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Force Profile study of Virtual Cutting

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Abstract

In recent years, virtual cutting simulation has advanced using tactile display. A polygonal model and a voxel model are used for expressing 3 dimensional virtual objects. Both models have advantages and disadvantages. In this research, virtual cutting simulation system was developed which surface is represented by a polygonal model; a voxel model is used for expressing the inside of a solid model locally. Cutting force was measured and compared between actual and virtual cutting. Validity was examined by considering cutting depth stiffness and clip friction force, improving the cutting simulation model and applying two cutting methods.

Key words: Virtual cutting, Cutting force , polygonal model, Voxel model, Tactile display, Force sensor

1. Introduction

Research of virtual surgical operations[1] has advanced in recent years based on virtual reality technology. . One basic operation is virtual cutting simulation[2]. In order to realize the virtual cutting, there are two types of research, i.e. using a voxel model[3] and a polygonal model. The voxel model expresses volume and is made by a small cube size. The polygonal model expresses the surface and is constructed by a triangular polyhedron. Tanaka's research[5, 4] using the voxel model allows the object to be cut through a simple algorithm that eliminates the interfering voxel between cutter and object.. Then, the cutting operation process, accompanied by the advance of the knife, can be easily visualized. However, it is difficult to express the smooth surface caused by the resolution of the voxel model.

To avoid this problem, the size of the cube can be reduced to improve the surface quality. However, the amount of data increases greatly and the processing of surgical simulation takes a long time. On the other hand, research using the polygonal model[6, 7] can construct a smooth surface. However, it is difficult to gather information about the inside of the object.

In this research, surface shape is represented by a polygonal model, and a voxel model is used for expressing the inside of the model locally. We developed the virtual cutting simulation system by combining the advantages of both the polygonal and voxel models. Moreover, the virtual cutting system is evaluated by an improved analysis model compared with real cutting. We use the force profile for comparison. Vo β's research[2] was not consider the force profile.

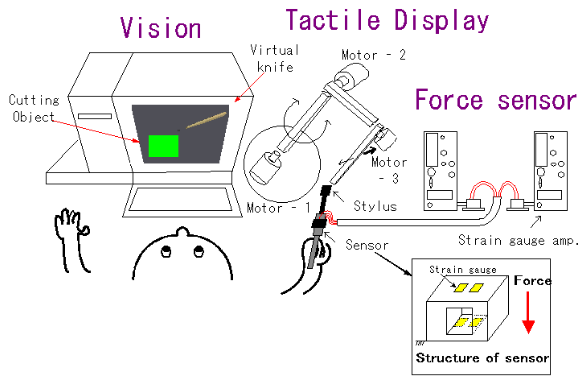


Fig. 1: Scheme of developed system

Chapter 2 describes the system configuration, Chapter 3 illustrates the validation experiment, and Chapter 4 offers a conclusion.

2. System configuration

This system constitutes from visualization, a tactile display, and a force sensor. This chapter outlines the research, the tactile display and the cutting simulation system.

2.1 Outline of virtual cutting simulation system

The composition of a development system is shown in Figure 1. Triangular polygon data is used for the 3D surface shape and robot mechanism (PHANToM, SensAble Technologies, Inc.), operated with the right hand, are used for tactile display. A force sensor[8] is constructed from two thin parallel detectors, inserted into the sensor body, and force is detected by 4 strain gauge. Cutting forces of actual and virtual are measured by attaching the force sensor to a knife and the tactile display handle.

2.2 Composition of tactile display

It is an intuitive method of grasping the object information and working on the environment so that a human can perceive touching the object. The tactile display has a robot mechanism, a position sensor, and three motors

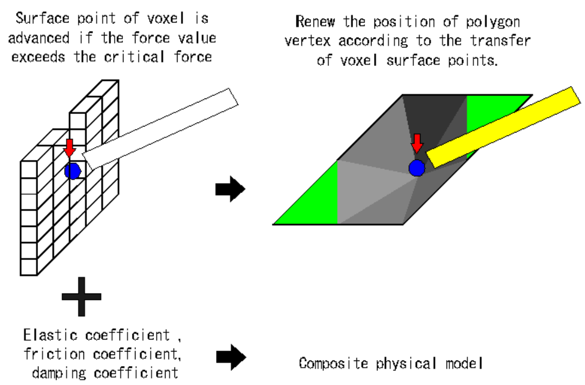


Fig. 2: Scheme of cutting mechanism

for generating the force and expressing the surface position. Here, the system creates a virtual cutting stick and detects the tip position of the cutting stick from position sensor's values. Interference between the 3D triangular polygon object and the cutting stick must be calculated at high speed. If contact has occurred, the contact point is represented by the holding position, which is controlled by the servo-motor. Presentation of a tactile sense is performed by 1000 [Hz].

2.3 Overview of cutting simulation system

The simulation system is developed using Reachin API3.0 software development tool (Reachin Technologies) and C++ language. Physical properties are simulated by this software library. 3D shape of cut object is defined as triangle polygon data using a VRML format.

Figure 2 shows the outline of the cutting operation. Moreover, operation of a virtual cutting system is shown below.

1)Read shape data
The 3-dimensional form of the cut object, which is represented by VRML data, is read, and registration to graphics and a tactile sense function is performed.

2)Generation of local voxel structure
Observing contact state between cutting stick and cut object, if contact has occurred, voxel data is built around the contact point locally. Voxel data structure is built by 3-dimensional alignment and interference points with polygon, which represent the surface point, are stored.

3)Cutting process
In the cutting process, surface points of voxel and vertex position of the polygon will be renewed. Recreation of surface points of voxel is constructed in two parts; one is depth direction and other is cut direction. For each direction, the force value of the cut simulation is investigated and the surface point is advanced if the force value exceeds the critical force for each direction. Critical value of force and exceed value are adjusted for cut material. Tactile display can formulate the force and contact points from polygon data, after which we must renew the position of polygon vertex according to the transfer of voxel surface points. The cutting stick is making progress in the object from the above-mentioned mechanism.

Here, elastic, friction, and damping coefficients are given as physical properties of a cut object. And, critical force value of depth and cut direction are given as a cutting parameter. In this case, as the size of the cutting stick and the triangular polygon are similar, then division of the polygon is not considered. Moreover, it is desirable to register the information of internal physical property to each voxel, thus we set uniform property of every voxel in this experiment.

2.4 Improving cutting analysis model

In the above section, the cutting process using burying threshold is explained. Cutting is executed by buring the knife edge in the material, instead of the point. It is line cutting. Then, local stiffness is added which increse by depth of cutting edge. Hereafter this local stiffness is called depth cutting stiffness (DCS). Coefficient of DCS is $0.066E$/mm from the experiment in which we measured the increment rate of different cutting depths. E is material stiffness.

Next, we consider the effect cutting edge thickness and the amount by which the cutting material is deformed by that thickness and receive the friction force, which is generated by reaction force. Then, friction force as expressed by equation (1) is considered. Here M is friction coefficient, Cl is cutting length, Cw is half of cutting edge width, dz is depth of cutting, and deform area is computed by $Cwdz$. Hereafter this force is called clip friction force (CFF).

$$Fh = MECwdz\frac{\sqrt{Cl^2+Cw^2}-Cl}{Cl}cos\left(tan^{-1}\left(\frac{Cl}{Cw}\right)\right) \quad (1)$$

3. Validation experiment

This experiment examines validity by measuring the cutting force between real and virtual cutting, on the following selected materials is sponge.

3.1 Force measurement of real cutting

Figure 3 shows the measuring method of actual cutting. A force sensor is fastened to the knife handle and force data is acquired from a personal computer for real cutting of sponge.

3.2 Force measurement of virtual cutting

Figure 4 shows the force measuring method of a virtual cut. A force sensor is affixed to the cut stylus handle of the tactile display and cutting parameters are set for executing the cutting simulation. The force is acquired from a force sensor and data is recorded with a personal computer. Here, the form of the cutting object is a cube shape, with each edge length 1mm for simplification and

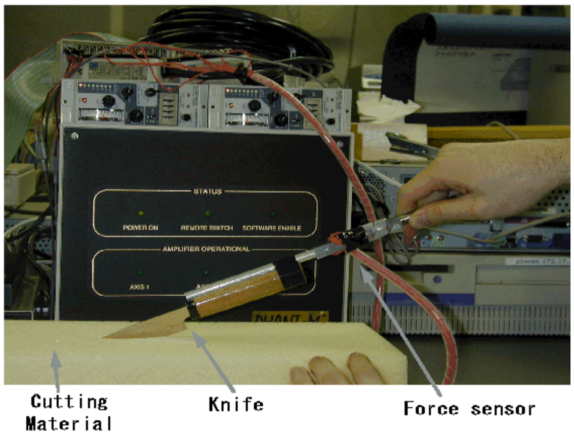


Fig. 3: Force measurement for cutting by knife

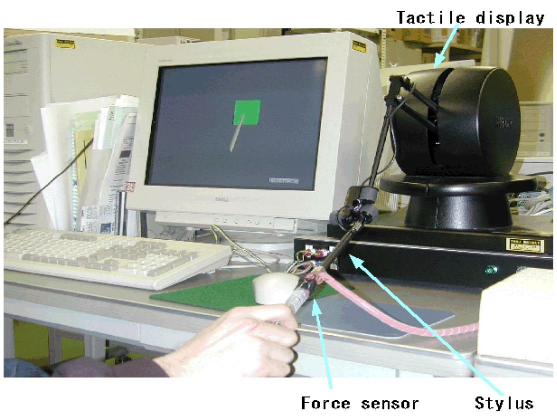


Fig. 4: Force measurement for virtual cutting

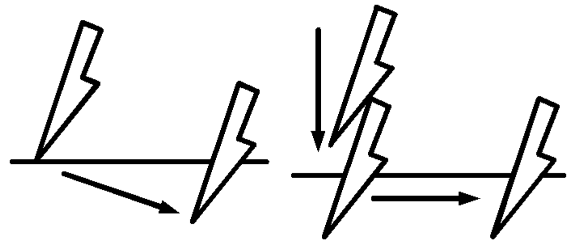
one surface divided into 800 triangular polygons. The tip of a cutting stick is set at a diameter of 0.04mm.

Table 1 shows parameter values of virtual cutting simulation. Elastic coefficient (N/m^2), friction coefficient, damping coefficient (NS/m^2), force critical value (depth direction), force critical value (cutting direction), advance length for voxel eliminating (exceeding critical force) of the cut material are selected for the cutting parameters. Here, elastic and friction coefficients are measured from the real cutting object and damping coefficient is selected from the material handbook.

Here, we consider two cutting methods, which are shown in Figure 5. In the first method, cutting depth is proportinal to cutting length (Proportinal depth cut). In the second method, the first cut is to depth direction until setting depth, and the next cut progresses at the same depth (Constant depth cut).

Table 1: Parameter value for cutting material

Parameters	Sponge
Elastic coefficient(N/m^2)	20.0
Friction coefficient	0.8
Damping coefficient(NS/m^2)	0.5
Force critical value [cutting direction](N)	0.1
Force critical value [depth direction](N)	0.3
Advance length for voxel eliminating(mm)	0.02



a) Proportional depth cut. b) Constant depth cut.

Fig. 5: Cutting method.

3.3 Experiment result

Figure 6 shows the cutting force profile of sponge and virtual cutting for proportional depth cut. Force is shown along a vertical axis and time is shown along a horizontal axis. In the figure, a) is a case without depth cutting stiffness and clip friction force, and force profile is smaller than actual cut b). On the other hand, c) is force profile which considers depth cutting stiffness; this profile is similar to actual cut b). And d) is force profile which considers both depth cutting stiffness and clip friction force; we can not observe much improvement with c). In these case, cutting length and cutting speed of each virtual and actual cutting were set almost same, but we have some difference of cutting speed caused by the human experimnet. Cutting depth of actual cut was measured from cutting material every 0.5mm distance.

Figure 7 shows the cutting force profile of sponge and virtual cutting for constant depth cut. In the figure, a) is a case without depth cutting stiffness and clip friction force, and force profile is smaller than actual cut b). On the other hand, c) is force profile which considers depth cutting stiffness; this profile is similar to actual cut b). And d) is force profile which considers both depth cutting stiffness and clip friction force; we can not observe much difference with c).

From the above mentioned result, force profile, which considers depth cutting stiffness, is similar to actual cut.

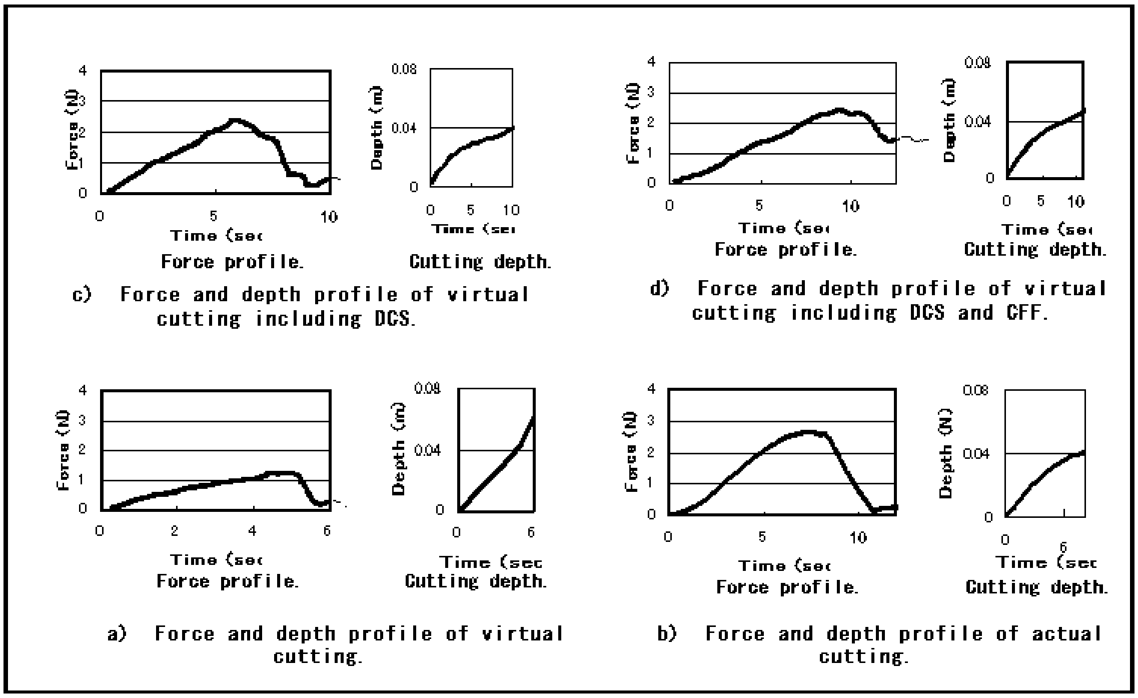


Fig. 6: Comparison with Force of virtual and actual cutting for proportional depth cut.

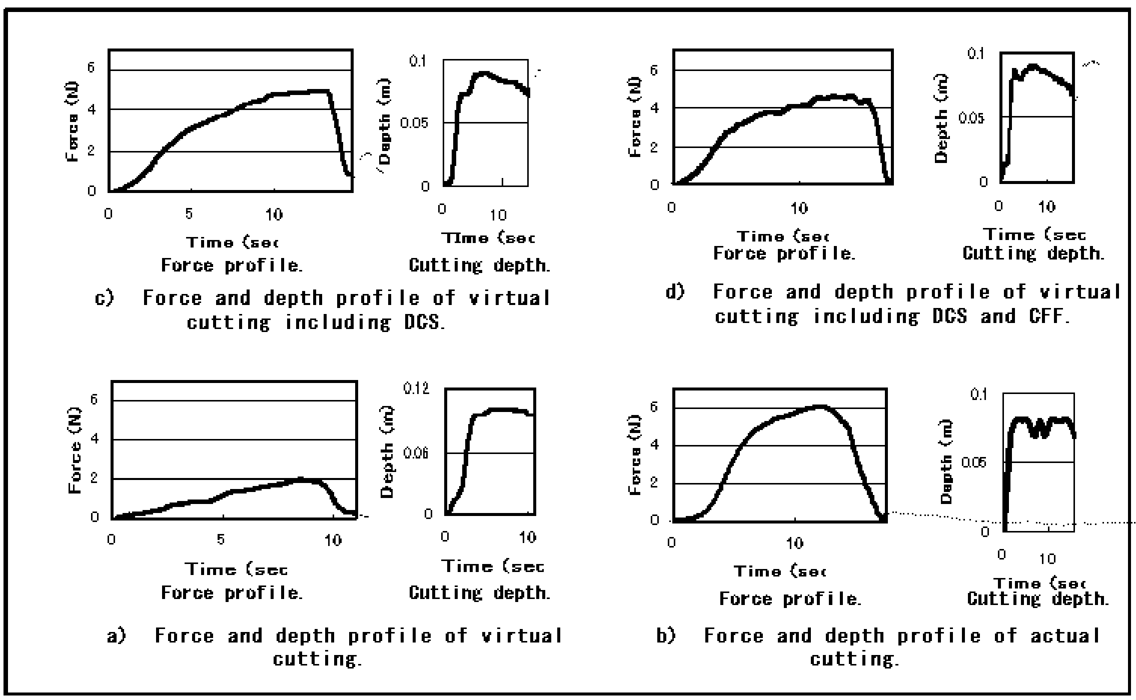


Fig. 7: Comparison with Force of virtual and actual cutting for constant depth cut.

4. Conclusion

We propose the multi-CG model be used for cutting objects in which the surface is represented by polygons and the inside area is constructed by voxel model locally. The cutting force is generated from the voxel and polygonal models and both models are adjusted for progress of the cutting tip each time. And virtual cutting simulation system equipped with a force sensor was developed. Our system can be easily considered inside property of the cutting object and calculation cost is reduced using local voxel model. Although 500X500X500 cubes are used for usual voxel model, our proposal model of this research are only used by 10X20X20 cubes.

Changing the force profile is confirmed with setting the variety of the cut parameter. Moreover, the force profile of cutting must be more precise, considering depth cutting stiffness, to make a similar virtual simulation as a real cut.

In this research, inside property is set uniformly. If the material properties of each voxel are set from CT data, we can make a more realistic virtual cutting simulation.

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