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Control of Dexterous Hand Master with Force Feedback

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Abstract

Both five-finger dexterous hand master (NTU master) and dexterous hand slave (NTU hand) have been developed. The NTU master is driven by tendons and the force feedback is applied by remote electric motors via flexible cable. The NTU master is ten DOFs, light weight, portable, easy to wear and has large workspace. In this paper, a DSP-based bilateral control between the master and the slave is developed so that the master can transmit the motion to the slave and receive the perceptual information from the slave by the control. A prediction method is proposed to resolve the time delay due to communication.

1 Introduction

In teleoperation, the use of robot hand as slave end effectors raises the problem of using appropriate master devices for control. When the human operator "wears" such device (the master), he can transmit his hand motion to the dexterous robot hand (the slave) and receive the perceptual information from the slave. The human operator feels as if he was doing the task himself instead of the remote dexterous robot hand [13]. Providing force feedback to the dexterous hand master, the operator will have a better judge to the task status and better prediction to the necessary grasping and manipulation forces. Thus, the operator can wear this dexterous hand master for teleoperation to protect him from adverse environments, such as space, undersea, or nuclear radiation. Virtual reality is another useful and important application of the master hand.

Both five-finger dexterous hand master (NTU master) and dexterous hand slave (NTU hand) have been developed in our laboratory [10,11]. In this paper, a DSP-based bilateral control between the master and the slave is developed so that the master can transmit the motion to the slave and receive the perceptual information from the slave by the control. A prediction method is proposed to resolve the time delay due to communication. The deformation model due to contact force is also further elaborated.

2 Man-machine impedance

The real conditions of grasping an object should be examined before studying the bilateral control of the dexterous hand master and the multifingered robot hand. The contact force will make the grasped object deformed. The degree of the deformation of the grasped object can be felt by the finger tip in accordance with the exerted force [9,14]. The NTU hand master is a glove with shielded metallic shell [13]. After the slave touches an object, the operator can exert force to the metallic shell of the master, then the magnitude of these contact forces will be sent to the slave to make the grasped object deformed. Finally, the amount of deformation of the object will be sent back to the glove (i.e., the hand master). In other words, the dexterous hand master will simulate the deformation of the grasped object after the fingers in contact with the object.

Though the hand master is placed remotely, the slave actually performs the object grasping. Whenever the operator exerts forces to the metallic shell of the master, he will feel his hand is really grasping an object. It is like the real condition that the operator grasps the real object. The whole period of the grasping is essentially the mapping between the magnitude of the contact force and the deformation of the grasped object, see Figure 1. According to the theory of impedance control [3-7], the impedance can be used to represent the relation between the magnitude of the contact force and the deformation of the grasped object. Namely, when the slave grasp an object, there will be an impedance relation between the magnitude of the contact force and the deformation of the grasped object. Note that the dexterous hand master will simulate this impedance, as shown in Figure 1.

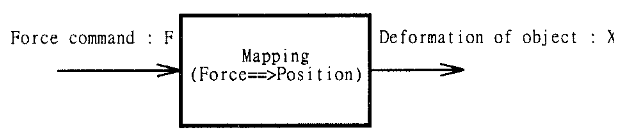

Figure 1 The relation between the force command and the deformation of the object

3 Information flow

In this paper, the master and the slave are controlled in two modes, free mode and constrained mode. The fingers are in the free mode when the fingers of the slave do not touch any objects, and in the constrained mode when the fingers of the slave have interactive force from the grasped object. The communication between the master and the slave is called information flow, as shown in Figure 2.

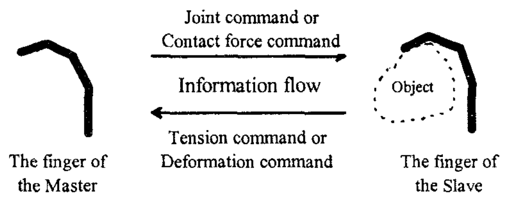

Figure 2 Information flow between the master and the slave

Free mode – from master to slave

The free mode can be separated into two phases: from master to slave and from slave to master. In the free space, the master sends position commands to the slave. Joint angles of the operator's fingers can be obtained from the sensors. The positions and orientations of the fingertips are obtained by the direct kinematics in the coordinates of the master, then compute the joint angles for the slave are computed by the inverse kinematics in the coordinates of the slave [12]. After the conversion of the joint angles between the coordinates of the master and the slave, these position commands (in the slave coordinates) are sent to the slave. Thus, the slave must follow these position commands.

Free mode – from slave to master

The slave provides position feedback to the master. If joints of the slave can not match the position command from the master, then the corresponding tensions are added to these joints according to experience.

$$T_{new} = T_{threshold} + ke^2 \quad (1)$$

where T_{new} is the new tension of the tendon; $T_{threshold}$ is the threshold (pre-load) tension of the tendon; k is the weighting value; e is the joint position error of the slave. Thus, the operator will feel hard to close his finger because the tension of the tendon has increased. The operator must slow down his motion of grasping in order to let the slave keep up with the master.

If the slave can follow position commands from the master, i.e., no joint angle error, then the controller of the sensing glove must keep the tensions of the tendons for a constant value, i.e., pre-load tension force $T_{threshold}$. In short, the master sends position command to the slave and the slave sends tension force command back to the master in free space.

Constrained mode – from master to slave

The fingers are in the constrained mode when the fingers of the slave have contact forces from the grasped object. Namely, the fingers of the slave are in contact with the objects, the operator's fingers exert force to the sensing glove. The tactile sensors are used to sense the contact forces when the finger of operator pushes against this metallic-shell master. These contact forces of the fingertip will be sent to the slave, then the slave should follow these commands of the contact forces for the fingertips. Namely, these contact forces are used to grasp the object.

Constrained mode – from slave to master

The operator wants to feel deformation of the object when the fingers of the slave exert force to the object. The information of deformation must be sent back to the master. Similarly, the transformation is applied to get joint angles of each finger of the master (in the coordinates of the master).

Because of the joint ranges of the NTU hand, not all solutions of the inverse kinematics are suitable for the NTU hand. The results from [13] show that all solutions for the finger 4 (little finger) are out of joint range of the NTU hand due to mismatched finger size. Thus, the above transformation method is not applicable for the finger 4.

4 Using prediction to eliminate time delay

Time delay will be occurred due to the communication between the master and the slave [1,8]. It causes that the slave can not receive the position or the contact force commands from the master immediately, and the operator can not feel the deformation immediately when his fingers exert force to the metallic shells.

These real situations are shown in Figures 3 and 4. $T1$ is the time delay due to communication from the master to the slave, and $T2$ is the time delay due to communication from the slave to the master.

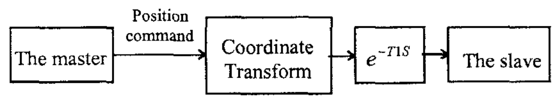

Figure 3 The slave can not receive the position commands immediately (in free mode)

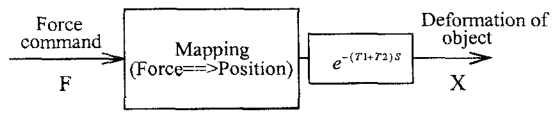

Figure 4 The operator can not feel deformation immediately (in constrained mode)

Predict position commands

In free mode, i.e., the finger of the slave does not touch any object, the polynomial approximation will be used to predict the trajectory of the position of the fingertip in order to eliminate the time delay.

The prediction of X(k+1) is based on the previous position of the finger tip, i.e., X(k), X(k-1),..., X(k-m). Given X(k), X(k-1), ..., X(k-m), an interpolating polynomial through these points can be obtained, and X(k+1) can be estimated from this polynomial.

Predict contact force

When the finger of the slave touches the object, i.e., the finger is in constrained mode, the above polynomial approximation can be used to predict the trajectory of the contact force. Thus, the estimated contact force $\hat{F}(k+1)$ can be obtained.

Predict deformation

Next task is to compute the approximation of deformation for the next time step. Assume that the contact force and the deformation has impedance relation as

$$F = M\frac{d^2x}{dt^2} + B\frac{dx}{dt} + K(x - x_r) \tag{2}$$

Let

$$x = x(k), \frac{dx}{dt} \approx \frac{x(k) - x(k-1)}{T}, \frac{d^2x}{dt^2} \approx \frac{x(k) - 2x(k-1) + x(k-2)}{T^2}$$

where T is the sampling period , then the impedance equation, Eq. (2), becomes

$$\begin{bmatrix} \frac{X(k)-2X(k-1)+X(k-2)}{T^2} & \frac{X(k)-X(k-1)}{T} & X(k) & 1 \\ \frac{X(k-1)-2X(k-2)+X(k-3)}{T^2} & \frac{X(k)-X(k-1)}{T} & X(k-1) & 1 \\ \cdot & \cdot & \cdot & \cdot \\ \cdot & \cdot & \cdot & \cdot \\ \frac{X(k-p+1)-2X(k-p)+X(k-p-1)}{T^2} & \frac{X(k-p+1)-X(k-p)}{T} & X(k-p+1) & 1 \end{bmatrix} \begin{bmatrix} M \\ B \\ K \\ -KXr \end{bmatrix} = \begin{bmatrix} F(k) \\ F(k-1) \\ \cdot \\ \cdot \\ F(k-p+1) \end{bmatrix} \tag{3}$$

M,B,K,Xr can be solved by least square method.

Thus the estimated contact force and Eq. (3) are used to predict the deformation of the grasped object for the next time step as

$$\hat{X}(k+1) = \frac{[\hat{F}(k+1) + (2M/T^2 + B/T)X(k) - M/T^2 X(k-1) + KXr]}{(M/T^2 + B/T + K)} \tag{4}$$

Flowchart of bilateral control

The control includes free mode and constrained mode. The tension of the tendon is controlled in free mode, and the position of the tendon is controlled in constrained mode. The control algorithm is given below:

1. Get the joint angles of the master's fingers. If the joint angles have been reached, then stop.
2. Compute the position of the finger tip by joint angles for each finger.
3. Judge if the finger tip touches an object for each finger.
4. If the finger has touched an object, then the finger is in constrained mode; otherwise it is in free mode, go to step 5.
5. Compute the joint angles of the slave by the position of the finger tip.
6. Send joint commands to the finger of the slave.
7. Get the deformation $X(k)$ of the grasped object.
8. Feedback the new tension of the tendon in terms of Eq. (1).
9. Get contact force $F(k)$ of the finger of the master.
10. Get the deformation $X(k)$ of the grasped object.
11. Compute parameters M,B,K, Xr by least square method.
12. Estimate the deformation for the next time step.
13. After coordinate transform, feedback the joint angles to the master. Go to step 1.

5 Control architecture

A control box is placed remotely to control and drive the NTU master. It includes controller, amplifier, motors, sensors and power protection circuit. The host workstation (Sparc 10) is connected to the NTU master via RS232 cable. The host workstation will simulate the NTU hand, and perform high level computation and 3D user interface. The overall system is shown in Figure 5 and the picture of the control box is shown in Figure 6.

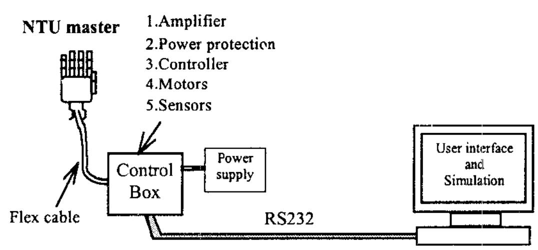

Figure 5 The overall bilateral control system

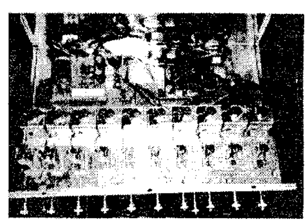

Figure 6 The picture of the control box

Communication

The master sends or receives data via serial connection with host workstation. An Intel 87C51 microprocessor in the control system provides communication with the host workstation. The 87C51 will reduce the load of digital central controller, and enhance the transmit rate up to 19200 baud rate. The data received from or sent to the host computer will be stored in a central memory which is between the digital central controller and the microprocessor.

The communication protocol between the NTU master and the host workstation is developed in this system, as given in Table 1 and 2. The NTU master and host workstation can "talk" to each other based on this protocol. For example, the master reports the values of all sensors (10 motor positions, 5 tactile sensors) to the slave by the protocol "(a,s),x1,x2,x3,.....,x15" (17 bytes), and the slave sends new commands to each joint of the master by the protocol "(y,c),#,x1,x2.....,x10" (13 bytes). Under 19200 baud rate, time delay is about 8.85 ms (17 bytes) in free mode and about 15.6 ms in constrained mode (17+13 bytes). Every talk function has a checksum byte for checking communication error. This checksum byte is the third byte of each data stream.

Protocol	Function Description
(o,k),#	Check if the communication is OK.
(u,b),#,x,x,x,x........	Download new DSP boot ROM.
(d,r),#	Reboot DSP.
(j,s),#,x1,x2	Send new joint state to each joint.
(y,c),#,x1,x2.....,x10	Send new commands to each joint.
(c,s), #	Query checksum of DSP boot ROM.
(m,r),#,x1,x2,x3	Query data of central memory unit, x1 & x2 are address; x3 is length.
(w,m),#,x1,x2,x3,x, x....	Write data to central memory unit, x1 & x2 is address x3 is length, others are data to write.
(q,d),#	Query condition of DSP.
(a,d),#	Check if DSP can response to 8751.
(b,d),#,x	Change baud rate (9600 or 19200 bps).
(t,p),#,x1,x2,x3,x4	Send new tension control parameters.
(p,p),#,x1,x2,x3,x4	Send new position control parameters.

Table 1 The protocol from workstation to 8751(# is the checksum of data stream)

Protocol	Function Description
(o,k)	Report the communication is OK.
(c,s),x1,x2	Report checksum of DSP boot ROM.
(m,r),x1,x2,x3,x,x,x, ...	Report data of central memory unit, x1&x2 is address; x3 is length.
(q,d),x1,x2	Report condition of DSP.
(a,s),x1,x2,x3,.....,x 15	Report values of all sensors.

Table 2 The protocol from 8751 to workstation

Controller

The overall control system shown in Figure 7 includes digital central controller, 87C51 microprocessor, central memory unit, peripherals, a fast-speed analog to digital converter (conversion time is 1.5 us), multiplexers, and analog controllers with power amplifier. This circuit board is four-layer PCB. The central controller is performed by a ADSP 2101 DSP chip [2]. The 87C51 microprocessor performs communication task between DSP chip and the host workstation. The central memory stores data used by the microprocessor and DSP. The DAC peripherals provide up to 19 channels DAC output. Ten DAC output are used here to control ten motors for the NTU master. The multiplexers which could switch up to 40 channels data. 25 channels are used to sense the values of the angles of 10 joints, 10 tension forces of the tendons and 5 tactile sensors. The analog controllers with power amplifiers can reduce the load of the digital central controller.

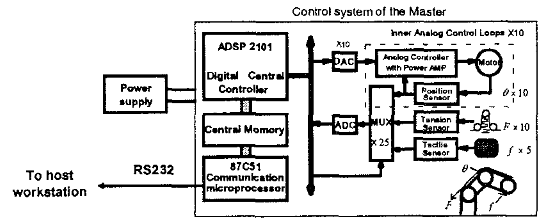

Figure 7 Control system of the NTU master

The multiplexers switch the channels to the required data and send this data to the analog to digital converter, as shown in Figure 8. After computation by digital central controller (DSP), the command will be sent to digital to analog converters, which is the command input of the analog control module. The digital central controller (shown in Figure 9) uses PID controller law, the sampling frequency is 200 Hz. The analog controller is a PD controller with a power amplifier, as shown in Figure 10. Its output can directly drive the motor.

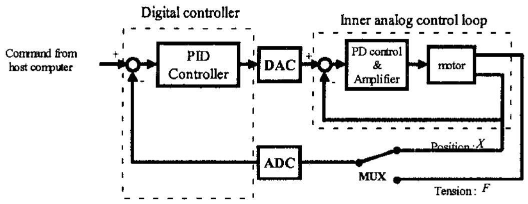

Figure 8 Control block diagram

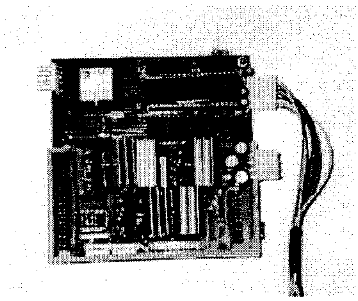

Figure 9 The digital controller with power amplifier

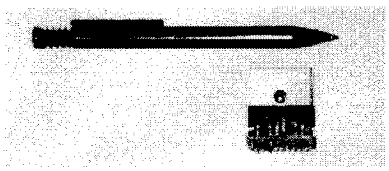

Figure 10 Analog controller with power amplifier

6 Simulations and Experiments

Estimate Grasp forces and deformations

The patterns of contact forces and deformations are obtained by using an experimental device which is used to simulate the conditions when we grasp objects. There are a tactile sensor and a potentiometer in this device. Thus, both contact forces and deformations can be obtained at the same time from this device. These patterns are acquired in terms of three different stiffness : low, medium and high stiffness. But only high stiffness (k = 1830 nt/m) case is shown here.

The true trajectories of the contact force and deformation are shown in Figures 11 and 12. The estimated force and deformation are shown in Figures 13 and 14.

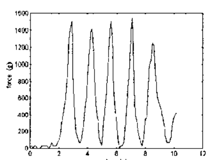

Figure 11 The trajectory of contact force (for high stiffness)

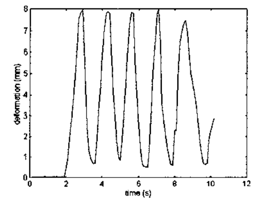

Figure 12 The trajectory of deformation (for high stiffness)

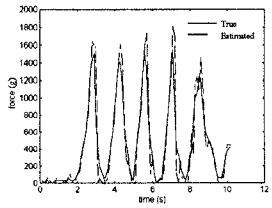

Figure 13 The trajectories of contact force and estimated force (for high stiffness)

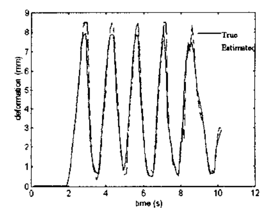

Figure 14 The trajectories of deformation and estimated deformation (for high stiffness)

Simulation of the NTU hand grasping an object

The simulation is performed on a SUN Sparc 10 workstation under the X environment. The 3D model of the NTU hand and the grasped object are built to view the motion of NTU hand in the screen. The impedance control (Eq. (2)) is used here to simulate the grasped object.

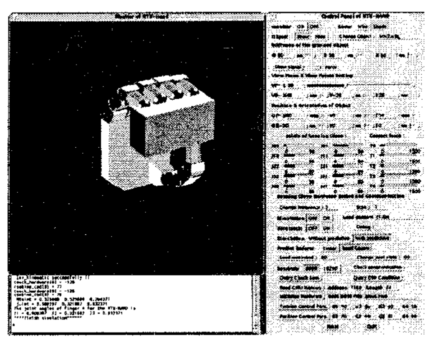

Figure 15 3D user interface

Results of experiment

A 3D graphic interface is used to simulate the NTU hand. The posture of the NTU hand can be viewed from the screen. The workstation sends commands to the NTU master and receives sensor data from the NTU master every 0.2 second. From the results of experiment, when the operator wears the NTU master and connects the NTU master to the host computer, the motion of the NTU hand can be seen in the graphic interface.

As the NTU hand grasps the object in the screen, the control mode will be changed immediately. Then, the posture of the NTU hand will be sent back to the NTU master. Thus, the operator feels as if he was grasping an object now. If the operator exerts force continuously, the object in the screen will be deformed.

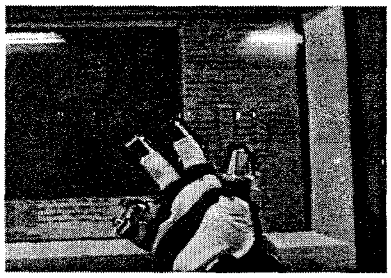

Figure 16 The NTU master is connected to the workstation

7 Conclusions

Bilateral control between the master and the slave is developed in this paper so that the master can transmit the motion to the slave and receive the perceptual information from the slave by communication. Both free mode and constrained mode are defined to control the fingers of the NTU master. The tensions of tendons are controlled in free mode, while the positions of tendons are controlled in constrained mode. In addition, a prediction method is used to resolve the time delay due to communication. The simulations show that the prediction results are good.

References

[1] R.J. Anderson and M.W. Spong, "Bilateral Control of Teleoperators with Time Delay, " *IEEE Transactions on Automatic Control*, pp.494-501. May 1989.

[2] DSP Division, *ADSP-2101/2102 User's Manual*, Analog Devices Inc., U.S.A., 1991.

[3] N. Hogan, "Impedance Control: An Approach to Manipulation: Part I - Theory, " *Journal of Dynamics System, Measurement, and Control*, vol.107, pp.1-7, March 1985.

[4] N. Hogan, "Impedance Control: An Approach to Manipulation: Part II - Implementation," *Journal of Dynamics System, Measurement, and Control*, vol.107, pp.8-16, March 1985.

[5] N. Hogan, "Impedance Control: An Approach to Manipulation: Part III - Applications," *Journal of Dynamics System, Measurement, and Control*, vol.107, pp.17-24, March 1985.

[6] N. Hogan, "Stable Execution of Contact Tasks Using Impedance Control, " *IEEE International Conference on Robotics and Automation*, pp.1047-1053,1987.

[7] N. Hogan, " Controlling Impedance at the Man/Machine Interface, " *IEEE International Conference on Robotics and Automation*, pp.1626-1631,1989.

[8] J.W. Lee and K. Rim, "Maximum Finger Force Prediction Using A Planar Simulation of A Middle Finger," *Proc. Instn. Mech. Engrs.*, Vol204, pp.160-178,1990.

[9] Y.J Li and C.Y. Tsai, "Transputer-Based Intelligent Control of Telerobotic Systems," Master thesis, Department of Mechanical Engineering, National Taiwan Cheng Kung University, R.O.C.,1995.

[10] L.R. Lin and H.P. Huang, "DSP-Based Fuzzy Control of A Multifingered Robot Hand," *IEEE International Conference on System, Man and Cybernetics*, pp.3672-3677, 1995.

[11] L.R. Lin and H.P. Huang, "Mechanism Design of A New Multifingered Robot Hand," *IEEE International Conference on Robotics and Automation*, pp.1471-1476, 1996.

[12] L. Pao and T.H. Speeter, " Transformation of Human Hand Positions for Robotic Hand Control," *IEEE International Conference on Robotics and Automation*, pp.1758-1763, 1994.

[13] Y.F. Wei, Design and Control of the Dexterous Hand Master with Force Feedback, M.S. Thesis, Dept. of Mechanical Engineering, National Taiwan University, 1996.

[14] K. Yamamoto, A. Ishiguro and Y. Uchikawa, "A Development of Dynamic Deforming Algorithms for 3D Shape Modeling with Generation of Interactive Force Sensation," *IEEE Annual Virtual Reality International Symposium Seattle*, pp.505-511, 1993.