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16

Softness Haptic Display Device for Human-Computer Interaction

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1. Introduction

In the field of virtual reality and teleoperation, haptic interaction between human operator and a computer or telerobot plays an increasingly important role in performing delicate tasks, such as robotic telesurgery, virtual reality based training systems for surgery, virtual reality based rehabilitation systems (Dario et al, 2003) (Taylor, Stoianovici, 2003) (Popescu, et al, 2000), etc. These applications call for the implementation of effective means of haptic display to the human operator. Haptic display can be classified into the following types: texture display, friction display, shape display, softness display, temperature display, etc. Previous researches on haptic display mainly focused on texture display (Lkei et al, 2001), friction display (Richard, Cutkosky, 2002) and shape display (Kammermeier et al, 2000). Only a few researches dealt with softness display, which consists of stiffness display and compliance display. The stiffness information is important to the human operator for distinguishing among different objects when haptically telemanipulating or exploring the soft environment. Some effective softness haptic rendering methods for virtual reality have already been proposed, such as a finite-element based method (Payandeh, Azouz, 2001), a pre-computation based method (Doug et al, 2001), etc. An experimental system for measuring soft tissue deformation during needle insertions has been developed and a method to quantify needle forces and soft tissue deformation is proposed (Simon, Salcudean, 2003). However, there are no effective softness haptic display devices with a wide stiffness range from very soft to very hard for virtual reality yet. The existing PHANToM arm as well as some force feedback data-gloves are inherently force display interface devices, which are unable to produce large stiffness display of hard object owing to the limitation of output force of the motors.
This chapter focuses on the softness haptic display device design for human-computer interaction (HCI). We firstly review the development of haptic display devices especially softness haptic display devices. Then, we give the general principles of the softness haptic display device design for HCI. According to the proposed design principles, a novel method to realize softness haptic display device for HCI is presented, which is based on control of deformable length of an elastic element. The proposed softness haptic display device is composed of a thin elastic beam, an actuator for adjusting the deformable length of the beam, fingertip force sensor, position sensor for measuring the movement of human

fingertip, and USB interface based measurement and control circuits. By controlling deformable length of the elastic beam, we can get any desirable stiffness, which can tracks the stiffness of a virtual object with wide range from very soft to hard, to display to a fingertip of human operator. For the convenience of user, a portable softness haptic display device is also developed, which is easy to be connected with a mouse. At last, we build a softness haptic human-computer interaction demo system, which consists of a computer with softness virtual environment, softness haptic modelling element, and the proposed softness haptic display device.

2. Review of haptic display device development

Haptic display devices (or haptic interfaces) are mechanical devices that allow users to touch and manipulate three-dimensional objects in virtual environments or tele-operated systems. In human-computer interaction, haptic display means both force/tactile and kinesthetic display. In general, haptic sensations include pressure, texture, softness, friction, shape, thermal properties, and so on. Kinesthetic perception, refers to the awareness of one's body state, including position, velocity and forces supplied by the muscles through a variety of receptors located in the skin, joints, skeletal muscles, and tendons. Force/tactile and kinesthetic channels work together to provide humans with means to perceive and act on their environment (Hayward et al, 2004).

One way to distinguish among haptic devices is their intrinsic mechanical behavior. Impedance haptic devices simulate mechanical impedance —they read position and send force. Admittance haptic devices simulate mechanical admittance — they read force and send position. Being simpler to design and much cheaper to produce, impedance-type architectures are most common. Admittance-based devices are generally used for applications requiring high forces in a large workspace (Salisbury K., Conti F., 2004).

Examples of haptic devices include consumer peripheral devices equipped with special motors and sensors (e.g., force feedback joysticks and steering wheels) and more sophisticated devices designed for industrial, medical or scientific applications. Well-known commercial haptic devices are the PHANToM series from Sensable Technology Corporation, and the Omega.X family from Force Dimension Corporation. These haptic devices are impedance driven.

Fig. 1. The PHANTOM desktop device

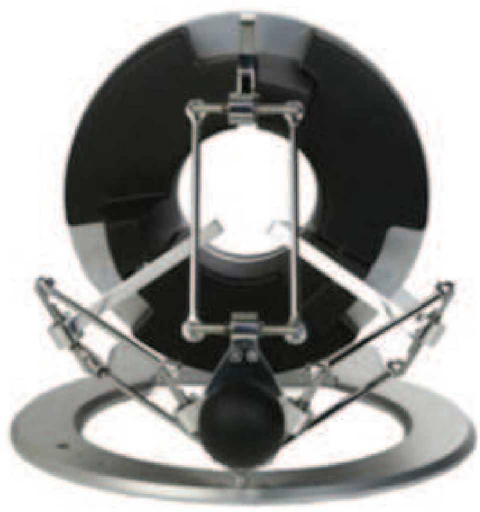


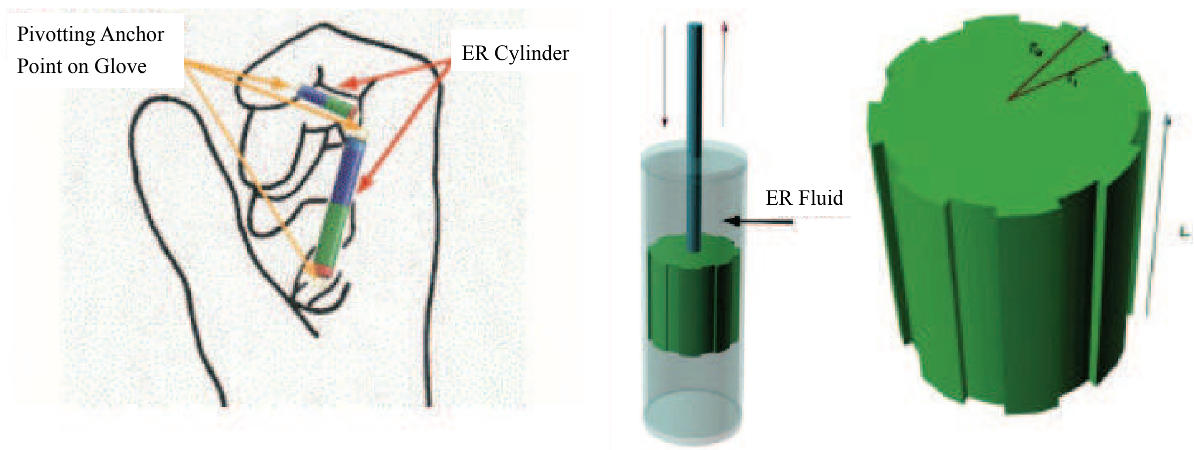
Fig. 2. The Omega.X device

In recent years, different research groups have developed laboratory prototypes of haptic display devices based on different principles. Haptic display devices previously developed explore servomotors (Wagner et al, 2002), electromagnetic coils (Benali-Khoudja et al, 2004), piezoelectric ceramics (Pasquero, Hayward, 2003) (Chanter, Summers, 2001) (Maucher et al, 2001), pneumatics (Moy et al, 2000), shape memory alloys (SMA) (Kontarinis et al, 1995) (Taylor, Creed, 1995) (Taylor et al,1997) (Taylor, Moser, 1998), Electro-magnetic (Fukuda et al,1997) (Shinohara et al, 1998), polymer gels (Voyles et al, 1996) and fluids as actuation technologies (Taylor et al, 1996).

A softness haptic display is important to distinguish between the different objects. This haptic information is essential for performing delicate tasks in virtual surgery or tele-surgery. However, at present only a few literatures have researched on the softness display device design. The existing softness display device design approaches can be divided into four categories of approaches as follows.

2.1 Softness haptic display device based on electro-rheological fluids

Mavroidis et al developed a softness haptic display device that could enable a remote operator to feel the stiffness and forces at remote or virtual sites (Mavroidis et al, 2000). The device was based on a kind of novel mechanisms that were conceived by JPL and Rutgers University investigators, in a system called MEMICA (remote Mechanical Mirroring using Controlled stiffness and Actuators) which consisted of a glove equipped with a series of electrically controlled stiffness (ECS) elements that mirrors the stiffness at remote/virtual sites, shown in Figure 3. The ECS elements make use of Electro-Rheological Fluid (ERF), which was an Electro-Active Polymer (EAP), to achieve this feeling of stiffness. The miniature electrically controlled stiffness (ECS) element consisted of a piston that was designed to move inside a sealed cylinder filled with ERF. The rate of flow was controlled electrically by electrodes facing the flowing ERF while inside the channel. To control the stiffness of the ECS, a voltage was applied between electrodes that are facing the slot and the ability of the liquid to flow was affected.



(a) MEMICA system (b) ECS element and its piston

Fig. 3. Softness haptic display device based on electro-rheological fluids

2.2 Softness haptic display device based on the fingertip contact area control

It has been reported that softness in the cutaneous sense can be produced by controlling contact area corresponding to contact force (Fujita et al, 2000).

Fujita and Ikeda developed a softness haptic display device by dynamically controlling the contact area (Ikeda, Fujita, 2004) (Fujita, Ikeda, 2005). The device consisted of the pneumatic contact area control device and the wire-driven force feedback device, shown in Figure 4. The contact area was calculated using Hertzian contact theory using the Young's modulus, which is converted from the transferred stiffness. The air pressure to drive the pneumatic contact area control device was controlled using the pre-measured device property. The reaction force was calculated based on the stiffness using Hook's law.

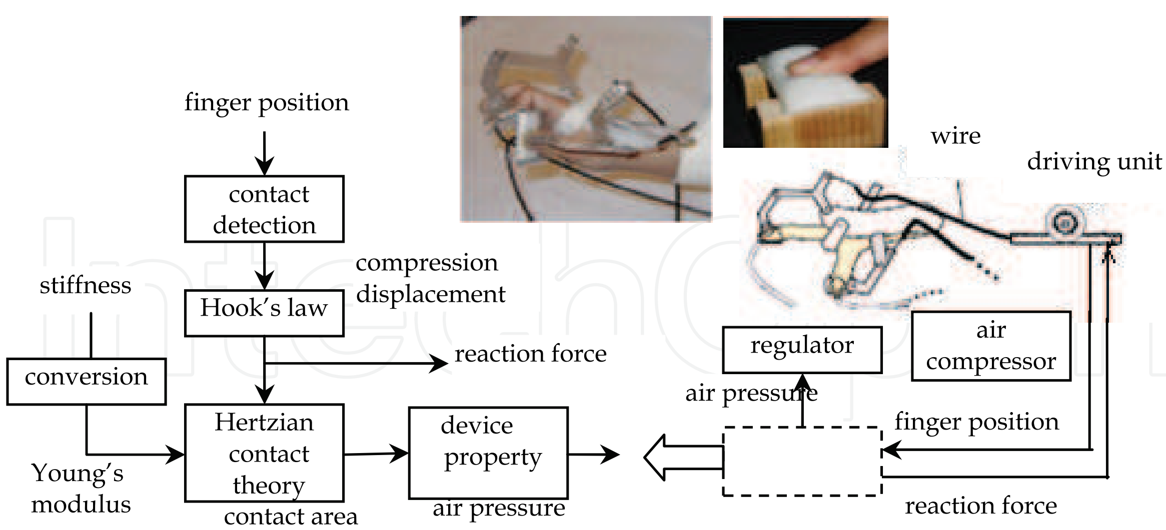


Fig. 4. Fingertip contact area control system

Fujita and Ohmori also developed a softness haptic display device which controlled the fingertip contact area dynamically according to the detected contact force, based on the human softness recognition mechanism (Fujita, Ohmori, 2001). A fluid-driven vertically moving cylinder that had rubber sheet at its top surface was utilized, because of the simplicity of development and the spacial resolution as shown in Figure 5. The piston of the device was installed on a loadcell for contact force detection. The inside of the piston was designed as empty, and fluid was pumped into the piston through the pipe at the side wall of the piston. The pumped fluid flaws out from twelve holes at the top of the piston, and the fluid push-up the rubber-top cylinder. Because the center of the rubber is pushed by the fingertip, the peripheral part is mainly pushed up. Therefore the contact area between the fingertip and the rubber increases. The pressure distribution within the contact area becomes constant because of the intervention of the fluid. The softness was represented as the increase rate of the contact area. The fluid volume control pump consisted of a motor-driven piston, a cylinder and a potentiometer to detect the piston position. The fluid volume in the device was indirectly measured and controlled by controlling the piston position of the pump. A DC servo control circuit was utilized for the pump control.

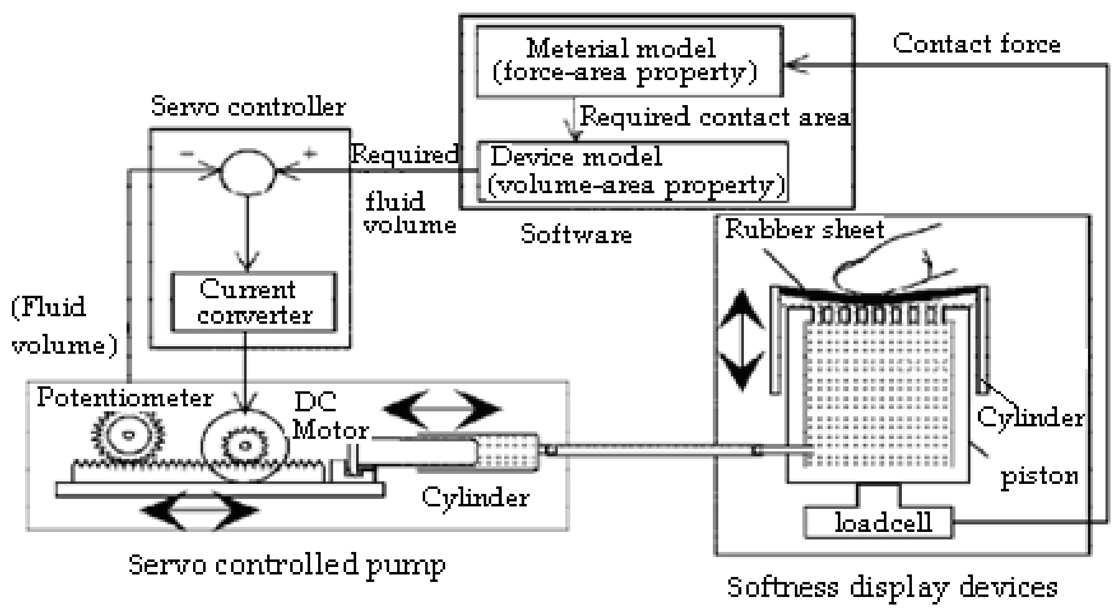


Fig. 5. Softness display system by controlling fingertip contact area based on detected contact force

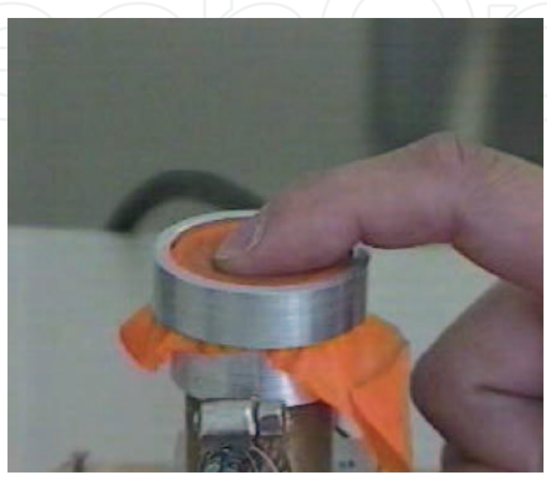


Fig. 6. Close-up the device and the finger

2.3 Softness haptic display device based on pneumatic array

Moy et al at University of California presented a softness haptic display device using pneumatically actuator, which consisted of two parts, the contact interface and the pneumatic valve array of tactor elements (Moy et al, 2001), Shown in Figure 7. A 5x5 array of tactor elements were spaced 2.5 mm apart and were 1 mm in diameter. The working frequency was 5 Hz. The contact interface was molded from silicone rubber in a one-step process. Twenty-five stainless steel pins were soldered to the back of the baseplate. Silicone tubing was placed around each of the pins. The silicone rubber bonds with the silicone tubing to form an airtight chamber. The contact interface was connected to the pneumatic valve array by hoses and barbed connectors. The pulse width modulated (PWM) square wave controlled the pressure in the chamber.

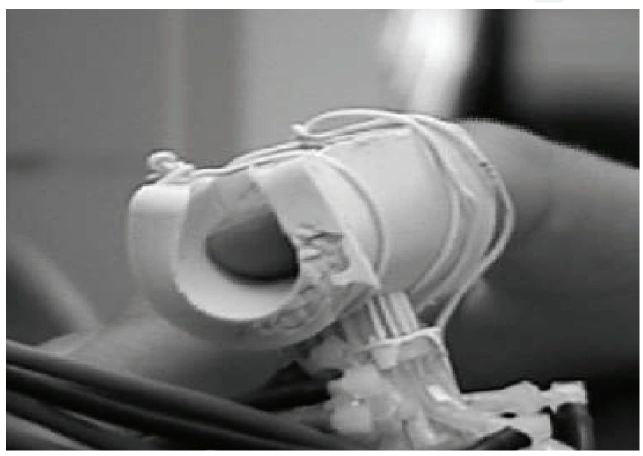


Fig. 7. The softness haptic display attached to the finger

2.4 Softness haptic display device based on elastic body

Takaiwa and Noritsugu at Okayama University developed a softness haptic display device that can display compliance for human hand aiming at the application in the field of virtual reality (Takaiwa, Noritsugu, 2000). Pneumatic parallel manipulator was used as a driving mechanism of the device, consequently, which yielded characteristic that manipulator worked as a kind of elastic body even when its position/orientation was under the control.

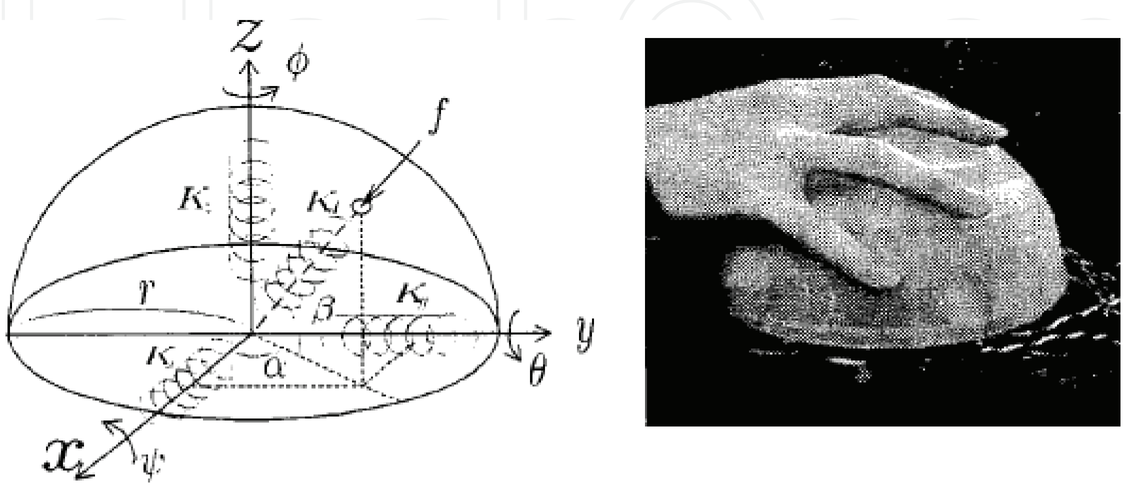


Fig. 8. The softness haptic display device based on elastic body

3. The general principles of the softness haptic display device for HCI

Each of these approaches has its own advantages/disadvantages. Humans use two different forms of haptic display devices: active and passive. Active haptic display devices have joints with motors, hydraulic actuators, or some other form of actuator that creates motion, adds energy, and reflects virtual forces. Passive haptic display devices have brakes or dampers that provide the user with feedback forces. The passive haptic display devices cannot force a user in a certain direction - it can only prevent or slow a user's motion. The benefit of a passive haptic display device over an active haptic display device is that force spikes generated by the virtual environment cannot do any damage to the human operator. Electrorheological (ER) fluids suspensions show swift and reversible rheological changes when the electric or magnetic field is applied. However, there are such defects as a restriction on usable temperatures so as to avoid evaporation or freezing of the water, an extreme increase in the electric current flow as the temperature raises, inferior stability caused by transfer of water, etc. The method based on the fingertip contact area control is easy to implement. However to different objects, confirming the relation between the dynamic changes of contact area and stiffness needs lots of psychophysiological experiments, and real time contact area control with high precision is difficult to guarantee. Pneumatically actuated haptic display devices have to overcome leakage, friction and non-conformability to the finger.

In this section we present four principles of designation of the softness haptic display devices as follow.

(a) Because the active haptic display devices are unable to produce very high stiffness, and the large force directly provided by the active element, such as electric motors, pneumatic drivers, hydraulic drivers, etc., sometimes may be harmful to the human operator. Passive haptic display devices are recommended for safety.

(b) The softness haptic display devices must be able to produce continuous stiffness display in wide range.

(c) The softness haptic display devices should be controlled accurately and rapidly.

(d) The size and weight are very important to the softness haptic display device design. To guarantee the high transparency of the softness haptic human-computer interaction system, small size and light weight is required. It is necessary to seek a portable haptic display device that can be taken easily.

4. A novel softness display device designation method

The environment dynamics is usually expressed by a mass-spring-damp model as follows:

$$f_e = m_e \ddot{x}_e + b_e \dot{x}_e + k_e x_e \tag{1}$$

where f_e is force acted on the environment, x_e is displacement of the environment, and m_e, b_e, k_e are mass, damp and stiffness of the environment, respectively. As to the soft environment discussed here, the displacement x_e represents local deformation of its surface, and m_e represents the local mass of its surface, which is relatively very small and usually can be omitted. If the damp is notable and the stiffness is small, the soft object is characterized by the compliance. If the reverse is the case, the soft object is characterized by the stiffness.

In this chapter, our research mainly focuses on the stiffness display, because for a lot of soft objects, such as most of the tissues of human body, stiffness is not only inherent, but also notable by comparison with damp or viscous. So that how to replicate the sense of stiffness to the user as if he directly touches with the virtual or remote soft environment is a primary issue in the softness display of the virtual environment and of the teleoperation.

We design and fabricate a novel haptic display system based on control of deformable length of an elastic element (CDLEE) to realize the stiffness display of the virtual environment, which is shown in schematic form in Figure 9(a). It consists of a thin elastic beam, feed screw, carriage with nut, and motor. The stiffness of the thin elastic beam is the function of deformable length of the beam *l* seen in Figure 10. So the stiffness can be easily and smoothly changed to any value by controlling the deformable length of the thin beam *l*. Here, a motor, together with a feed screw and a nut, is used to control the position of the carriage, which determines the deformable length *l*.

In ideal case, when the human operator's fingertip pushes or squeezes the touch cap of the softness haptic display interface device, he will feel as if he directly pushes or squeezes the soft environment with a small pad, seen in Figure 9(b).

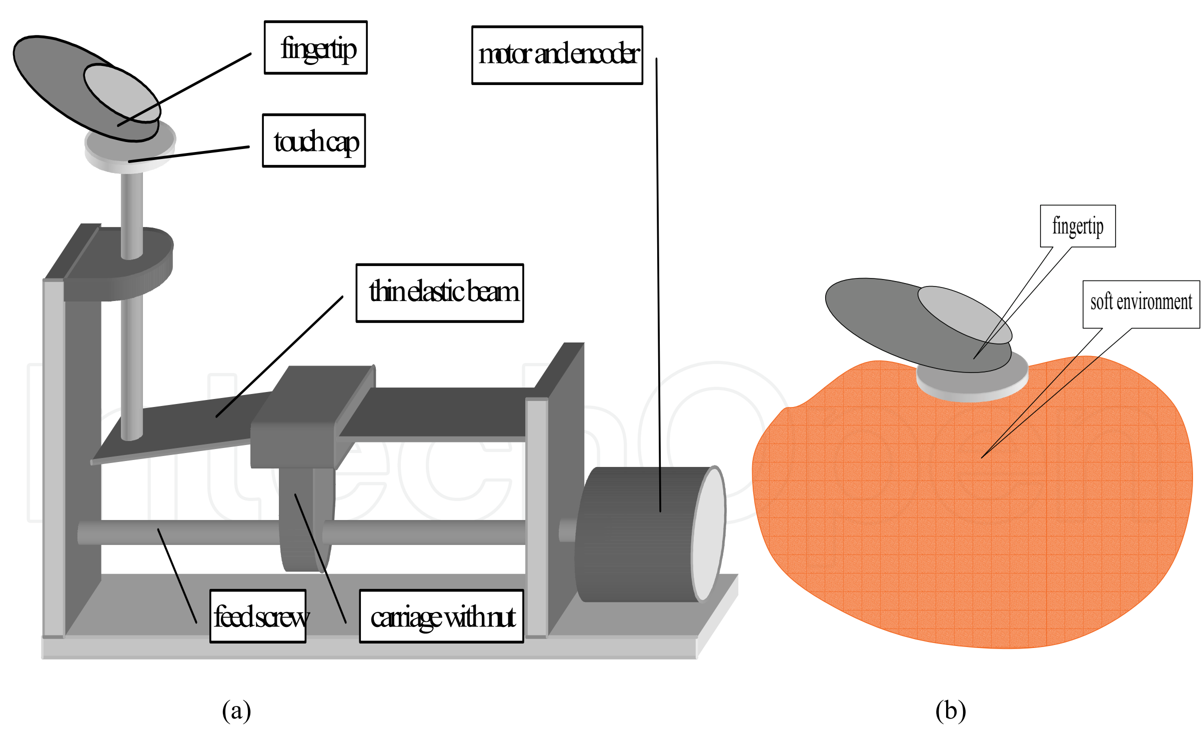


Fig. 9. Softness display of virtual soft environment

Figure 10 shows the principle of the softness display based on CDLEE. Where, y is vertical displacement of the end of the thin elastic beam when force f acted on that point.

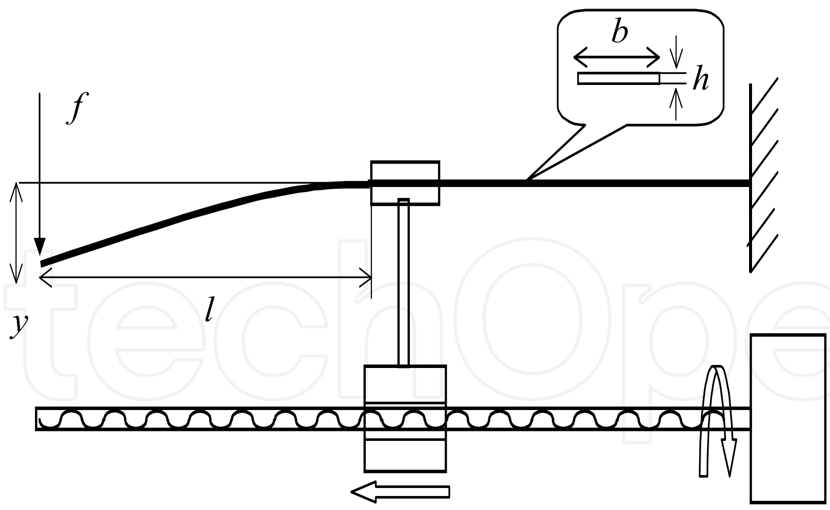


Fig. 10. Principle of the softness display based on CDLEE

According to the theory of Mechanics of materials, the deformation of the thin elastic beam under the force *f* can be given as:

$$y = \frac{fl^3}{3EI} \tag{2}$$

where *E* is Young's modulus, and *I* is moment of inertia of the thin elastic beam.

$$I = \frac{bh^3}{12} \tag{3}$$

b and *h* are width and thickness of the thin elastic beam, respectively. Substituting equation (3) into equation (2) gives:

$$y = \frac{4fl^3}{Ebh^3} \tag{4}$$

Thus, the stiffness of the thin elastic beam, which is felt by the human fingertip at the touch cap of the device, can be expressed by an elastic coefficient as

$$k = \frac{f}{y} = \frac{Ebh^3}{4l^3} = \rho\frac{1}{l^3} \tag{5}$$

$\rho = \frac{Ebh^3}{4}$ is the gain of the stiffness. Equation (5) shows the stiffness at the free end of the cantilever k is proportional to the third power of reciprocal of the deformable length l, which indicates that the stiffness k can be changed with wide range as l is changed.
Differentiating both sides of equation (5) with respect to time yields stiffness change ratio as

$$r_k = \frac{dk}{dt} = \frac{dk}{dl}\frac{dl}{dt} = -3\rho\frac{1}{l^4} \times v_{motor} \tag{6}$$

From the above formula, we know r_k is proportional to the fourth power of reciprocal of the deformable length l, which indicates that the stiffness k can be changed very quickly as l is changed, especially when $l \to 0$, $r_k \to \infty$. Therefore the above formula means the ability of real time stiffness display based on CDLEE in our device.

5. Position control for real time softness display

Section 4 implies the key issue of the real time softness display actually is how to realize the real time position control of the carriage, which determines the deformable length l of the elastic beam. Here, PD controller is employed for the real time position control. The control structure for the real time softness display is seen in Figure 11.

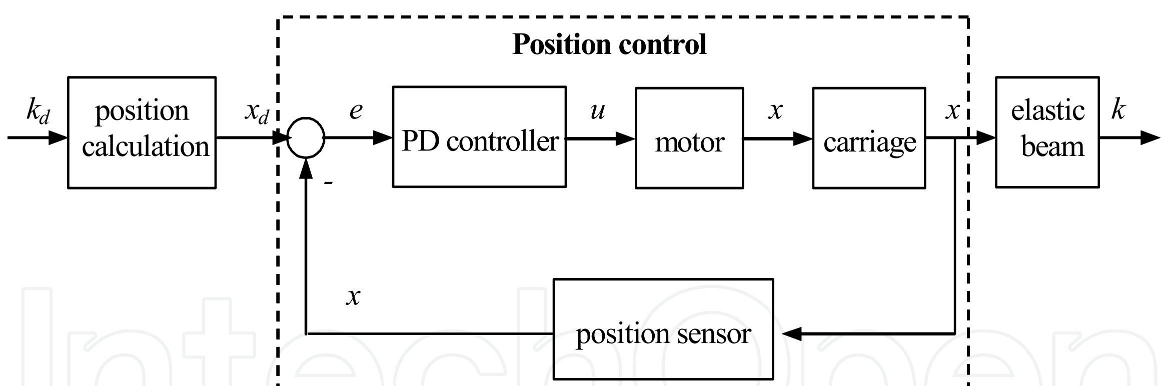


Fig. 11. Control structure for real time softness display

where k_d is a destination stiffness to display, which comes from the virtual or remote soft environment. x_d is a destination position of the carriage, which equals to the destination deformable length of the thin elastic beam l_d. Rewriting equation (5), we have

$$l_d = \sqrt[3]{\rho / k_d} \tag{7}$$

$$x_d = l_d = \sqrt[3]{\rho / k_d} \tag{8}$$

ρ can be estimated by calibrating the stiffness change with respect to the deformable length of the thin elastic beam l. To simplify the estimation of ρ, let $z = 1/l^3$, and substitute it into equation (5), so that the power function in equation (5) can be transformed into a linear function as

$$k = \rho \cdot z \tag{9}$$

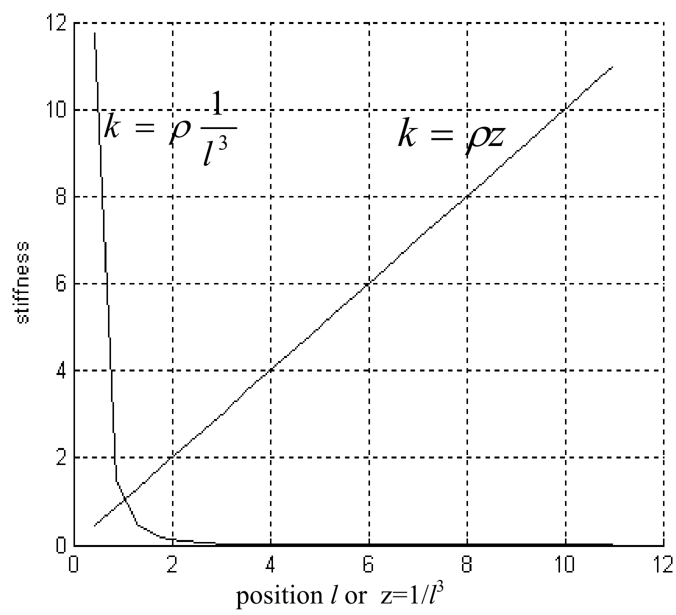


Fig. 12. Transform the power function into linear function

LMS method is used to estimate the parameter ρ as follows

$$\frac{\partial \sum_{i=1}^{n} |e_i|^2}{\partial \hat{\rho}} = 0 \tag{10}$$

where e_i is error of each measurement point.

$$e_i = k_i - \hat{\rho} \cdot z_i \qquad i = 1,\Lambda\ ,n \tag{11}$$

where k_i is the ith measurement value of stiffness at the ith point z_i.
So that,

$$\sum_{i=1}^{n}(k_i - \hat{\rho}\cdot z_i)z_i = 0$$

$$\hat{\rho} = \frac{\sum_{i=1}^{n} k_i z_i}{\sum_{i=1}^{n} z_i^2} \tag{12}$$

The PD controller used here for position control of the carriage can be expressed as

$$u = K_p e + K_d \frac{de}{dt} \tag{13}$$

$$e = x_d - x \tag{14}$$

where K_p is proportional control gain, K_d is differential control gain, and e is error between the destination position x_d and the current real position x.

6. Real time softness haptic display device

The real time stiffness display interface device based on CDLEE method is shown in Figure 13, which is composed of a thin elastic beam, a motor with an encoder, feed screw, carriage with nut, force sensor, position sensor, and a touch cap.

The material of the thin elastic beam in the stiffness display interface device is spring steel, whose Young's modulus of elasticity is $E = 180\times10^9\ N/m^2$. The size of the thin elastic beam is set as 80mm long × 0.38mm thick × 16.89mm wide.

Substituting the above parameters into equation (5) can yield the minimum stiffness of the device:

$$k_{\min} = 0.1287\times10^3 N/m = 0.13N/mm$$

K_{min} is the minimum stiffness of the softest object. Thus, the stiffness display range of the device is from 0.13×10^3N/m to infinite, which almost covers the stiffness range of soft tissues in human body.

The position of the carriage is measured by an encoder with resolution of 8000 CPR. The displacement of the touch cap, which equals to the deformation of the end point of the thin elastic beam, is measured by a resistance based position sensor with 1% linearity. And the force acted by a fingertip on the touch cap is measured by a full bridge arrangement of resistance strain gauges with 0.05N accuracy. The range of up-down movement of the touch cap when human fingertip jiggles it is from 0 to 2 cm.

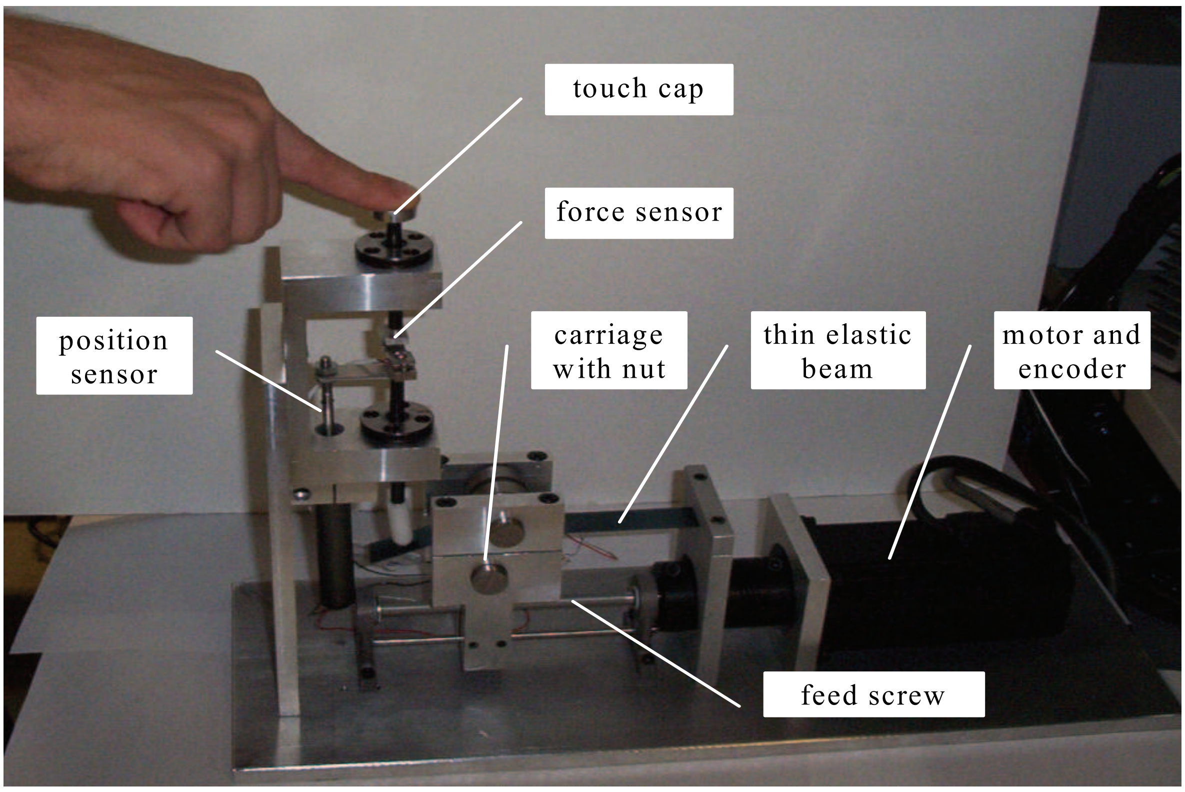


Fig. 13. Real time softness haptic display device

7. Calibration results

The results of stiffness calibration of the softness haptic display device are shown in Figure 14. According to equation (12), the fitting curve of the relation between stiffness and $z = 1/l^3$ is shown in Figure14, and the $\hat{\rho}$ is estimated as

$$\hat{\rho} = 4.05 \times 10^4 (N \cdot mm^2)$$

The Figure 14 and Figure 15 demonstrate the validity of the equation (5), although there exists some difference between experimental curve and fitting curve. The difference mainly comes from the effect of friction between the cantilever beam and the carriage, and from the effect of nonlinear property when the length of the cantilever beam becomes small and the ratio of end point deformation to the length of the cantilever beam becomes large.

In order to overcome the bad effects of friction and nonlinear property so as to control the deformable length of the thin elastic beam precisely, we make a table to record the relationship between the stiffness and the deformable length of the beam point by point based on calibration data. And a table-check method is used for transforming a destination stiffness to a destination length of the cantilever beam.

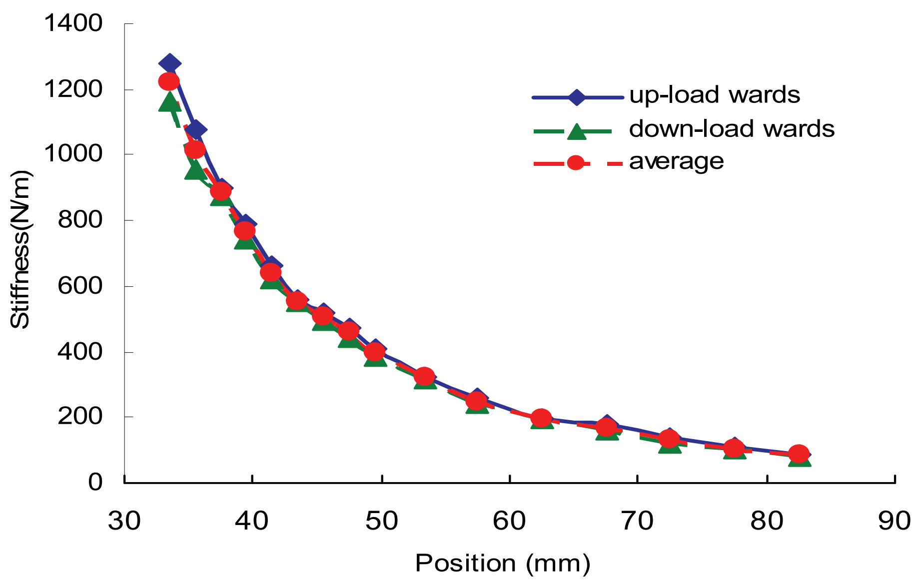


Fig. 14. Results of stiffness calibration

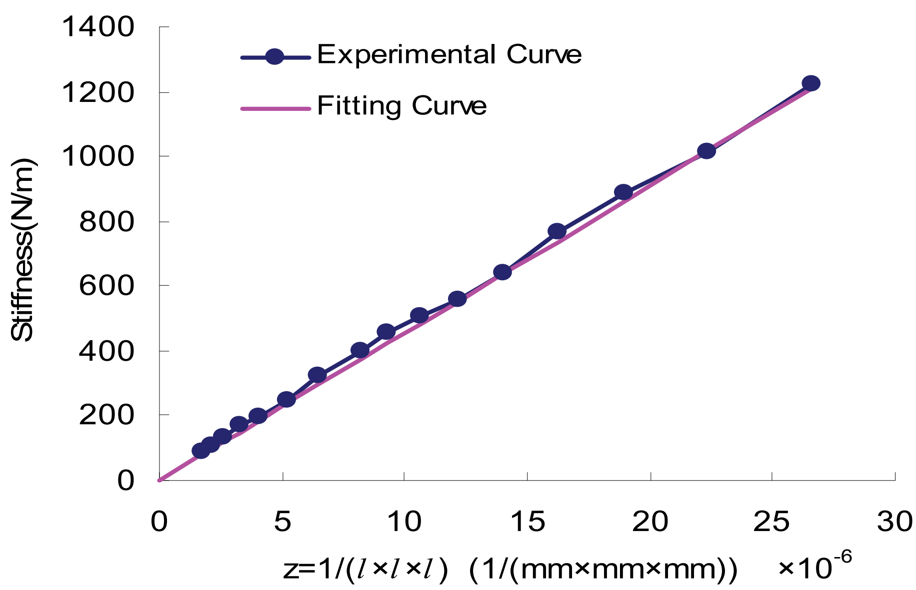


Fig. 15. Fitting curve of characteristic of stiffness

The result of the position control of the carriage is shown in Figure 16. Here, the proportional control gain and the differential control gain of the PD controller are set as

$$K_p = 5 \times 10^{-3}$$

$$K_d = 1.6 \times 10^{-4}$$

The above setting is based on experience and some experiment results.
Figure 16 implies the control of deformable length of the thin elastic beam is real time control.

The trajectory of stiffness display which tracks the destination stiffness change of a virtual soft object is shown in Figure 17. Note that the destination stiffness is set as step square pulses, which corresponds to the typical change of stiffness of some soft tissues with blood vessels beneath the surface.
The stiffness display experiment results demonstrate that the stiffness display interface device is able to replicate the stiffness of the virtual soft object quickly and accurately.

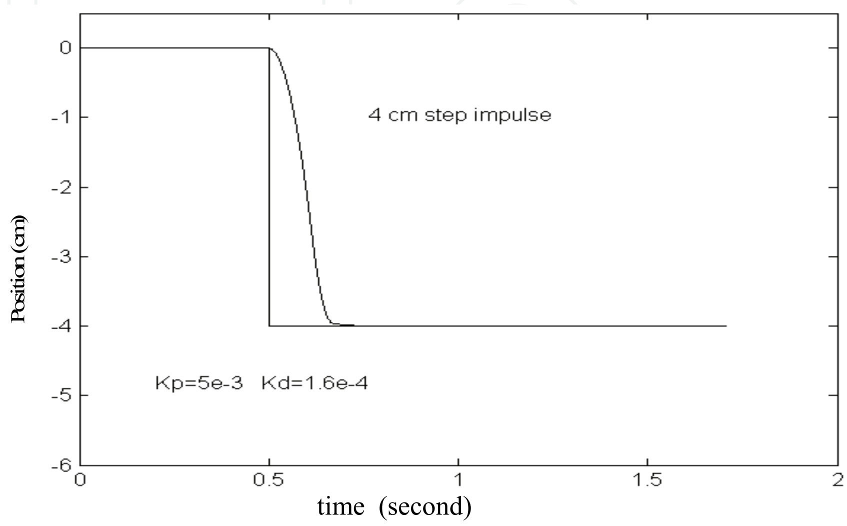


Fig. 16. Position control result

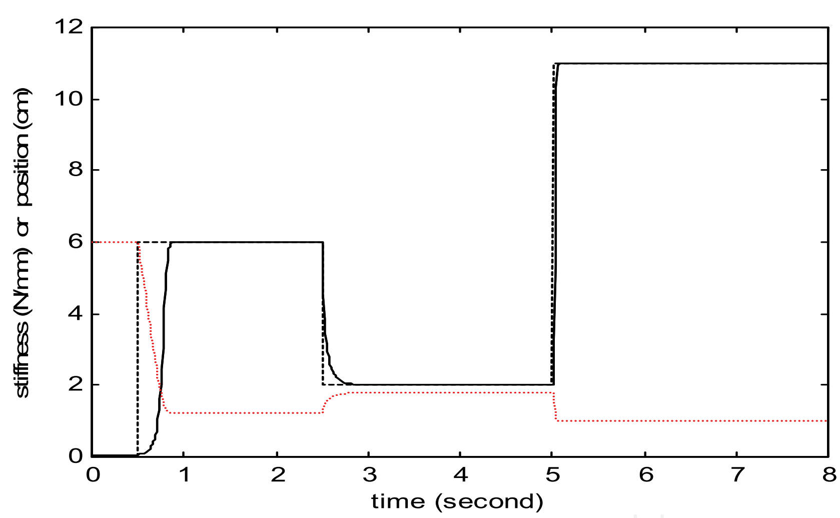


Fig. 17. Stiffness display experiment results. The solid line represents displayed stiffness, the dashed line represents destination stiffness, and the dotted line represents position of the carriage controlled by PD controller.

8. Portable softness display device

During the past decade, many haptic display devices have been developed in order to address the somatic senses of the human operator, but only a few of them have become widely available. There are mainly two reasons for that. Firstly, the costs of devices are too expensive for most people to afford. Secondly, most of the devices are not easy to carry around. It is necessary to seek a more efficient implementation in terms of cost, performance and flexibility.

Based on the softness display device proposed in section 7, a new low-cost, truly lightweight and highly-portable softness haptic display device is presented shown in Figure 18. This device can be easily carried in the user's hand with compact dimensions (10cm x 7cm x 15 cm). Its total expense is less than 150 US Dollars. Thus it will encourage people to use haptic devices.

The material of the elastic thin beam is spring steel, whose Young's modulus of elasticity is $E=180\times10^9 N/m^2$. The size of the thin elastic beam is chosen as 9 mm long, 1 mm thick, and 0.3 mm wide. The stiffness display range of this device is from 25N/m to 1500N/m.

The position of the carriage is measured by a step motor. The displacement of the touch cap, which is equal to the deformation of the end point of the thin elastic beam, is measured by a Hall Effect position sensor fixed under the touch cap with 0.1 mm accuracy. And the force applied by a human fingertip on the touch cap is measured by a touch force sensor fixed on the top of the touch cap with 9.8 mN accuracy.

The most important advantage of this device is that a computer mouse can be assembled at the bottom of the device conveniently. Two shafts are designed and installed on each side of the touch cap and contact to the left and right mouse buttons, respectively, which is used for transferring the press of human fingertip to the left and right mouse buttons, respectively, so the human finger is easy to control the left and right mouse buttons when he use the portable softness haptic display device. The device is a good interface that succeeded to combine both pointing and haptic feature by adding stiffness feedback sensation.

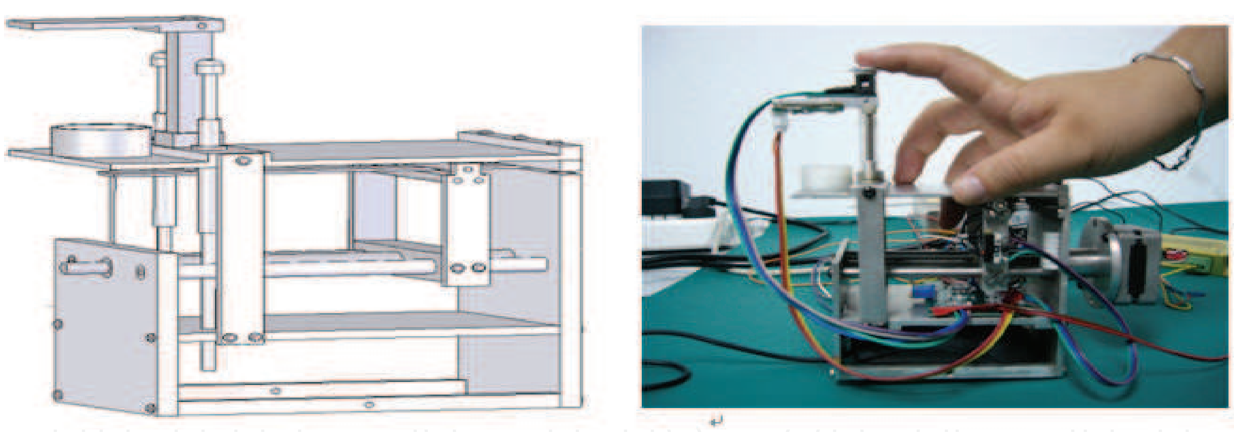


Fig. 18. Portable softness haptic display device

9. Softness haptic human-computer interaction demo system

Most human–computer interaction systems have focused primarily on the graphical rendering of visual information. Among all senses, the human haptic system provides unique and bidirectional communication between humans and their physical environment. Extending the frontier of visual computing, haptic display devices have the potential to increase the quality of human-computer interaction by accommodating the sense of touch. They provide an attractive augmentation to visual display and enhance the level of understanding of complex data sets. In case of the palpation simulator, since the operator wants to find an internal feature of the object by touching the object, the haptic information is more important than the visual information. In this section, we construct a softness haptic human-computer interaction demo system by using the softness haptic display device. The haptic human-computer interaction system is shown in Figure 19, which provides visual and haptic feedback synchronously allowing operators to manipulate objects in the virtual environment. The virtual environment consists of 3D virtual object models, a visual feedback part and a stiffness feedback part.

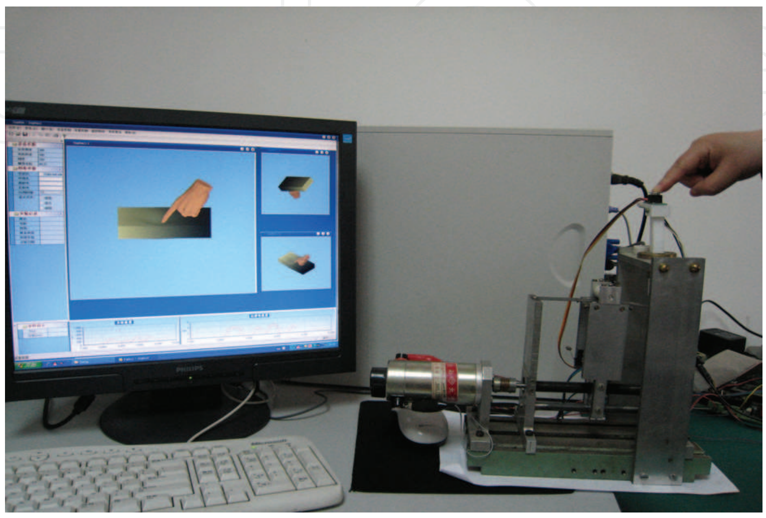


Fig. 19. Haptic human-computer interaction demo system based on the softness haptic display device

The software of the demo system is implemented by Visual C + + MFC and OpenGL programming based on MVC (Model-View-Controller) pattern. The MVC pattern divides an interactive application into three parts. The model contains the core functionality and data. Views display information to the user. Controllers handle user input. Views and controllers together comprise the user interface. A change propagation mechanism ensures consistency between the user interface and the model. Figure 20 illustrates the basic Model-View-Controller relationship. The purpose of the MVC pattern is to separate the model from the view so that changes to the view can be implemented or even additional views created, without affecting the model.

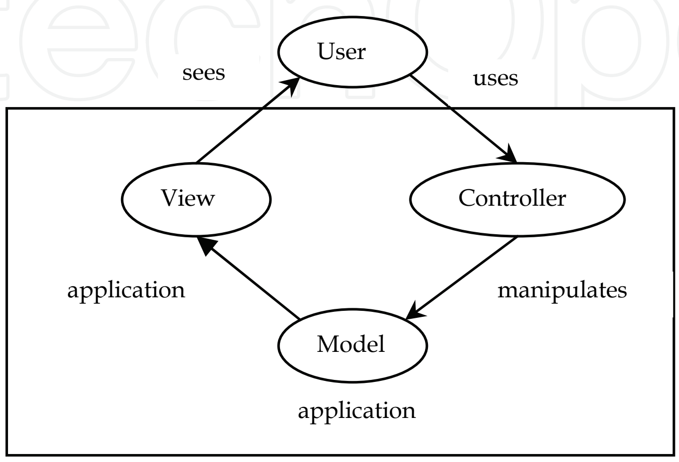


Fig. 20. The basic Model-View-Controller relationship

A 3D virtual model plays an important role in many simulators. Due to the computational burden, the main type of virtual objects for various stimulators is a surface model. We adopt a shortcut method of three dimensional simulated realization combining OpenGL programming technology and 3DS MAX software. The simulated surfaces are divided into small triangles. The Gauss deformation model is used to simulate the deformation of virtual objects. Figure 21 shows the sequence diagram of the system.

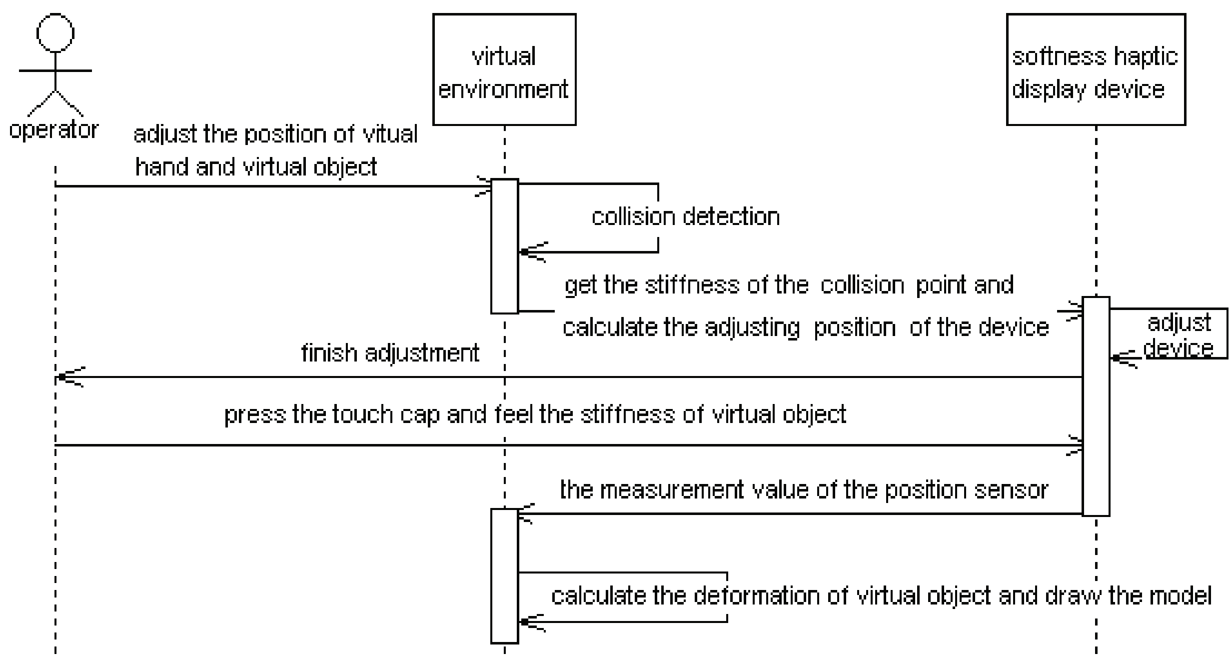


Fig. 21. Sequence diagram of the haptic Human-computer interaction system

A human operator controls the position of the virtual hand by mouse and keyboard. When the virtual hand contacts with the virtual object, the stiffness of the virtual object at the touch point is calculated and fed back to the softness display haptic device. Then by controlling the elastic beam deformable length based on PD controller, its stiffness tracks the stiffness of a virtual object, which is directly felt by the fingertip of human operator. The up-down displacement of the operator's fingertip is measured by the position sensor as command to control the movement of virtual fingertip up-down. At the same time, the deformation of the virtual object is calculated by deformation algorithm. The human operator could feel the stiffness of the virtual object via a softness haptic display device and observe a real time graphics in the screen simultaneity.

We use two virtual objects for simulation. A virtual cube with different stiffness distribution (nonhomogeneous object) in the surface is modeled using 5600 triangular meshes with 3086 nodes. And a liver with same stiffness distribution (homogeneous object) has 6204 triangular meshes with 3104 nodes. Figure 22 and Figure 23 show the deformation simulation. According to the softness haptic model, when a virtual hand finger contacts with the virtual object, the softness haptic display device is able to replicate the stiffness of the virtual object quickly and accurately.

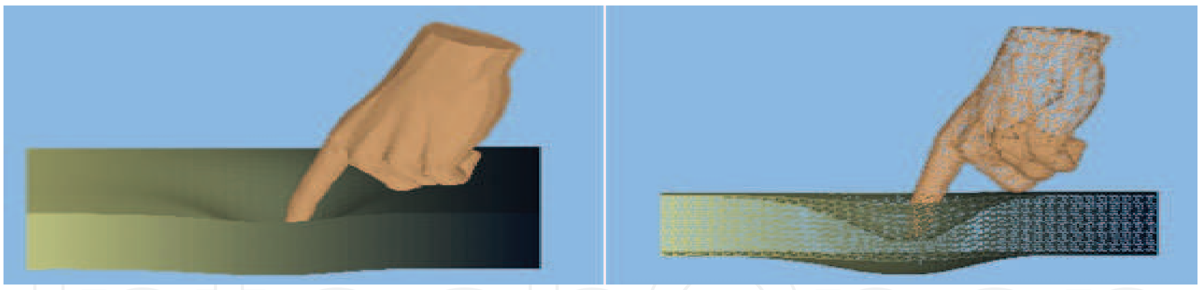


Fig. 22. Deformation simulation of a virtual soft cube with different stiffness distribution

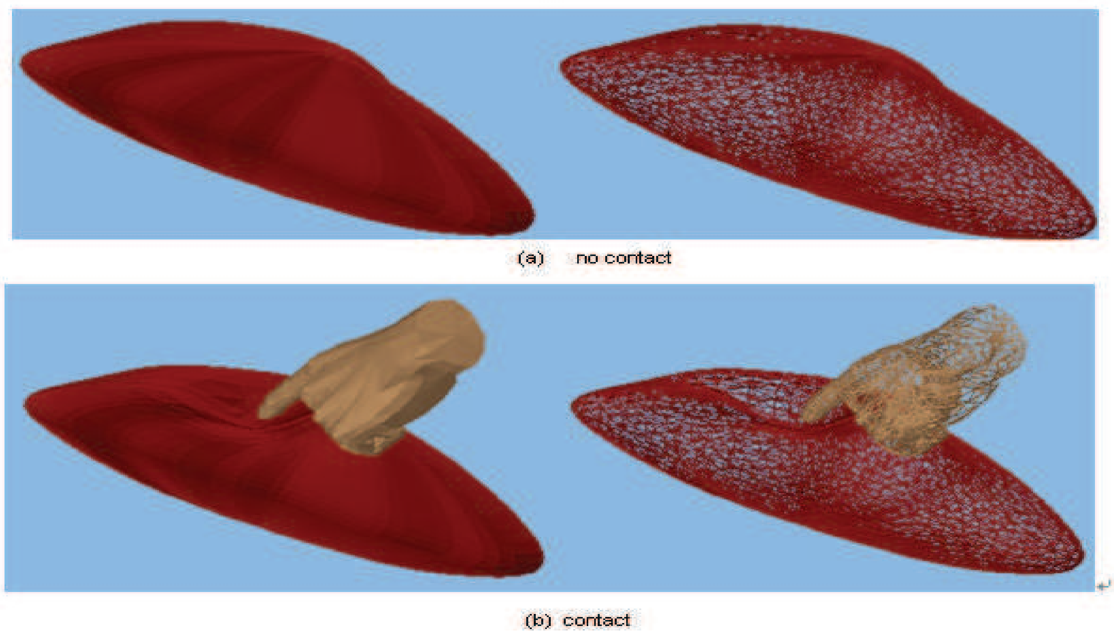


Fig. 23. Deformation simulation of a virtual liver with constant stiffness distribution

To establish the realism to the human operator, the softness haptic display device must be kept operating at 100Hz at least. But an acceptable refresh rate for stable visual feedback is 30Hz. This can be accomplished by running different threads with different servo rates. In our program, three main threads exist. The visual-rendering thread is typically run at rates of up to 30 Hz. The acquisition thread is run as fast as possible congruent with the simulated scene's overall complexity. A collision-detection and deformation thread, which computes a local representation of the part of the virtual object closest to the user avatar (e.g. virtual hand), is run at slower rates to limit CPU usage.

10. Conclusion

This chapter reviews the development of haptic display devices especially softness haptic display devices, and give the general principles of the softness haptic display device design for HCI. According to the proposed design principles, a novel method based on control of deformable length of elastic element (CDLEE) to realize the softness haptic display for HCI is proposed. The proposed softness haptic display device is composed of a thin elastic beam and an actuator to adjust the deformable length of the beam. The deformation of the beam under a force is proportional to the third power of the beam length. By controlling the deformable length of the beam, we can get the desirable stiffness quickly. And a portable softness haptic display device is also developed, which is convenient to be connected with a mouse. The softness haptic human-computer interaction demo system based on the proposed device demonstrates the softness haptic display device is well suitable for haptic human-computer interaction.

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