Modeling of Force Sensing and Validation of Disturbance Observer for Force Control

Seiichiro Katsura, *Student Member, IEEE*, Yuichi Matsumoto, and Kouhei Ohnishi, *Fellow, IEEE*

Department of System Design Engineering
Keio University
3-14-1 Hiyoshi, Kohoku, Yokohama, 223-8522 JAPAN
Tel:+81-45-563-1151(ext. 43037) Fax:+81-45-566-1720
katsura@sum.sd.keio.ac.jp matsuyu@sum.sd.keio.ac.jp ohnishi@sd.keio.ac.jp

Abstract— **Controlling robots in contact with environment is the important problem in industry applications. In order to solve the instability in force control, the velocity feedback gain is enlarged. The system becomes unstable with small velocity feedback gain, and robot's response becomes slow with large one. Since there is trade-off between stability and responsivity, it is thought that force control by robots is difficult. In the conventional force control, great many researches have paid attention to develop novel force control systems and implemented force sensors to detect external force.**

This paper shows that feedback of the value of force sensor makes attainment of force control difficult. The novel analysis technique of force control that force sensor is modeled by 2 mass resonant system is shown. Force control is attainable with the construction of the easiest force control system by feedback the value of reaction torque observer. Sensor-less force control is the one of the fundamental techniques for evolution of human-cooperating robot, tele-robotics, robotic virtual reality and so on.

The numerical and experimental results show viability of the proposed method.

Keywords— **Motion Control, Disturbance Observer, Force Sensor, Force Control, Haptics**

I. Introduction

CONTROLLING robots in contact with environment is the important problem in industry applications. Robots are subjected to interaction forces whenever they perform task involving motion that is constrained by environment, such as precise assembly, grinding, deburring and so on. In such motions, the interaction forces must be accommodated rather than suppressed to adapt to environment constraints. The robot force control can be divided into three modes: free motion, contact transition, and force tracking modes. Large impact force and bouncing may occur during the contact transition. They may influence contact motion during the force-tracking mode. Thus, a robust contact transition and force tracking control in an unknown or changing environment has been required.

Since contact operation contains the difficult problems of filling position control and force control at the same time, various techniques have been proposed. A suitable compliant behavior of the robot is required to accommodate the interaction. The basic strategy to achieve this purpose is stiffness control [1] which corresponds to proportional-derivative (PD) control with gravity compensation. The proportional gain sets the robot's stiffness which has to be properly tuned versus the environmental stiffness. Stiffness control is designed to achieve a static behavior of the interaction.

Active compliance can be provided by using either hybrid position/force control [2] or impedance control [3]. In hybrid position/force control, the task space is divided into two orthogonal and nonconflicting position and force controlled subspaces. As introduced in [3], the objective of an impedance controller is to establish a desired dynamic relationship between the endpoint position and the environmental force. Hence, robot appears as specified impedance from the environment.

Generally, in order to solve the instability in force control, the velocity feedback gain is enlarged [4]. However, when a viscous term is enlarged, there is a problem that robot's response becomes slow. Therefore, the system becomes unstable with small velocity feedback gain, and robot's response becomes slow with large one. Since there is trade-off between stability and responsivity, it is thought that force control by robots is difficult. Contact transition control via acceleration feedback [5] and neural network control scheme for force control [6] are proposed. Research which used other than motors, such as hydraulic pressure [7], is also done.

In the conventional force control, great many researches have paid attention to develop novel force control systems, and implemented force sensors to detect external force. Attention has not been paid about the structure of force sensor in force control. This paper shows that feedback of the response of force sensor makes realization of force control difficult. Since force sensor uses the strain gauge, force sensor has a soft portion on structure. The novel analysis technique of force control that force sensor is modeled after 2 mass resonant system is shown. Furthermore, force control is attainable by the construction of the easiest force control system by feedback the reaction torque observer [8]. Thus, attainment of force control is the one of the fundamental techniques for evolution of human-cooperating robot [9]. The robots with such a haptic ability will have an important role in the future aging society.

0-7803-7906-3/03/$17.00 ©2003 IEEE.

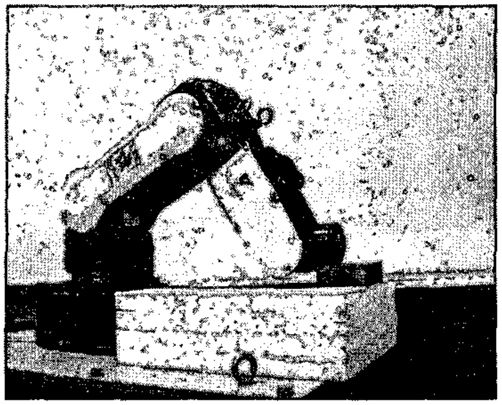


Fig. 1. 6 D.O.F Manipulator

This paper is organized as follows. Robot model is shown in Section II. In Section III, mechanism of contact with environment is considered. Force sensing is addressed in Section IV. In Section V, simulation results are shown. In Section VI, proposed method applied to industrial 6 D.O.F manipulator. Experimental results are presented together with a thorough comparative discussion. At the last section, this paper is summarized.

II. Modeling of Robot

Industrial 6 D.O.F. manipulator is shown in Fig. 1. Kinematic equations are as follows.

$$\boldsymbol{x} = f(\boldsymbol{\theta}) \tag{1}$$

where, $\boldsymbol{x}$ denotes position in respect to world coodinate system, and $\boldsymbol{\theta}$ denotes joint angle. Velocity relation is defined by Jacobian matrix $\boldsymbol{J}_{aco}$.

$$\dot{\boldsymbol{x}} = \boldsymbol{J}_{aco}\dot{\boldsymbol{\theta}} \tag{2}$$

Robot's dynamics is described as (3).

$$\boldsymbol{M}(\boldsymbol{\theta})\ddot{\boldsymbol{\theta}} + \boldsymbol{h}(\boldsymbol{\theta}, \dot{\boldsymbol{\theta}}) + \boldsymbol{V}\dot{\boldsymbol{\theta}} + \boldsymbol{G}(\boldsymbol{\theta}) - \boldsymbol{J}_{aco}^{T}\boldsymbol{F}_{ext} = \boldsymbol{\tau} \tag{3}$$

where, the first term denotes inertia, the second term denotes Coriolis force, the third term denotes friction force, the forth term denotes gravity term, and the fifth term denotes external force.

III. Contact with Environment

Mechanism of contact with environment is considered. Mechanism of contact motion is shown in Fig. 2. Environment is represented as a spring-damper model. K_{env}, D_{env} denote spring and damper coefficient of environment, respectively.

Robot's behavior is unstable due to reaction force loop, when robot contacts with environment. Robot is detached due to oscillation and robot motion is stable due to disappearance of reaction loop. The above-mentioned phenomenon is repeated. Thus, robot's behavior is unstable during contact with environment by perpetual chattering due to structure change.

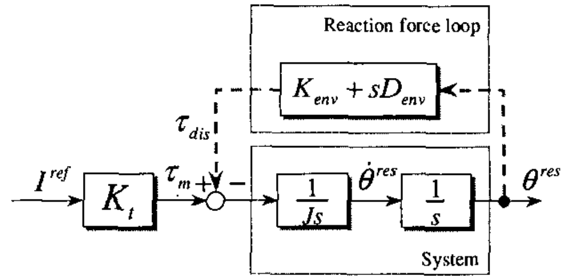


Fig. 2. Environment model

IV. Force Sensing

A. Force Sensor

A.1 Mechanism of Sensing

In the conventional force control, great many researches have implemented force sensors to detect external force. Force sensors detect starin of the strain gauge. Starin of the strain gauge is assumed external force. It is difficult to detect reaction force when the environment is distorted at the time of contact. Moreover, external force is detected only at the position where the force sensors are implemented. It will be a problem for complicated environment.

A.2 Modeling of Force Control System

Force sensors are modeled to springs with stiffness K_f, since force sensors have a flexible structure. Modeling of force control system using force sensor is shown in Fig. 3 Force sensor implemented in robot can be modeled after 2 mass resonant system. 2 mass resonant system is the model that robot and force sensor are assumed rigid bodies, and they are connected with a flexible spring. Modeling of 2 mass resonant system is shown in Fig. 4.

Motion equations of 2 mass resonant system are as follows.

$$J_m\ddot{\theta}_m = \tau_m - \tau^{spring} - \tau_{dism}' \tag{4}$$
$$J_s\ddot{\theta}_s = \tau^{spring} - \tau_{diss} \tag{5}$$
$$\tau^{spring} = K_f(\theta_m^{res} - \theta_s^{res}) \tag{6}$$

J	:	Inertia
θ	:	Angle
τ	:	Torque
K_f	:	Spring coefficient of force sensor
τ_{dis}	:	Disturbance torque
τ^{spring}	:	Reaction torque due to spring
(subscript)m	:	Motor
(subscript)s	:	Sensor

The block diagram of force control system using force sensor is shown in Fig. 5. The force control system consists of the easiest controllers that only the response of force sensor is fed back and divided by equivalent inertia M.

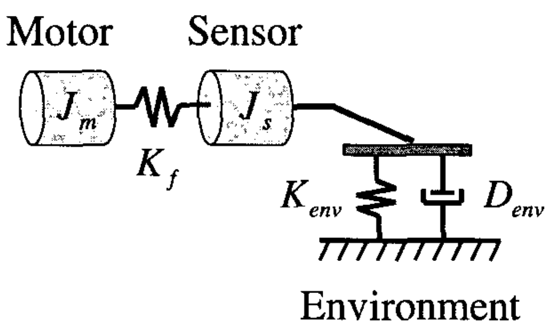


Fig. 3. Modeling of force control system using force sensor

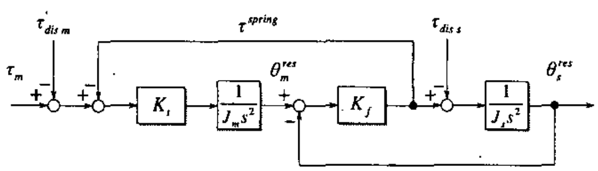


Fig. 4. Modeling of 2 mass resonant system

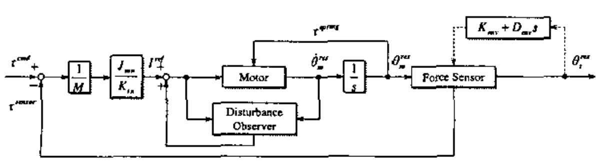


Fig. 5. Block diagram of force control system using force sensor

Fig. 5 shows that the structure of system changes to 2 mass resonant system by the spring of force sensor, when the response of force sensor is fed back. This change of the structure of system is the main factor of the instability of force control. Conventionally, there is little research which pointed out the instability and the validity of the model is confirmed through simulation and experiment in this paper.

B. Reaction Torque Observer

B.1 Mechanism of Sensing

Reaction torque observer can calculate the disturbance torque of motor without sensors. Block diagram of reaction torque observer is shown in Fig. 6.

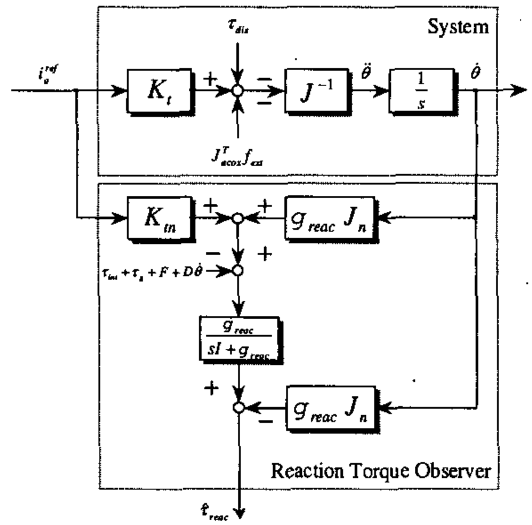


Fig. 6. Reaction torque observer

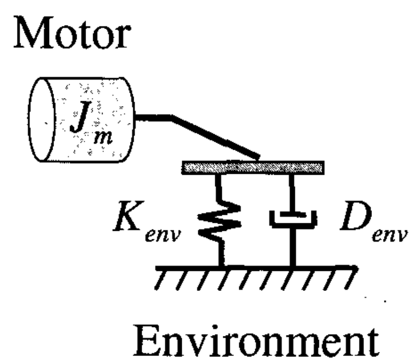


Fig. 7. Modeling of force control system using reaction torque observer

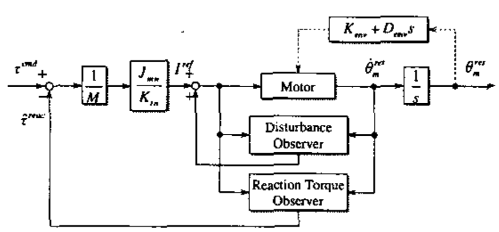


Fig. 8. Block diagram of force control system using reaction torque observer

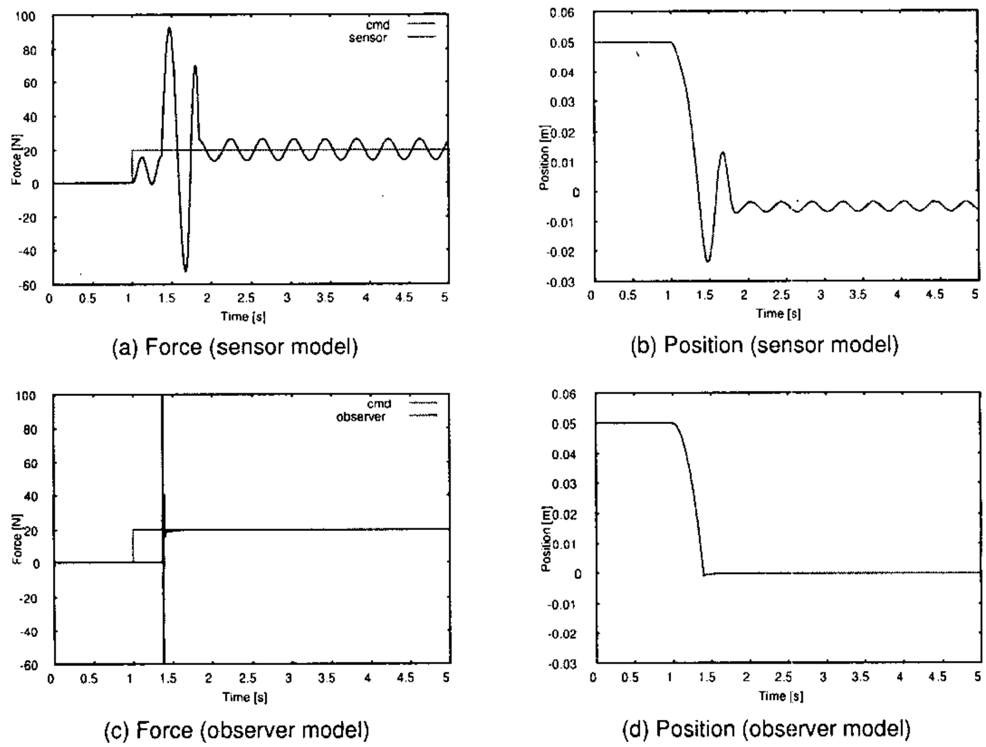


Fig. 9. Simulation

Estimated reaction torque is shown as follows.

$$\begin{aligned}\hat{\tau}_{reac} &= \frac{g_{reac}}{s+g_{reac}}(I_a^{ref}K_{t_n} + g_{reac}J_n\dot{\theta} \\ &- \tau_{int} - \tau_g - F - D\dot{\theta}) - g_{reac}J_n\dot{\theta} \end{aligned} \quad (7)$$

where,

$\hat{\tau}_{reac}$	:	Estimated reaction torque
τ_{int}	:	Interference torque
τ_g	:	Gravity torque
F	:	Coulomb friction
$D\dot{\theta}$	:	Viscous friction
g_{reac}	:	Gain of reaction torque observer
I_a^{ref}	:	Current reference
K_{t_n}	:	Nominal torque constant
J_n	:	Nominal inertia

B.2 Modeling of Force Control System

When reaction torque observer is implemented, force control system does not include a soft mechanism between robot and environment. Since motor actuators sense environmental information, modeling of force control system is shown in Fig. 7. The block diagram of force control system using reaction torque observer is shown in Fig. 8. The force control system consists of the easiest controllers that only the value of reaction torque is fed back and divided by equivalent inertia M. Reaction torque observer needs precise identification of gravity term and coulomb friction.

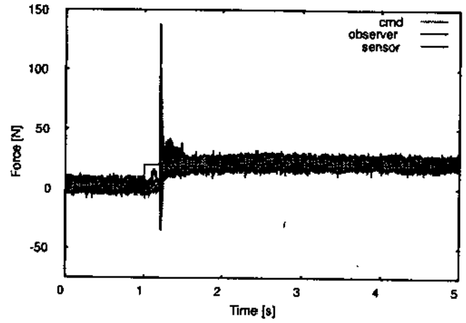
V. Simulation

Simulation is performed to compare two force sensing model. The force controller is simple; stability of the system is very affected by stiffness of environment. In the simulation, initial position is set to 0.05m. One second later, force command is changed from 0.0 to 20.0N. The force response and position response are shown in Fig. 9. (a) and Fig. 9. (b) respectively, when the model of force sensor is used. The force response and position response are shown in Fig. 9. (c) and Fig. 9. (d) respectively, when the model of reaction torque observer is implemented. According to the results of the simulation, the force response is vibrating when force sensor model is used. On the other hand, the force response is stable when reaction torque observer model is implemented. Because force sensor has a soft part, the system becomes complicated. It is difficult for robot to contact with environment stably when force sensor is used.

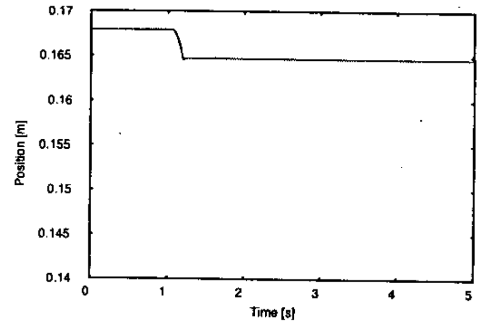
VI. Experiment

Industrial 6 D.O.F. manipulator is shown in Fig. 1. Experimental setup is shown in Fig. 12. Control software is written in C language under RT–Linux3.1. Sampling time is 1ms.

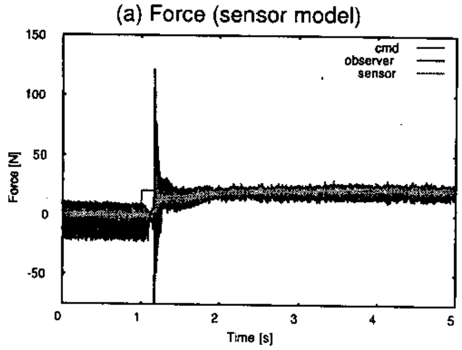
In order to compare force sensor with reaction torque observer, the following force control experiments are conducted.



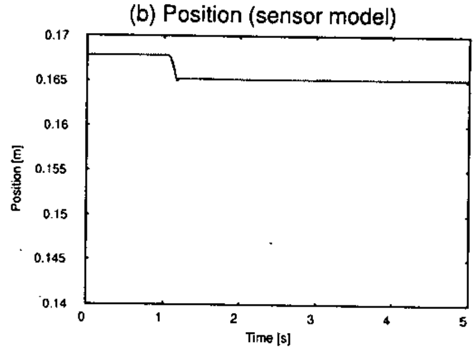
(a) Force (sensor model)



(b) Position (sensor model)

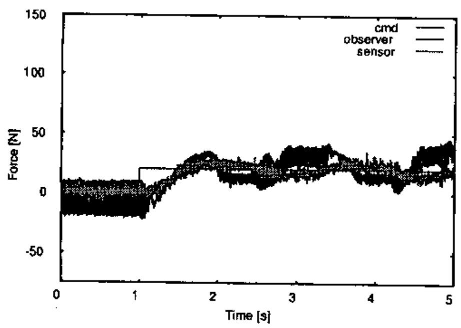


(c) Force (observer model)

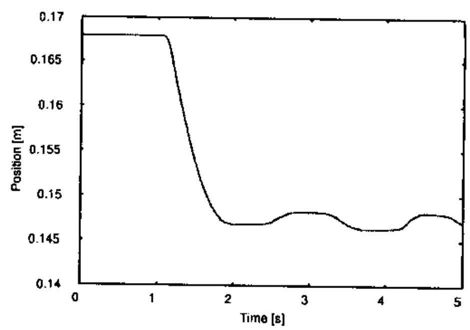


(d) Position (observer model)

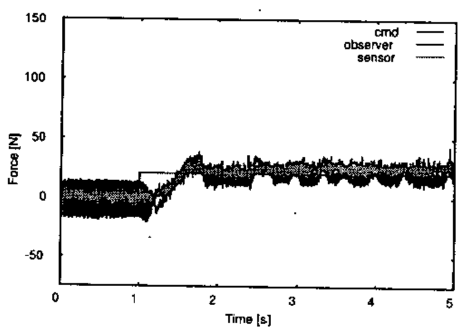
Fig. 10. Experiment (Hard environment)



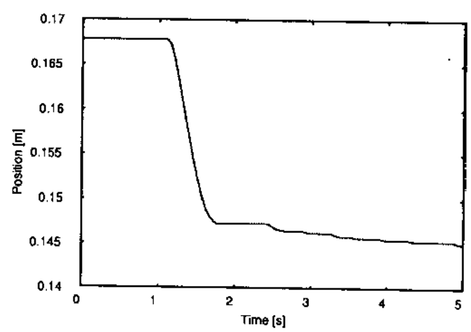
(a) Force (sensor model)



(b) Position (sensor model)



(c) Force (observer model)



(d) Position (observer model)

Fig. 11. Experiment (Soft environment)

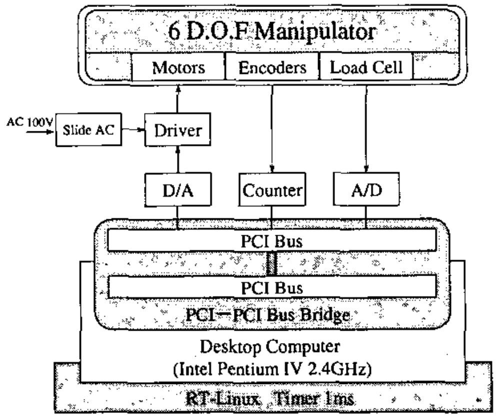


Fig. 12. Experimental setup

- Hard environment(steel plate)
- Soft environment(styrene foam)

Experimental results that manipulator contacts with environment from free motion are shown. Cutoff frequency of reaction torque observer is 500.

A. Hard Environment

Fig. 10. (a, b) show results with feedback the value of force sensor, and Fig. 10. (c, d) show results with feedback the value of reaction torque observer. It turns out that stable contact with environment is attained using both force sensor and reaction torque observer. Although environmental stiffness is comparatively large, stable contact is attainable, without enlarging a viscous term.

B. Soft Environment

Fig. 11. (a, b) show results with feedback the value of force sensor, and Fig. 11. (c, d) show results with feedback the value of reaction torque observer. Experiment results show that stable contact with environment cannot be attained, when force sensor information is used for force control. Moreover, the value of reaction torque observer at this time is vibrated with the almost same value. Thus, it is thought that the cause of vibration depends on change of the structure of the system. On the contrary, when reaction torque observer is implemented, it turns out that stable contact with environment is attained.

In Fig. 11. (a), the value of force sensor differs from the value of reaction torque observer. Generally, sensors have a proportion type and a balance type. It is known that the balanced type sensor is more accurate. Force sensor cannot sense force, unless it is accompanied by the deviation of position. Thus, force sensor is a kind of proportion type sensor. Reaction torque observer calculates the disturbance torque of motor without recourse to the deviation of position. Reaction torque observer is considered as a balanced type force sensor.

If stable force control system is attained in any environment, robots will take an active part in human society.

VII. Conclusions

This paper showed that feedback of the value of force sensor makes realization of force control difficult. The novel analysis technique of force control that force sensor is modeled by 2 mass resonant system was shown. Because force sensor has a soft part, the system becomes complicated. It is difficult for robot to contact with environment stably when force sensor is used.

Force control was attainable with the construction of the easiest force control system by feedback the value of reaction torque observer. Reaction torque observer calculates the disturbance torque of motor without recourse to the deviation of position. Thus, reaction torque observer is considered as a balanced type force sensor. The proposed method was applied to industrial 6 D.O.F. manipulator. The numerical and experimental results show viability of the proposed method.

Sensor-less force control is the one of the fundamental techniques for evolution of human-cooperating robot.

Acknowledgement

This research was partially supported by the Ministry of Education, Culture, Sports, Science and Technology, Grant-in-Aid for Scientific Research (A), 14205041, 2002.

References

[1] J.K.Salisbury : "Active Stiffness Control of a Manipulator in Cartesian Coordinates" Proceedings of the 19th IEEE Conference on Decision and Control, pp. 95–100, 1980.

[2] M.H.Raibert, J.J.Craig : "Hybrid Position/Force Control of Manipulators" Transactions of ASME Journal of Dynamic Systems, Mesurement, and Control Vol. 102, pp. 126–133, 1981.

[3] N.Hogan : "Impedance Control Part 1–3" Transactions of ASME Journal of Dynamic Systems, Mesurement, and Control Vol. 107, pp. 1–24, 1985.

[4] Stefano Chiaverini, Bruno Siciliano, Luigi Villani : "A Survey of Robot Interaction Control Schemes with Experimental Comparison" IEEE/ASME Transactions on Mechatronics, Vol. 4, No. 3, pp. 273–285, 1999.

[5] W.L.Xu, J.D.Han, S.K.Tso : "Experimental Study of Contact Transition Control Incorporating Joint Accrleration Feedback" IEEE/ASME Transactions on Mechatronics, Vol. 5, No. 3, pp. 292–301, 2000.

[6] Seul Jung, T.C.Hsia : "Robust Neural Force Control Scheme Under Uncertainties in Robot Dynamics and Unknown Environment" IEEE Transactions on Industrial Electronics, Vol. 47, No. 2, pp. 403–412, 2000.

[7] Shahram Tafazoli, Septimiu E.Salcudean, Keyvan Hashtrudi-Zaad, Peter D.Lawrence : "Impedance Control of a Teleoperated Excavator" IEEE Transactions on Control Systems Technology, Vol. 10, No. 3, pp. 355–367, 2002.

[8] K.Ohnishi, M.Shibata, T.Murakami : "Motion Control for Advanced Mechatronics" IEEE/ASME Transactions on Mechatronics, Vol. 1, No. 1, pp. 56–67, 1996.

[9] Hun-ok Lim, Kazuo Tanie : "Collision-Tolerant Control of Human-Friendly Robot With Viscoelastic Trunk" IEEE/ASME Transactions on Mechatronics, Vol. 4, No. 4, pp. 417–427, 1999.

[10] K.Yuki, T.Murakami, K.Ohnishi : "Vibration Control of 2 Mass Resonant System by Resonance Ratio Control" IEEE International Conference on Industrial Electronics IECON'93, Vol. 3, pp. 2009–2014, 1993.

[11] S.Katsura, K.Ohnishi : "A Wheelchair Type mobile Robot Taking Environmental Disturbance into Account Based on Compliance Control" IEEJ Transactions on Industry Applications Vol. 122-D, No. 9, pp. 942–947, 2002.

[12] Y.Matsumoto, S.Katsura, K.Ohnishi : "Bilateral Control with the Virtual Supporting Point for Minimally Invasive Surgery" IEEJ Technical Meeting on Industrial Instrumentation and Control, IIC-03-33, pp. 93–97, 2003.