A CONSTRUCTION METHOD OF VIRTUAL HAPTIC SPACE(II)
— A Shape Model of an Object in Virtual Environment
Suitable for Representing Shape with Surfaces and Edges —

HIROSHI HOSHINO

RYOKICHI HIRATA

TARO MAEDA

SUSUMU TACHI

RCAST, The University of Tokyo
4-6-1 Komaba, Meguro-ku, Tokyo 153 Japan
+81-3-3481-4468/4580 (phone/fax)
hoshino@star.rcast.u-tokyo.ac.jp

ABSTRACT

We have proposed a system which enables an operator to feel himself/herself touching an arbitary surface with edges. This system represents the shape of an object by locally constructing its shape around his/her finger tip with a special device called Shape Approximation Device, of which each surface has convex and concave edges. In this paper we propose a shape model of an object in virtual environment for this local construction of its shape using Beziere surface representation and we succeeded in representing complex surfaces with an edge by constructing a system based on this model.

1 Introduction

It is significant in Tele-Existence to develop the system which displays the shape to an operator when touching an object in virtual environment, and many researches have been studied for developing the shape display system.

Conventional shape display systems are based on the following method: An operator is equipped with the device with actuators, and actuators are driven according to his/her motion such that they apply him/her the force which is equal to one applied to him/her when touching an object in virtual environment.

However this method involves the following problems.

- The dynamics of the actuators constrains an operator's motion even if he/she dose not touch an object in virtual environment.
- These systems require high performance of controlling actuators because it is necessary to switch the control algorithm of actuators at the moment an operator touches an object in virtual environment. Therefore it is difficult to represent an object like a solid wall, which doesn't move even if it is pushed.

- Although it is possible to represent differentiable smooth surface by the conventional method, it is impossible to represent edges or vertices, which are not differentiable, because of the limitation of actuators.

We proposed the following method and showed its feasibility by test hardware[Tachi et al., 1994]: An operator can recognize the shape only around the contact point, therefore, it is sufficient to represent the shape only around the contact point with a real object according to his/her motion.

Our method has the following advantages over the conventional method: Firstly an operator's motion is not constrained because he/she doesn't have to be equipped with the device with actuators. Secondly it is not necessary to switch the control algorithm because the system represents the shape not by applying the force but by constructing it with a real object, and therefore it is easy to represent an object like a solid wall.

McNeely et al.[1993] proposed a system based on a similar method but they didn't refer how to represent a general shape in their first report, and their system succeeded in representing few kinds of shape using test hardware[Boeing, 1995].

Hirota and Hirose[1993, 1995] has developed a system on a similar method as well and succeeded in representing a curved surface, but haven't succeeded in representing a shape with edges or vertices.

We succeeded in representing a surface with edges[Tachi et al., 1994], and representing an object with motion[Tachi et al., 1995]. In this paper we propose the shape model of an object in virtual environment suitable for representing the shape with surfaces and edges. This model enables the system to represent the shape with an edge in real time and we confirmed its feasibility by test hardware.

2 System[Tachi et al., 1994]

Figure 1 shows the concept of our system. A motion of an operator's limb is measured by a light weight goniometer called Passive Master Arm. The position and orientation of Shape Approximation Device(SAD), the real object which an operator touches, is controlled by a 6 degrees-of-freedom manipulator, Active Environment Display(AED), so that SAD represents the shape around the contact point. SAD has a shape such that each surface has a convex edge and a concave edge (Fig.2), and therefore is able to represent variety of shapes with edges[Tachi et al., 1994]. Fig.3 shows the diagram of our system. Computer A manages the shape model of an object in virtual environment. It measures an operator's finger tip position with Passive Master Arm and transmits Computer B information of the object being touched. It runs at a speed of 5–10msec per cycle.

Computer B controls AED by using the information received from Computer A so that SAD represents the shape of the object being touched. It runs at a speed of about 5msec per cycle.

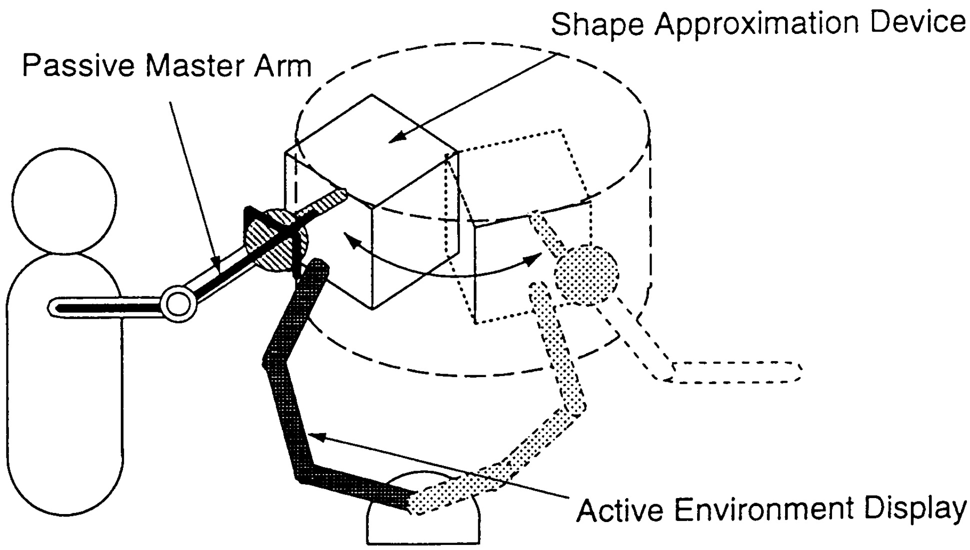

Figure 1: Conceptual Diagram of the Proposed System

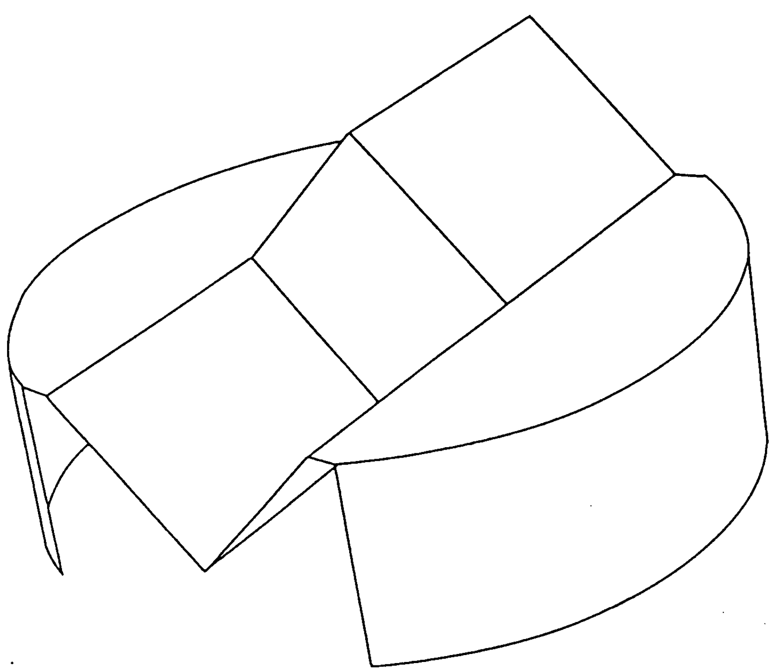

Figure 2: Shape Approximation Device

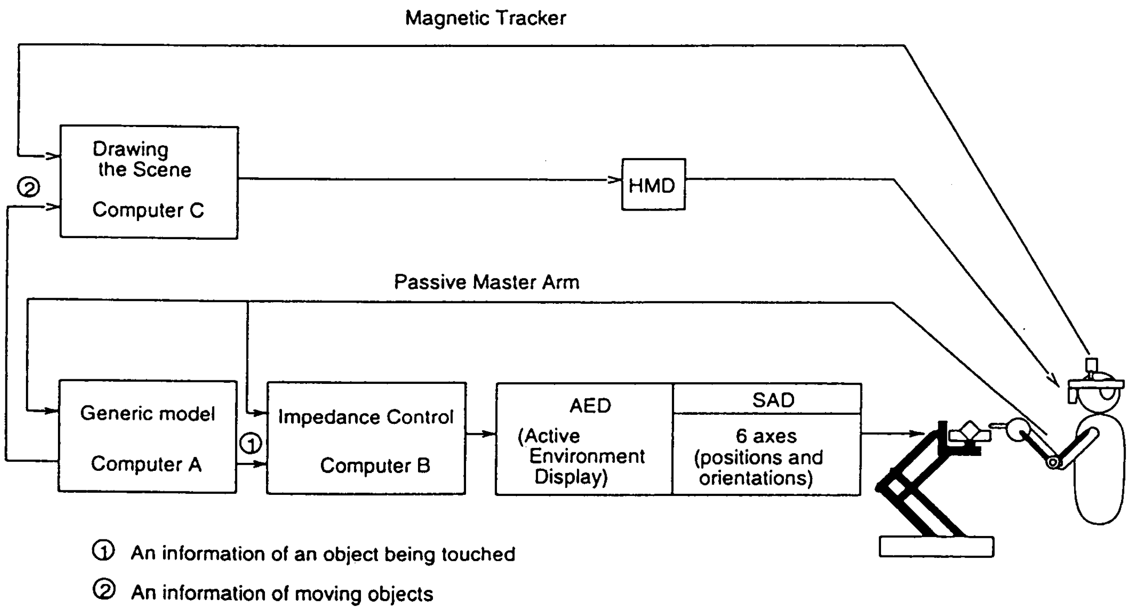

Figure 3: Block Diagram of Virtual Visual and Haptic Space Presentation System

Computer C measures the position and orientation of an operator's head with a magnetic tracker and displays to an operator the images of virtual environment through Head Mounted Display(HMD). It runs at a speed of about 100msec per cycle.

We realized fast and asynchronous transmission among the computers by using shared memory and therefore it is possible to control AED while calculating the shape model of the virtual environment.

3 Shape Model

Our system requires a shape model satisfying the following conditions.

- it enables us to calculate the shape with surfaces and edges in real time.
- it requires only the small amount of information transmitted between the computers.

Therefore we divide an object into small quadrilaterals, i.e "patches" and represent its shape at each patches as Beziere surfaces as of Eq. (1).

$$p(u,v) = \begin{bmatrix} (1-u)^3 & 3(1-u)^2u & 3(1-u)u^2 & u^3 \end{bmatrix} [Q] \begin{bmatrix} (1-v)^3 \\ 3(1-v)^2v \\ 3(1-v)v^2 \\ v^3 \end{bmatrix} \quad (1)$$

$$[Q] = \begin{bmatrix} q_{00} & q_{01} & q_{02} & q_{03} \\ q_{10} & q_{11} & q_{12} & q_{13} \\ q_{20} & q_{21} & q_{22} & q_{23} \\ q_{30} & q_{31} & q_{32} & q_{33} \end{bmatrix} \quad (2)$$

where $\{q_{ij}\}$ are control points, which determine the shape of Beziere surface.

We gain the following benefit by expressing the shape model in this way.

- It is easy to express a curved edge because Beziere surface is equivalent to Beziere curve on the boundary of its patch.
- We can decrease the amount of shape information transmitted between computer A and computer B, for it is sufficient to transmit shape information only at patches around the finger tip.

In our model the patches have not only information of the control points $\{q_{ij}\}$ but also following information.

- information indicating the adjacent patches.
- information indicating whether or not the patch has any edge and whether it is convex or concave if it has an edge.

It will be referred in section (3.1) and section (4) how to use these piece of information.

3.1 *Information Transmission*

Computer A transmits shape information to Computer B according to the finger tip position as follows.

Computer A measures the finger tip position by using Passive Master Arm and determines the nearest patch from the finger tip. Then, it searches three patches which is adjacent to the nearest one by using information indicating the adjacent patches(Fig.4).

At last it transmits information of control points $\{q_{ij}\}$ and information of edges of these four patches.

Note: It is necessary to transmit not only the shape information at the nearest patch but at the three neighbouring patches in case Computer B cannot represent the shape when the finger tip goes out the nearest patch.

4 Control of the position and orientation of SAD

It is also necessary to decide which parts of SAD should be used for representing the shape. Though SAD has seven surfaces which can be used for representing the shape, we used only two adjacent surfaces among them because of the limitation of the reachable workspace of AED, and therefore we limit the represented shape to a curved surface or shape with two curved surfaces and a convex edge.

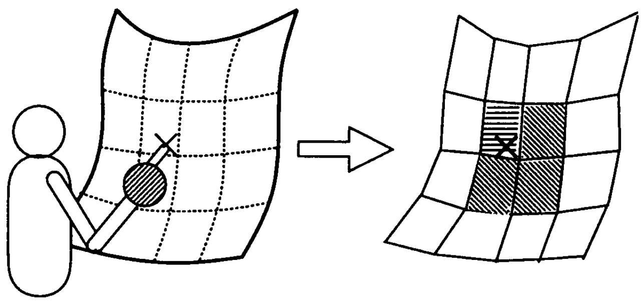

Figure 4: Three Neighbouring Patches

Computer B controls the position and orientation of SAD by using the information of control points $\{q_{ij}\}$ and the information of edges at the four patches received from Computer A as follows.

1. Determine the nearest one among the four received patches from the finger tip.

2. Check whether or not the four patches have any edge.

3. Calculate the shape at the patch determined at step 1 by using the information of control points $\{q_{ij}\}$ and the result at step 2.

4. If the shape checked at step 2 has no edge, the position and orientation of SAD is controlled so that its surface is equal to tangent plane of the represented shape. If it has an edge, the position and orientation of SAD is controlled so that its edge is equal to tangent line of the edge of the represented shape.

We assume that a patch is parallelogram. At step 1 we set the projection plane as Fig.5, whose normal is parallel to the sum of the normals of the four patches, and project the finger tip position p_{finger} and the four vertices of the patch to this plane.

Let p_{finger} be projected to p'_{finger}, four vertices of the patch, $\{r_{00}, r_{01}, r_{10}, r_{11}\}$ be projected to $\{r'_{00}, r'_{01}, r'_{10}, r'_{11}\}$, then we obtain the following linear relation.

$$p'_{\text{finger}} = \alpha(r'_{10} - r'_{00}) + \beta(r'_{10} - r'_{00}) \tag{3}$$

Because $\{r_{ij}\}_{i,j=0,1}$ are equivalent to $\{q_{ij}\}_{i,j=0,3}$, we obtain the following equation.

$$p'_{\text{finger}} = \alpha(q'_{30} - q'_{00}) + \beta(q'_{30} - q'_{00}) \tag{4}$$

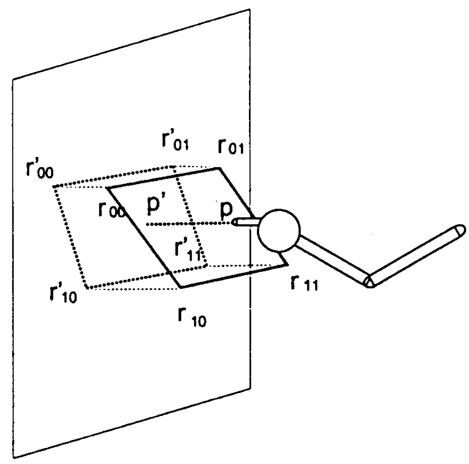

Figure 5: Projection of the Patch

We calculate (α, β) in Eq.(4) for the four patches and determine the nearest patch, that is, the one whose (α, β) satisfies $0 \leq \alpha, \beta \leq 1$.

Step 2 is easy by using information received from Computer A.

At step 3 the shape is expressed as Eq.(1), thus (u, v) in (1) should be properly calculated according to the finger position tip p_{finger}. If the patches have no edge, we set (u, v) to (α, β) calculated at step 1. If they have an edge, it is enough to calculate (u, v) in the way mentioned above and then to fix u or v to 0 or 1, for Beziere surface is equivalent to Beziere curve on its boundary.

If the calculated shape has no edge, the position and orientation of SAD is controlled at step 4 so that its surface is equal to tangent plane of the represented shape at the contact point(Fig.6 Left). If it has an edge, the position and orientation of SAD is controlled so that its edge is equal to tangent line of the edge of the represented shape. (Fig.6 Right).

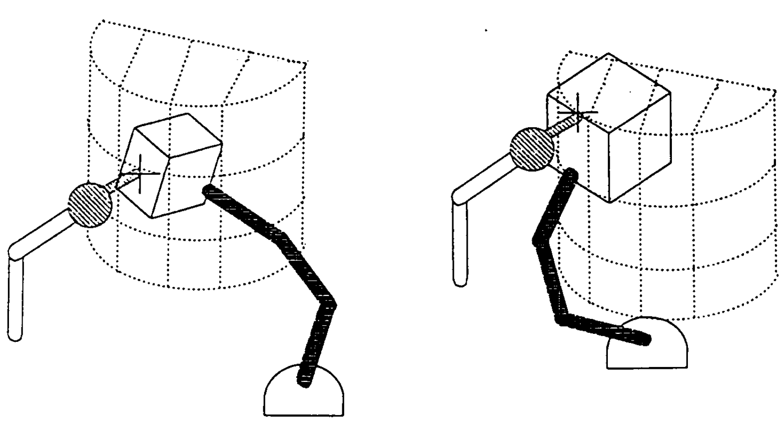

Figure 6: Shape Display by Using SAD

5 Results

Figure 7 shows the image which is displayed to an operator through HMD. Fig.8 shows the situation of constructing the shape with SAD. A mesh in Fig.8 indicates

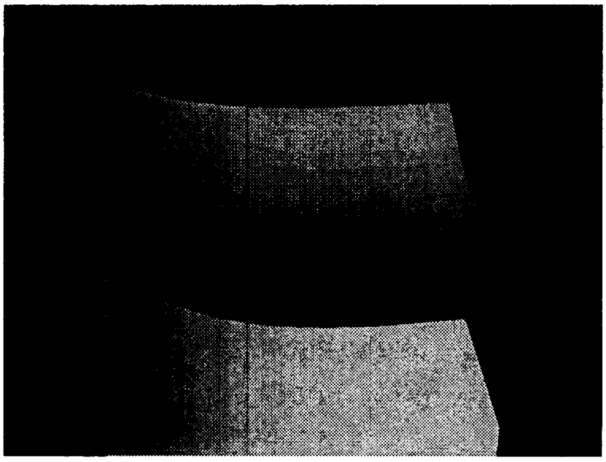

Figure 7: Virtual Environment

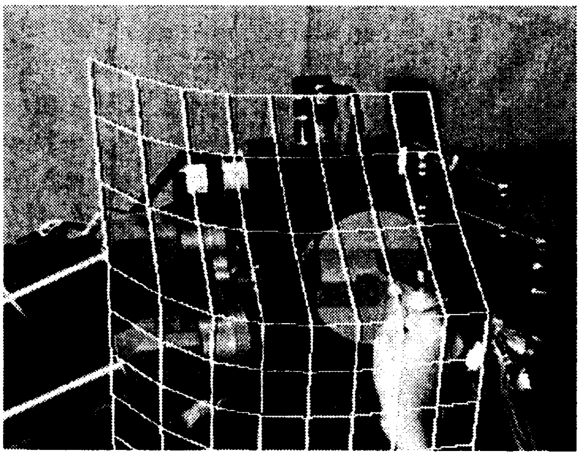

Figure 8: Real Environment

the patches of this object. The detailed results of the experiments conducted using the proposed model are shown in the Video Proceedings of ICAT '95, which is accompanied with this paper proceedings.

This shape consists of sixty-four patches and the size of each patches is approximately 50mm by 50mm in size.

6 Summary

We proposed the shape model suitable for representing the shape with surfaces and edges using Beziere representation. The proposed model has following advantages:

- it decreases the amount of transmitted information by dividing an object into patches and transmitting the shape information around the nearest patches to the finger tip.
- it is easily able to represent the shape with surfaces and edges and therefore is able to calculate it in real time

Future problems to be solved are extention of the reachable workspace of AED and emancipation from the following assumptions which limit possible shape represented:

- A patch is assumed to be parallelogram.
- An object is assumed to be divided by patches.

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