A Teddy-Bear-Based Robotic User Interface

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A robotic user interface (RUI) is part of a concept in which a robot is used as an interface for human behavior. Our RUI is a system for interpersonal exchange that uses robots as agents for physical communication. In this article we propose a new type of RUI for interactive entertainment. This RUI enables people to directly interact with the information world.

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General Terms: Design, Experimentation, Human Factors

Additional Key Words and Phrases: Robotic user interface, haptic feedback, entertainment, virtual reality

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1. INTRODUCTION

The concept of a graphical user interface (GUI) originated at Engelbart's NLS (On-Line Systems) [Engelbart and English 1968] and at Alan Key's Alto [Key 1977], and changed the way computers were used. GUIs simplified the use of computers and played an important role in their spread for public use. However, because GUIs are based on a combination of WIMP (window, icon, menu, pointing device), the interaction method used by GUIs is now recognized as limited when interacting with real- world situations.

NaviCam [Rekimoto 1997], Tangible Bits [Ishii and Ullmer. 1997], and ActiveCube [Watanabe et al. 2004.] are attempts to overcome the limitations of GUIs by using a physical object that exists in the real world as the interface. Many use a see-through head-mounted display (HMD) or a projector to output information to the user. Therefore, considering that direct interaction with any outputted information is still limited, we believe that an output method utilizing a real object remains to be established.

For example, industrial robots have chiefly been considered as machines that perform work in place of human beings. On the other hand, personal robots such as pet robots [Fujita and Kitano.1998] and interactive robots [Brooks et al. 2004.] are good examples of utilizing real objects. A robot can be regarded as a computer with a physical body that enables it to interact with the real world. Hence, if one considers the characteristics of

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their physical embodiment, robots can also be seen as interfaces for human beings. A robot used as an interface between the real and information worlds can be referred to as a robotic oser interface (RUI). We believe that the concept of an RUI will provide an efficient interface that has both input and output methods in real-world situations.

An RUI has three features.

- *Portable humanoid interface.* Humanoid robots have been developed to assist or communicate with people [Tachi et al. 1989; Brooks 1997; Yamaguchi et al. 1998; Hirai et al. 1998]. And so, for convenience, the size of a humanoid robot should be the size of a human being. To apply a humanoid robot as a user interface, we developed a portable humanoid robot. Operations on the robot, such as modifying its posture or changing its shape and motion, are input; while the shape or movements of the robot are output. Hence, the humanoid robot used for an RUI system needs a back-drive-torque that can be easily managed using a single hand. It can be said that a humanoid robot designed for use as a user interface is a new type of robot.

-*Intuitive interaction design.* There are two kinds of input methods when a person interacts with the information world. One is an indirect interaction, such as the operation of a computer-generated (CG) character using a joystick or a joy pad in fighting or role-playing games. The other is a direct interaction, such as EyeToy™ [Marks et al. 2001] that uses the person's body action. On the other hand, visual and auditory information are used mostly for output. Force feedback uses haptic information from the vibrations and resistance of a joystick in the entertainment field; but this is far from equaling the haptic information that we obtain in daily life.

With an RUI system, a user operates the humanoid robot with the shape and physicality of a virtual avatar in the information world. The RUI and an avatar are always synchronized. Hence, by operating the RUI a user can input the motion to an avatar and

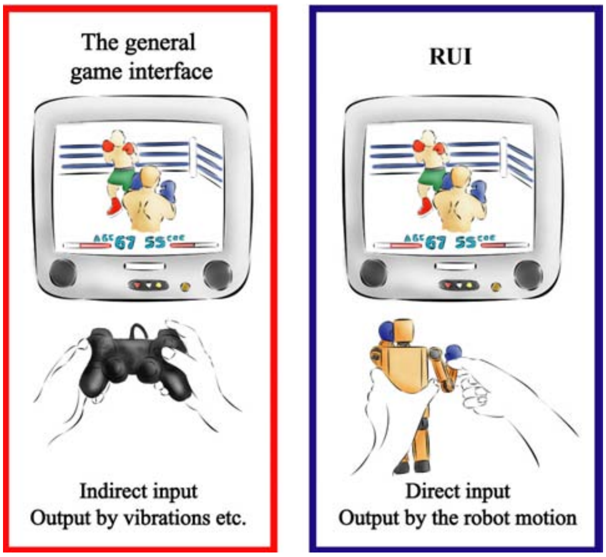

Figure 1. The general game interface and RUI.

obtain output information from the motion of the RUI. By using an RUI as an input-output device, a user can operate a humanoid robot intuitively via his or her own body image and obtain haptic, shape and visual information through the shape and motion of the RUI.

-*Humanoid robot for haptic display.* Various haptic displays have been developed [Tachi et al. 1994; Massie and Salisbury. 1994; Ishii and Sato 1994], most are attached to part of the user's body; however, it is still too difficult to provide haptic information to the entire body. The RUI is another approach for whole body haptic display. When a user interacts with an RUI system, the humanoid robot and the virtual avatar act as his/her avatar. This humanoid robot enables a metaphorical display of whole body haptic information through the avatar; that is to say, exo-centric haptics.

On the other hand, by using the user's body image without looking at the RUI, the user can only get the robot's shape information as the hand senses it through the RUI. However, by looking at the humanoid robot, the user gets shape and motion information of the avatar. Thus it can be said that the RUI is a haptic, shape, and motion display.

An RUI that uses a humanoid robot enables interactions in the physical world, the display of visual information by shape and motion of the RUI, and the input of information by changing the shape of the robot.

In this article we present a new type of haptic display that uses an RUI system and an application based on the physical model that is necessary in order to use the RUI as a haptic display in the entertainment field.

2. TEDDY-BEAR BASED ROBOTIC USER INTERFACE

Our teddy-bear based RUI is a new type of interface that has a physical body which enables the user to interact with the information world by using both hands to operate the RUI's hands or feet, etc. The respective interaction methods using a GUI or an RUI are explained. With a GUI, the operation of a mouse and a keyboard is the input, which results in a graphics input displayed as the output. With an RUI, the robot is used for the input and output, for example the operation of the portable humanoid robot is the input and the shape and motion of the robot is the output. Hence, a GUI uses the symbolic representation mainly composed of language and the operation of a symbol, whereas an RUI chiefly utilizes active and iconic representation that uses the body image acquired at an early stage of growth.

Consideration is given to an entertainment application for which GUIs or RUIs are suitable. As before, a GUI uses symbolic representation and is suitable for deskwork applications (e.g., users selecting a file in the desktop of a PC with a mouse, opening and

Table I. GUI and RUI

	GUI	**RUI**
Input	Mouse, Keyboard	Operating the robot
Output	Display	Motion and shape of the robot
Application	Desk Work	Entertainment
Metaphor	Desktop	Human Body

Figure 2. RobotPHONE.

writing sentences with a keyboard, etc.). An RUI chiefly uses enactive and iconic representation and the humanoid robot as an interface, so an RUI enables users to obtain intuitive input and to get haptic, shape, and visual information by operating the humanoid robot and synchronizing the CG character. Hence it is thought that an RUI is more suitable than a GUI for entertainment applications based on an avatar.

The following differences in an application of a boxing game are thought to exist between using a general game interface such as a joy pad and using an RUI. Using a game interface, users can make the CG character move, punch, and guard by pushing a button; hence users operate the character indirectly. The output to the user is a vibration of the interface. On the other hand, the RUI system utilizes a humanoid robot that has the same shape as the character in the game, and the robot is synchronized with the character. Users can make the CG character move, punch, and guard by operating the robot. Hence, by using the RUI, players operate the character directly. The output is not only the vibration of the robot but also the visual information such as the motion and shape of the robot.

Most games like fighting, role-playing, and action games are played with a user's avatar. The RUI can be used to play games based on the avatar as the input-output device for directly operating the avatar or assisting the interface. In addition, users can communicate and interact with each other by exchanging shape and motion through the RUI via a network, as in the Massively Multiplayer Online Role Playing Game (MMORPG) that enables thousands of players to play in a virtual world at the same time over the Internet.

The areas of difference between an RUI for haptic display and existing haptic displays follow:

- *As a method to display haptic information.* When users use existing haptic displays, haptic interfaces are attached to a part of the user’s body or the haptic interface is held in the user’s hand. In this case, the haptic interface displays haptic information to the user’s body directly. The RUI is another approach for haptic display. The RUI uses a humanoid robot that enables a metaphorical display of whole-ody haptic information. Hence, this RUI displays haptic information to the user indirectly.

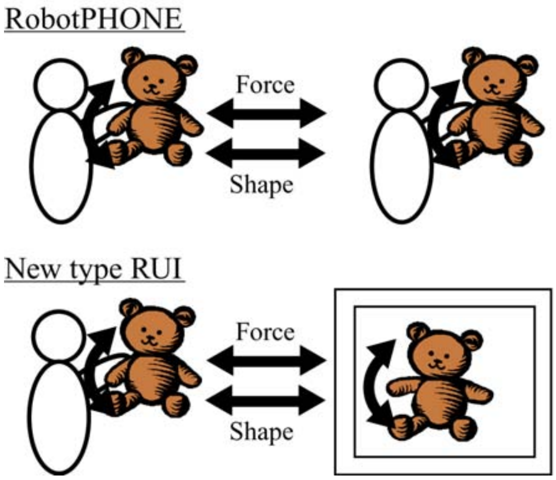

Figure 3. Shape-sharing of RUI

-*A method for interacting with the information world.* When using most existing haptic interfaces, a user interacts with the information world that has the same size as the real world. However, the CG model of the RUI exists in the information world and the user interacts with the information world through the RUI that exists in the real world

-*Applications for haptic display*. Existing haptic interfaces can be used for application programs that match the shape and direction of the interfaces. If the shape of the interface is a pen, the CG model of the pen exists in the information world and the user interacts through the pen. Using the RUI system, a CG model of the RUI that is the user's avatar exists in the information world and the RUI can use various tools. Hence, the RUI is an interface that has generality and can be used for various applications.

3. STRUCTURE OF THE RUI

We have been developing RobotPHONE [Sekiguchi et al. 2001] (Figure 2) as an RUI that can be used as a haptic-device. The RobotPHONE system employs robots that are called shape-sharing devices. Remote shape-sharing devices are always synchronized, so users of RobotPHONE can communicate and interact with each other by exchanging the robots' shapes and motions .We propose another type RUI that synchronizes shapes and motions between the RUI in the real world and a virtual avatar in the information world.

Users operate the RUI by holding it with both hands and interacting with the information world. As a requirement for its operation, this teddy bear-like robot has 2 degrees of freedom in each arm and 4 degrees of freedom overall. Each joint is composed of a servomotor that consists of a potentiometer for measuring the joint angle and a DC motor for moving the joint. All DC motors are controlled by a one-chip microcontroller. A pulse width modulation (PWM) and a full-bridge driver IC drive the DC motors. The motor of each joint is driven using the value of a potentiometer in order to shape-share and get force feedback from the virtual world.

Users can operate the RUI and obtain haptic, shape, and visual information via touching the RUI or by seeing the RUI's shape and motion changes. We chose a servo-

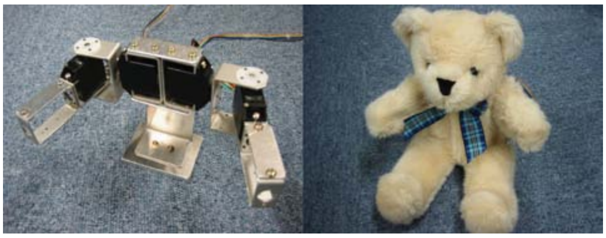

Figure 4. Teddy bear based RUI.

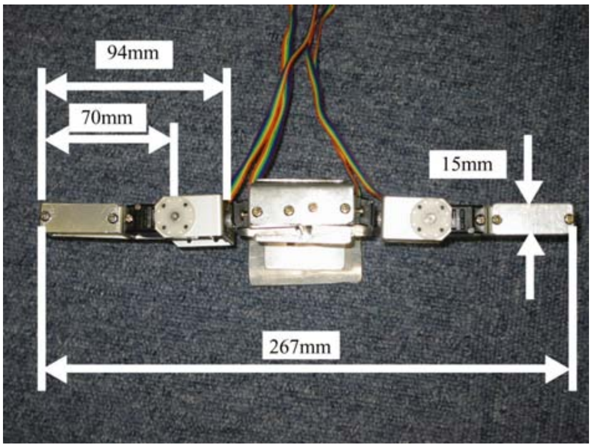

Figure 5. The size of RUI (top view)

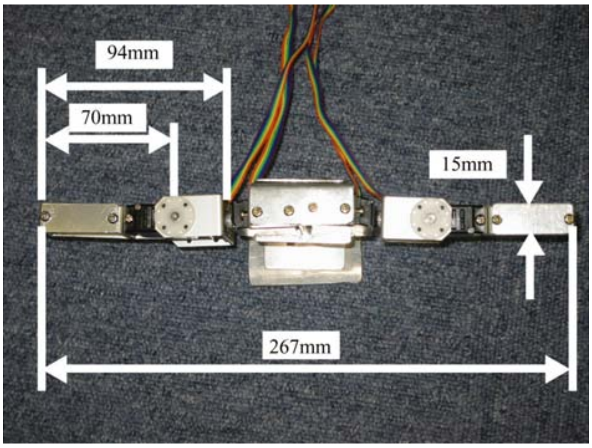

Figure 6. The size of RUI (front view)

motor that could easily be handled with one hand, designed the size of the robot as to not lose operatability and physicality, and gave the RUI the appearance of a teddy bear. The RUI specification is as follows. The length of the arm unit is 94[mm], the length with both arms outstretched as though on a cross is 267[mm] and the weight is 260[g].

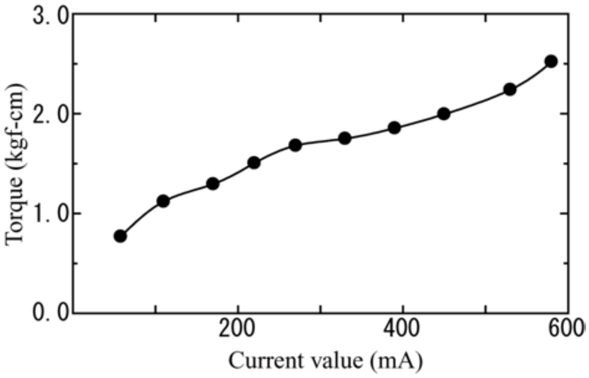

Figure 7. The relation between current value and torque.

The gear reduction ratio of the servomotor is 410:1. The maximum torque that can be presented is 6.4 [kgf-cm]. The torque necessary for bending a joint of the arm unit is 0.69 [kgf-cm], which is a torque that can be operated easily by adults or children.

This RUI is a haptic display. We changed the current value input to the servomotor and measured the torque that can be presented in this system. The power supply for the servomotor drive is DC6V.

Figure 7 shows the results of torque measurement, that the torque is proportional to the current value, and that its range is from 0.7 to 2.7[kg-cm].

4. PHYSICAL MODEL

4.1 Discrete-Time Equation for Motion

For computer simulations of kinematics, it is necessary to solve the equation of motion via discrete mathematics. To solve the kinematics and dynamics of our physical model we use Euler's method, which is suitable for real-time processing.

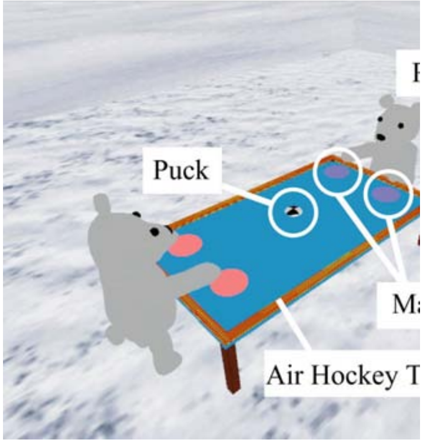

Fig. 8. AirHockey application window.

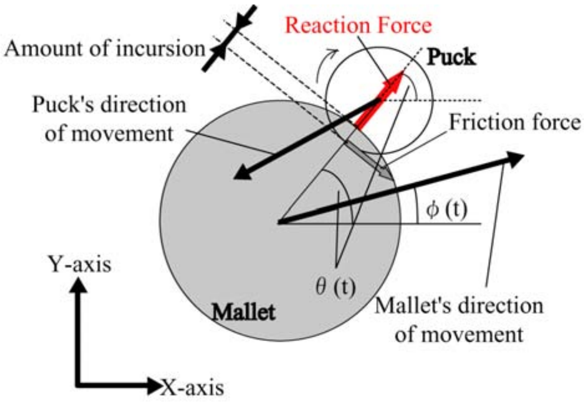

Figure 9. Repulsion of puck and mallett.

For our experimental system, we developed an AirHockey game, in which the puck is represented as a thin disk that moves and rotates in a two-dimensional surface. In the simulation, there is a mallet on the circumference of the circle, the center is the root of the arm, and the radius is its length. The mallet moves according to the value of the potentiometer in the servomotor that actuates the arms of the RUI. The motor has a proportional control.

When the mallet collides with the puck, haptic information is displayed to the user. The structure of this RUI arm is two orthogonal links, and it performs in a way that enables the display of one-dimensional haptic information. The reflection forces of the mallet and the puck are calculated by the simulation and applied to the set point of the servomotor.

$$F = ma = m\frac{dv}{dt} = m\frac{d^2x}{dt^2} \tag{1}$$

$$Fz \times r = I\frac{d\omega}{dt} = I\frac{d^2\theta}{dt^2} \tag{2}$$

The equations of motion for the puck are arrived at by solving Eqs. (1) and (2), and Eqs. (3) to (8) are then obtained. These equations of motion are used for dynamic simulations of the puck in this AirHockey game.

$$x(t+dt) = x(t) + vx(t)dt \tag{3}$$

$$y(t+dt) = y(t) + vy(t)dt \tag{4}$$

$$vx(t+dt) = vx(t) + \frac{F\cos\theta}{m}dt \tag{5}$$

$$vy(t+dt) = vy(t) + \frac{F\sin\theta}{m}dt \tag{6}$$

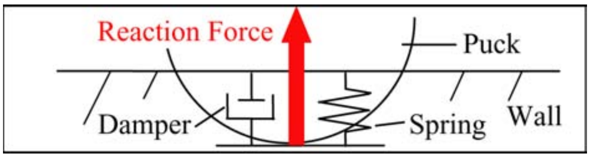

Figure 10. Penalty method.

$$\theta(t+dt)=\theta(t)+\omega(t)dt \tag{7}$$

$$\omega(t+dt)=\omega(t)=\frac{Fz\times r}{I}dt \tag{8}$$

4.2 Simulation of a Rigid Body

In the simulation the puck is a rigid body, and when it collides with a wall or a mallet, it rebounds. There are various previous methods for consideration as the collision simulation algorithm for rigid body dynamics simulation systems.

Barraff [1989] proposed to analytically calculate the forces between rigid bodies with a method that solves for contact forces in respect to momentum conservation and shows the characteristics of rigid bodies that don't mutually invade. However, when a lot of contacts occur at the same moment, the resulting computation takes a long time.

Mirtich and Canny [1995.] reported a method in which the reaction force is calculated according to the impulsive force between two objects at the time of collision. Collisions between two objects are sequentially processed. In this method, the computation for processing one collision is not so great, but when many collisions occur within a short period, processing collisions sequentially requires a lot of computation.

McKenna and Zeltzer [1990] presented a method using spring-damper models. The contact force is calculated from the amount of penetration, and hence this method is called the “penalty method.” Penalty methods put multiple spring-damper models for multiple contact points, and multiple contact forces are solved at once. Because the contact force is calculated directly from the spring-damper model, the penalty method takes a linear computational complexity.

Short computation times for each time step are important for real-time simulations. The Barraf, Mirtich, and Canny methods sometimes need a lot of computation, or indeed various computations, and thus aren’t suitable for real-time simulations. On the other hand, penalty methods are simple and suitable for real-time simulations, so we chose a penalty method for this experimental system.

5. HIGH UPDATE RATE OF MOTION SIMULATION

Using the penalty method, a high update rate of motion simulation is necessary. If the update rate is low, it causes a lot of penetration between objects, which receive a large reflection force, and the haptic information can’t be stably displayed.

Love and Book [1995] reported that an update rate of 1 [kHz] is necessary to display haptic information in a stable manner. Moreover, in a high update rate haptic simulation, the presence of a hard object becomes possible. We aimed for an update rate of 10 [kHz], with at least 1 [kHz] to stably display and present hard objects.

Further, we developed an experimental system running on Microsoft Windows, a general OS, not a real-time one. In the experiment, we used PCs with various performances; we named the PC with two CPUs "Dual1" and the PC with one CPU "Single1,"and so on.

Table II. PCs for the Experiment

PC Name	CPU	Memory	Graphics card
Single1	Celeron 1.4GHz	382.48 [MB]	No Graphics card 36.00[MB]
Single2	Celeron 1.4GHz	383.48 [MB]	GeForce4 Ti4800 124.38[MB]
Dual1	P-3 800MHz	255.48 [MB]	GeForce2 MX 100/200 59.12[MB]
Dual2	Xeon 3.06GHz	1793.62 [MB]	ELSA GLADIAC FX 736Ultra 123.96[MB]

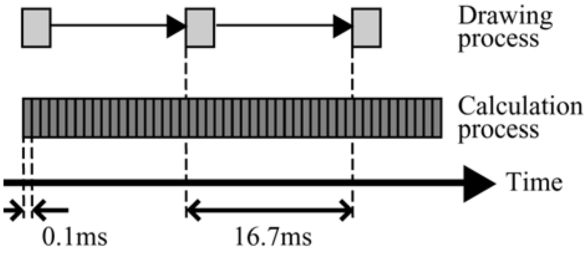

Figure 11. Method A.

In this experiment, the two following methods are evaluated. Method A uses a multithreading paradigm and a mutex to synchronize the calculating and drawing threads. In the first experimental method A, the calculating and drawing threads were run at the same time, and the elapsed time in every loop for the calculating thread was measured. To render the graphics, we used DirectX, which has a different way of rendering in Windows mode and full-screen mode, so we experimented in both modes. As a result, we defined data that exceeded 0.2 [ms], an error; an error rate was acquired by the error number per total number.

Figure12 shows the experimental results. (W) is the result of running in the Windows mode, and (F) represents the result of running in the ful-screen mode. The PC with two CPUs shows a higher update rate for the simulation.

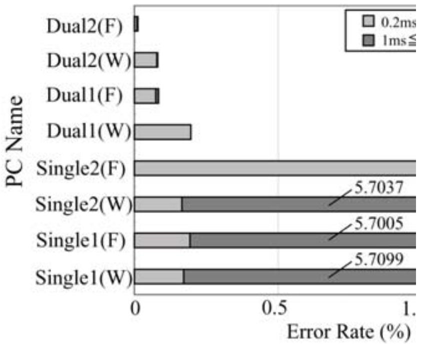

Fig. 12. The result of Method A.

The second method, MethodB, focuses on using a general PC with one CPU. This method sequentially uses drawing and calculating processes. To supplement the drawing time, calculations are repeated according to the elapsed time of the drawing. By using this method, the calculating process can be managed at a 10 [kHz] update rate. Haptic information is displayed according to the general drawing update rate of 60 [fps]. Important points for the haptic presentation have two elements; one is the continuity of the calculation process and the other is the timing of the presentation. Continuity is necessary for accurately presenting the hardness of the object, and so the update rate of the calculation process should be 1 [kHz] or more. The timing of the presentation is related to human perceptions such as vision and aurality. In this system, there is a gap in the drawing update rate of about 1/60 seconds. However, feelings of incompatibility from the gap are small.

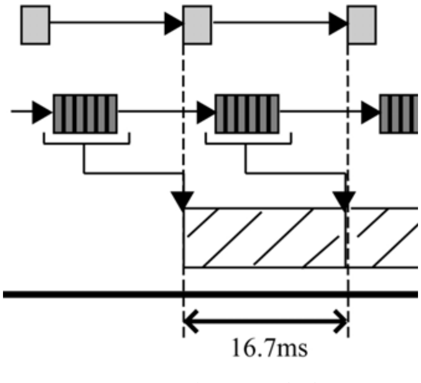

Fig. 13. Method B.

Using method B with the penalty method, we evaluated the accuracy of the collision and rebounding dynamics of the object. The experiment went as follows. There are two thin disks, A and B, which move only in one direction. At first, disk A is rested and B is moved to A at a constant speed. Then disk B collides with A, and the disks rebound. We evaluated the conservation of momentum after the collision and before. The mass of disk A is 40 [g] and disk B is 120 [g]. The spring constant is 1000 [N/m] and the coefficient of viscosity is 10 [N/ms-1].

Figure14 shows the experimental results. Conservation of momentum can be observed in the same way as in the case calculated analytically; though here it was calculated in discrete mathematics. Hence, by using the penalty method with method B, the calculation process can be managed at a high update rate, and the dynamics calculation becomes accurate.

On the other hand, in the penalty method based on the spring-damper model, the collision dynamics depend on the spring constant, the coefficient of viscosity, the mass of the object, and the update rate of the calculation. Therefore, it is difficult to set a restitution coefficient for the objects. Moreover, as previously described, conservation of momentum can be observed with the penalty method and the restitution coefficient between the objects can be solved from the result of the collision and rebound movements. From the results, the restitution coefficient between disks A and B was estimated at about 0.75.

6. IMPLEMENTATIONS TO IMPROVE ENTERTAINMENT

6.1 Multiuser Type Application

For this experimental system, we prepared one RUI unit in the real world and two CG models in the information world. One CG model synchronizes the RUI and the other is automatically operated by a computer program. So a user can play a single-user type AirHockey game.

In the entertainment field, there are multiuser type applications. Examples of a multiuser type are games where some people gather in one place and play by cooperating or fighting, and where many people in remote places play together through networks such as MMORPG. It is believed that multiuser type applications improve the entertainment value of games; the advantage being that it is not only an interaction with the information world but also has the ability to communicate with people who live in remote locations, compared with the single-user type application. Therefore, we developed a multiuser type application for our experimental system.

By preparing two RUI units in the real world and CG models of these in the information world, two users can play AirHockey at the same time and place. Further, the AirHockey game was developed so it can be played by two users at same time or from different places via a network. In this system, DirectPlay, a part of Microsoft's DirectX API, is used for communication between PCs; the network communication model is based on a client server model. The dynamics and kinematics are calculated only at the sever PC, while the client PC transmits information about the joint angles of the RUI to the server.

The experimental results of this system showed that in the local network experiment the drawing update rate, the controllability of the RUI, and the haptic presentation felt, subjectively, the same as the single-user type; however, there might be some problems regarding controllability and haptic presentation in a global type network.

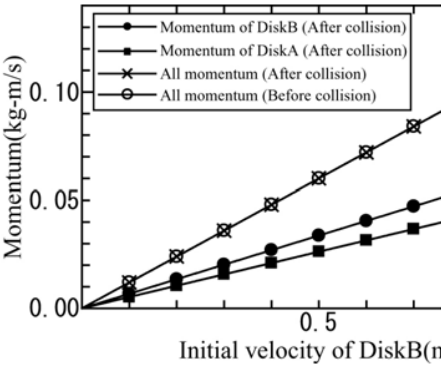

Figure 14. Relation of momentum in collision.

6.2 Sound Presentation

It is thought that aural output can improve the presentation of the game; thus, we added background music and a collision sound to the application. To increase reality, the collision sound was generated according to the dynamics.

7. CONCLUSION

In this article we presented details of an entertainment system that uses a teddy-bear based RUI. Our system enables the calculation of the dynamics of a puck and mallets, and displays a reflection force that the avatar receives through the RUI in real-time.

In general games, calculations of dynamics in the information world contain ambiguities, and only poor information such as vibration and joy stick resistance are usually displayed. A game based on an accurate dynamics model has recently been advocated; however, its display is still poor because there hasn't been a suitable interface. By using the RUI developed here, haptic information can be displayed along with the physical model; therefore, it is considered that an RUI is more effective than other interfaces for applications based on models with accurate dynamics and kinematics.

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