Project FEELEX: Adding Haptic Surface to Graphics

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Abstract

This paper presents work carried out for a project to develop a new interactive technique that combines haptic sensation with computer graphics. The project has two goals. The first is to provide users with a spatially continuous surface on which they can effectively touch an image using any part of their bare hand, including the palm. The second goal is to present visual and haptic sensation simultaneously by using a single device that doesn't oblige the user to wear any extra equipment. In order to achieve these goals, we designed a new interface device comprising of a flexible screen, an actuator array and a projector. The actuator deforms the flexible screen onto which the image is projected. The user can then touch the image directly and feel its shape and rigidity. Initially we fabricated two prototypes, and their effectiveness is examined by studying the observations made by anonymous users and a performance evaluation test for spatial resolution.

CR Categories: H.5.1 [Information Interface]: Multimedia Information System—Artificial, augmented, and virtual realities; H.5.2 [Information Interface]: User Interface—Haptic I/O

Keywords: haptics, interactive graphics, deformable screen, actuator array

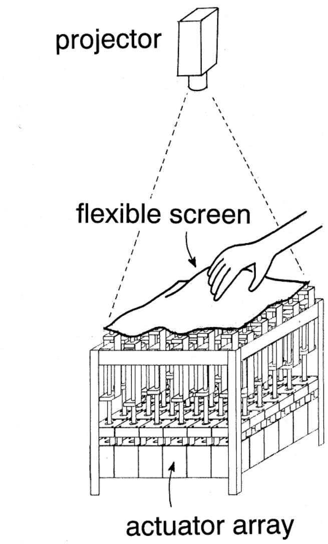

Figure 1: Basic idea of the FEELEX

1 INTRODUCTION

The use of force feedback to enhance interactive graphics has often been discussed. A Haptic interface is a feedback device that generates sensation to the skin and muscles, including a sense of touch, weight and rigidity. Scientific visualization is a good example of an area of application for a haptic interface [1][18]. Compared to ordinary visual and auditory sensations, haptics is difficult to synthesize. Visual and auditory sensations are gathered by specialized organs, the eyes and ears. On the other hand, a sensation of force can occur at any part of the human body, and is therefore inseparable from actual physical contact. These characteristics lead to many difficulties when developing a haptic interface.

We have been developing various haptic interfaces for many years. In 1989, we proposed the concept of a desktop force display that combined haptics and graphics. A typical example of a desktop force display is presented by Iwata [7]. This device provides force feedback for finger-hand manipulation. Currently available haptic interfaces, such as PHANToM, are usually designed to be used on a desktop. These haptic interfaces are commercially available, and various applications for them have already been developed.

We have demonstrated our haptic interfaces to a number of people, and we have found that some of them were unable to fully experience virtual objects through the medium of synthesized haptic sensation. There seem to be two reasons for this phenomenon.

Firstly, these haptic interfaces only allow the users to touch the virtual object at a single point or at a group of points. These contact points are not spatially continuous, due to the hardware configuration of the haptic interfaces. The user feels a reaction force thorough a grip or thimble. Exoskeletons provide more contact points, but these are achieved by using Velcro bands attached to specific part of the user's fingers, which are not continuous. Therefore, these devices cannot recreate a natural interaction sensation when compared to manual manipulation in the real world.

The second reason why they fail to perceive the sensation is related to a combination of the visual and haptic displays. A visual image is usually combined with a haptic interface by using a conventional CRT or projection screen. Thus, the user receives visual and haptic sensation through different displays, and therefore has to integrate the visual and haptic images in his/her brain. Some users, especially elderly people, have difficulty in this integration process.

Considering these problems, we have developed some new interface devices. The project is named "FEELEX." The word FEELEX is derived from a conjunction of "feel" and "flex."

The major goals of this project are:
(1) to provide a spatially continuous surface that enables users to feel virtual objects using any part of the fingers or even the whole palm.
(2) to provide visual and haptic sensations simultaneously using a single device that doesn't oblige the user to wear any extra appara-

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tus.

In order to achieve these goals, we designed a new configuration of visual/haptic display. Figure 1 illustrates the basic concept of the FEELEX. The device is composed of a flexible screen, an array of actuators, and a projector. The flexible screen is deformed by the actuators in order to simulate the shape of virtual objects. An image of the virtual objects is projected onto the surface of the flexible screen. Deformation of the screen converts the 2D image from the projector into a solid image. This configuration enables the user to touch the image directly using any part of their hand. The actuators are equipped with force sensors to measure the force applied by the user. The hardness of the virtual object is determined by the relationship between the measured force and its position of the screen. If the virtual object is soft, a large deformation is caused by a small applied force.

We have been implementing this idea, and this paper presents a history of the project and an evaluation of the prototypes.

2 RELATED WORK

2.1 Haptic Interface

A haptic interface, or force display, is a mechanical device that generates a reaction force from virtual objects. Research activities into haptic interfaces have recently been a rapidly growing area, although the technology is still in a state of trial-and-error. There are three approaches to implementing haptic interfaces: the exoskeleton type of force display, the tool-handling type of force display and the object-oriented type of force display.

(1) Exoskeleton type force display

An exoskeleton is a set of actuators attached to a hand or a body. In the field of robotics research, exoskeletons have often been used as master-manipulators for tele-operations. However, most master-manipulators entail a large amount of hardware and therefore have a high cost, which restricts their application areas. Compact hardware is needed in order to use them in human-computer interactions. The first example of a compact exoskeleton suitable for desktop graphics was published in 1990 [7]. The core element of the device is a 6 DOF (degree-of-freedom) parallel manipulator, in which three sets of pantograph link mechanisms are employed. Three actuators are set coaxially with the first joint of the thumb, the forefinger and the middle finger of the operator.

Lightweight and portable exoskeletons have also been developed. Burdea used small pneumatic cylinders to apply the force to the fingertips [2]. Cyber Grasp is a commercially available exoskeleton, in which cables are used to transmit the force [6].

(2) Tool-handling-type force display

The tool handling type of force display is the easiest way to realize force feedback. The configuration of this type is similar to that of a joystick. Unlike the exoskeleton, the tool-handling-type force display is free from the need to be fitted to the user's hand. It cannot generate a force between the fingers, but it has practical advantages.

In 1993, we developed a typical example of this category, the pen-based force display [8]. A pen-shaped grip is supported by two 3DOF pantographs that enables a 6DOF force/torque feedback. Another example of this type is the Haptic Master, which was demonstrated at the Edge venue of SIGGRAPH 94. The device has a ball-shaped grip to which 6 DOF force/torque is fed back [9]. This device employs a parallel mechanism in which a top triangular platform and a base triangular platform are connected by three sets of pantographs. This compact hardware has the ability to carry a large payload. Massie and Salisbury developed the PHANToM, which has a 3 DOF pantograph [14]. A thimble with a gimbal is connected to the end of the pantograph, which can then apply a 3DOF force to the fingertips. The PHANToM became one of the most popular commercially available haptic interfaces.

(3) Object-oriented-type force display

The object-oriented-type of force display is a radical idea for the design of a haptic interface. The device moves or deforms to simulate the shapes of virtual objects. A user of the device can physically contact with the virtual object by its surface.

An example of this type can be found in Tachi's work [21]. Their device consists of a shape approximation prop mounted on a manipulator. The position of the fingertip is measured and the prop moves to provide a contact point for the virtual object. McNeely proposed an idea named "Robotic Graphics" [15], which is similar to Tachi's method. Hirose developed a surface display that creates a contact surface using a 4X4 linear actuator array [5]. The device simulates an edge or a vertex of a virtual object.

In addition to these three categories, there are several other approaches to the haptic interface. The tactile display that stimulates skin sensation is a well-known technology. A sense of vibration is relatively easy to produce, and a good deal of work has been done using vibration displays [11][16]. The micro-pin array is also used for tactile displays. Such a device has enabled the provision of a teletaction and communication aid for blind persons [4][10]. It has the ability to convey texture or 2D-geometry [3]. However, the stroke distance of each pin is short, so the user cannot feel the 3D-shape of a virtual object directly. The micro-pin array looks similar to the object-oriented-type force display, but it can only create the sensation of skin. A force display stimulates muscle sensation, which contributes strongly to shape recognition.

A passive input device equipped with force sensors is a different approach to the haptic interface. Murakami and Nakajima used a flexible prop to manipulate a 3D virtual object [17]. The force applied by the user is measured and the deformation of the virtual object is determined based on the applied force. Sinclair developed a force sensor array to measure pressure distribution [20]. These passive devices allow the user to interact using their bare fingers. However, these devices have no actuators, so they cannot represent the shape of virtual objects.

2.2 Real-World Graphics

Image projection on physical objects is an advanced technique of human-computer interaction. Wellner proposed the DigitalDesk, in which physical and electronic desktops are merged [23]. The DigitalDesk is composed of a computer-controlled camera and a projector above a physical desk. It adds electronic features to physical paper, and it also adds physical features to electronic documents. The system allows the user to interact with both paper and electronic objects by touching them with a bare finger.

Siio developed the InfoBinder, which is composed of a push button and an ID [19]. The ID is recognized by a camera above the desk. The system provides the user with access to the electronic properties of physical objects such as the telephone.

Ishii proposed a conceptual infrastructure named the Luminous Room [22]. It provides a graphical display and an interaction at each surface of an interior architectural space. The experimental Luminous Room space is constructed by using a two-way optical transducer called an I/O bulb, which both projects and captures pixels. The user can manipulate the graphics by handling the physical objects.

2.3 FEELEX

The FEELEX is a combination of an object-oriented-type force display and real-world graphics. A user of a real-world graphics system, such as the DigitalDesk or the Luminous Room space, interacts with rigid objects. On the other hand, the FEELEX system presents deformable objects, just like living creatures. This function provides a new interaction style compared to the object-oriented-type force display and real-world graphics.

In 1995, we started to develop a preliminary implementation of the FEELEX. A rubber screen was put on top of five linear actuators. An image was projected onto the screen and was deformed by the motion of the linear actuators. The basic function of the FEELEX was confirmed by this prototype. We developed further prototypes using down-sized actuators that improved the resolution of the haptic surface.

3 DESIGN SPECIFICATIONS AND IMPLEMENTATION OF PROTOTYPES

3.1 FEELEX 1

We developed the FEELEX 1 in 1997. It was designed to enable double-handed interaction using the whole of the palms. Therefore, the optimum size of the screen was determined to be 24cm X 24cm. The screen is connected to a linear actuator array that deforms its shape. Each linear actuator is composed of a screw mechanism driven by a DC motor. The screw mechanism converts the rotation of an axis of the motor to the linear motion of a rod. The motor must generate both motion and a reaction force on the screen. The diameter of the smallest motor that can drive the screen is 4cm. Therefore, a 6X6 linear actuator array can be set under the screen. The deformable screen is made of a rubber plate and a white nylon cloth. The thickness of the rubber is 3mm. Figure 2 shows an overall view of the device. Figure 3 illustrates the mechanical configuration of each linear actuator.

The screw mechanism of the linear actuator has a self-lock function that maintains its position while the motor power is off. We learned of the difficulty involved in representing a hard virtual wall from our experiences with the tool-handling-type force display. Considerable motor power is required to generate the reaction force from the virtual wall, which often leads to uncomfortable vibrations. The screw mechanism is free from this problem. A soft wall can be represented by the computer-controlled motion of the linear actuators based on the data from the force sensors. A force sensor is set at the top of each linear actuator. Two strain gauges are used as a force sensor. The strain gauge detects small displacements of the top end of the linear actuator caused by the force applied by the user. The position of the top end of the linear actuator is measured by an optical encoder connected to the axis of the DC motor. The maximum stroke of the linear actuator is 80mm, and the maximum speed is 100mm/s.

The system is controlled via a PC. The DC motors are interfaced by a parallel I/O unit, and the force sensors are interfaced by an A/D converter unit. The force sensors provide interaction with the graphics. The position and strength of the force applied by the user are detected by a 6X6 sensor array. The graphics projected onto the flexible screen are changed according to the measured force.

3.2 FEELEX 2

The FEELEX 2 is designed to improve the resolution of the haptic surface. In order to determine the resolution of the linear actuators, we considered the situation where a medical doctor palpates a patient. We interviewed several medical doctors and found that they usually recognized a tumor using their index finger, middle finger, and third finger. The size of a tumor is perceived by comparing it to the width of their fingers, i.e. two-fingers large or three-fingers large. Thus, the distance between the axis of the linear actuators

Figure 2: Overall view of the FEELEX 1

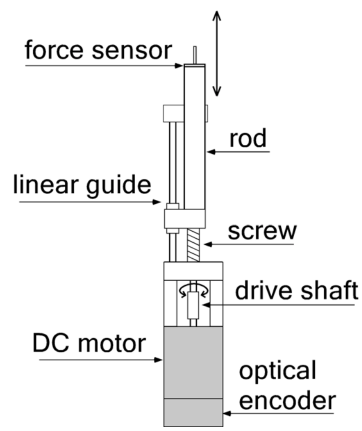

Figure 3: Linear actuator

should be smaller than the width of a finger. Considering the above condition, the distance is set to be 8mm. This 8mm resolution enables the user to hit at least one actuator when he/she touches any arbitrary position on the screen. The size of the screen is 50mm X 50mm, which allows the user to touch the surface using three fingers.

In order to realize 8mm resolution, a piston-crank mechanism is employed for the linear actuator. The size of the motor is much larger than 8mm, so the motor should be placed at a position offset from the rod. The piston-crank mechanism can easily achieve this offset position. Figure 4 illustrates the mechanical configuration of the linear actuator. A servo-motor from a radio-controlled car is selected as the actuator. The rotation of the axis of the servo-motor is converted to the linear motion of the rod by a crank-shaft and a linkage. The stroke of the rod is 18mm, and the maximum speed is 250mm/s. The maximum torque of the servo-motor is 3.2Kg-cm, which applies a 1.1Kgf force at the top of each rod. This force is sufficient for palpation using the fingers.

The flexible screen is supported by twenty-three rods, and the servo-motors are set remotely from the rods. Figure 5 shows an overall view of the FEELEX 2. The twenty-three separate sets of piston-crank mechanisms can be seen in the picture.

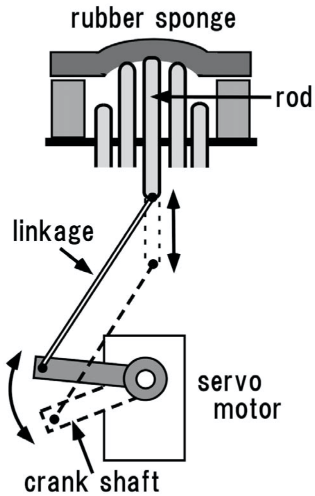

Figure 4: Piston-crank mechanism

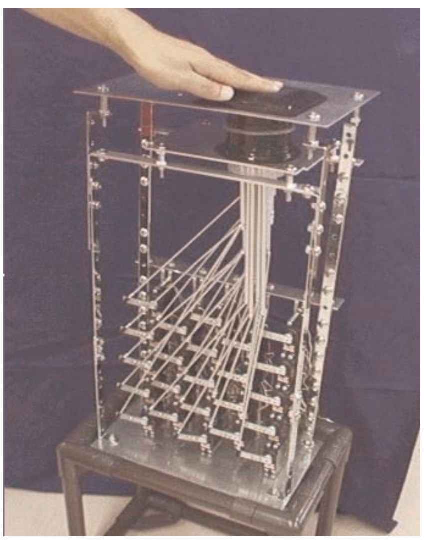

Figure 5: Overall view of the FEELEX 2

Figure 6 shows the top end of the rods. The photo is taken while the flexible screen is off. The diameter of each rod is 6mm. We cannot put a strain gauge on the top of the rod because of its small size, so we therefore measure the electric current going to each servo-motor to sense the force. The servo-motor generates a force to maintain the position of the crank-shaft. When the user applies a force to the rod, the electric current on the motor increases to balance the force. We measured the relationship between the applied force and the electric current. The applied force at the top of the rods is calculated using data from the electric current sensor. The resolution of the force sensing capability is 40gf.

3.3 Hardware performance of the FEELEX

The performance of existing haptic interfaces is usually represented by the dynamic range of force, impedance, inertia, friction, etc. However, these parameters are only crucial while the device is attached to the finger or hand. In the case of the tool-handling-type haptic interface or the exoskeleton, the devices move with the hand even though the user doesn't touch the virtual objects. Therefore inertia or friction degrades the usability and the dynamic range of

Figure 6: Top end of the rods

force determines the quality of the virtual surface. On the other hand, the FEELEX is entirely separate from the user's hand, so it's performance is determined by the resolution and speed of the actuators. The resolution of the actuator corresponds to the smoothness of the surface and the speed of the actuator determines the motion of the virtual object. The FEELEX 2 has improved resolution and motion speed compared to the FEELEX 1. Each actuator of the FEELEX 2 has a stroke rate of up to 7Hz, which can simulate the motion of a very fast virtual object. The rod pushes the rubber sponge so that the user feels as if the object was pulsating. 7Hz is much faster than the human pulse rate.

4 GRAPHICS FOR THE FEELEX

The graphics for the FEELEX are projected from a projector set above the flexible screen. The curvature of the screen makes the image appear to be solid. Figure 7 shows a grid projected onto the deformed screen.

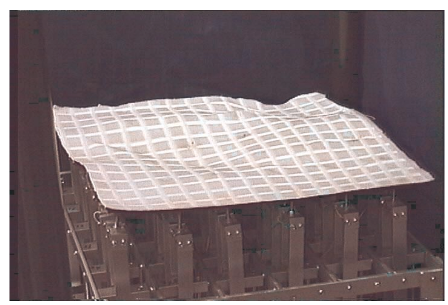

Figure 7: Projected grid on the defomed screen

Compared with the size of the screen, the vertical stroke of the actuators is limited, and therefore there is no need for distortion correction.

The graphics are generated by using either an OpenGL or by random access to pre-recorded AVI files. We developed a virtual Anomalocaris as part of the content of the FEELEX 1. Anomalocaris is the name given to an animal that was supposed to have lived during the Cambrian Era. Figure 8 shows an image of the Anomalocaris projected onto the flexible screen. The creature appears to be in motion depending on the force applied by the user. If the user pushes its head, it gets angry and struggles. The image of the Anomalocaris is pre-rendered and stored in AVI files. We use the DV format for compression of the motion picture, and the resolution of the image is 720 X 480. We prepared sixteen patterns of motion. Four patterns represent the state of anger. The motion of the Anomalocaris is generated by combining these patterns. This method does not require a high specification PC to display a high-quality interactive image.

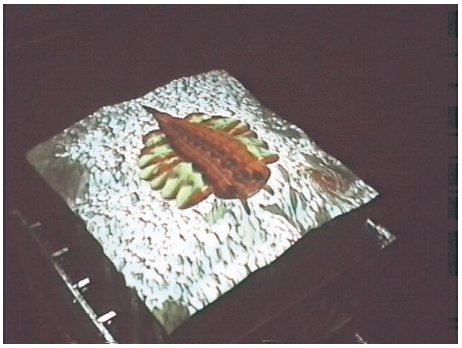

Figure 8: Anomalocaris

5 EVALUATION

5.1 Observation of Users' Behavior

As a usability test of the prototype of the FEELEX, we examined the behavior of novice users of the device. We are especially interested in the behavior of first-time users. In order to collect subjects for this purpose, we brought the FEELEX 1 to the Enhanced Realities venue of SIGGRAPH 98. The major area of interest in this experiment is how first-time users interact without instruction or explanations.

Test environment:

We used the Anomalocaris for this experiment, specially chosen to attract participants' attention. We put up a sign telling observers "You can touch the screen." This was the only instruction given to the users. We observed the participants and took note of their behavior.

Subjects:

We observed the behavior of the participants for three days during the conference, and we recorded information for 1,992 participants.

Result:

We recorded the part of the hand that the subject used to interact with the creature. We categorized the subjects' behavior into three classes:

(1) Touched the creature using a single finger

(2) Touched the creature using multiple fingers

(3) Touched the creature using the whole hand including the palm.

Table 1 shows the number of subjects who fell into each category.

category	number of subjects
1	299 (15%)
2	319 (16%)
3	1374 (69%)

Table 1: Behavior of the subjects

Discussion:

The result of the experiment shows that 85% of the subjects used multiple fingers or their palms. This finding indicates that the prototype system almost achieved the first goal of this research; it allows users to feel virtual objects using any part of their fingers or even their whole palm. They spontaneously used the surface of their hands, although the main function of the system wasn't explained to them.

The subjects who used only one finger seemed to touch it gingerly. Since the subject was an unknown creature, this behavior could be a natural response.

Another finding of the experiment was that multiple participants touched the screen simultaneously. The system provides haptic sensation at any part of the screen, so it has the ability to support multiple users. Haptics was originally experienced by a single person. Exoskeletons or tool-handling-type force displays can also only support one user, but multiple users of the FEELEX system can share haptic sensations.

5.2 Performance Evaluation

5.2.1 Psychology in haptics

There have been many findings regarding haptic sensation. Most of these are related to skin sensation, and research activities that include muscle sensation are very few in number. Among these, Lederman and Klatzky's work is closely related to the design of the force display [12]. Their latest work involves spatially distributed forces [13]. They performed an experiment involving palpation. The subjects were asked to find a steel ball placed underneath a foam-rubber cover. The results showed that steel balls smaller than 8mm in diameter decreased the score. This finding supports our specification for the FEELEX 2 in which the distance between rods is 8mm.

5.2.2 Recognition performance of spatial resolution

Task:

We examined the performance of the prototype using the FEELEX 2. We set three patterns of virtual objects, and Figure 9 illustrates these patterns. The small circles in the figure represent the horizontal position of the rods.

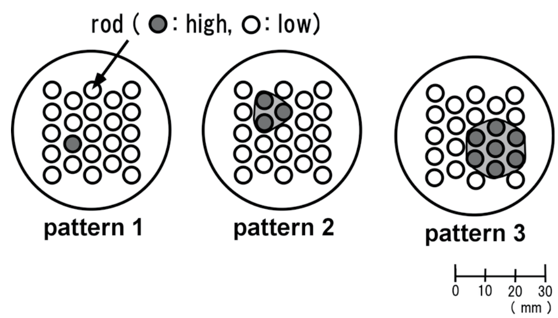

Figure 9: Displayed objects

Patterns 1,2 and 3 are created by one, three and seven rods, respectively. The higher positioned rods simulate a hard object, which the subjects can feel as if it were a tumor. These three patterns are displayed at random positions. In this experiment, a sponge is set above the screen so that the subjects can't see the shape of the displayed object. The subjects are asked to draw the position and shape of each object on a piece of paper. A circle is marked on each paper to indicate the test space.

Subjects:

The subjects are 9 university students (7 males, 2 females) who voluntarily participated in the experiment. They ranged in age from 22 to 24.

Procedure:

We prepared three trials for each pattern. The subjects were asked to draw the object that they perceived for each trial. The three patterns are displayed in random order, and thus each subject completed a total of 9 trials for this experiment.

Results:

The precision of the perceived object is evaluated from the subject's drawings. We calculated the size and central position (center of mass) of each object. The size of a perceived object is represented by the approximated diameter of the figure drawn by the subjects. We assumed that each figure was a circle. We measured the area of the figure so that the diameter is given by the following equation:

$$d = \sqrt{4S/\pi}$$

where
d = approximate diameter
S = measured area

Figure 10 shows the diameters of the displayed objects and the mean diameters of the objects perceived by the subjects. The error bars represent the standard deviation. The results show that the subjects overestimated the size of the objects. The differences between the displayed and the perceived objects of patterns 1,2 and 3 are 8mm, 4mm and 1mm respectively.

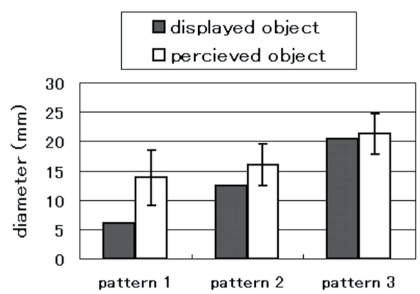

Figure 10: Size of perceived objects

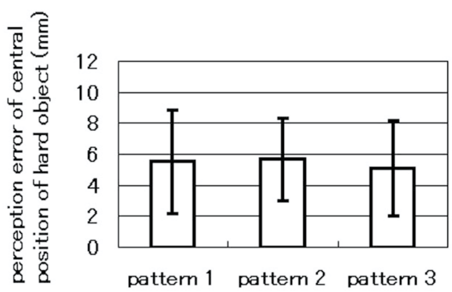

Figure 11: Position error of perceived objects

Figure 11 shows the distance between the central positions of the perceived and displayed objects. The error bars represent the standard deviation. The results show that the average perception errors ranged between 5mm and 6mm.

Discussion.

The errors in perception of the size of the objects ranged from 1mm to 8mm. The errors are much smaller than the width of a finger. This result indicates that the FEELEX 2 succeeded in the presentation of a virtual tumor in terms of its size. Overestimation by the subjects seems to be caused by the rubber sponge set above the rods. The size of the displayed object is calculated from the position of the edge of higher-positioned rods. However, the subjects felt the edge through the rubber sponge, which makes the object feel larger. The mean error in the distance between the perceived and the displayed objects is less than 6mm. Since the distance between the rods is 8mm, this error is reasonable.

6 GENERAL DISCUSSION

The major advantage of the FEELEX is that it allows natural interaction using only the bare hand. In SIGGRAPH 98, 1992 subjects spontaneously enjoyed the haptic experience. One of the subject contents of the FEELEX 1 system, known as Anomalocaris, was selected as a long-term exhibition at the Ars Electronica Center (Linz, Austria). The exhibition has been popular among visitors, and especially children. Another advantage of FEELEX is safety. The user of FEELEX doesn't wear any special equipment while the interaction is taking place. The exoskeleton and tool-handling-type force displays have control problems in their contact surface for the virtual objects. Vibration or unwanted forces can be generated back to the user, which is sometimes dangerous. The contact surface of the FEELEX is physically generated, so it is free from such control problems.

The major disadvantage of the FEELEX is the degree of difficulty in its implementation. It requires a large number of actuators that have to be controlled simultaneously. The drive mechanism of the actuator must be robust enough for rough manipulation. Since the FEELEX provides a feeling of natural interaction, some of the users apply large forces. Our exhibit at the Ars Electronica Center suffered from overload of the actuators.

Another disadvantage of the FEELEX is its limitation in the shape of objects that can be displayed. The current prototypes cannot present a sharp edge on a virtual object. Furthermore, the linear actuator array can only simulate the front face of objects. Some of the participants of the Anomalocaris demonstration wanted to touch the rear of the creature, but an entirely new mechanism would be required in order to also simulate the reverse side of the object.

7 APPLICATIONS FOR THE FEELEX

Palpation. Medical applications for haptic interfaces are currently growing rapidly. Various surgical simulators have been developed using a tool-handling-type force display. Palpation is typically used in medical examinations. The FEELEX 2 is designed to be used as a palpation simulator. If we display a virtual tumor based on a CT or MRI image, a medical doctor can palpate the internal organs before surgery, and this technique can be also applied to tele-medicine. Connecting two FEELEXs together via a communication line would allow a doctor to palpate a patient remotely.

3D shape modeling. The design of 3D-shapes definitely requires haptic feedback. A typical application of the tool-handling-type force display is in 3D-shape modeling. One of the most popular applications of the PHANToM system is as a modeling tool. Such a tool-handling-type force display allows a user to point contact, and point contact manipulation is most suited for precision modeling tasks. However, it isn't effective in when the modeling task requires access to the whole shape. Designers use their palm or the joints of their fingers to deform a clay model when carrying out rough design tasks. The FEELEX has the ability to support such natural manipulation.

Touch screen. Today, touch-screens are widely used in automatic teller machines, ticketing machines, information kiosks and so on. A touch-screen enables an intuitive user interface, although it lacks haptic feedback. Users can see virtual buttons but they can't feel them. This is a serious problem for a blind person. The FEELEX provides a barrier-free solution to the touch-screen-based user interface. Figure 12 shows an example of a haptic touch-screen using the FEELEX 1.

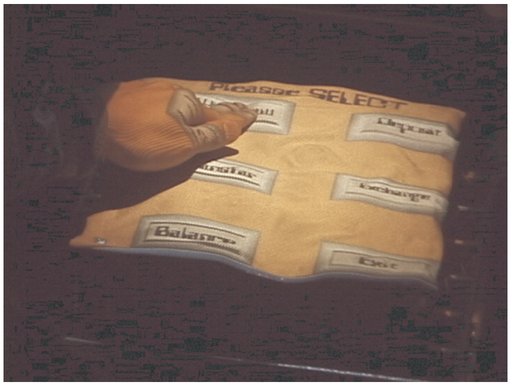

Figure 12: Haptic touch screen

Art. Interactive art may be one of the best applications of the FEELEX system. As we discussed in section 5, the Anomalocaris has been exhibited at a museum in Austria. It succeeded in evoking haptic interaction with many visitors. The FEELEX can be used for interactive sculptures. Visitors are usually prohibited from touching physical sculptures, but not only can they touch sculptures based around FEELEX, they can also deform them.

8 CONCLUSIONS

This paper presents the concept of a new interaction technique using a flexible screen and an actuator array. Two prototypes have been developed to exemplify the effectiveness of the idea. The first prototype was used for the observation of anonymous users. The basic finding is that it provides an intuitive haptic experience. Visitors to SIGGRAPH 98 and the Ars Electronica Center could enjoy its potential functions without the need for further instructions. The second prototype has improved the resolution and dynamics of the actuators. Performance evaluation tests showed its capability for palpation. The current prototypes have fabrication problems and limitations in the type of shapes that can be displayed. Future work will include a new mechanical design for the actuators.

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