4+4 Fingers Haptic Display in the Mixed Reality Environment

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Abstract

A system with direct manipulation environment is proposed. A user is allowed to use both of his/her hands to manipulate virtual objects in the simulated virtual world. 3D graphical displays with 3D virtual hands represented the user's real hands in the virtual world showing the manipulation works in the virtual world to the user. The 3D virtual hands move corresponding to the behavior of the real hands.

We have developed a two-handed multi-fingers string-based haptic interface device. By using this device, force feedback can be displayed at the eight fingertips (4 fingers on each hand) of the user. Eight fingertip positions measured from the user's real hands are used in modeling 3D virtual hands. By computing the joint angles of the fingers, the virtual hands pose can be estimated.

In this paper, we have discussed about design policy of the system. Algorithms and computation are also given in detail. A manipulation of the virtual Rubik's cube is constructed and is given as an application of the proposed system.

Key words: String-based haptic interface device, 3D virtual hand, Direct manipulation

1. Introduction

With recent improvements of computer system, virtual reality (VR) system has shown high performance and abilities to simulate many kinds of task. The simulation can be for various kinds of purpose, such as training, education, working in the remote site or in the dangerous place, etc. An effective simulation requires natural interaction between human and the system in the same way as performing in real world. Conventional 2D computer input/output devices, such as 2D-mice or keyboards, are insufficient and difficult to perform the simulated VR tasks.

Consider human interactions in real world, many tasks involve the usage of our hand(s). For example, an interaction likes object manipulation by a hand, we perceive the sense of touch (haptic feedback) when grasping the object in our hand. This haptic feedback tells us the existence of the object, that why we can grasp it stably. The sight (visual feedback) of the object and our hand helps us to move the hand and reach for the object correctly and precisely. We can place our fingers at the right position on the object and watch the object being manipulated by hand as desire. Although, human being also uses some other sensory feedbacks when interacting with the environment, such as, audio, temperature, odor, etc., but haptic and visual feedbacks are two major information that human often uses intuitively for the interaction.

It is still difficult to integrate and to provide all of the sensory feedbacks that human used in real world on the current VR systems. At present, any VR system that can also be considered as an effective system, at least, it should be able to provide good quality of haptic and visual feedbacks and its user can perform the simulation task naturally in similar way as in the real world. Therefore, there are many research works are now working to achieve this goal.

In recent years, many input and output devices have been developed and proposed as hand haptic interface device. PHANToM[7] is a haptic interface devices widely used for VR simulation tasks. However, it is only single-point interface device in which user can directly use a finger or, indirectly, controls through its stylus pointer. We often see the combination of two PHANToM systems use in grasping a virtual object effectively. However, to employ PHANToM to every finger on user's hand is not an applicable way of implementation. The system will become too complex, bulky, and expensive. Next, the input device for a hand likes the DataGlove[6] can only measure positions on the user's hand but cannot display any force feedback. Also, some others hand haptic interface device, called Exoskeleton[2-5], requires complex structure to be installed on user's hand for position measurement and force generation. The complexity of the system and the weight of the device itself are its main drawbacks. Meanwhile, the string-based haptic interface device is simpler in structure and control, safe, and light-weighted. The SPIDAR[16-18] systems are successful examples of this type of device. However, the interference of string, either by part of user's body or among the other strings, is always cause problems to this type of device.

In this paper, we propose a system for human interaction with the virtual world. The system provides force feedback to the user by using string-based haptic interface device. At the same time, the system provides graphical display of virtual world with 3D virtual hands mirror the movement of the user's real hands. We consider many issues on construction of the proposed system to provide quality of haptic and visual feedbacks to the user.

2. Design policy of the proposed system

2.1 Two-handed multi-fingers string-based haptic interface device; SPIDAR-8

The proposed system is an improved version of SPIDAR[16-18]. The early systems use four strings attaching to a finger of the user, however, the proposed system uses only three strings. As shown in Fig. 1, three strings from each corner of the frame are connected together and to be attached to a fingertip of the user. By the structure of the rectangular frame, the system has eight interface points in which four points are to be attached to four fingers on the left hand and the other four points are to be attached to four fingers on the right hand. Therefore, a user can use both hands and multi fingers to interact with the virtual world. There is no string passing between both hands to reduce chance of the interference of strings. Since the proposed system allows a user to use eight fingers, we have named the system as SPIDAR-8[19-22].

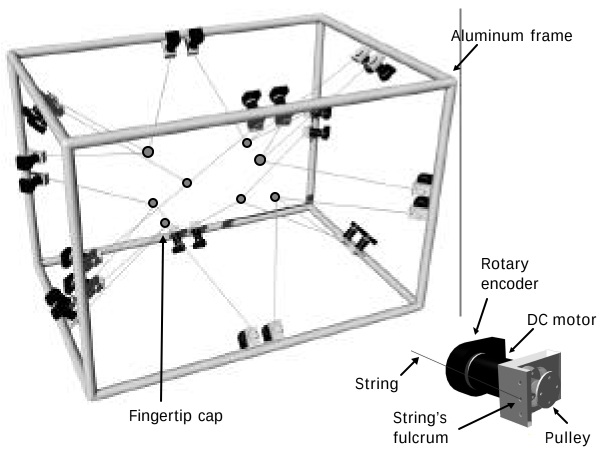


Fig. 1 SPIDAR-8

2.2 Two-handed multi-fingers string-based haptic interface device; SPIDAR-8

Because the user needs only to wear fingertip caps on his/her eight fingers when using the proposed system and only a small value of tension force (about 0.2N) is applied to straighten each string for the purpose of position measurement, the user can have full freedom of movement and the usage of hands to direct manipulate the virtual objects. Force feedback is displayed at the fingertips of the user by controlling the tension of the strings. Since there is no interface with the whole finger or palm of the user's hand, the system cannot display power-grasping-force by whole hand. However, with force feedback at fingertips, the dexterous object manipulation using fingertips can be effectively performed.

2.3 Two-handed multi-fingers string-based haptic interface device; SPIDAR-8

Vision is an important part of the interaction as it can increase the level of immersion. The proposed system models 3D virtual hands that mirror the movement of the user's real hands. Consider an example of grasping an object by a hand, the thumb is seen in front, the object is in the palm, and the other fingers are occluded behind the object. By displaying the virtual hands, it is possible to present such appearance with correct position and orientation of virtual thumb, fingers, and palm grasping the virtual object. That means the user using the proposed system can perceive the visual feedback in the same appearance of real hand grasping real object.

3. Overview of the proposed system

The processes of the whole system can be divided into 3 subsystems as shown in Fig. 2.

1. Haptic subsystem
2. Virtual world management subsystem
3. Visual subsystem

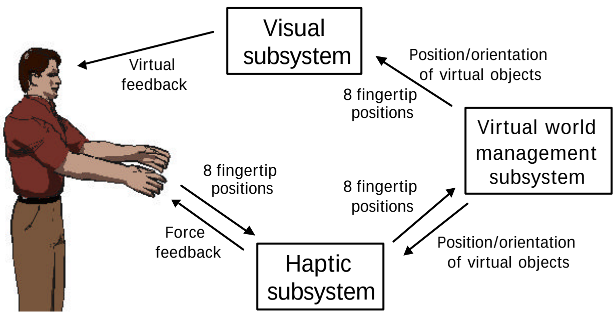


Fig. 2 Block diagram of the system

First, in the haptic subsystem, SPIDAR-8 is used to measure eight fingertip positions on the user's real hands. The fingertip positions with reference to the virtual world are calculated and sent to the virtual world management subsystem.

Next, the virtual world management subsystem is in charge of collision detection of positions of fingertips and the virtual objects. Force feedback value for each finger is calculated in this subsystem and sent back to haptic subsystem when the collision is occurred. The haptic subsystem controls tension of strings according to force feedback value for each finger and displays forces to user's fingertips. The motion of the virtual object in virtual world is the result of the collision forces acting on the object.

In the visual subsystem, 3D computer graphics of virtual world is rendered. The updated fingertip positions update the model and motion of the virtual hands. The motions of the virtual objects are updated by the updated position/orientation of the virtual objects. On the display screen, the user can see the virtual objects in the virtual world being manipulated according to the behavior of his/her real hands.

4. System implementation

4.1 Haptic subsystem

4.1.1 Position measurement

From the structure of frame of SPIDAR-8 and the attachment of three strings to one finger, the measurement and calculation of all fingertip positions can be performed in the same configuration. By measuring the length of three strings and substituting the corresponding positions of string's fulcrums, position of each fingertip can be calculated by the following computation.

Let $l_i (i = 1,2,3)$ is the length of each string measured from a fingertip position P to corresponding string's fulcrum $A_i (i = 1,2,3)$. The vectors $\vec{n}_1$ and $\vec{n}_2$ are unit vectors along the vectors $\overrightarrow{A_2 A_1}$ and $\overrightarrow{A_3 A_1}$ respectively. And $\vec{n}_3$, is the cross product of $\vec{n}_1$ and $\vec{n}_2$.

$$\vec{n}_1 = \frac{A_2 - A_1}{\|A_2 - A_1\|},\ \vec{n}_2 = \frac{A_3 - A_1}{\|A_3 - A_1\|},\ \vec{n}_3 = \vec{n}_1 \times \vec{n}_2$$

From the diagram shown in Fig. 3, the position of point P can be found by the following equation.

$$P = A_1 + \alpha_1 \vec{n}_1 + \alpha_2 \vec{n}_2 + \alpha_3 \vec{n}_3 \quad (1)$$

where the values of α_1, α_1, and α_1 can be derived from the following.

$$\alpha_1 = \frac{1}{\sin^2\Theta}\left(\frac{K_1}{d_1} - \cos\Theta \cdot \frac{K_2}{d_2}\right)$$

$$\alpha_2 = \frac{1}{\sin^2\Theta}\left(\frac{K_2}{d_2} - \cos\Theta \cdot \frac{K_1}{d_1}\right)$$

$$\alpha_3 = \sqrt{l_1^2 - \|\alpha_1 \vec{n}_1 + \alpha_2 \vec{n}_2\|^2}$$

and

$$\Theta = \cos^{-1}(\vec{n}_1 \cdot \vec{n}_2)$$

$$d_1 = \|A_2 - A_1\|,\ d_2 = \|A_3 - A_1\|$$

$$K_1 = \frac{1}{2}\left\{d_1^2 - (l_2^2 - l_1^2)\right\},\ K_2 = \frac{1}{2}\left\{d_2^2 - (l_3^2 - l_1^2)\right\}$$

4.1.2 Force feedback generation

SPIDAR-8 displays force feedback at the fingertips of the user by controlling the amount of electric current entering the DC motors. The tension force on each string, $t_i (i = 1,2,3)$, and the unit vector $\vec{u}_i (i = 1,2,3)$ are used to compose the resultant force vector as in the following equation.

$$\vec{f} = \sum_{1}^{3} t_i \vec{u}_i \quad (2)$$

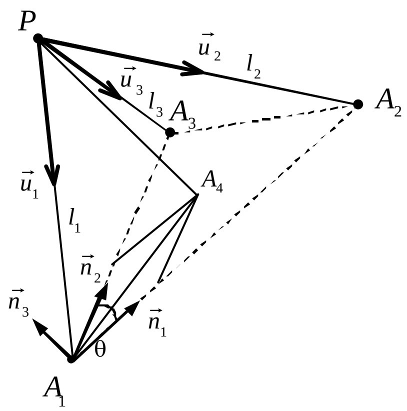


Fig. 3 Position measurement and force generation

where

$$\vec{u}_i = \frac{A_i - P}{\|A_i - P\|}$$

The connection of three strings from three fulcrums to a point is forming a triangle cone of force display for each finger. Force feedback can be displayed correctly in the case that the resultant force vector lies inside the force cone. However, in the case that the resultant force vector is outside the force cone, the projection of the force vector back to the force cone is computed and the resultant force vector is recomposed. By this way, SPIDAR-8 can display appropriated force feedback to the user using tension of string(s).

4.2 Virtual world management subsystem

4.2.1 Collision detection

A virtual object is defined by its dimension and position in the virtual world. If Q is a point on the plane of virtual object, and $\vec{N}$ is a normal vector pointing inside the virtual object, then the collision of fingertip position P can be detected by examining the sign of $(P - Q) \cdot \vec{N}$.

$$(P - Q) \cdot \vec{N} \begin{cases} > 0; & P \text{ is inside} \\ < 0; & P \text{ is outside} \\ = 0; & P \text{ is in contact} \end{cases} \quad (3)$$

4.2.2 Force and motion of object

A repulsive force, f, is generated using the conventional penalty-based method in which the amount of force is in proportional to the amount of penetration, d, into the virtual object (k=force constant).

$$f = kd \quad (4)$$

The motion of the virtual object is computed by using fundamental Newton's law of motion.

$$m \frac{dv}{dt} = f \quad (5)$$

$$I \frac{d\omega}{dt} = (p - r) \times f \quad (6)$$

where

m : mass of the object

v : velocity of the object at center of gravity

f : force acts on the object

I : inertia tensor matrix

ω : angular velocity of the object

p : position where f acts on

r : center of gravity of object

4.3 Visual subsystem

In the previous system [20], SPIDAR-8 attached strings to three fingertips and a position on the wrist for each hand of the user as shown in Fig. 4. These measured positions are used to model a virtual hand. In that case, the user can use only three fingertips on each hand for virtual objects manipulation with force feedback sensation. There is no force feedback generated at the wrist position. In the present system, strings are attached to four fingertips and the system allows the user to use four fingertips in the manipulation and perceive force feedback. The strings are attached to the Thumb, index finger, middle finger, and ring finger on each hand of the users (see Fig. 4). With four fingers, the ability to manipulate the virtual object is obviously increased. The user can grasp the virtual objects naturally, more stable, and less finger's fatigue compared to using three fingers. Moreover, the user can even rotate a virtual object grasped in a hand by using four fingers. It is almost impossible to perform such manipulation by only three fingers. Position and orientation of the virtual hand (6 DOF) is now assigned to be the parameters of the model of a virtual hand (17 DOF). It can be computed and used to estimate virtual hand pose from four fingertip positions. Detail of virtual hand pose is described in the following sections.

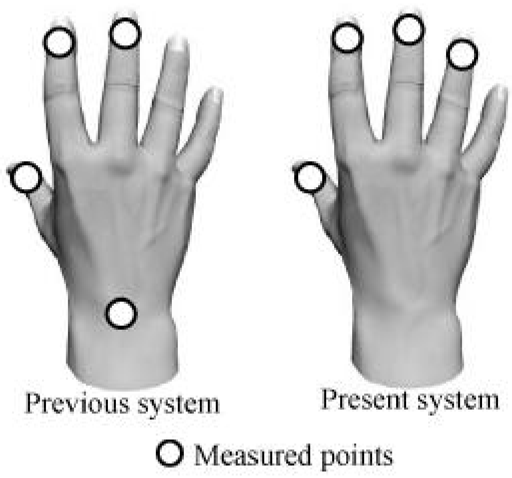


Fig. 4 Measured points

4.3.1 Model of human hand

Joint motion of all fingers defines the number of degree of freedom (DOF) on a hand. Each finger has 4 DOF, two at the connection with the palm and one at the end of first finger part and one at the second finger part. Figure 5 shows simple structure of a hand and DOF on each of the joint. 20 DOF of all finger joints and 6 DOF of translation and rotation of hand measured at the wrist make one human hand a 26 DOF manipulator.

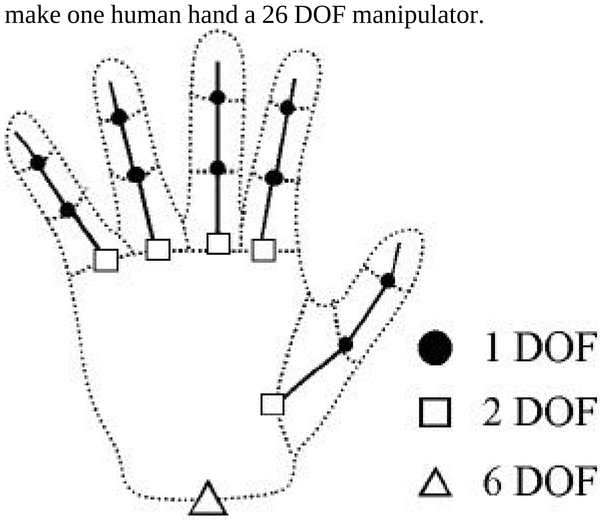


Fig. 5 Model of hand

4.3.2 Simplified model of virtual hand

Since SPIDAR-8 can measure four fingertip positions in 3D space, which is equivalent 12 DOF, we have found that it is too difficult to model a hand of 26 DOF by using only 12 known values. Thus, we have set up the criterions to reduce the number of DOF of the real hand for the virtual hand.

Criterions for reducing the number of DOF are as follows.

1. SPIDAR-8 does not measure position of little finger. Joint motion of each finger part of little finger is assigned to be the same as the corresponding part of ring finger.

2. A human finger has the property that it is impossible to move the joint closest to the fingertip without moving the next closest to the fingertip joint and vice-versa. Therefore, there is a dependency between these two joints, which causes by the same tendon used for moving inside the finger.

After measuring several times of these two joint angles as shown in Fig. 7, we found that it is reasonably approximated the dependency by a second-degree polynomial equation as shown in Eq. 7.

$$\Theta_2 = 1.1341\Theta_1^2 - 0.286\Theta_1 \quad (7)$$

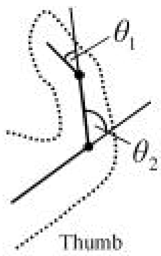


Fig. 6 Joint angles on thumb

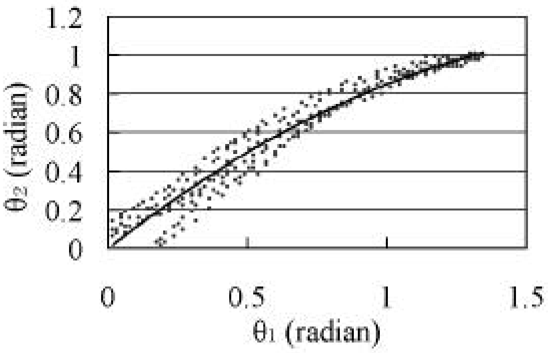


Fig. 7 Joint angle

3. The middle finger does not move side by side in most cases of grasping the object without forcing the finger to move in unnatural way. The joint motion at the connection of finger part and the palm of the middle finger can be reduced to 1 DOF.

Finally, the simplified model of a virtual hand after applied the above criterions has the number of DOF reduced to 17 DOF.

4.3.3 Virtual hand pose estimation

Forward kinematics is used to calculate joint angles of the fingers. To estimate virtual hand pose by placing the fingertips at the locations in the next update, inverse kinematics is required.

The algorithm for virtual hand pose estimation consists of the following steps.

Step 1. Retrieve fingertip position of thumb, index finger, middle finger, and ring finger sent by the virtual world management subsystem.

Step 2. Find the difference of the fingertip positions retrieved from Step 1 and the current fingertip positions of the virtual hand.

Step 3. If there is no difference, no hand pose estimation is performed. The process is finished and left the algorithm, otherwise, is preceded to the next step.

Step 4. Reduce the differences of fingertip positions by revising the model parameter of the virtual hand.

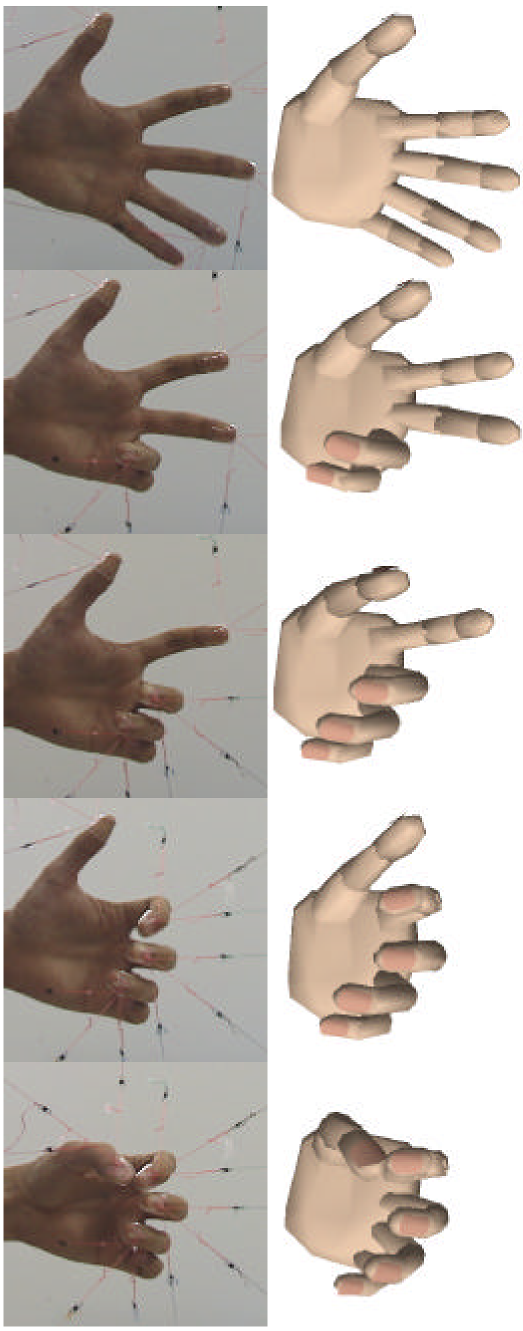
Step 5. Repeat the process from Step 2 again.

The process in the Step 4 of above algorithm, which is used for estimating hand pose, can be described in detail as follows.

Fingertip positions are expressed as matrix P and the model parameters (17 DOF) of the virtual hand are expressed as matrix Θ as shown in Eq. 8 and 9 respectively.

$$P = (p_1, \ldots, p_{12})^t \quad (8)$$

$$\Theta = (\theta_1, \ldots, \theta_{17})^t \quad (9)$$



(a) (b)

Fig. 8 Results of hand pose estimation (a) real hand of user, (b) virtual hand

Fingertip positions can be expressed as a function of model parameters.

$$P = f(\Theta) \qquad (10)$$

Substitute the function of model parameter by jacobian and the change quantity of fingertip positions can be derived from the change quantity of model parameters as shown in Eq. 11.

$$dP = J(\Theta)\, d\Theta \qquad (11)$$

The pseudo-inverse matrix of jacobian $J(\Theta)^{+}$ is computed and the change quantity of model parameter can be found as in Eq. 12

$$d\Theta = J(\Theta)^{+} dP \qquad (12)$$

where, the pseudo-inverse matrix of jacobian is shown as Eq. 13.

$$J(\Theta)^{+} = (J(\Theta)^{t} J(\Theta))^{-1} J(\Theta)^{t} \qquad (13)$$

Results of virtual hand pose estimation can be shown in Fig. 8. The left hand side column shows images of user's real hand in different postures and the right hand side column shows the virtual hand in the corresponding posture.

5. The constructed system and its application

5.1 Configuration

The configuration of the proposed system is shown as in Fig. 9. Frame of SPIDAR-8 is 80cmX60cmX60cm in dimension. The working space of both hands of the user is equivalent to the space enclosed by the frame. A user stands in front of SPIDAR-8 and forwards both of his/her hands to the center of the frame, where the virtual objects to be manipulated are located. An 18-inch LCD display is installed on top of the frame and is away from the user by the distance of 50cm. The 3D Computer graphics scene of the manipulation task is rendered and displayed to the user on the display.

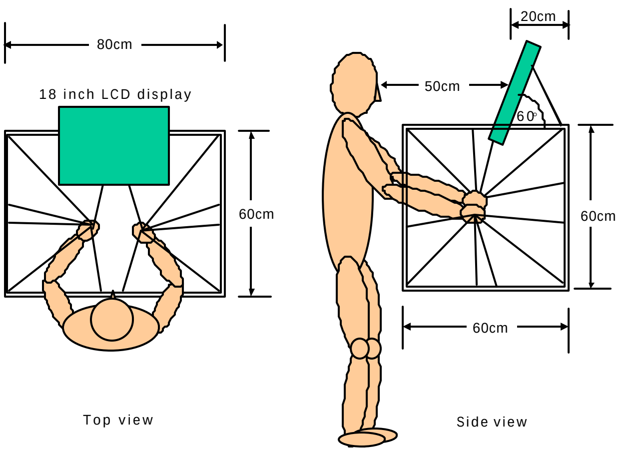


Fig. 9 System configuration

5.2 Application

The manipulation of a virtual Rubik's cube is selected as an application of the proposed system. Virtual Rubik's cube is a 2x2x2 cell, which its column-cell and row-cell can be rotated in the same way as the real Rubik's cube. The manipulation of the virtual Rubik's cube can clearly show the abilities of the system. Grasping or rotating cells of the cube is considered as a dexterous manipulation task using multi fingers. The rotation of two adjacent column-cells or row-cells requires both hands to perform in a cooperative way, in which one hand must grasp on one column-cell or row-cell and another hand grasps on the opposite column or row and rotates each hand in the opposite direction. If the cube is grasped by either left or right hand, the whole cube is rotated according to that hand's rotation. As shown in Fig. 10, a user is manipulating the virtual Rubik's cube by his real hands and, on the screen, the manipulation as a snapshot shown in Fig. 11 is presented.

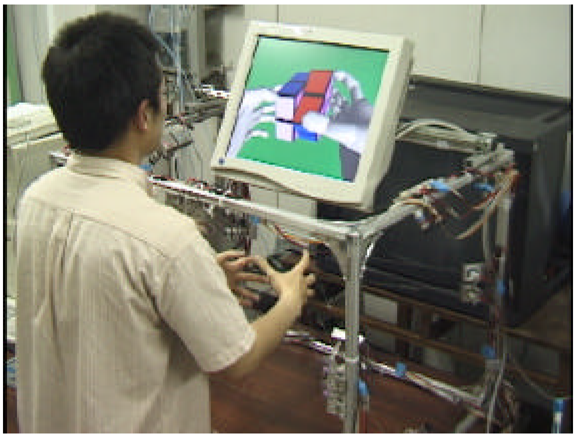


Fig. 10 A user is using SPIDAR-8 manipulate virtual Rubik's cube

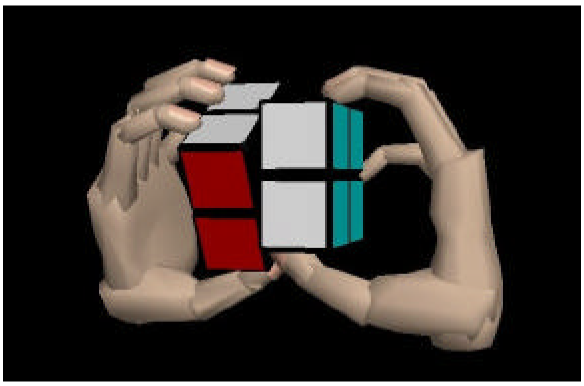


Fig. 11 Snapshot of virtual Rubik's cube manipulation

6. Conclusion and future works

A system with direct manipulation environment for the interaction with the virtual world is proposed. In the constructed environment, a user can perceive force and visual feedback, which allows he/she to manipulate the virtual objects in the same way as performing in the real world. We had developed a two-handed multi-fingers string-based haptic interface device named SPIDAR-8. By using our haptic interface device, a user can perceive force feedback at eight fingertips when manipulating the virtual objects. The system displays 3D virtual hands representing real hands of the user in the virtual world. Using eight fingertip positions, 3D virtual hands are modeled and joint angle of the fingers are computed. Then, virtual hands pose can be estimated by the joint angles of the fingers. 3D virtual hands move naturally according to the movement of the user's real hands.

There are some future issues of this work to be further investigated.

1.The implementation of visual feedback using stereoscopic vision system.

In the present work, visual feedback is displayed on 2D computer screen in which the user has complained about the difficulty in perceiving of the depth, for example, when he is trying to grasp the virtual object, it is difficult to locate the fingers at the back of the object. The stereoscopic may be a solution as the 3D scene with depth can be seen. However, the coupling of haptic and stereopsis on depth perception[23] is still unclear and must be carefully considered.

2.The implementation of a mixed reality system.

Instead of displaying 3D virtual hands, the images of real hands of the user are merged into the virtual world. VDO camera is used to take image of user's real hands. Real-time images of hands combine with computer generated 3D virtual world by the technique of chroma-keying. This work is now under the implementation.

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