Volume Haptization

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Abstract

This paper describes about haptic representation of volume data. Volume visualization is a powerful tool in the field of scientific visualization. However, visual representation of full three-dimensional volume is hard to comprehend because of occlusion. Higher-dimensional and multi-parameter data sets are also difficult to present by visual image. This paper proposes methods for presentation of volume data by force sensation. A 6 degree-of-freedom force reflective master manipulator is used for haptization. The manipulator is combined to real-time visual image of volume data. Methods of haptic representation of scalar, vector, and tensor data are discussed. Recognition performance tests of scalar and multi parameter volume data are examined.

1.Introduction

Scientific visualization is one of a major application area of virtual reality[1]. The recent evolution of computer graphics technology enables real-time interactive presentation of scientific data. Simulations and scientific experiments often produce data in the form of a large number of values within a three-dimensional coordinate space. This information is often hard to comprehend in numerical form. Volume visualization is a powerful tool for investigators of those data[2].

Visual information is essentially consists of two-dimensional image. Three-dimensional scene is recognized by binocular parallax cues or motion parallax. Complex 3D objects are often difficult to comprehend because of occlusion. A possible method for visual representation of such objects is semi-transparent graphics. However, multiple objects are overlapped in the image. This drawback leads to difficulty in distinguishing objects.

Visual representation of higher-dimensional and multi-parameter data sets is a much harder problem. A typical technique for visualizing those data is iconification. For example, vector field of fluid dynamics is visualized by stream line. Effectiveness of the technique depends on icon design. Inadequate design of icons leads to misunderstanding of volume data. Moreover, higher-dimensional values, such as 4 or 5, are difficult to be mapped to icons.

The major objective of our research is representation of volume data by force sensation. Force sensation plays important rolls in recognition of 3D objects. An example of haptic representation of scientific data is found in the work of Brooks et al.[3]. A complex molecular docking task is assisted by a force reflective master manipulator. In this work, force display is used for magnifying length and scales of molecules. We are proposing the haptic mapping of general physical fields.

Force sensation contains 6 dimensional information: 3 dimensional force and 3 dimensional torque. Therefore, higher-dimensional data can be represented by force sensation. The basic idea of volume haptization is mapping voxel data to force and/or torque(Figure 1). We developed a desktop 6 degree-of-freedom force display[4]. This device is used for volume haptization. The force display is combined to real-time visual image of volume data.

2. System Configuration

The hardware configuration of the system is indicated in Figure 2. Force feedback is realized by a 6 degree-of-freedom master manipulator. Visual information is displayed by HMD(head-mounted display). The system employs two computers: a

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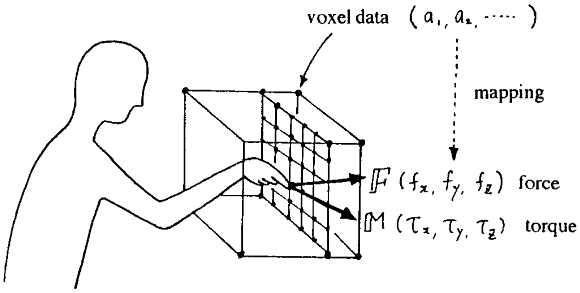

Figure 1. Haptic representation of voxel data

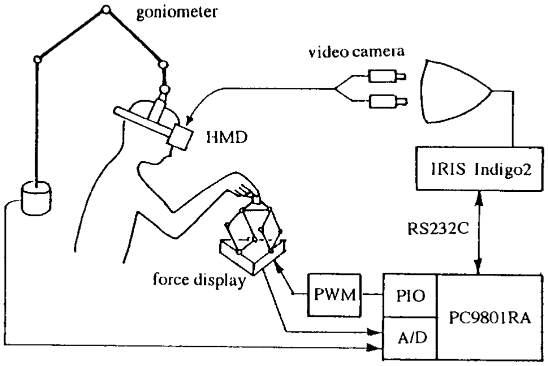

Figure 2. Hardware configuration of the system

graphics computer for real-time image of virtual space and an I/O computer which supervises sensors and actuators.

The I/O computer is equipped with analog-to-digital (A/D) convertors and a parallel input/output unit. The graphics and I/O computers are connected by a serial (RS-232C) communication line. The graphics computer is an IRIS Indigo2; the I/O computer is an NEC PC-9801. Overall view of the system is shown in Figure 3.

(1) Desktop force display

A 6 degree-of-freedom manipulator was developed as a force display. The manipulator applies reaction forces to the fingers of the operator. The manipulator employs parallel mechanism. The typical design feature of parallel manipulators is an octahedron called "Stewart platform". In this mechanism, a top triangular platform and a base triangular platform are connected by six length-controllable cylinders. This compact hardware has the ability to carry a large payload. The structure, however, has some practical disadvantages in its small working volume and its lack of backdrivability (reduction of friction) of the mechanism.

Figure 3. Overall view of the system

In our system, three sets of parallelogram linkages(pantograph) are employed instead of linear actuators. The mechanism is illustrated in Figure 4. Each pantograph is driven by two DC motors. Each motor is powered by a PWM(Pulse Width Modulation) amplifier. The top end of the pantograph is connected with a vertex of the top platform by a spherical joint. This mechanical configuration has the same advantages as an octahedron mechanism has. The pantograph mechanism improves the working volume and backdrivability of the parallel manipulator. The inertia of motion parts of the manipulator is so small that compensation is not needed.

The working space of the center of the top platform is a spherical volume whose diameter is approximately 30 cm. Each joint angle of the manipulator is measured by potentiometers. Linearity of the potentiometers is 1%. The maximum payload of the manipulator is 2.3 Kg, which is more than a typical hand. We generate the reaction force from the following formula:

$$\mathbf{L} + \mathbf{L}_{offset} = \sum_{i=0}^{2} \mathbf{F}_i \qquad (1)$$

$$\mathbf{M} = \sum_{i=0}^{2} \left[(\mathbf{h}_i - \mathbf{p}) \times \mathbf{F}_i \right] \qquad (2)$$

$$\mathbf{F}_i \cdot \left[(\mathbf{b}_k - \mathbf{b}_j) \times (\mathbf{h}_i - \mathbf{h}_j) \right] = \mathbf{M}_{motor} \qquad (3)$$

where
P: center of the grip point
p: position vector of P
L: force vector at P
M: moment vector at P
$\mathbf{M}_{motor}$: moment vector of the weight of the motors
$\mathbf{L}_{offset}$: force vector of the weight of the top triangle
$\mathbf{F}_i$: force vector at H_i
$\mathbf{h}_i$: position vector at H_i
$\mathbf{b}_i$: position vector at B_i

The formula (1) indicates the balance of force. The formula indicates the balance of moment. The formula (3) indicates that F_i is involved in the same plane as the pantograph link. The formula (1),(2), and (3) leads to nine dimensional simultaneous equation. The F_i are obtained by solving the equations by the Gaussian method. The weight of the motors and the top triangle are compensated(formula (1) and (3)). The user of the force display is free from the weight of the manipulator by this compensation.

The PC-9801 executes coordinate transformation for position detection of the hand and calculation of actuator torque for reaction force/torque generation. Computational time of these process is 13 msec. Update rate of the force display is 50Hz. Each cycleincludes data communication between PC-9801 and IRIS Indigo2. The CPU of the PC-9801 is Cx486(20MHz) with Cx487 math co-processor.

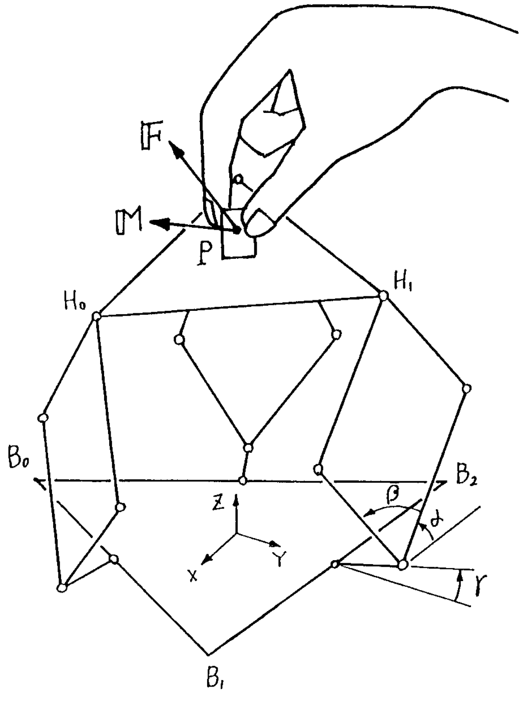

Figure 4. Mechanical configuration of the force display

(2) Graphic computer and HMD

Image of the virtual space is generated by a graphics work station IRIS Indigo2. The Extreme graphics engine provides real-time image of volume data. The graphics performance is 415K TriangleMesh Polygons/sec. The CPU of the Indigo2 is R4000, which manages volume data and its haptic representation. The image on the CRT of the Indigo2 is converted to NTSC standard video signal, and sent to the HMD. Two four-inches LCD(liquid crystal display) are mounted on the HMD, which presents stereoscopic image. Each LCD has 10,400 pixels. The effective field of view is 30 degrees.

The motion of the head is tracked by a 6 degree-of-freedom goniometer attached to the HMD. Scene of a virtual space is generated corresponding with the position and orientation of the head.

3. Methods of Haptization

Volume data consists of scalar or vector or tensor data found in a three-dimensional space. Data consists of single scalar values is the simplest case. Often multiple parameters occur at the same voxel, some of which are sets of scalar and vector. For example, data from computational fluid dynamics may consists of a scalar for density and vectors for velocity. Visualization of such multi-parameter data sets is a difficult problem. A combination of visualization techniques can be used, but there is a danger of the image becoming confusing.

We propose representation of volume data by force sensation. Our force display has an ability to apply 6 dimensional force and torque at the fingertips. Values at each voxel can be mapped to force and/or torque. Visual information has an advantage in presenting whole image of objects. On the other hand, haptic information has an advantage in presenting complex attributes of local region. In our system, visual image of volume data is represented by direct volume rendering using semi-transparent graphics. Figure 5 shows an example of visual image. A cross-line cursor indicates the position of the viewer's hand. This image is updated in 15Hz.

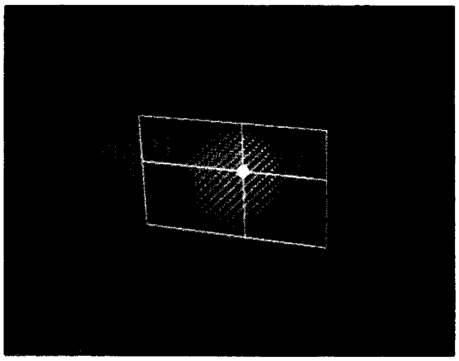

Figure 5. Visual image of voxel data

Methods of haptization can be classified to following three categories:

(1)Haptic representation of scalar data

There are two possibilities for mapping scalar data to force/torque. One is mapping scalar values to torque vector(formula (4)).

$$T_Z = a[S(x,y,z)] \qquad (4)$$

where S(x,y,z): a scalar value at each voxel
a : scaling factor

In this case, direction of these torque vectors are the same. The user's hand is twisted at each voxel. The other method is mapping gradient of scalar values to three dimensional force vectors(formula(5) and Figure 6).

$$\mathbf{F} = a[\,-\mathit{grad}\; S(x,y,z)] \qquad (5)$$

This formula converts the scalar field to a three dimensional potential field. The user's hand is pulled toward low potential area. This method magnifies transition area of density data. As for medical imaging such as ultrasound scanner, voxel data are classified according to density. Representation of gradient by force will be effective in such application.

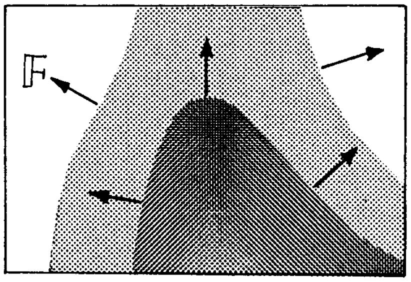

Figure 6. Haptic representation of density

(2)Haptic representation of vector/tensor data

Vector data has three components, so it can be directly mapped to force(formula (6)).

$$\mathbf{F} = a\mathbf{V}(x,y,z) \qquad (6)$$

where V(x,y,z): vector data at each voxel

Tensor data is given by matrix which has 9 components. These components cannot be directly mapped to haptic channel. Some components must be selected according to the user's interest(formula (7)).

$$\mathbf{F} \text{ or } \mathbf{T} = a\,(T_{ij}, T_{kl}, T_{mn}) \qquad (7)$$

where T_{ij} : selected component of tensor data at each voxel

In case of data from computational fluid dynamics, velocity is mapped to force and one component of vorticity is mapped to torque whose axis has the same direction as the velocity vector(Figure 7). Velocity and vorticity are simultaneously represented by force display.

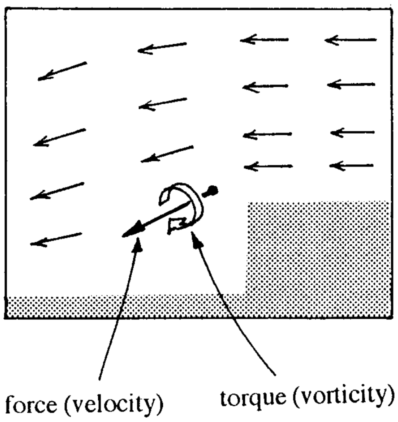

Figure 7. Haptic representation of flow field

(3)Haptic representation of multi-parameter data sets

Multi-parameter data sets which consists of one or more scalars and vectors can be mapped to force and torque. For example, velocity is mapped to force and density is mapped to one component of torque(formula(8) and (9)).

$$F = aV(x,y,z) \qquad (8)$$

$$T_Z = b[S(x,y,z)] \qquad (9)$$

Representation of multi-parameter data sets is rather difficult in selection of components of haptic channel. If two different data such as density and temperature are mapped to two components of torque, it may confuse the user. In such case, one scalar data may possibly represented by auditory channel.

4. Recognition Performance Test of Scalar Fields

4.1 Test Space

As a usability test of the volume haptization system, we examined recognition performance of a scalar field. Volume density data is selected as a scalar field. Subjects of this experiment are instructed to search high density areas. The test space includes several spherical high density areas. Distribution of each density data is determined by following function:

$$D_i(x,y,z) = D_{\max i}[\,1 - \exp[\,c_i(\,l - a_i\,)]\,]^{-1} \qquad (10)$$

where $D_i(x,y,z)$: density value of "i"th high density area at each voxel

$D_{\max i}$: density value at the central point

l: distance from the central point

a_i: radius of isosurface whose density value is $D_{\max i} / 2$

c_i: reduction factor

The shape of this function is indicated in Figure 8. The value "a_i" in the formula(10) determines width of high density area. The value "c_i" in the formula(10) determines gradient of density. High density areas are randomly located in the test space, some of which are overlapped. By this method, complex scalar fields are formed. The density value at each voxel D(x,y,z) is summation of all the density values given by the formula(10).

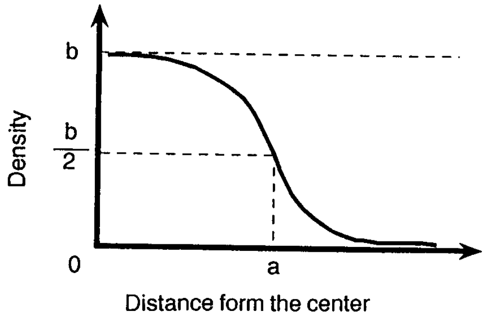

Figure 8. Distribution of density

$$D(x,y,z) = \sum_{i=1}^{N} D_i(x,y,z) \qquad (11)$$

The test space is a rectangular parallelepiped area whose dimension is 100(W) x 100(D) x 60(H) mm. We divide the space into cubes to generate volume data. The length of the side of each cube is 5mm. Total number of voxels is 20 x 20 x 12 = 4800. The force display can apply 700gf force and 7000gfcm torque at any voxel.

Visual information of the test space is given by direct volume visualization. Intensity of each voxel is determined by the density data. Figure 9 shows an example of visual information of the test space. The subjects see the image by HMD. They can see the space from arbitrary selected points of view.

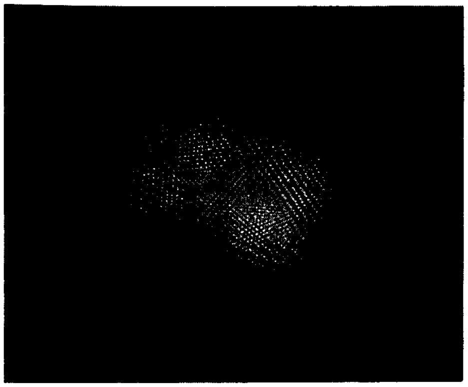

Figure 9. Test space of a scalar field

Haptic representation of the scalar field is implemented by following three methods:

(1) Density values are mapped to torque vectors as indicated in formula (12).

$$T_Z = a[D(x,y,z)] \qquad (12)$$

where a: scaling factor

The direction of these torque vectors are vertical. The user's hand is twisted at each voxel. The scaling factor "a" is set so that the maximum density value is represented by 7000gfcm torque. This method directly represents density values.

(2) Gradient of scalar values are mapped to three dimensional force vectors as indicated in formula(13).

$$\mathbf{F} = b[\, - \mathit{grad}\, D(x,y,z)] \qquad (13)$$

The user's hand is pulled toward low density area. The scaling factor "b" is set so that the maximum gradient value is represented by 700gf force. This method enhances transition area of density data.

(3) Both torque vector $\mathbf{T}_Z$ and force vector **F** are applied to the subjects. This method combines the advantages of the method (1) and (2).

4.2 Experiment

We set several small high density areas nested in a large high density area. The large one's parameters of the formula(10) are $a_i = 50$(mm), $b_i = 0.5$, and $c_i = 2.0$. Those of the small one's are $a_i = 15$(mm), $b_i = 0.5$, and $c_i = 2.0$. Figure 9 indicates four small high density areas in the large one. The number of the small high density area is randomly selected from 1 to 4. The minimum distance between the centers of those areas is 40mm. The subjects are instructed to count the number of high density areas and point the center of each area by the 3D cursor.

Four conditions are set for the experiment:
(1) haptic representation by force (**F**)
(2) haptic representation by torque (**T**)
(3) haptic representation by force and torque (**F** + **T**)
(4) without haptic representation, only visual (**V**)
Each condition contains 15 trials. When the subject point the center of the high density area, the position of the 3D cursor is recorded. Mean pointing error is calculated after all the trials are finished. Protocol data (verbal report during trials) of the subjects are also recorded.

We took three volunteer subjects from the students of our university. All subjects are novice users of the volume haptization system. They took practice before the trial.

4.3 Results

Figure 10 shows the result of the experiment. Horizontal axis indicates four conditions of the experiment. Mean pointing errors of three subjects are indicated by bar chart. The data includes error bars which indicates standard deviation. Average pointing errors of haptic representation (condition (1),(2), and (3)) are half as that of condition (4). The result shows that haptic feedback increases accuracy of recognition task of the scalar field.

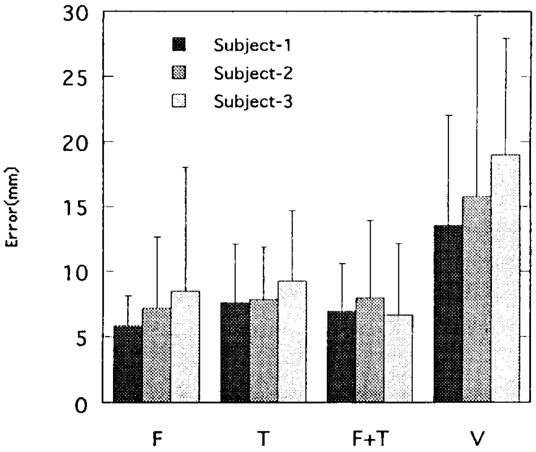

Figure 10. Pointing errors of scalar fields

4.4 Discussion

We cannot find significant difference among three conditions of haptic representation from the pointing errors. However, we can find qualitative differences from the protocol data. All the subjects reported that haptic representation by torque is most useful. They could feel boundaries of high density areas by haptic representation by force, but they often misunderstood whether the pointer is inside or outside the area. We expected that haptic representation by both force and torque is most useful. The subjects, however, reported that the torque applied in condition (3) is weaker than that in condition (1), and they executed the task mostly by force sensation.

5. Recognition Performance Test of Multi-parameter Data sets

5.1 Test Space

As a further usability test of the volume haptization system, we examined recognition performance of multi-parameter data sets. Two different data sets are set in the test space: parameter 1 is a scalar field and parameter 2 is a vector field. Volume density data as presented in formula (10) and (11) is selected as a scalar field. The vector field is determined by gradient of the scalar field as presented in formula (10) and (11).

Subjects of this experiment are instructed to search these two parameters. The test space includes six high density areas, which are closely overlapped each other.

The method of generation of volume data is the same as indicated in the section 4. Visual information of the test space is given by direct volume visualization. Intensity of each voxel is determined by the density data. The color of parameter 1 is green and that of parameter 2 is blue. Figure 11 shows an example of visual information of the test space. Haptic representation of these data sets are:

(1)Parameter 1 is mapped to torque as represented in formula (12)

(2)Parameter 2 is mapped to force as represented in formula (13)

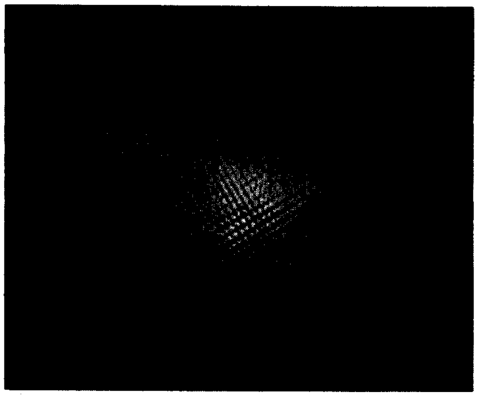

Figure 11. Test space of multi-parameter data sets

5.2 Experiment

We set six high density areas for the experiment. The parameters of the formula(10) are $a_i = 15$(mm), $b_i = 0.5$, and $c_i = 2.0$. The number of the areas which represent the parameter 1 is randomly selected from 2 to 4. The rests represent the parameter 2. The minimum distance between the centers of those areas is 20mm. The subjects are instructed to distinguish two parameters and point the center of those areas by the 3D cursor.

Two conditions are set for the experiment:

(1) haptic representation by force and torque (F + T)

(2) without haptic representation, only visual (V)

Each condition contains 5 trials. Overall number of the pointing tasks is 30. When the subject point the center of the high density area, the position of the 3D cursor is recorded. Mean pointing error is calculated after all the trials are finished. Protocol data of the subjects are also recorded.

We took four volunteer subjects from the students of our university. Three subjects are the same as previous experiment.

5.3 Results

Figure 12 shows the result of the experiment. Horizontal axis indicates two parameters for each condition. Mean pointing errors of the four subjects are indicated by bar chart. The data includes error bars which indicates standard deviation. Average pointing errors of the condition (1) is 7.6mm, and that of the condition (2) is 10.4mm. Standard deviation of pointing errors of the condition (1) is 3.9mm, and that of the condition (2) is 4.4mm. The result shows that haptic feedback increases accuracy of recognition task of scalar fields. In this experiment, the subjects sometimes mistook the

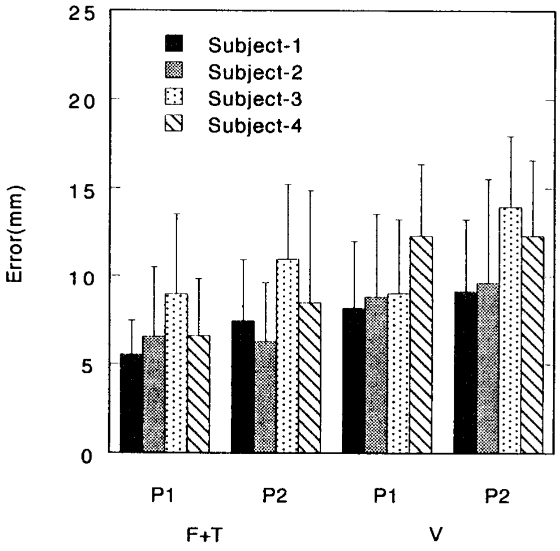

Figure 12. Pointing errors of multi-parameter data sets

pointing task. If the distance is over 18mm, visual and haptic cues are too weak to recognize. Therefore, we regarded pointing errors which exceed 18mm as mistakes. Those mistakes are excluded from the data as shown in Figure 12. Rate of mistakes of the condition (1) is 19%, and that of condition (2) is 35%.

5.4 Discussion

All the subjects reported that force and torque representation helped the task. However, closely overlapped six areas are hard to distinguish. The subjects seemed to need more practice. In case of visual representation only, the subjects changed the view point frequently. This action helped recognition of the test space.

6. Conclusion

This paper has shown the basic idea of haptic representation of volume data. We have developed an apparatus for volume haptization and performance of the system is examined by complex volume data. Future direction of this research are:

(1) There are wide variation in mapping voxel data to force and torque. Further studies on usability of those mapping method are strongly required.

(2) Experiments on cross influence between force and torque sensation are needed.

(3)Volume haptization will be effective in research field of fluid dynamics, solid dynamics, and medical simulation. Practical application on these areas are desired.

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