Virtual Cutting with Force Feedback

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Abstract

Cutting is an essential operation for forming and designing shapes. We implemented a virtual cutting work space, in which we can create objects of various shapes through cutting operations. The object in the work space was defined as a closed surface that consists of triangle patches. The cutting operation was performed as boolean operations between an object and a cutting surface corresponding to the motion of the cutting blade. Also, we employed a force feedback device and liquid crystal shutter glasses to represent force sensation while cutting and to provide stereo-scopic view on the work space.

1 Introduction

In virtual reality, primary attention has been paid on objects which do not undergo any physical changes as a result of interaction. Navigation is a typical example. Recently people started to pay attention on deformable objects which changes own shapes with an external force[1]. With deformation, however, the topology of the objects does not change. This paper deals with virtual cutting which changes the topology of target objects.

It is an interesting application to form shape in a virtual environment through direct manipulation interface. There are past works that proposed the idea of forming shapes by implementing deformable virtual objects, and deforming them using fingers or tools[2]. In such applications, FEM and spring networks are frequently used to represent deforming objects[3].

Cutting is also an essential operation in shape forming task and some shapes of objects may be thought to be formed as the result of cutting. So we believe that cutting operations will play an important role in virtual reality.

Cutting has two sides: force and geometry. Objects are cut or separated when we place force on the cutting blade. It is said that people has difficulties in carrying out precision work without force feedback[4]. The geometric side implies that the objects under and after the cutting operation change their geometric shapes. Since cutting is usually an operation that locally destructs the object by concentrating stress, physical simulation on the phenomenon is too complicated to execute it in real-time.

In several previous studies, operations similar to cutting were implemented by using voxel models[5, 6, 7]. However, the model can not represent a shape whose dimension is smaller than that of a voxel, and therefore it is difficult to represent smooth surface by the model.

Most of the the virtual object model is defined based on a polygon model, because the model provides various preferable characteristics for real-time interaction. Geometrical operations on a polygon model has been studied in the field of CAD (computer aided design)[8] . We employed the concept of boolean operation on solid models for the implementation of the geometrical side of cutting.

Sensation of force is thought to provide important information in cutting operation, such as whether the cutting tool is intersecting with the object or not. We provide the sensation using a force feedback device.

2 Cutting based upon Geometric Modeling

2.1 Cutting via Boolean Operations

In the cutting process using a jigsaw, the cutting operation is performed by removing a thin volume around the locus of the saw. We implemented this removing operation by using boolean operation. In the geometrical calculation, the width of the saw can be thin enough so that the user does not feel the loss of the volume. Namely, the cutting operation using knife or some other tools can be simulated by this method. Suppose our object A and a locus of cutting device B are defined. Then it is well known that the object after cutting is represented by A AND (NOT B).

2.2 Implementation of Boolean Operations

Our objects of interest and the cutting device given in solid models are all converted into a set of triangular patches with normal directions indicating the external direction. Each patch is represented by three nodes or three edges. We need to check mutual interactions of all the surfaces of the object and of the cutting device. Each step in this checking is shown in Figure 1. Details are as follows.

(1) Intersections of Polygons: Let A and B represent the object of interest to be cut and the cutting device (or the locus of the cutting blade). The mutual interactions of triangles belong to A and those to B are checked through interaction of triangles belonging

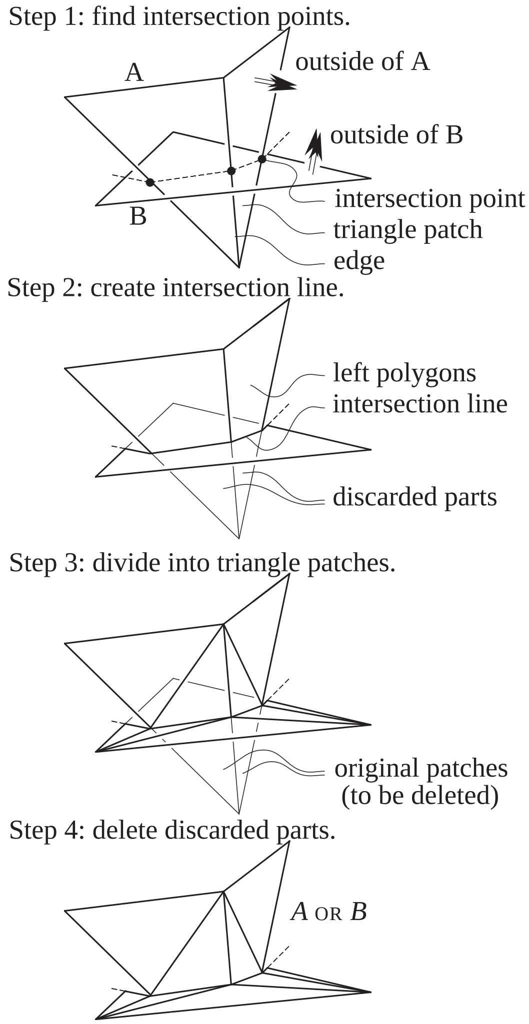

Figure 1: Steps of Boolean Operation

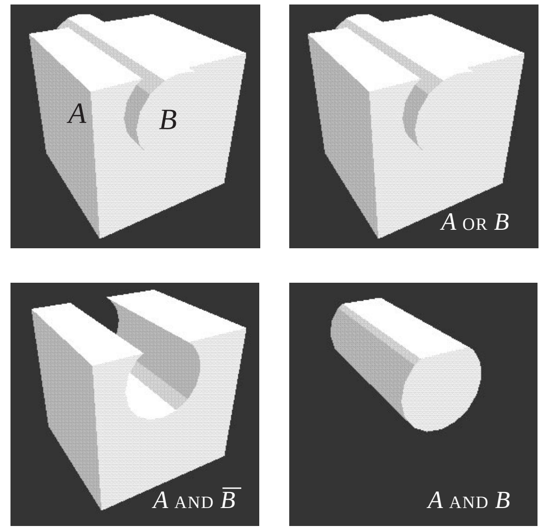

Figure 2: Boolean Operations for 3D Objects

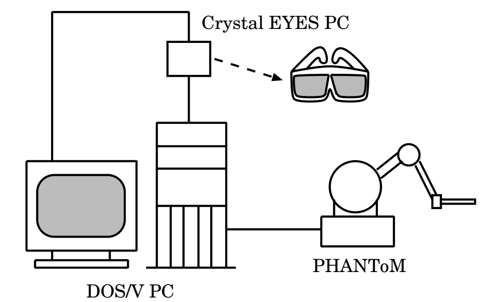

Figure 3: System Configuration

to A or B and edges belonging to B or A, respectively. When duplications appear, this check is skipped. As long as interactions are found, we compute intersecting points.

(2) Intersection Lines: The intersecting lines are those of connecting the intersecting points computed above. The intersecting points are listed as new nodes on the edge. Also new edges are generated by connecting the new nodes on a same plain. In this manner new polygons corresponding to the cut surface are generated. Some of them may be polygons other than triangles at this step.

(3) Decomposition into Triangles: The polygons other than triangles generated above are decomposed into triangular patches. Here this decomposition is performed to the nodes and edges which were on the same triangular patches before cutting. In addition, neighboring triangles are identified.

(4) Elimination of Unneeded Elements: Some parts are to be discarded after cutting and others remain. Explicitly, each node on the intersecting lines belonging to the object A is marked and those not marked are to be discarded.

Based upon the procedure described in the above, we will show an example of operations on a 3D object. With reference Figure 2, the object is a cube marked by A and the cutting device is marked by B. The shape after the cutting by the device will be obtained by a boolean operation of A AND (NOT B), where A is the object of interest.

3 Experimental System

Based upon the approach described in the previous section we implemented an experimental system. As mentioned in Introduction, it is very important to include the sensation of force in the cutting operation. In our system we employed resistance in manipulating a cutting device to derive a force. We will describe our system in details.

3.1 System Configuration

Figure 3 shows the configuration of our system. We employed PHANToM(SensAble Device)[9] as the input device for realizing virtual cutting like a hack saw and also as the device for force feedback. In addition,

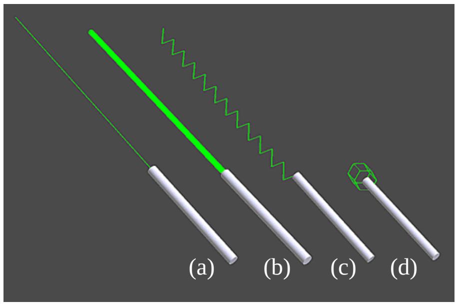

Figure 4: Variation of cutting tools

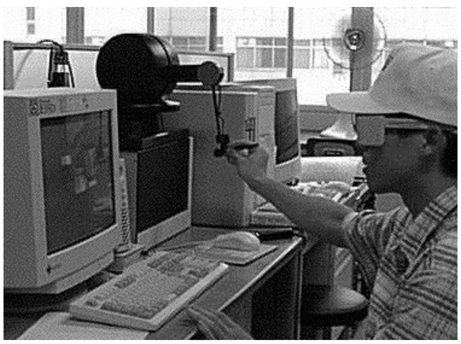

Figure 5: Operation Scene

we employed Crystal Eyes PC(Stereo Graphics) to enable stereo viewing. A DOS/V PC with a Pentium Pro 200MHz was employed for all the computations involved in the virtual cutting.

3.2 Intersecting

As the first step of our implementation, we used a simple form of cutting, that is, cursive lines for cutting or intersecting. The begin and end signals were given to the system using a switch. The cursor controlled by the PHANToM specifies the intersecting lines.

On considering the variety of cutting tools in the real world, four shapes of blade were implemented (see Figure 4): (a) straight line, (b) straight line with the loss of volume, (c) polygonal line, and (d) closed polygonal line.

3.3 Force Feedback

In the cutting operation, the blade of the cutting device has a finite surface dimension. And the generated force is determined by the interaction between the surface of the blade and the part of the object being cut. In our implementation as a first step, the cutting friction increases in proportion to the velocity of the cutting blade. This assumption is held better in the case where the object is soft and the sides of cutting edge cause little friction with the object.

Since the cutting friction appears as the distribution of force on the edge, not only force but also torque needs to be taken into account. This problem is to be discussed in the section of conclusion. In the cutting process, the human recognition of the device touching or interfering the target object plays a very important role. We assumed the force generated is proportional to the speed of the motion of the cutting device.

As described above, we regarded the cutting blade as a polygonal line whose direction is manipulated by the input device PHANToM. The interferencing or interaction of the blade with the target object is easily done by checking whether all the polygons (triangles) interact with the straight lines. If no interaction, the force $\vec{0}$ is obtained. If an interaction exists, we calculated the force as follows: Let $\vec{P_t}$ be its present position and let $\vec{P_{t-\tau}}$ be its position at a cycle prior. Then the force $\vec{F}$ is given as:

$$\vec{F} \quad = \quad k \times (\vec{P_{t-\tau}} - \vec{P_t})/\tau$$

where τ is a cycle and is set to be 1[ms]. Also k is a constant between force and speed and is set to be 0.2N/(m/s)].

With the availability of force feedback an operator can perceive or feel the object through force and feel the begin and end timing of cutting without any visual feedback.

3.4 Execution of Cutting

We will describe how our experimental system works. Figure 5 shows a scene of an operator executing a cutting process. At the present time there is no overlay of the cursor on the display and the hand of PHONToM .

Figure 6 depicts the cutting process on the display. In Figure 6(a) the plate to be cut and the cutting blade are shown. The cutting blade was moved from the middle top to the left corner. Figure 6(b) shows the cutted locus. Figure 6(c) illustrates the fact that two pieces are indeed separated as the result of cutting. The direction of the blade does not have to be perpendicular to the surface of the plate. Figure 7 shows an example of a case where the locus of the blade tip may intersect itself. In the Figure, (a), (b), and (c) show the display under cutting, after cutting, and separated pieces after cutting, respectively.

We have shown cases of a single cutting where a cutting blade is operated on a cutting plate only once. We can cut the piece already cut. The piece shown in the center of Figure 8 is an example. A "V" shaped piece was rotated about 90 degrees and was cut like "R".

The effect of the loss of volume is shown in Figure 9. Also, examples of applying tools of polygonal blade are shown in Figures 10 and 11. The calculation of the cutting operation in Figure 10 took about five seconds, where the object and the cutting volume consisted of 12 and 996 polygons, respectively.

4 Conclusion and Future Works

We described realization of virtual cutting and our experimental system. We proposed cutting through boolean operations on a 3D object and the cutting device (or more precisely the 3D locus of the cutting blade). Cutting is performed based upon the relationship between the polygons of the object and those of the cutting blade locus. We implemented our experimental system on a PC and a PHANToM. With

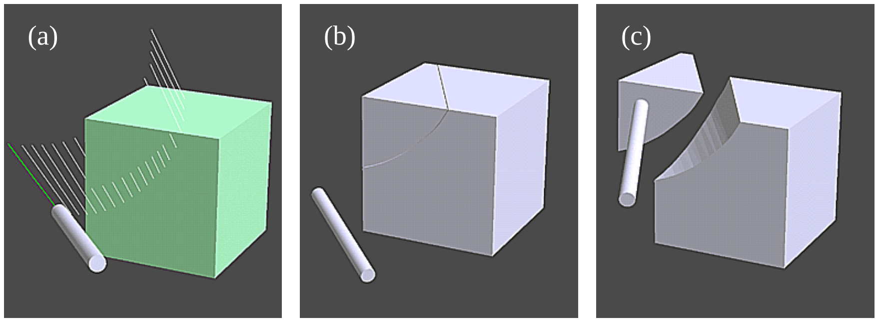

Figure 6: Cutting Process

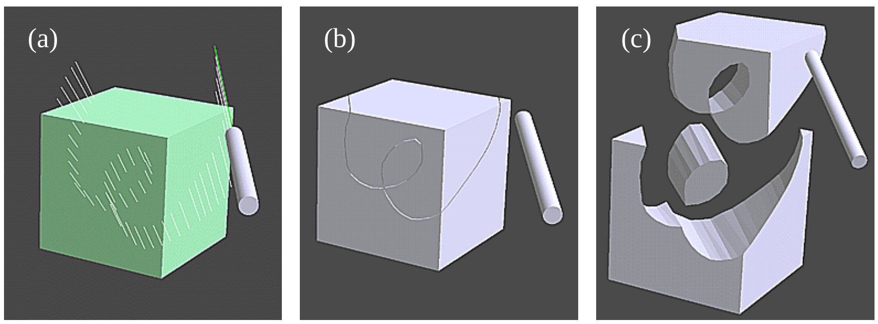

Figure 7: Cutting Process where a cutting line intersects itself

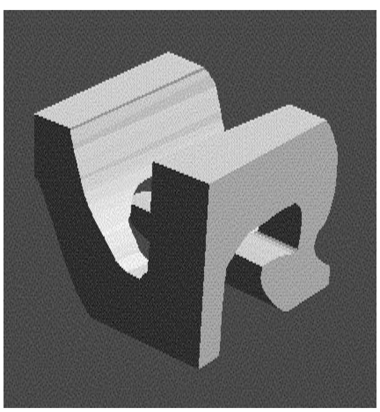

Figure 8: An example of created shape

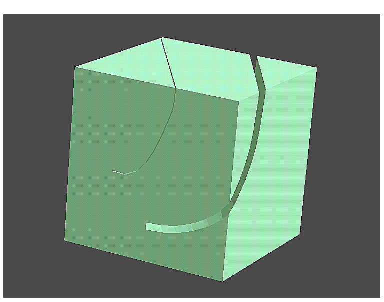

Figure 9: Loss of volume in cutting operation

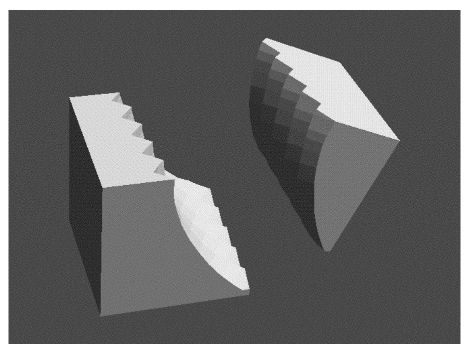

Figure 10: Cutting by the edge of polygonal shape

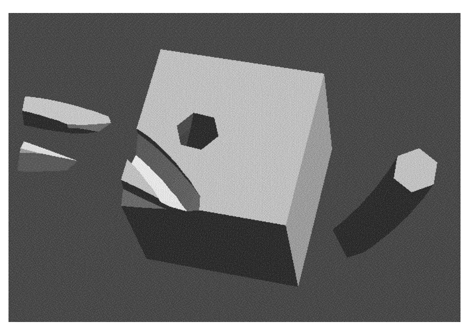

Figure 11: Cutting by the edge of closed polygonal shape

the availability of the force feedback, cutting can be performed more intuitively than with visual feedback alone.

A problem of cutting through direct manipulation interface is that the sway of the user's hand is directly reflected on the created surface. The feedback of force may be used to reduce the effect of sway and stabilize the cutting motion.

We feel that a device with three degrees of freedom (e.g. PHANToM) is not enough for cutting. We would like to extend our system with a device with torque feedback. For the representation of torque, we need to define the distribution of force on the edge and sides of cutting tool.

We are also interested in the simulation of cutting soft materials that deform during the operation. The simulation of this kind is thought to be indispensable for applications such as surgical simulation on soft tissues.

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