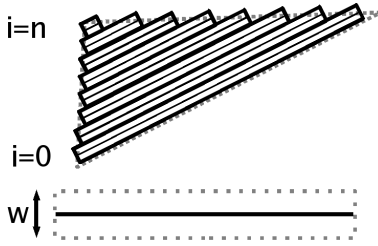


Figure 6: Approximated contact surface

With such a model, the computation of $S(t)$ can be approximated by

$$S(t) \approx \sum_{i=0}^n d_i(t)w$$

with $d_i(t)$ the penetration depth of the segment representing the elementary surface. Equation 7 becomes:

$$F_{vs} = wK'_v \sum_{i=0}^n d_i(t)\hat{x}_i(t) \quad (8)$$

For one given segment with a penetration depth of d_i (d for the cutting edge), the application point of the approximated F_{vs} (resp. F_{ve}) is located at a distance of $d_i/2$ of the end point of this segment (which is the center of mass of the part of the segment currently in contact with the material). We note $p_i(t)$ the application point of an elementary surface (resp. $p_e(t)$ the application point of the cutting edge).

Moreover, since these application points are not located at the virtual contact point H between the hand and the virtual tool (see figure 10), we compute the resulting force and torque at this point as:

$$F(P, t) = \sum_i (F_{vs,i}(p_i)) + F_{ve}(p_e) \quad (9)$$

$$M(P, t) = \sum_i \vec{p}_i \vec{P} \times F_{vs,i}(p_i) + \vec{p}_e \vec{P} \times F_{ve}(p_e)$$

These successive approximations decrease the precision of the interaction forces. The final impact of these approximations still has to be evaluated. On the other hand, the computation of contact forces is lowered of an order of magnitude, since only segment intersections are computed instead of surface intersections.

3.5 State machine

As the elastic and cutting behavior are supposed to be successive states, a state machine can be proposed which switches between the two models. The trigger is based on the effort $|F|$ imposed by the material on the tool. We consider that under a given threshold F_t the material does not undergo any topological modification, *i.e.* is not cut: the elastic model is active. As soon as $|F| > F_t$, the material is cut and the second model — cutting and friction — is used.

Consequently, we choose two thresholds $F_0 < F_1$. Ideally, $F_0 \simeq F_1 \simeq F_t$, but these thresholds must be different to prevent continuous switching between the two states of the machine. Initially, the elastic model is active. As soon as $F > F_1$, the cutting model is enabled, until $F < F_0$. An overview of the state machine is presented in figure 7.

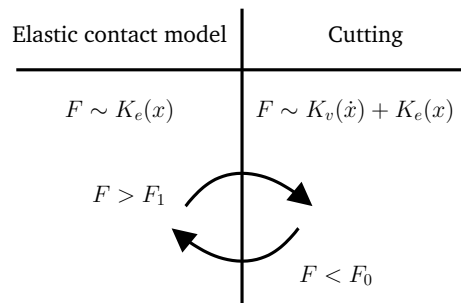


Figure 7: State machine

4 Experimental setup

4.1 Limited case study

In order to focus on the design of the model and the simulation of contact efforts, we will study a limited case of cutting environment.

First of all, the tissue is supposed to be a semi-space limited by a plan P , defined by $z_m < 0$. This restriction implies that the collision detection is not a problem any more, and is solved in constant time.

Then, the problem of topological changes will not be assessed, as well as the global behavior of the material. A first possibility would be to use one purely geometrical topological change, and not take into account the physical behavior of the tissue. [7] also proposes an interesting method for topology modifications.

With such assumptions, the gray blocks in figure 2 do not need to be implemented to test the interaction model.

4.2 Hardware configuration

From the user's point of view, presented in figure 8, the experimental setup is composed of:

- a screen, providing a visual feedback
- a haptic device, providing:
 - absolute position (6 DOF) and speed (3 DOF) measures
 - 6 DOF haptic feedback

The haptic device is a Sensable 6 DOF PHAN-ToM ®. The computer is a dual Xeon ®1.8 GHz with 1 GB of RAM running Linux.

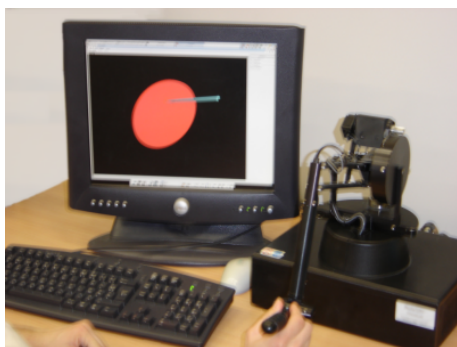


Figure 8: Hardware setup

4.3 Virtual setup

The virtual environment can be represented by three main elements. The world is an artificial element representing the environment and is supposed to have a fixed position. The material is the element we are trying to interact with; it can be moved in the world. Finally, the tool is the item manipulated by the user.

These different frames are associated to these elements. The material's frame is arbitrarily chosen and can be changed during the simulation. The tool's frame depends on the position of the user's hand. These virtual frames are shown in figure 9 in the real environment.

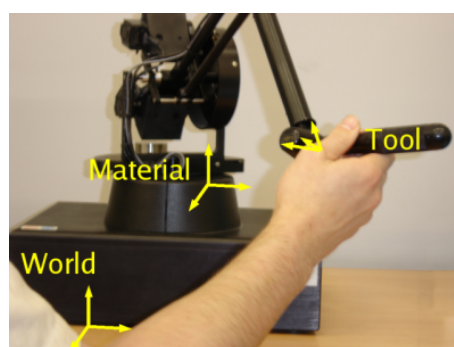


Figure 9: World, material and tool frames

5 Results

We present here some experimental results, including open loop behaviour, and some closed loop experiments. These tests represent simple cutting situations in order to evaluate the behaviour of the model.

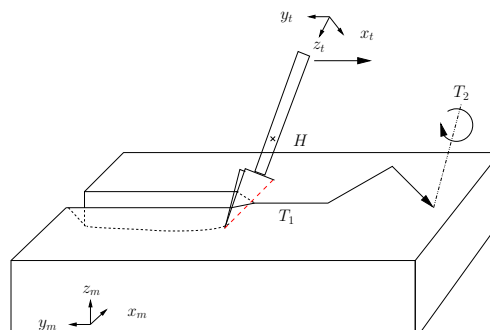


Figure 10: Sample paths

5.1 Cutting operation

This test is composed of a normal cutting operation, followed by an abnormal cutting operation. The expected path is noted T_1 in figure 10, and the actual path is presented in figure 11. During the whole operation, the orientation of the blade did not change, *i.e.* $x_{\text{tool}} \simeq -x_m$, $y_{\text{tool}} \simeq +y_m$, and $z_{\text{tool}} \simeq -z_m$. In this section, we focus on the movement along the surface, *i.e.* not along the z_m axis.

In the first part (from 0 ms to 800 ms), the path is downward the y_m axis, as presented in figure 12. The resulting efforts and torque are presented in figure 13. The most important effort is along the y_m axis and its direction is the opposite of the velocity. Moreover, a torque around the x_m axis is applied to the tool by the material.

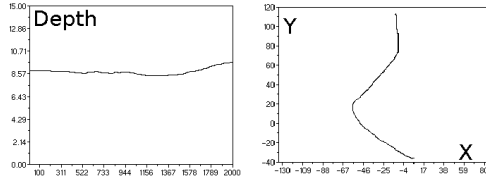


Figure 11: Test path T_1

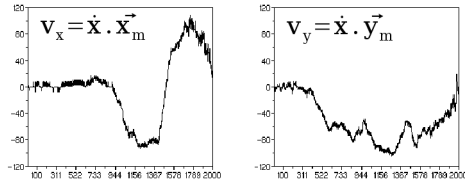


Figure 12: T_1 closed-loop velocity mesures

In the second part, we move the tool along the x_m axis which is normal to the surface of the blade. Since this movement is not a normal movement for a scalpel, it should be harder to perform. Figure 13 provides significant results: with an approximately equal speed along the two axes, the interaction model transmits some harder collision informations for this abnormal movement.

Such a model tends to prevent abnormal cutting operation, providing a more realistic force feedback.

5.2 Rotation along the main axis

In the second test T_2 , we move the virtual blade around its main axis (see figures 1 and 10). The

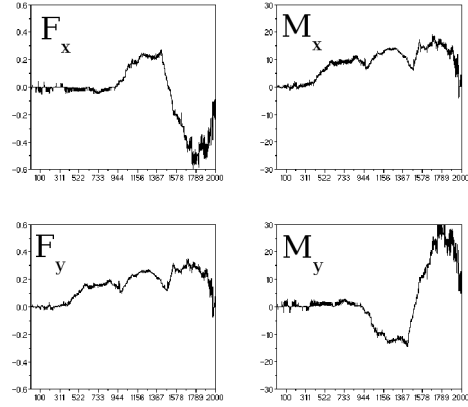


Figure 13: T_1 closed-loop haptic feedback

real path and penetration depth are presented in figure 14.

The corresponding feedback should be an opposed torque around the main axis of the blade. Due to the way we compute the movement of each elementary surface (3 DOF), a momentum around the main axis of the blade is seen as a curve in the (x, y) plan. Considering the mesured velocities (figure 15), the model does not provide adequate torque feedback around the $z_t = z_m$ axis (figure 16).

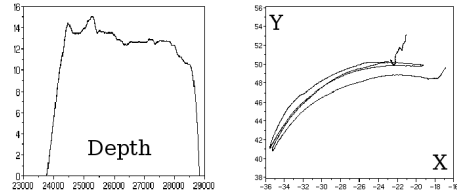


Figure 14: Test path T_2

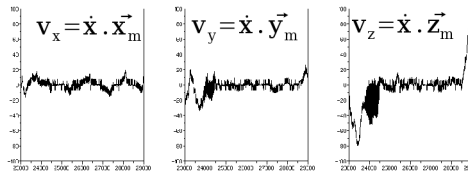


Figure 15: T_2 closed-loop velocity mesures

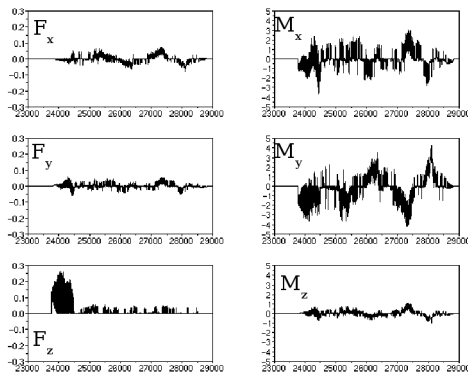


Figure 16: T_2 closed-loop haptic feedback

6 Conclusion and future work

This first implementation shows promising results, providing more realistic feedback than a simple *point-and-segment* blade model. The interaction is anisotropic, depending on the orientation of the blade and the direction of the movement.

This experimental setup still needs to be completed with additional experiments. A first step is to allow an arbitrary shape for the tissue, which implies an efficient collision detection. This collision detection should be simpler to design than general collision detection, since the geometry of the tool is limited to segments.

Moreover, the two kinds of elastic behaviour (equations 2 and 5) depend on the geometry of the material: we need to model the behaviour of this material. A purely geometric (*i.e.* not physically realistic) might be enough to ensure the credibility of the animation.

Finally, each coefficient has been arbitrarily chosen: we expect to identify the different physical parameters in order to provide a more credible haptic feedback and to evaluate the performances of the model.

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