Design of A Force-Reflecting Device and Embedded Controller

Dae-Hyun Kim*, Cheol-Hong Moon**, Han-Soo Choi***, and Yeong-Dong Kim***

*Department of Photoelectronic Information Engineering, Chosun College of Science & Technology, Gwangju, Korea
(Tel : +82-230-8036; E-mail: daehkim@chosun.ac.kr)
**Division of Photocommunication and Electronics Engineering, Gwangju University, Gwangju, Korea
(Tel : +82-670-2293; E-mail: chmoon@gwangju.ac.kr)
***Department of Information, Control and Instrumentation Engineering, Chosun University, Gwangju, Korea
(Tel : +82-62-230-7185, 7032; E-mail: hschoi, ydkim@chosun.ac.kr)

Abstract: It is well understood that force reflecting coupled with visual display can be an important two-way communication channel in human-computer interaction. In this work, important components for a high-fidelity system bandwidth are force reflecting device and that all the computations including contact determination and response computation have to be performed in less than a millisecond. This paper describes a force-reflecting device and an embedded controller. The realized force-reflecting device is based on a novel serial type mechanical structure, and features compactness, high sustained output force capability, low friction, zero backlash, and enough workspace. The embedded controller reduces software computational load via main processor and simplifies hardware strictures by the time-division control. The device is integrated with existing dynamic simulation algorithms running separate workstation, so that objects can be manipulated in real time and the corresponding forces felt back by the operator.

Keywords: force-reflecting, embedded controller, virtual reality, simulation

1. INTRODUCTIONS

Virtual reality system is a powerful tool for training, simulation, and computer aided design. This system is based three main techniques such as computer graphics, force sensation or haptic display, and audio. In most of the current applications the focus is in providing a good visual display to the user, trying to improve the tracking registration and the resolution-refresh rate of head mounted displays [1-3]. However, the lack of force sensation makes the interaction unreal and more difficult to manipulate virtual environment. To increase the reality, the representation of force sensation has become an important topic of research for improvement of reality in a virtual environment [4-6]. A force reflecting interface is a device that lets the user touch, feel and manipulate virtual objects with the force sensation. To provide realistic interaction between the user and the simulated environment a force reflecting interface must accurately reproduce the dynamic behavior of the simulated environment and be easy and natural for the user to manipulate. It is well known that force-reflecting interfaces need to have low inertia, good dynamic response, workspace, and very smooth motion to avoid imparting artificial sensations to the user [7].

The history of force reflecting interfaces dates back to the 1950s, when a master-slave system was proposed by Goertz [8]. Since then, a number of master devices have been developed. The main desirable characteristics are quick response and a wide workspace. In addition, compactness is also desirable, since the force reflecting interface should be treated in a way similar to a conventional computer 3D mouse. An exoskeleton type master device is one possible solution for displaying arm motion within a large workspace. However, practical realization is difficult [9], and besides, one cannot expert quick motion. In terms of quick motion, the magnetic levitation haptic interface of Berkelman [10] is very appealing, but its workspace is very small. Quick motion can be also achieved through a wired system, e.g. SPIDER [11]. Such devices occupy, fully 6-DOF parallel mechanisms [12-13] are characterized with restricted workspace for orientation. To increase the workspace, parallel mechanisms with kinematic redundancy can be employed [14].

The solution in commercial force-reflecting devices such as Sensable Device [15] and Immersion's Impulse Engine [16] is to use low-friction, low inertia DC servomotors connected to a linkage through a cable transmission. These devices, that provide torque feedback in addition to force display within a large translation and rotational range of motion, are very useful for such applications. Although a number of commercial and research force-reflecting devices are becoming available, their applications have been limited. This is mainly due to the higher cost and the complexity of accurate calculation of all the contacts and restoring forces that must be computed in less than one millisecond. This consideration moved us to develop an embedded controller which reduces software computational load via main processor and simplifies hardware strictures by the real-time control.

This paper introduces a 6 degree-of-freedom force reflecting device whose design is based on serial mechanism. The device designed to have compact size, low friction, zero backlash, enough workspace and high mechanical rigidity. The inner links are driven by dc servo motors through tensioned cable drive. In addition, the embedded controller was developed. The current implementation of the controller is based on usb processor [17]. The controller contains 6-channel encoder counters, 3-channel digital to analog converter for end-effector sensors and general digital I/O, etc. This would make the system more mobile and allow multiple devices to be run simultaneously.

2. DESING SPECIFICATIONS

An ideal force-reflecting device should be able to display motion in 6 degree-of-freedom, to realized quick motion, to provide enough workspace, and to have compactness. The quick motion is needed to display mainly a free motion of the object. In addition, the ability of quick motion yields also a possibility of texture representation. The enough workspace is needed to avoid saturation on terms of position/orientation. The compactness is needed to satisfy the desktop environment constraints. Furthermore, a compact force-reflecting has the potential of a new 3 dimensional input/output device which can determine a new and appealing way of interaction between

computer and human.

(a) Front view   (b) Rear view

(c) Top view   (d) Cable transmission
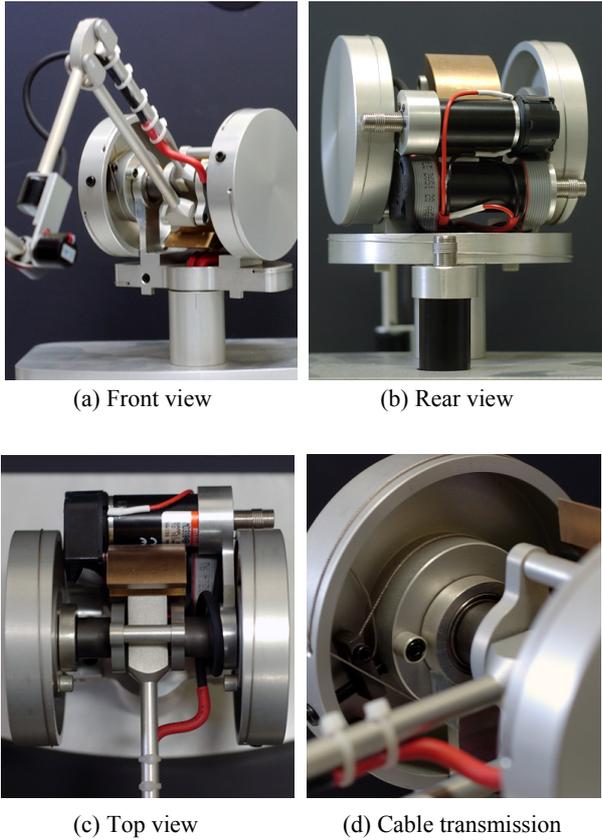
Fig. 1 Photographs of the force-reflecting device
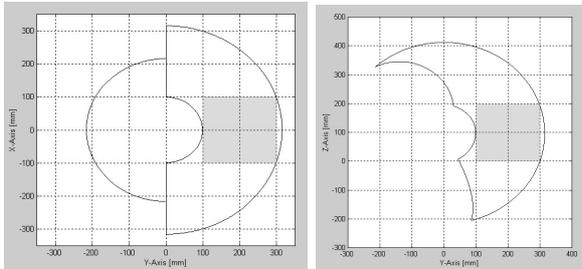
Fig. 2 Effective workspace of the force-reflecting device

To realize such a force-reflecting device, we decided to use serial linkage mechanisms as shown Fig.1. A serial mechanism has the ability of high power, high precision motion, and large workspace. One of the design criteria was that the transmission should be zero backlash. Several readily available gear reductions were examined, but all had at least 0.2 degrees of backlash. A direct-driven design that would need no transmission reduction was considered, but this required using motors with a higher stall torque. It was decided that only a cable transmission could meet the zero backlash specification with very little friction, while at the same time achieving a transmission reduction. Because the cables can be pretensioned as shown Fig.1(d), the backlash in a cable transmission can be made zero. The transmission also consists of a four-bar linkage with preloaded bearings and a pretensioned cable reduction. The maximum exertable force of the device was mea-

sured with the device located in the center of the workspace. The force-reflecting device was capable of exerting 11.2 newtons of peak force along the x and z axes, see Fig. 2. Due to slight higher transmission ratio for the first motor, a peak force of 12.7 newtons was possible along the y axis. The device has a workspace as shown in Fig. 2. The workspace is such that, a user resting his forearm on a table, will not be able to reach the limits of the device with stopper shown in Fig. 1(d). Although the workspace is large rectangular in nature, a box with dimensions of 20 by 20 by 20[cm] would fit within the space.

3. COMPENSATION FOR GRAVITY BALANCE

The compensation for gravity balance is extended from the design of [18]. Since the dynamics of joint 0 is not affected by gravity, only the dynamics of joint 1 and 2 are considered. The dynamic equations of joints are

$$\tau_1 = I_{11}\ddot{\theta}_1 + I_{12}\ddot{\theta}_2 + (\partial I_{12}/\partial\theta_2)\dot{\theta}_2^2 + \varphi_1,$$
$$\tau_2 = I_{21}\ddot{\theta}_1 + I_{22}\ddot{\theta}_2 + (\partial I_{21}/\partial\theta_1)\dot{\theta}_1^2 + \varphi_2, \qquad (1)$$

where, τ_i is the motor torque, I_{ij} is an element of the inertia matrix, φ_i is the derivative of potential energy with respect to joint angle θ_i, $\ddot{\theta}_i$ and $\dot{\theta}_i$ are joint angular acceleration and velocity respectively. The last term of the right hand side represents the gravity effect on the manipulator. Therefore, the compensation aims to eliminate this term. The I_{12}, I_{21} and φ_i are expressed as

$$I_{12} = I_{21} = (m_3 l_2 l_{c3} - m_4 l_1 l_{c4})\cos(\theta_2 - \theta_1), \qquad (2)$$
$$\varphi_1 = g(m_1 l_{c1} + m_3 l_{c3} + m_4 l_1)\cos\theta_1, \qquad (3)$$
$$\varphi_2 = g(m_2 l_{c2} + m_3 l_2 - m_4 l_{c4})\cos\theta_2. \qquad (4)$$

where m_i is the mass of link and g is the gravitational acceleration.
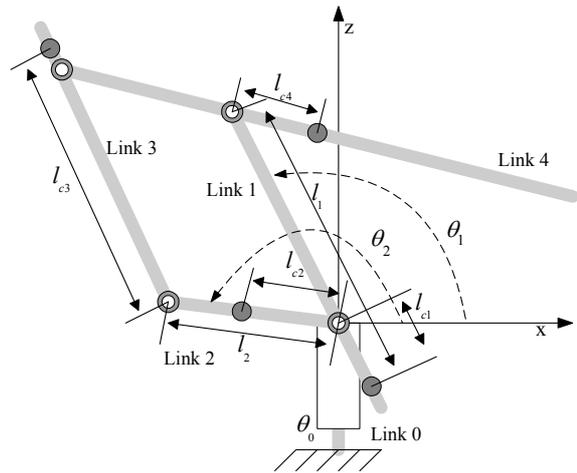
Fig. 3 Schematic of the gravity balanced manipulator

The following conditions are used in [18] to decouple the joint dynamics and cancel the gravity effect on joint 2.

$$m_3 l_2 l_{c3} = m_4 l_1 l_{c4}, \qquad (5)$$
$$m_2 l_{c2} + m_3 l_2 = m_4 l_{c4}. \qquad (6)$$

Consequently, the terms I_{12}, I_{21} and φ_2 become zero. Also, the manipulator has the property of $l_{c3} > l_1$. A similar method is used to cancel the gravity effect on joint 1. By having a negative value of l_{c1}, a solution can be found for

$$m_1 l_{c1} + m_3 l_{c3} + m_4 l_1 = 0 . \tag{7}$$

Consequently, φ_1 in Eq. (3) becomes zero. The physical interpretation of a negative l_{c1} is to place the center of mass of link 1 on an extension as shown in Fig. 3. The complete dynamic equation of the gravity balanced manipulator becomes

$$
\begin{aligned}
\tau_0 &= (I_{11}\cos^2\theta_1 + I_{22}\cos^2\theta_2)\ddot{\theta}_0 - (I_{11}\dot{\theta}_1 + I_{22}\dot{\theta}_2)\dot{\theta}_0 \\
\tau_1 &= I_{11}\ddot{\theta}_1 + 0.5 I_{11}\dot{\theta}_0^2 \\
\tau_2 &= I_{22}\ddot{\theta}_2 + 0.5 I_{22}\dot{\theta}_0^2
\end{aligned}
\tag{8}
$$

The force-reflecting device has gravity balance in all configurations and decoupled dynamics between joint 1 and 2.

4. EMBEBBED CONTROLLER DESIGN

The force-reflecting device has three active joints and three passive joints, each of which is equipped with an encoder for position sensor, and dc servo motors for three active joints. There are no controllers with these functions commercially but exist controllers which have separated function at high cost. The following are some of the things we considered when designing the force-reflecting system: 1) never assume motors are at ambient temperature when an application starts, 2) provide for absolute torque limits at all times, 3) do as may calculations as possible on dedicated processor to reduce the workload on the application computer, 4) reduce or eliminate complexity. Based on the above design philosophy, we created a controller for the force-reflecting device. We provide additionnal processors between the force-reflecting device and the application computer. This would make the system more mobile and allow multiple devices to be run simultaneously. One of those processors is essentially an embedded controller which controls the force-reflecting device directly using information received from the application computer over an USB connection. Fig. 4 shows the force-reflecting system overview. Using this controller, the programmer no longer needs to set and read bits directly on the application software. The user can create small packets of information, like torque, positions, and convey those directly to the controller over the USB pipeline stream. Information is conveyed back to the application using the same communication channel.
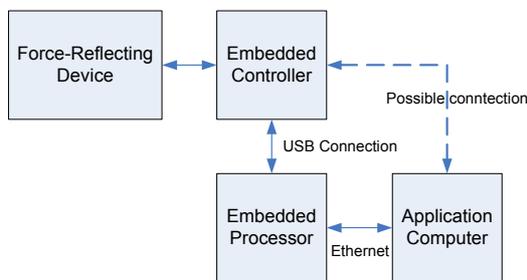
Fig. 4 The force-reflecting system setup

The developed controller includes 6 channel encoder counters, a 12-bit digital-to-analog converter for motor amplifiers, a fast-speed analog-to-digital converter for current measurement, and digital I/O. The joint positions measured by encoders are acquired through 24-bit counter chips, and the servo values for current amplifiers are controlled through 12-bit converters so that the joint torque is set to the desired value. To send data to a USB peripheral, we use the fast and interrupt transfer modes.
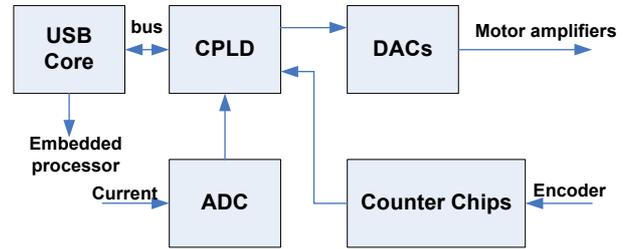
(a) Block diagram

(b) Photography of the controller
Fig. 5 Embedded controller block diagram

The fast transfer mode gave us the minimization of the transfer time from controller also supplies external FIFO read and write strobes to synchronize the transfer. A firmware of the controller provides the USB connectivity and 64byte data transformation at a time. The current implementation of the embedded processor is based on 2.4 GHz Pentium running a real time Linux operating system. Fig. 5 shows the block diagram consist of the controller and specifications of each component are summarized in Table 1.

Table 1 Major specification lists of the controller

Items	Major Specifications	Manufacturer
Encoder Counter	No.: LS7166 Resolution: 24Bit Input Signal: A, B phase	US-Digital
D/A Converter	No.: DAC7744E 12 Bit resolution, 4 channel	TI
A/D Converter	No.: ADS7805 12Bit resolution	TI
USB	No.: AN2131QC Include 8051 core	Cypress
CPLD	No.: EMP7160 family Programmable logic device	Altera

5. APPLICATION: VIRTUAL PUZZLE

5.1 Friction model

Static friction is particularly simple to model within the

virtual point framework as shown in Fig. 6. The force exerted on the virtual point by the user can be estimated by the simple equation $f = k_p(vp - p)$, where vp is the position of the virtual point, p is the position of the finger and k_p is the proportional gain of the control system. For a given constraint plane let f_n and f_t be the components of the force on the virtual point normal and tangential to the constraint plane, respectively. If the given constraint surface has a static parameter μ_s, then the virtual point is in static contact if $\|f_t\| \le \|f_n\|$. When any constraint surface is in static contact the virtual point is left unchanged.
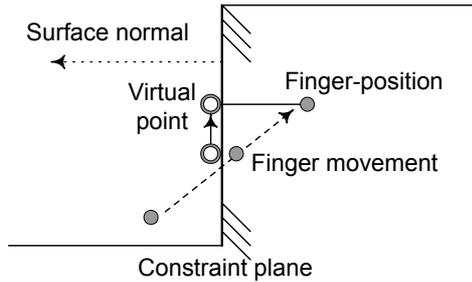
Fig. 6 Constraint plane for puzzle piece

Viscous and dynamic friction can be modeled by observing the motion of a one-dimensional object. The equation of motion of an object with mass m moving in a viscous field, along a surface that exhibits dynamic friction [19] is

$$f - \mu_d f_n = m\ddot{x} + b\dot{x} \qquad (9)$$

where b is a viscous damping term, μ_d is the coefficient of Coulomb friction. As the mass of the object approaches zero, the body quickly reaches its saturation velocity. In dynamic equilibrium, the velocity of the object is given by

$$\dot{x} = (f - \mu_d f_n)/b \qquad (10)$$

This limit can be used to bound the amount that the virtual point can travel in a given frequency period. In the event that the maximum velocity is negative, then the dynamic friction term is sufficient to resist all movement and the virtual point is not changed. In case that $b = 0$, no viscous term exists and the maximum velocity is not limited. This approach does not use the finger's velocity and is therefore not susceptible to errors caused from trying to estimate this value from encoder readings.

5.2 Virtual Puzzle

The graphic rendering system normally utilizes very expensive high-end workstations with dedicated graphic cards and graphic software to generate high fidelity visual image. In this paper, an economical, yet very efficient visual system computer has been set up with a Pentium IV 3 GHz and a Glint 500TX 3D graphic accelerator which runs under Windows NT®. Class library, so we called GL2004, has been developed using OpenGL [20] and GLUT, and virtual objects have been modeled using VRML. The update frequency of the graphic rendering was 25Hz and that of the force was 1 KHz. We have developed a simple virtual puzzle game as shown in Figure 7. Operator can move a puzzle piece in virtual environment. In the free space shown in Figure 7(a), the operator can freely move the hand. The contact state as in Figure 7(b), the

operator feels the contact on the puzzle piece as if he/she pushes the virtual wall continually. The contact is stable without any undesired vibration since sufficient damping is provided. When the operator moves the puzzle piece to a desired position and orientation as shown in Figure 7(c), the reaction force directed backward increases as the puzzle piece that is constrained by the stiffness moves forward. Although the sounds played for the audio feedback are not precisely synthesized based on the mechanical model of contacting and moving, it assists the operator for recognizing the state transition as well as the force sensation.
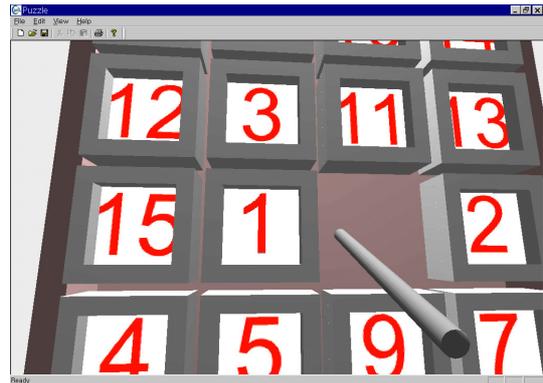
(a)   Free state at the beginning
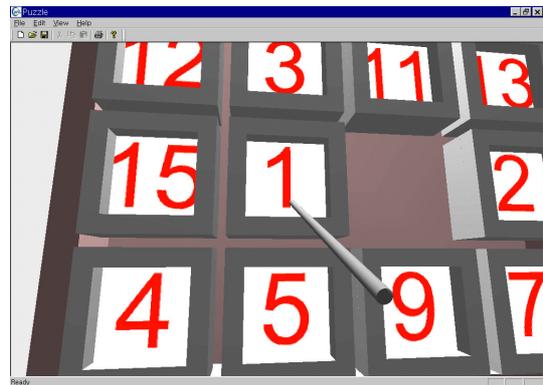
(b)   Contact state on a puzzle piece
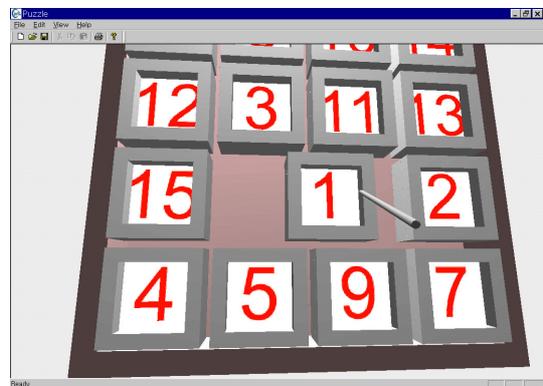
(c)   Move state with surface friction

Fig. 7 Contacting and moving of puzzle

6. CONCLUSIONS

In this paper, the 6 degree-of-freedom force reflecting device whose design is based on serial mechanism. The device designed to have compact size, low friction, zero backlash, enough workspace and high mechanical rigidity. The device has a gravity balance and position compensation for passive link. The force sensation was implemented on the force reflecting interface and experimentally confirmed to provide a realistic sensation of contacting and moving that enable the operator to manipulate the virtual puzzle application. And, the embedded controller was designed. The controller has a good performance under Windows NT system and reduces software computational load via application processor and simplifies hardware strictures by the time-division control. The device is integrated with existing dynamic simulation application running separate workstation, so that objects can be manipulated in real time and the corresponding forces felt back by the operator.

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