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Haptic Display for Object Grasping and Manipulating in Virtual Environment

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Abstract

A haptic display for grasping and manipulating virtual objects in a CAD environment is investigated for the development of rapid prototyping technology. The operator receives the sensation of contacting and tracing of the surface of the virtual object, and of grasping and manipulating the object from the haptic display. After the control of the haptic display is formulated, it is implemented on the Sarcos Dexterous Arm Master. The proposed haptic display is experimentally confirmed to provide realistic sensation that enables the operator to grasp and manipulate the virtual object easily as intended.

1. Introduction

In this paper, a haptic display is presented for grasping and manipulating of virtual objects designed in an advanced CAD modeling system, Utah's *Alpha_1* [4]. The final goal of this research is a realization of realistic haptic sensations for interactive rapid prototyping in a virtual CAD environment. The hope is to reduce the duration of the cyclic iteration of design, evaluation and modification of prototypes. A fundamental task is considered of grasping of a virtual object by two fingers, manipulating it to a desired position and orientation and releasing the object at a new location.

In order to apply the sensation of grasping and manipulating the virtual object to the operator, the haptic display device should provide force-controllable degrees of freedom at the arm and hand as well as large workspace where the object is manipulated. Additionally, both of the following two forces, namely, the external force and the internal force need to be generated:

External force
The net force-moment applied to the operator that does not cancel in the operator's body. This force is caused by an object's gravity load, inertia, contact with the environment, and so on.

Internal force
The force applied at the fingers that cancels together in operator's body. This force is caused by squeezing the object by the fingers.

However, in reviewing conventional haptic display devices, they do not satisfy the requirements described above. Namely, a conventional haptic display device does not provide a large workspace [7] for manipulation or is capable of generating only one of the external force [1][3][5] or the internal force [2].

For this problem, the authors employed the Sarcos Dexterous Arm Master shown in Fig. 1 as the haptic interface. The master arm provides seven joints at the arm, one at the index finger and two at the thumb. The operator grabs the hand rest at the wrist and inserts the index finger and thumb into the finger attachment while interacting with the master arm. Since the joints of the master arm are capable of force control, it is possible to apply specified forces at the wrist, index and thumb of the operator.

2. Fundamental formulae for virtual grasping and manipulating

In the proposed haptic display, the following assumptions are made for providing the sensation of grasping and manipulating to the operator by the master arm:

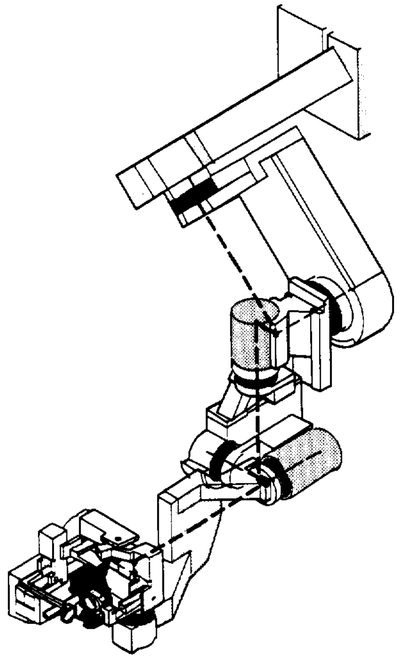


Fig. 1 Sarcos Master Dexterous Arm.

1. Only two points, at the tips of the index finger and the thumb of the master arm, interact with the virtual object.
2. The object is fixed in the absolute coordinate system when it is not grasped by the master arm.
3. When only one fingertip makes contact on the object, the contact is frictionless.
4. When an object is grasped by two fingers, each fingertip sticks on the object surface without slip.
5. Although the object is grasped only by two fingers, its rotation around the axis that connects two fingertips is constrained.
6. While manipulating the object, its dynamics due to inertia is omitted.

As a preparation for the formulation, two coordinate systems, namely the absolute coordinate system o^a-$x^a y^a z^a$ and the object coordinate system o^o-$x^o y^o z^o$ fixed on the object, are defined as shown in Fig. 2. The superscripts a and o represent the parameters described in the absolute and object coordinate systems, respectively. Also the subscripts i, t, w and o represent the parameters for index, thumb, wrist and object, respectively.

The positions of the tip of the index finger, the tip of the thumb and the wrist of the master arm are represented in the absolute coordinate system by the vectors $\boldsymbol{x}_i^a$, $\boldsymbol{x}_t^a$, $\boldsymbol{x}_w^a \in \Re^3$, respectively. The object position is located by the vector $\boldsymbol{x}_o^a \in \Re^3$ to the origin of the object coordinate system o^o. The object orientation is represented by vector $\xi_o^a \in \Re^3$, which consists of roll, pitch and yaw (RPY) angles of the object coordinate system relative to the absolute coordinate system. The orientation of the wrist of the master arm is represented by RPY angles $\xi_w^a \in \Re^3$ relative to the absolute coordinate system.

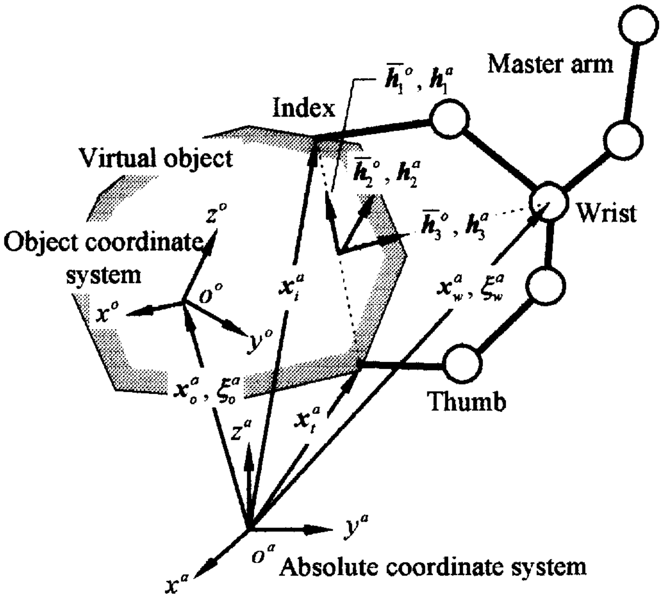


Fig. 2 Coordinate system describing the position, orientation of master arm and object.

The rotation matrix $\boldsymbol{R}(\xi_o^a) \in \Re^{3\times 3}$ that converts the vector described in the absolute coordinate system to the corresponding vector described in the object coordinate system is defined as follows:

$$\boldsymbol{R}(\xi_o^a) = \begin{bmatrix} c_y c_z & c_x s_z + s_x s_y c_z & s_x s_z - c_x s_y c_z \\ -c_y s_z & c_x c_z - s_x s_y s_z & s_x c_z + c_x s_y s_z \\ s_y & -s_x c_y & c_x c_y \end{bmatrix} \tag{1}$$

where,

$$\xi_o^a = \begin{bmatrix} \xi_{o\,x}^a & \xi_{o\,y}^a & \xi_{o\,z}^a \end{bmatrix}^T$$

$$c_x = \cos\xi_{o\,x}^a, \quad c_y = \cos\xi_{o\,y}^a, \quad c_z = \cos\xi_{o\,z}^a$$

$$s_x = \sin\xi_{o\,x}^a, \quad s_y = \sin\xi_{o\,y}^a, \quad s_z = \sin\xi_{o\,z}^a$$

Consequently, the positions of the tip of the index finger and of the thumb $\boldsymbol{x}_i^o$, $\boldsymbol{x}_t^o \in \Re^3$ in the object coordinate system are described as:

$$\boldsymbol{x}_i^o = \boldsymbol{R}(\xi_o^a)\left(\boldsymbol{x}_i^a - \boldsymbol{x}_o^a\right) \tag{2}$$

$$\boldsymbol{x}_t^o = \boldsymbol{R}(\xi_o^a)\left(\boldsymbol{x}_t^a - \boldsymbol{x}_o^a\right) \tag{3}$$

When a fingertip of the master arm collides with the virtual object, the penetration of the fingertip into the object is calculated. The penetration is the minimum distance between the fingertip and the object surface. Therefore, the penetration is directed toward the surface normal of the object.

For the index finger and thumb, the penetrations of the fingertips into the object in object coordinate system $\boldsymbol{p}_i^o$, $\boldsymbol{p}_t^o \in \Re^3$ are determined from the fingertip position $\boldsymbol{x}_i^o$, $\boldsymbol{x}_t^o$ relative to the object coordinate system by the function P_o that is defined based on the geometry of the object surface as:

$$\boldsymbol{p}_i^o = P_o(\boldsymbol{x}_i^o) \tag{4}$$

$$\boldsymbol{p}_t^o = P_o(\boldsymbol{x}_t^o) \tag{5}$$

The penetration vector of the index finger and thumb relative to the object coordinate system is converted to that in the absolute coordinate system $\boldsymbol{p}_i^a$, $\boldsymbol{p}_t^a \in \Re^3$ by rotational transformation between coordinate systems as:

$$\boldsymbol{p}_i^a = \boldsymbol{R}^{-1}(\xi_o^a)\boldsymbol{p}_i^o \tag{6}$$

$$\boldsymbol{p}_t^a = \boldsymbol{R}^{-1}(\xi_o^a)\boldsymbol{p}_t^o \tag{7}$$

3. Haptic display for object grasping and manipulating

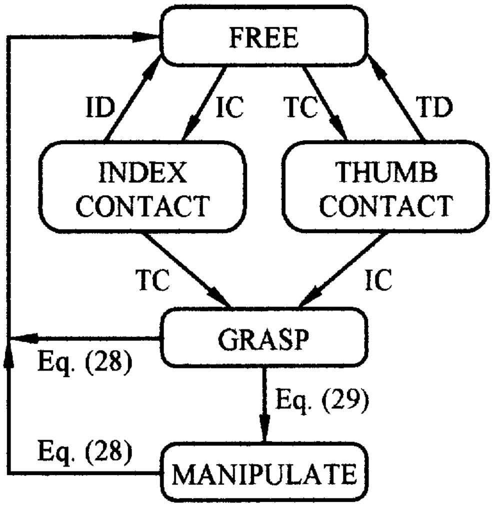
The state transition diagram of the haptic display is shown in Fig. 3. The control consists of five states, namely FREE, INDEX CONTACT, THUMB CONTACT, GRASP and MANIPULATE. In order to create a haptic sensation of object grasping and manipulating, the posture of the operator's hand and arm is measured from the joint angles of the master arm. The joint torque is controlled according to the current state and the geometric relation between the master arm and virtual object as described next.

FREE state

In this state, no interaction exists between the operator and the object. When the tips of both the index finger and the thumb of the master arm are positioned outside the virtual object, the control is in the FREE state. No force or moment is applied to the operator while controlling the joint torques of the master arm $\tau^j \in \Re^N$ (N: Number of joints) to only counteract the gravity loading on the master arm:

$$\tau^j = \tau_g^j(\theta^j) \qquad (8)$$

where $\tau_g^j \in \Re^N$ is the joint torque for gravity compensation of the master arm which is determined from the joint position $\theta^j \in \Re^N$.



IC:	Index contact on object
ID:	Index detach from object
TC:	Thumb contact on object
TD:	Thumb detach from object
Eq. (28):	Fingertip separates
Eq. (29):	Reactive force counteracts the gravity

Fig. 3 State transition of the haptic display.

INDEX CONTACT, THUMB CONTACT state

In these states, the operator touches and traces the object surface with one fingertip while feeling frictionless contact. The object is still fixed in the absolute coordinate system. When the tip of the index finger moves into the internal region of the virtual object, the control transits from the FREE to the INDEX CONTACT state. Based on the contact model that contains nonlinear stiffness and damping [6], the contacting force at the index finger $f_i^a \in \Re^3$ that realizes the sensation of stable contact is exerted according to the penetration of the tip of the index finger p_i^a into the virtual object as follows:

$$f_i^a = -\left(K_c + B_c \frac{\mathrm{d}\left|p_i^a\right|}{\mathrm{d}t}\right)\sqrt{\left|p_i^a\right|}\,\frac{p_i^a}{\left|p_i^a\right|} \qquad (9)$$

where K_c is a constant specifying the nonlinear stiffness of the contact that the force is proportional to the square-root of the penetration. On the other hand, B_c is a constant for the nonlinear damping that the force is proportional to the product of the differentiation and the square-root of the penetration. Since the contacting force is exerted in the same direction of the penetration of the fingertip that is parallel to the surface normal of the virtual object, the operator senses frictionless contact while tracing the surface of the object with the index finger.

The contact force at the index finger is converted to the corresponding joint torque of the master arm τ^j by the Jacobian matrix $J_i \in \Re^{3\times N}$, which relates the deviation of the index fingertip position x_i^a and the joint position θ^j while appending the gravity compensation torque:

$$\tau^j = J_i^T f_i^a + \tau_g^j(\theta^j) \qquad (10)$$

$$J_i = \frac{\partial x_i^a}{\partial \theta^j} \qquad (11)$$

On the other hand, the state transits from FREE to THUMB CONTACT when the tip of the thumb moves into the internal region of the object. In the THUMB CONTACT state, as well in the INDEX CONTACT state, the contact force at the thumb is determined according to its penetration and converted into joint torque.

The control transits to the FREE state when the fingertip moves outside of the object.

GRASP state

In this state, both the index finger and the thumb stick on the virtual object without slip and grasp it. However, the object is constrained by virtual springs that suspend the object in the absolute coordinate system. When the other fingertip that is separated from the object at INDEX CONTACT or THUMB CONTACT state comes into the internal region of the virtual object, the control transits to the GRASP state. At the moment of transition to the GRASP state, the position of the index finger, thumb, and wrist, and the position and orientation of the object for the absolute coordinate system is preserved as $\bar{\mathbf{x}}_i^a$, $\bar{\mathbf{x}}_t^a$, $\bar{\mathbf{x}}_w^a$, $\bar{\mathbf{x}}_o^a$, $\bar{\xi}_o^a \in \Re^3$, respectively. Also, the following vectors $\bar{\mathbf{h}}_1^o$, $\bar{\mathbf{h}}_2^o$, $\bar{\mathbf{h}}_3^o \in \Re^3$ relative to the object coordinate system are calculated and preserved.

$$\bar{\mathbf{h}}_1^o = \mathbf{R}(\bar{\xi}_o^a)\frac{\bar{\mathbf{x}}_i^a - \bar{\mathbf{x}}_t^a}{\left|\bar{\mathbf{x}}_i^a - \bar{\mathbf{x}}_t^a\right|} \tag{12}$$

$$\bar{\mathbf{h}}_2^o = \frac{\bar{\mathbf{h}}_1^o \times \mathbf{R}(\bar{\xi}_o^a)\left(\bar{\mathbf{x}}_i^a - \bar{\mathbf{x}}_w^a\right)}{\left|\bar{\mathbf{h}}_1^o \times \mathbf{R}(\bar{\xi}_o^a)\left(\bar{\mathbf{x}}_i^a - \bar{\mathbf{x}}_w^a\right)\right|} \tag{13}$$

$$\bar{\mathbf{h}}_3^o = \bar{\mathbf{h}}_1^o \times \bar{\mathbf{h}}_2^o \qquad (\left|\bar{\mathbf{h}}_1^o\right| = \left|\bar{\mathbf{h}}_2^o\right| = \left|\bar{\mathbf{h}}_3^o\right| = 1) \tag{14}$$

As illustrated in Fig. 2, $\bar{\mathbf{h}}_1^o$, $\bar{\mathbf{h}}_2^o$ and $\bar{\mathbf{h}}_3^o$ are orthogonal to each other. Vector $\bar{\mathbf{h}}_1^o$ is aimed toward the tip of the index finger from that of the thumb. Vector $\bar{\mathbf{h}}_3^o$ is in the plane that contains the tip of the index finger, thumb and wrist.

Additionally, the position of the midpoint between the fingertips relative to the object coordinate system is preserved as $\bar{\mathbf{x}}_m^o \in \Re^3$:

$$\bar{\mathbf{x}}_m^o = \mathbf{R}(\bar{\xi}_o^a)\left(\frac{\bar{\mathbf{x}}_i^a + \bar{\mathbf{x}}_t^a}{2} - \bar{\mathbf{x}}_o^a\right) \tag{15}$$

While in the GRASP or MANIPULATE state, the position and orientation of the virtual object are determined according to the motion of the master arm so that $\bar{\mathbf{h}}_1^o$ to $\bar{\mathbf{h}}_3^o$ and $\bar{\mathbf{x}}_m^o$ is kept constant in the object coordinate system. As a result, the rotation of the object around $\bar{\mathbf{h}}_1^o$ is artificially constrained although the object is grasped by only two fingers.

After preserving the above parameters at the transition, the position and orientation of the virtual object are determined according to the configuration of the master arm while it is moved by the operator. At first, vectors $\mathbf{h}_1^a$, $\mathbf{h}_2^a$, $\mathbf{h}_3^a \in \Re^3$, which correspond to $\bar{\mathbf{h}}_1^o$ to $\bar{\mathbf{h}}_3^o$ but relative to the absolute coordinate system, are determined from the position of the tips of the index finger $\mathbf{x}_i^a$ and the thumb $\mathbf{x}_t^a$ and of the wrist $\mathbf{x}_w^a$ as:

$$\mathbf{h}_1^a = \frac{\mathbf{x}_i^a - \mathbf{x}_t^a}{\left|\mathbf{x}_i^a - \mathbf{x}_t^a\right|} \tag{16}$$

$$\mathbf{h}_2^a = \frac{\mathbf{h}_1^a \times \left(\mathbf{x}_i^a - \mathbf{x}_w^a\right)}{\left|\mathbf{h}_1^a \times \left(\mathbf{x}_i^a - \mathbf{x}_w^a\right)\right|} \tag{17}$$

$$\mathbf{h}_3^a = \mathbf{h}_1^a \times \mathbf{h}_2^a \qquad (\left|\mathbf{h}_1^a\right| = \left|\mathbf{h}_2^a\right| = \left|\mathbf{h}_3^a\right| = 1) \tag{18}$$

The constraint that vectors $\mathbf{h}_1^a$ to $\mathbf{h}_3^a$ should coincide with $\bar{\mathbf{h}}_1^o$ to $\bar{\mathbf{h}}_3^o$ in the object coordinate system is expressed as:

$$\mathbf{R}(\xi_o^a)\left[\mathbf{h}_1^a \quad \mathbf{h}_2^a \quad \mathbf{h}_3^a\right] = \left[\bar{\mathbf{h}}_1^o \quad \bar{\mathbf{h}}_2^o \quad \bar{\mathbf{h}}_3^o\right] \tag{19}$$

From this equation, the rotation matrix $\mathbf{R}(\xi_o^a)$ between the absolute and object coordinate systems is given as:

$$\mathbf{R}(\xi_o^a) = \left[\bar{\mathbf{h}}_1^o \quad \bar{\mathbf{h}}_2^o \quad \bar{\mathbf{h}}_3^o\right]\left[\mathbf{h}_1^a \quad \mathbf{h}_2^a \quad \mathbf{h}_3^a\right]^{-1} \tag{20}$$

Reviewing Eq. (1), the orientation of the object ξ_o^a is determined as follows, where R_{mn} represents the element of matrix $\mathbf{R}(\xi_o^a)$ at the m-th column and n-th row.

$$\xi_o^a = \begin{bmatrix} \operatorname{atan2}(-R_{32}, R_{33}) \\ \operatorname{atan2}\left(R_{31}, \dfrac{R_{11}}{\cos(\operatorname{atan2}(-R_{21}, R_{11}))}\right) \\ \operatorname{atan2}(-R_{21}, R_{11}) \end{bmatrix} \tag{21}$$

The object position $\mathbf{x}_o^a$ is determined from the position of the fingertips $\mathbf{x}_i^a$, $\mathbf{x}_t^a$, the object orientation ξ_o^a, and the position of the midpoint of the fingertips $\bar{\mathbf{x}}_m^o$ preserved at the transition to the GRASP state using Eq. (15):

$$\mathbf{x}_o^a = \frac{\mathbf{x}_i^a + \mathbf{x}_t^a}{2} - \mathbf{R}^{-1}(\xi_o^a)\bar{\mathbf{x}}_m^o \tag{22}$$

After determining the position and orientation of the object through this process, the force and moment that apply the sensation of grasping to the operator are determined.

Since the object is constrained by virtual springs, the reactive force and moment are exerted at the wrist of the master arm. The force and moment at the wrist $\mathbf{f}_w^a$, $\mathbf{m}_w^a \in \Re^3$ relative to the absolute coordinate system are made proportional to the translation and rotation of the object from the initial condition at the transition to the GRASP state:

$$\begin{bmatrix} \mathbf{f}_w^a \\ \mathbf{m}_w^a \end{bmatrix} = -\begin{bmatrix} K_{ox}\left(\mathbf{x}_o^a - \bar{\mathbf{x}}_o^a\right) \\ K_{o\xi}\left(\xi_o^a - \bar{\xi}_o^a\right) \end{bmatrix} \tag{23}$$

In above equation, K_{ox} and $K_{o\xi}$ specify the translational and rotational stiffnesses that constrain the object motion.

Besides the force and moment exerted at the wrist, a grasping force is exerted between the tips of the index finger and the thumb in order to provide the sensation of squeezing the object. As well as the contact force exerted at the INDEX CONTACT and THUMB CONTACT states, the grasping force f_g that consists of nonlinear stiffness and damping specified by K_g and B_g, respectively, is exerted according to the distance between the fingertips $|x_i^a - x_t^a|$ as:

$$f_g = \left(K_g - B_g \frac{\mathrm{d}|x_i^a - x_t^a|}{\mathrm{d}t} \right) \sqrt{|\bar{x}_i^a - \bar{x}_t^a| + d_h - |x_i^a - x_t^a|} \tag{24}$$

The grasping force that varies for quasi-static change of the distance between the fingertips is illustrated in Fig. 4. When the control transits to the GRASP state at A where the fingertip distance is $|\bar{x}_i^a - \bar{x}_t^a|$, the grasping force is immediately exerted (A→B). While in the GRASP state, the grasping force increases nonlinearly as the virtual object is squeezed (B→C). In case the object is going to be released, the grasping force decreases to zero as the fingertips separate (C→B→D→E). The control transits to the FREE state at D and the object is considered to be released. Due to the hysterisis of the grasp d_h (A-D), the control will not transit from FREE to GRASP state again until the operator squeezes the fingers to A. Therefore, undesired frequent transition between FREE and GRASP state are prevented.

Both the reactive force and moment at the wrist and the grasping force at the fingers are converted to corresponding joint torques by the Jacobian matrix $J_w \in \Re^{6 \times N}$ for the motion of the wrist and $J_g \in \Re^{1 \times N}$ for the distance between fingertips as:

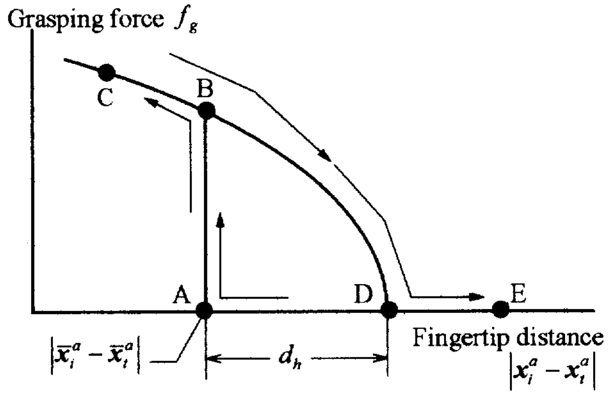


Fig. 4 Quasi-static change of grasping force.

$$\tau^j = J_w^T \begin{bmatrix} f_w^a \\ m_w^a \end{bmatrix} + J_g^T f_g + \tau_g^j(\theta^j) \tag{25}$$

$$J_w = \frac{\partial \begin{bmatrix} x_w^a \\ \xi_w^a \end{bmatrix}}{\partial \theta^j} \tag{26}$$

$$J_g = \frac{\partial |x_i^a - x_t^a|}{\partial \theta^j} \tag{27}$$

The GRASP state transits to the FREE state when the distance between the fingertips increases beyond the initial distance plus the hysterisis for grasping (D in Fig. 4) as:

$$|x_i^a - x_t^a| \geq |\bar{x}_i^a - \bar{x}_t^a| + d_h \tag{28}$$

In this case, the object returns to its initial position and orientation $\bar{x}_o^a$, $\bar{\xi}_o^a$ preserved at the transition to the GRASP state.

On the other hand, the GRASP state transits to the MANIPULATE state when the reactive force produced by the stiffness increases to counteract the gravity of the object as:

$$f_w^a \cdot g^a \leq -M_o |g^a|^2 \tag{29}$$

where $g^a \in \Re^3$, M_o represent the gravity acceleration relative to the absolute coordinate system and the mass of the virtual object, respectively. Since the gravity load of the object is applied to the operator in the MANIPULATE state as mentioned later, the vertical force applied to the operator varies continuously at the transition from GRASP to MANIPULATE states.

MANIPULATE state

In this state, the operator can freely manipulate the object without any constraint while sensing the gravity load of the virtual object. Instead of the reactive force-moment exerted by the stiffness in the GRASP state, the force-moment due to the gravity load of the object is exerted at the wrist as:

$$\begin{bmatrix} f_w^a \\ m_w^a \end{bmatrix} = \begin{bmatrix} M_o g^a \\ \left[x_o^a + R^{-1}(\xi_o^a) x_g^o - x_w^a \right] \times M_o g^a \end{bmatrix} \tag{30}$$

where $x_g^o \in \Re^3$ represents the position of the object's center of gravity relative to the object coordinate system. The inertia force-moment exerted by the object acceleration is currently omitted to simplify the control.

Similar to the GRASP state, the position and orientation of the object is determined according to the configuration of the master arm through the same process of Eqs. (16)

to (22). Also, the control transits to the FREE state and the object is located at a new position and orientation when the fingertips separate over the threshold in Eq. (28).

4. Implementation

The haptic display is implemented on the system shown in Fig. 5 consisting of the Sarcos Dexterous Arm Master, two single board computers (Motorola 68040 and PowerPC 604e) and an SGI graphics workstation. The single board computers hosted on a VME bus communicate together through shared memory.

The Sarcos Dexterous Arm Master has ten joints, each of which is equipped with a hydraulic actuator, a potentiometer for position sensor and load cell for torque sensor.

The Motorola 68040 manages the signal I/O and joint torque control of the master arm. The joint position and torque measured by sensors are acquired through 12 bit A/D converters. The acquired sensory data are written to the shared memory to be read by the PowerPC 604e. The desired joint torque is written to the shared memory by the PowerPC 604e, and the servo valves are controlled through 12 bit D/A converters so that the joint torque is set to the desired value.

The PowerPC 604e executes the main body of the haptic display. For both single board computers, the ControlShell (Real-Time Innovations, Inc.) object-oriented real-time software package that runs on VxWorks® (Wind River Systems, Inc.) real-time kernel and development environment is employed. The sampling rate of the control is 1920Hz.

The PowerPC 604e transmits the configuration of the master arm and the position and orientation of the virtual object to the SGI graphics workstation through the Myrinet local area network (Myricom, Inc.). On the workstation, the *Alpha_1* OPEN-GL viewer draws the solid model of the master arm and the object as the visual display to the operator. The transmission and refresh rate of the visual display is 32Hz, which is fast enough compared to the scanning rate of the CRT display.

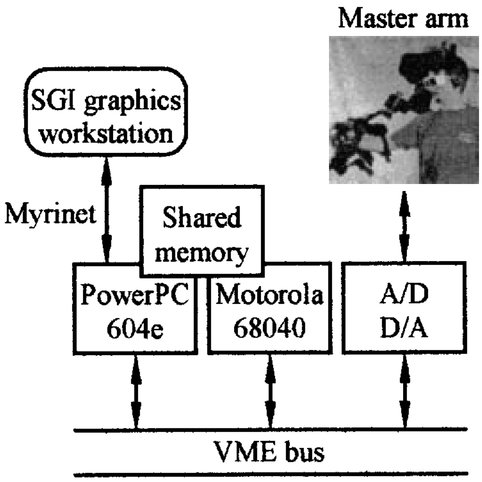


Fig. 5 Haptic-visual display system.

On the other hand, previously recorded sounds that correspond to each transition are replayed when the control transits to a new state. This audio feedback assists the operator for recognizing the state transition while touching, grasping and manipulating the virtual object.

5. Experimental results

A model of a cylinder (diameter: 0.1m, length: 0.4m, mass: 2kg) is created as the object in the virtual environment to be grasped and manipulated. The parameters for stiffness and damping for contacting and grasping is set as:

$$K_c = 130\mathrm{N/m}^{0.5}, \quad B_c = 100\mathrm{Ns/m}^{1.5}$$
$$K_g = 1000\mathrm{N/m}^{0.5}, \quad B_g = 800\mathrm{Ns/m}^{1.5}$$

In the FREE state shown in Fig. 6 (a), the operator can freely move the hand and arm while the gravity loading on the master arm is compensated until the tip of the index finger or the thumb collides with the virtual cylinder.

In the INDEX CONTACT state as in Fig. 6 (b) and the THUMB CONTACT state as in Fig. 6 (c), the operator feels the contact on the cylinder by one fingertip. The contact is stable without any undesired vibration since sufficient damping is provided. The operator can easily recognize the shape of the cylinder by tracing its surface while receiving the contact force at the fingertip.

The control transits to the GRASP state as shown in Fig. 6 (d) when the operator contacts the cylinder with the tips of both the index finger and the thumb. The steep increase of the grasping force at the transition (A→B in Fig. 4) applies significant sensation of grasp to the operator. The operator feels as if the cylinder is suspended by translational and rotational springs since the reactive force-moment is applied at the wrist. Also the operator receives the sensation of squeezing the cylinder since the grasping force is exerted at the fingers.

As the operator lifts the cylinder, the reaction force directed downward increases as the cylinder that is constrained by the stiffness moves upward. When the reaction force increases to counteract the gravity load of the cylinder, the control transits to the MANIPULATE state. This transition applies a natural sensation to the operator because the vertical force applied by the master arm varies continuously.

The operator can manipulate the cylinder freely in the MANIPULATE state as shown in Fig. 6 (e) while feeling both the gravity load of the cylinder at the wrist and the grasping force at the fingers. The operator can sense the position of the cylinder's center of gravity since the moment is determined according to it. As a result, when the operator grasps the eccentric part of the cylinder, it can be recognized and the eccentricity of the gravity load is sensed to vary while the operator rotates the grasped cylinder.

After the cylinder is manipulated to a desired position and orientation, the operator can place it there by releasing the hand as shown in Fig. 6 (f). As a whole, the operator receives a natural sensation of grasping and manipulating the cylinder easily as intended.

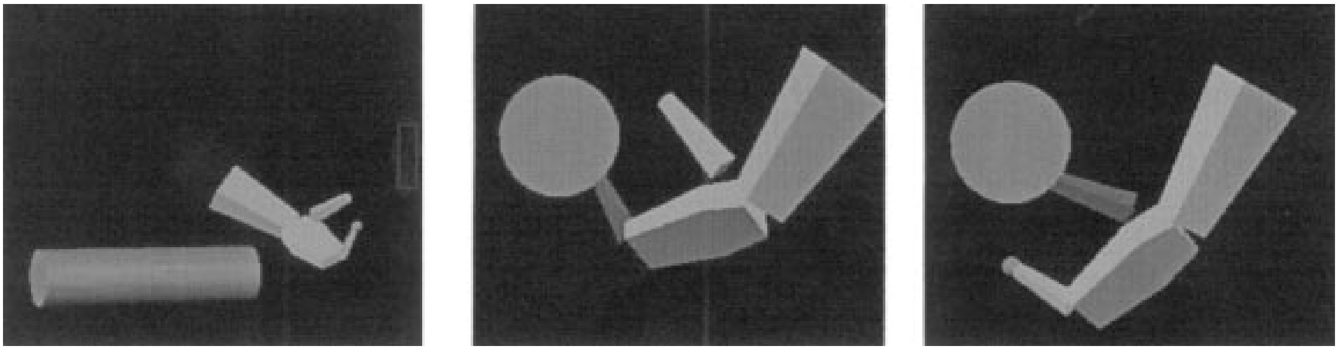
Although the sounds played for the audio feedback are not precisely synthesized based on the mechanical model of contacting, grasping and manipulating, it assists the operator for recognizing the state transition as well as the force feedback.

6. Conclusion

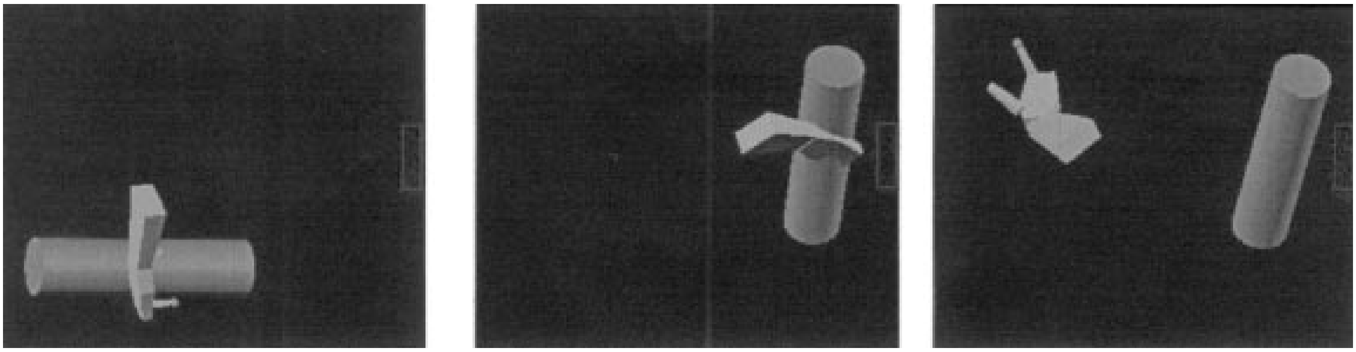
In this paper, a haptic display for object grasping and manipulating is proposed as a fundamental technique for rapid prototyping in a virtual environment. The haptic display is implemented on the Sarcos Dexterous Arm Master and experimentally confirmed to provide a realistic sensation of grasping and manipulating that enables the operator to manipulate the virtual object easily as desired.

Since the final aim of this research is a realization of haptic display in a CAD environment, it is important how realistic is the haptic sensation that the operator receives. Although such a quantitative evaluation from a psychological viewpoint is not discussed in this paper, it will be investigated in the future.

In addition to the virtual grasping and manipulating achieved here, more complicated tasks such as assembling multiple parts, checking the interference, confirming the motion of the mechanism and so on would be required for advanced rapid prototyping. The realization of a haptic display capable of providing the sensation of such tasks will be a next target.



(a) FREE state at the beginning. (b) INDEX CONTACT state. (c) THUMB CONTACT state.



(d) GRASP state. (e) MANIPULATE state. (f) FREE state at the end.

Fig. 6 Experimental grasping and manipulating of cylinder.

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