'95 KACC (1995. 10. 23 ~ 25)

AN EASILY ATTAINABLE AND EFFECTIVE BILATERAL CONTROL FOR TELEOPERATION

°J. B. Son*, Y. Youm*, W. K. Chung* and K. W. Jeong**

* School of Mech. Eng., Pohang Univ. of Science & Tech., Pohang, KOREA
Tel:+82-562-279-2844; Fax: +82-562-279-5899; E-mail: jbson@risbot.rist.re.kr

** Research Institute of Industrial Science & Tech., Pohang, KOREA
Tel:+82-562-279-6733; Fax: +82-562-279-6599; E-mail: jeong@risnet.rist.re.kr

Abstracts Teleoperating system has been developed for several decades, and many control schemes for it have been suggested. But the implementation for real application needs very simple but effective controller. In this paper, an advanced control scheme for this purpose is suggested, which is the combination of a modified internal model controller and variable filter for force reflection. And we verify the effectiveness of the proposed scheme through the experiment. We use PUMA-560 as the slave robot, which is operated by velocity servo loop with geared motor. Both the responses of free motion and contact motion are shown.

Keywords Teleoperation, Force-Reflection, Internal model control

1. INTRODUCTION

Since teleoperation became one of the various fields of robotcs, a lot of control concepts have been introduced. Some of them have been adapted from other fields directly, some through modification, and some have been developed for teleoperation itself. But many control schemes cannot be easily implemented. For example, though dynamic control is very effective in both position and force control, it is hardly adapted for the slave robot of geared type or velocity servo type. And many control schemes require sufficient database about environment or show slow response.

In force reflection problem, there also exists many implementation problems. Generally, typical force reflection, position-error based force reflection, or combination of them has been used. Any of them would give best performance in ideal situation. But for real situation, these schemes would show poor performance than expected.

Conventional force reflection may reflect the inevitable high frequency component of force/torque sensor. Furthermore, impact with time-delay, which is invoked from communication or filtering, may cause instability. So we get the limit in using low pass filter. As a result, it is impossible to give relatively large force reflection gain for more sensitive motion.

Position-error based force reflection has such advantages that force/torque sensor is not necessary, and it is more stable than force signal in high frequency because position signal is the double intergration of acceleration. But this scheme cannot return the information for various contact object. For general case, we cannot measure the deformation caused from the stiffness of contact object, and cannot distinguish reflection from position error and contact position error. Human operator will get same feeling for various stiffness. Furthermore, if force/torque sensor is not used, and if position error of free motion and that of contact motion is not sufficiently different to each other, the contact information is distorted. This scheme will be effective under good slave control scheme, and in the system with sufficient compliance and position data resolution. In general system, position-error based force reflection is hard to implement with good preformance.

In this paper, we proposed more easy and efficient control schemes for slave system control and force reflection control, respectively. We adapt the concept of internal model control for the slave system. Internal model control doesn't need feedforward input, and computation is relatively simple. Internal model concept gives robust tracking preformance for teleoperation. And the change of internal model can give more compliant contact motion. In force reflection, we suggest a modified force reflection through a simple filter technique.

2. SLAVE SYSTEM CONTROL

We need the slave robot to track the setpoint from the master system, and additionally to have sufficient compliance during contact motion. For this purpose, shared compliant control(SCC) and impedance control scheme are widely adapted in the teleoperation task. But shared compliant controller dosen't give more than the stability through the simple gain decrease. A common impedance controller requires a good impedance model of the slave system.

On the other side, internal model controller is computed fast, doesn't need to know the plant model exactly, and well behave without dynamic control environment. So we control the slave using the internal model controller combined with impedance concept.

$$\frac{\tau}{\mathbf{e}} = \frac{\mathbf{P}_n^{-1}\mathbf{Q}}{1-\mathbf{Q}} \tag{1}$$

Eq. 1 and Fig. 1 shows the basic concept of internal model controller. Here, $\mathbf{P}$ is the the plant to be controlled, $\mathbf{P}_n$ the desired nominal plant, $\mathbf{q}_d$ the desired input, $\mathbf{q}$ the output, $\mathbf{e}$ the error, τ the control input, and $\mathbf{Q}$ is the low pass filter for proper system. We let desired input as $\mathbf{q}_d$ only, because only master position information is transfered to the slave system

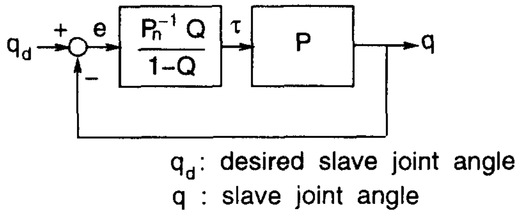

Fig. 1. Block Diagram of Internal Model Control

in usual case. Here, when we shape this block diagram to a closed form, the equation becomes

$$\frac{\mathbf{q}}{\mathbf{q}_d} = \frac{\mathbf{QP}}{(1-\mathbf{Q})\mathbf{P}_n + \mathbf{QP}} \tag{2}$$

Nominal human action reside in low frequency region, which is around 5 Hz. Considering this, if we let the low pass filter **Q** resonably, the gain of **Q** will be 1. Then the transfer function in low frequency region becomes

$$\frac{\mathbf{q}}{\mathbf{q}_d} \simeq \frac{\mathbf{QP}}{\mathbf{QP}} \simeq 1 \tag{3}$$

So the controlled slave robot will follow the desired position accurately. When the slave robot contacts to a stiff object, the impact motion resides in relatively high frequency region, which is between 10 Hz and 30 Hz. Then in high frequency region, **Q** becomes very small, and we can see **QP** will become very small, too. Then,

$$\frac{\mathbf{q}}{\mathbf{q}_d} \simeq \frac{\epsilon}{\mathbf{P}_n + \epsilon} \tag{4}$$

As a result, the motion of the slave will be dominated by the nominal plant which is pre-determined. If the gain of the nominal plant $\mathbf{P}_n$ becomes larger, **q** will become small. If the gain of $\mathbf{P}_n$ becomes ∞ then, **q** will be zero independent of $\mathbf{q}_d$. In bilateral force reflection, impact can be the very undesirable force reflection, which distabilizes the system. But with the property of **Q**, we can stabilize the slave system independent of the reaction of human.

Here, we need to raise the nominal plant gain in high frequency region for more stability. Desired nominal plant should be changed by the motion frequency. For this varible nominal plant, we choose an impedance model for the slave robot.

$$\mathbf{P}_n = \frac{1}{\mathbf{M}s^2 + \mathbf{B}s + \mathbf{K}} \tag{5}$$

This gives the conceptual advantage for force handling. **Q** of Eq. (2) is chosen as

$$\mathbf{Q} = \frac{\mathbf{T}^3}{(s+\mathbf{T})^3} \tag{6}$$

for the proper system. **T** is selected from desired filter bandwidth. We want the slave to be controlled by typical internal model controller in free motion. And we know if we lower the stiffness **K** of $\mathbf{P}_n$, the gain of $\mathbf{P}_n$ increases, and we can get the desired behavior in contact motion. So when we choose the slave model as

$$\mathbf{P}_n = \frac{1}{\mathbf{M}s^2 + \mathbf{B}s + \frac{\mathbf{K}}{1+\alpha|\tau_{ext}|}} \tag{7}$$

the desired property is fulfilled. It is easily verified that this variable slave model will become more compliant model with external force. The overall block diagram for the slave system is shown in Fig. 2

Then we can construct resultant control law like this:

$$\tau = \frac{(\mathbf{M}s^2 + \mathbf{B}s + \frac{\mathbf{K}}{1+\alpha|\tau_{ext}|})(\frac{\mathbf{T}^3}{(s+\mathbf{T})^3})}{1 - \frac{\mathbf{T}^3}{(s+\mathbf{T})^3}} \tag{8}$$

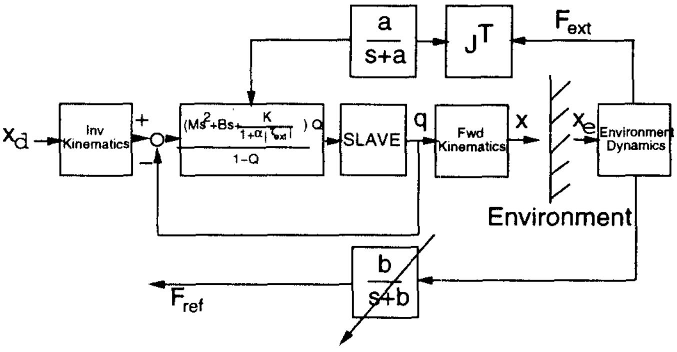

Fig. 2. Suggested Control Scheme

3. VARIABLE FILTER FOR FORCE REFLECTION

Usual impact force magnitude is hundreds times larger than that of other situation. Raw force reflection returns very high impact, and make contact motion with high stiffness object unstable, so that we are forced the force reflection gain to be small. Unreasonable cutting of high impact may give wrong information, so that we cannot recognize the stiffness of contact object by impact. Low pass filter with high order invokes severe time-delay, and distablizes the system.

A nonlinear mapping is a good solution of this problem, but this is computation-time consuming problem. So we suggest an variable low pass filter with first order as the supplement for conventional force reflection. This is an linear mapping in frequency domain, But not in other domain.

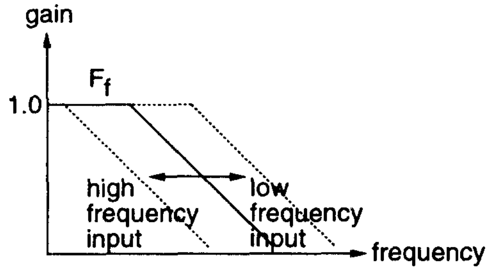

Fig. 3. Variable Filter for Force Reflection

This is shown in Fig. 3. High frequency input moves the low pass filter to left side, and get high gain reduction. Since the filter here is first order, short computation time and smaller time-lag can is obtained. In normal motion, this filter moves to high frequency, and gives almost no time-lag. When impact occurs, this filter moves low, and gives high gain reduction. After impact, this filter returns to pre-state, and no effect to time-lag, again.

4. EXPERIMENT

4.1 System Configuration

The hardware of teleoperating system for this experiement is composed of three subsystems: 1) Real-Time Controller: VMEbus System, 2) master system: POSTECH Master Arm III, 3) slave system: PUMA-560. System control software, developed on the basis of VMExec real-time O/S, creates four processes for three VME target boards and additional interface cards. First process supervise all processes and checks error which may occur (300ms). Second computes the kinematics of POSTECH Master Arm III and PUMA-560 (16ms). Third gorvens all interface cards and high level control (4ms). Last one deals F/T sensor I/O (16ms). We simplify the control problem only using first three axes. Fig. 4 shows the overall system configuration.

Proposed control scheme runs in the process for high level control. The implemented controller is very compact, and the calculation load is only double or triple of that of PD control. And the variable force reflection filter is easily implemented by changing the filter argument with force reflection command change.

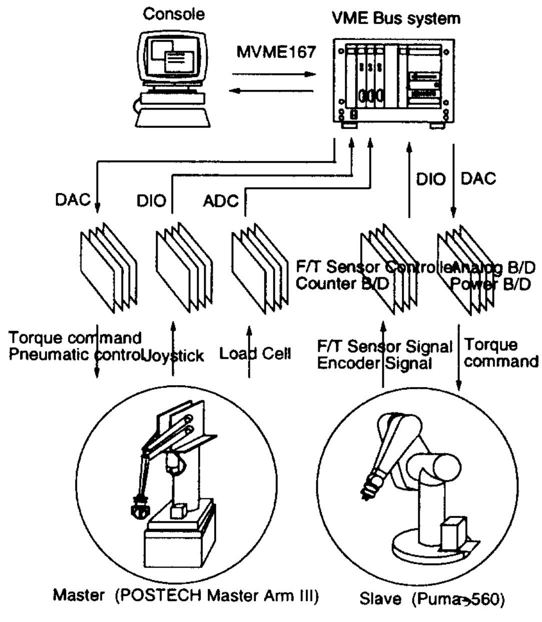

Fig. 4. System Configuration

4.2 Experimental Parameters

We choose experimental parameters shown in Table. 1. For internal impedance model, inertia paramter is obtained from [1], and the others are determined from trial and error. For high gear ratio, we let **B** and **K** high. Explaining with pole, one pole is near to origin for fast response, and the other pole is much pulled to left for removing its effect. Because of the application to velocity-input type, input value is scaled to 0.005. **Q** is set to $\frac{500^3}{(s+500)^3}$ as the common case, and α is 3000.0.

4.3 Free Motion

We expect, in free motion, the proposed controller behave as typical internal model controller. For the tracking test in free motion, we give a sinusoidal input with the master arm. The result is shown in Fig. 5, and 6. Since the sine input is generated by operator, we give slightly larger amplitude for the proposed controller, intentionally. Internal model controller shows smaller time-delay and smaller maximum error. PD contoller has maximum error of 18 mm, whereas internal model controller has 8 mm. The unsymmetric shape of PD controlmeans the gravity effect, which is not found in internal model controller.

TABLE 1. Nominal Parameter of the Slave Robot (SI unit)

	M	B	K
1	0.00083	0.04233	0.04150
2	0.00059	0.03009	0.02950
3	0.00040	0.02040	0.02000

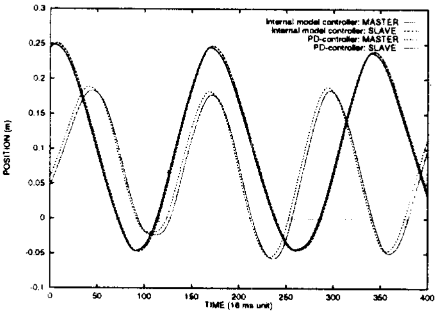

Fig. 5. Free Motion

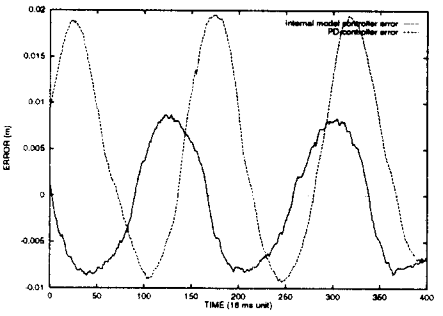

Fig. 6. Free Motion Error

4.4 Contact and Tracking Motion

Contact motion is very delicate and easily unstabilized task. But for the bilateral teleoperation, it is the critical problem to be solved besides a few special case. For contact motion, we test the contact and tracking on a vertical testbed wall, of which the surface is the rigid engineering plastic. Regretfully, the exact stiffness of the testbed wall doesn't measured, but it is estimated to be between 1.0×10^4 and 5.0×10^4 N/m from a few test. Fig. 7, 8, and 9 is the result which is measured simultaneouly in same experiment.

Fig. 7 is the trajectories of master and slave, respectively. Nominal approach speed is 10 *cm/sec*, which is shown from the time vs. position slope of Fig. 7. At 2.3 sec, contact occurs, and at 3 sec, tracking is begun. During tracking motion, the position error between master and slave is maximum 4 mm.

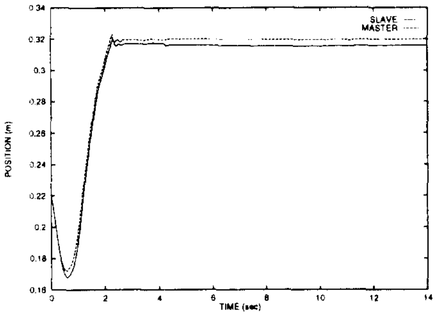

Fig. 7. Contact and Tracking Motion

The control input during contact motion is shown in Fig. 8. We can find the decrease of the servo input after 2.3 sec (impact instance). It is implied that the control scheme works well with geared and velocity-input type robot, as well as direct drive type.

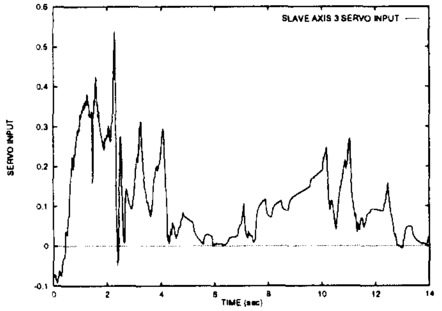

Fig. 8. Contact Servo Input

Fig. 9 is the contact force during the experimental task. Because the testbed wall is not so rigid, impact force is no more than 42.5 N. But with the effect of stiffness decrease, fast mode change to tracking is appeared. Here, we experience that with no filtering or too strong filtering, mode change to tracking is impossible. And we got the variable filtering is most effective than others for contact motion. The ripple of contact force at tracking motion is due to the uncertainty of human motion and the impedance difference between the master and the slave system.

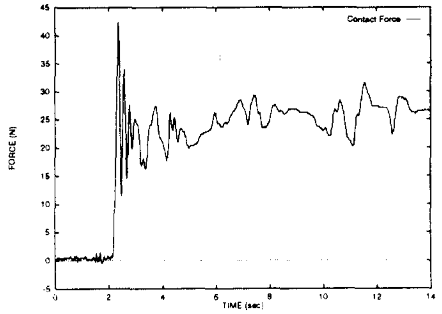

Fig. 9. Contact Force

5. CONCLUSION

In this paper, we proposed an advanced controller for teleoperating system. It was developed from the introduction of impedance concept to internal model controller. In addition, we proposed a force reflection scheme in order to improve the conventional one. With experiments, the effectiveness of proposed scheme was shown. In free motion, the maximum position error decreased to a half of that of PD control case. In contact motion, we showed proposed scheme gives very good force control, with the wall of 1.0×10^4 N/m and 10 cm/sec of approach speed.

REFERENCES

[1] Armstrong, B., Khatib, O., and Burdick, J., "The Explicit Dynamic Model and Inertial Parameters of the PUMA 560 Arm", *Proc. IEEE Int. Conf. Robotics and Automation*, Vol. 1, April 1986, pp. 510–518

[2] Anderson, R. J., and Spong, M. W., "Bilateral Control of Teleoperators with Time Delay", *Proc. IEEE Int. Conf. System, Man, and Cybernetics*, Vol. 1, Aug 1988, pp. 131–138

[3] Cha, D. S., "A Study on the Stability of Force Reflecting Teleoperation", M.S. Thesis, POSTECH, 1993

[4] Chapel, J. D., "Performance Limitations of Bilateral Force Reflection Imposed by Operator Dynamic Characteristics", pp. 91–100

[5] Choi, H. S., "Design and Control of POSTECH Master Arm III", M.S. Thesis, POSTECH, 1995

[6] Doyle, J. C., Francis, B. A., and Tannenbaum, A. R., "Feedback Control Theory", Maxwell Pub. Co.,1992

[7] Hannaford, B., and Fiorini, P., "A Detailed Model of Bilateral Teleoperation", *Proc. IEEE Int. Conf. System, Man, and Cybernetics*, Vol. 1, Aug 1988, pp. 117–121

[8] Hogan, N., "Impedance Control: An Approach to Manipulation: Part I, II, III", *ASME Jr. Dynamic Systems, Measurement, and Control*, Vol. 107, March 1985, pp. 1–23

[9] Karnik, A. M., and Sinha, N. K., "A direct Approach to Modeling an Industrial Robot from Samples of Input-Output Data", *Robotica*, Vol. 2, 1984, pp. 161-167

[10] Kim, W. S., Hannaford, B., and Bejczy, A. K., "Force-Reflection and Shared Compliant Control in Operating Telemanipulators with Time Delay", *IEEE Trans. Robotics and Automation*, Vol. 8, No. 2, April 1992, pp. 176–185

[11] Lawrence, D. A., "Stability and Transparency in Bilateral Teleoperation", *IEEE Trans. Robotics and Automation*, Vol. 9, No. 5, Oct. 1993, pp. 624–637