THE FIRST INTERNATIONAL SYMPOSIUM ON MEASUREMENT AND CONTROL IN ROBOTICS (ISMCR '90)
GILRUTH CENTER, NASA/JOHNSON SPACE CENTER, HOUSTON, TEXAS, USA JUNE 20-22, 1990

IMPEDANCE CONTROL OF A DIRECT DRIVE MANIPULATOR WITHOUT USING FORCE SENSORS

SUSUMU TACHI*, TAISUKE SAKAKI**, AND HIROHIKO ARAI*

* Mechanical Engineering Laboratory, MITI
1-2, Namiki, Tsukuba Science City, Ibaraki, 305, Japan

** Yaskawa Electric Mfg. Co., Ltd.
2346, Fujita, Yahatanishi-ku, Kitakyusyu, 806, Japan

ABSTRACT

This research is concerned with a unified approach to a simple force control with using a simple manipulator mechanism to exert stable contact tasks. In this paper, a compact impedance control is proposed for a DD manipulator by using acceleration feedback in stead of force or torque sensors. Dynamic interaction between a robot and its environment is controlled by regulating the apparent mechanical impedance of a manipulator. However, previous impedance control implementation methods require force or torque sensors with which the system is very complex and high-costed. A DD manipulator is ideal to get a simple dynamics model, thus a compact control algorithm is derived from the model and inner sensor information. Angular velocity and angular acceleration of the joints are estimated, and by using the model, necessary torque is applied to each joint to attain the desired impedance. The unified control strategy and the stability conditions from free space motion to contact task are also discussed.

I. INTRODUCTION

When controlling a manipulator to execute a contact task, the importance of using the information of not only position but also force has been argued for a long time [1][15][16][17]. One of the typical force control is hybrid position/force control [2][18], but the hybrid control still contains many problems; selecting the position and the direction of controlling position/force, sensing a boundary of an object, and switching the mode of position/force in an actual handling task.

Another typical method is impedance control[6]. When performing a contact task, the relationship between the robot and its environment is regulated to execute stable force control. The regulation appears as a change of the robot's apparent dynamics (inertia, viscosity and stiffness) [7].

Impedance control is the generalized method of stiffness control[3][4] and damping control[5]. The stiffness and compliance controls are similar to impedance control, but these methods regulate only static contact force. In the damping control a velocity effect is considered but it doesn't imply inertia terms. Impedance control includes not only the stiffness or the viscosity but also the apparent moment of inertia.

Impedance control was systematized by N.Hogan[6], and was verified to be effective for contact tasks on rigid objects[7]. C.H.An and J.M.Hollerbach[8] have researched dynamic stability during force control. Currently the measurement of environment impedances and the optimal target impedance of a manipulator have been researched[19][20][21][22][23]. The optimal target impedance is designed to reduce the impact of the first contact to the environment, and it is also regulated to continue a stable contact. The unified approach to the stability analysis of those contact tasks has been presented with using *Hamiltonian*, which means the whole energy of both a manipulator and its environment [25][26].

However, since most of all these methods use either force or torque sensors, the construction becomes very complex. Therefore, the production cost is raised and the manipulator stiffness is reduced. In addition, if a force sensor is mounted on the wrist, an external force cannot be measured except on the end-effector. On the other hand, several methods for external force detection using only internal sensors have been researched; dynamic compensation by M.Uchiyama[9], and internal feedback for active power assistance by H.Arai and S.Tachi[10]. However, these strategies do not make use of impedance.
This research proposes an impedance control using no force sensors but using accelera-

tion feedback. In this method, angular velocity and angular acceleration of the joints are estimated from inner sensor information, and, by using the simple computer model of the manipulator given by the direct drive mechanism, necessary torque is applied to each joint to attain the desired impedance. The feasibility of the method was demonstrated by the surface following and collision experiments with an experimental three degree-of-freedom vertically articulated DD (Direct Drive) manipulator. This method allows that the construction of a manipulator is simple, the stiffness of the arm is kept high, and the impedance is controlled with an external force on any parts of the arm.

In addition, the implementation of impedance control simplifies the control algorithms and gives us the intuitive understanding of the stability analysis. In the next section, we give the unified but compact control algorithm from free space to contact tasks.

II. IMPEDANCE CONTROL WITHOUT USING FORCE SENSORS

A. Impedance Control of Generalized Motion by Using Acceleration Feedback

A DD manipulator is a robot arm which links are jointed each other with no backlash or no friction. Therefore the motion of one link influences dynamically the motions of other links. However, the specification is ideal to get a simple dynamics model, and the compact impedance control algorithm will be derived from that.

First, the manipulator's equation of motion is defined as follows:

$$I\ddot{\theta} + Dv\,\dot{\theta} + C(\theta,\dot{\theta}) = Ta + J^T Fe \qquad (1)$$

where I, Dv and $C(\theta,\dot{\theta})$ are an inertia matrix, a viscous friction coefficients matrix, and gravity, Coulomb friction and other non-linear term respectively. These coefficients are able to be easily identified. We will further define the next notations. Ta, Fe, θ and J^T are an actuator output torque vector, an external force vector from the environment, a Rotational angular vector of each axis ,and a Transposed Jacobian matrix respectively.

Next, we will establish the target impedance $Z(j\omega)$ (multi-directional impedance of the target position and posture Xo of the end-effector) when a manipulator contacts its environment. Here, the mechanical impedance is defined using the analogy of voltage-force.

$$Z(j\omega) = B + j(M\omega - K/\omega) \qquad (2)$$

The equation of motion for the system having desired target impedance is expressed as follows:

$$Fe = M(\ddot{X} - \ddot{X}o) + B(\dot{X} - \dot{X}o) + K(X - Xo) \qquad (3)$$

This is the generalized method with a desired motion, $(\ddot{X}o(t), \dot{X}o(t), Xo(t))$. Here, M, B, K and X are a virtual inertia matrix, a virtual viscous friction matrix, a virtual stiffness matrix, and a position and posture vector in Cartesian space. $Xo = Xo(t)$ is virtual equilibrium point which shows the trajectory including target position and posture as a function of time t. θ and X have the following relationship due to coordinate transformation.

$$X = L(\theta) \qquad (4)$$
$$\dot{X} = J\dot{\theta} \qquad (5)$$
$$\ddot{X} = J\ddot{\theta} + \dot{J}\dot{\theta} \qquad (6)$$

Substituting equations (4),(5) and (6) in equation (3), the following equation is obtained.

$$\begin{aligned} J^T Fe = {} & J^T M J\ddot{\theta} + J^T M \dot{J}\dot{\theta} + J^T B J\dot{\theta} \\ & - J^T M \ddot{X}o - J^T B \dot{X}o \\ & + J^T K(L(\theta) - Xo) \end{aligned} \qquad (7)$$

From equation (1) and (7), the output torque of actuator Ta necessary to achieve the target impedance is calculated as follows:

$$\begin{aligned} Ta = {} & (I - J^T M J)\ddot{\theta} + (Dv - J^T M \dot{J} - J^T B J)\dot{\theta} \\ & + J^T M \ddot{X}o + J^T B \dot{X}o + J^T K(Xo - L(\theta)) \\ & + C(\theta,\dot{\theta}) \end{aligned} \qquad (8)$$

If the manipulator coefficients have been identified, the joint rotational angle, angular velocity and angular acceleration are measured from the joint sensors, the target impedance of equation (2) is achieved by the output torque in equation (8). Fig.1 shows the block diagram of the feedback control. In this diagram, the nonlinear term $C(\theta,\dot{\theta})$ is neglected.

B. Stability Analysis of the Impedance Controlled Manipulator Concerned with a Contact Task

If the target impedance of the manipulator is fixed, the arm may become unstable in contact to an object in some cases [6][7][8][25][26]. Therefore, it is neces-

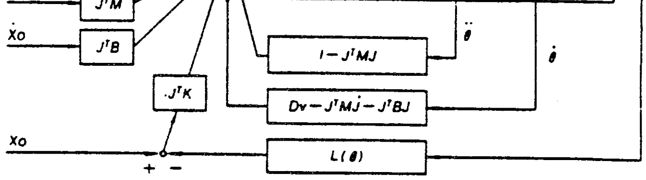

Fig.1 Block diagram of the proposed impedance control

sary to regulate the target impedance in concerned with the object impedance. We will discuss the stability of the whole dynamics both of a manipulator and its object, and will get the strategy to regulate the target impedance in *unified but simple* approach to both free motion and contact task.

Assume that a commanded motion is given as $(\ddot{X}o, \dot{X}o, Xo)$, and the impedance controlled manipulator has the apparent dynamics (3). When the manipulator moving in a free space, the external force is zero.

$$Fe = 0 \tag{9}$$

Then the system moves as follows:

$$\ddot{e} + M^{-1}B\,\dot{e} + M^{-1}K\,e = 0 \tag{10}$$

where,

$$e = X - X_0 \tag{11}$$

The error, e, is a six dimensional vector.

$$e = \begin{bmatrix} e_1 \\ \vdots \\ e_6 \end{bmatrix} \tag{12}$$

The error, e, converges stably and rapidly to zero under the next *critical damping* conditions.

$$(M^{-1}B)^2 = 4M^{-1}K \tag{13}$$

$$\left| sI + M^{-1}B/2 \right| = 0 \tag{14}$$

If the real parts of the root, s, of the characteristic equation from equation (14) are set to the negative values so that their absolute values are sufficiently large, and the target impedance is determined to satisfy the condition (13), the error converges to zero and a stable trajectory control is realized. Then, the control is the same as the conventional trajectory following control including feedforward terms of manipulator dynamics[11][12].

Now, assuming that a manipulator contacts to an object by non-perfect elasticity collision, the external force is given to the manipulator as follows:

$$Fe = -M'(\ddot{X}-\ddot{X}_1) - B'(\dot{X}-\dot{X}_1) - K'(X-X_1) \tag{15}$$

where M', B', K' are object dynamics, $(\ddot{X}_1, \dot{X}_1, X_1)$ is the object motion before the contact. The whole system dynamics is:

$$M(\ddot{X} - \ddot{X}o) + B(\dot{X} - \dot{X}o) + K(X - Xo) + M'(\ddot{X} - \ddot{X}_1) + B'(\dot{X} - \dot{X}_1) + K'(X - X_1) = 0 \tag{16}$$

Then,

$$(M + M')[\ddot{X} - (M + M')^{-1}(M\ddot{X}o + M'\ddot{X}_1)] + (B + B')[\dot{X} - (B + B')^{-1}(B\dot{X}o + B'\dot{X}_1)] + (K + K')[X - (K + K')^{-1}(K Xo + K' X_1)] = 0 \tag{17}$$

We define the unified motion of the manipulator and the object as $(\ddot{X}e, \dot{X}e, Xe)$.

$$\begin{aligned} \ddot{X}e &= (M + M')^{-1}(M\ddot{X}o + M'\ddot{X}_1) \\ \dot{X}e &= (B + B')^{-1}(B\dot{X}o + B'\dot{X}_1) \\ Xe &= (K + K')^{-1}(K Xo + K' X_1) \end{aligned} \tag{18}$$

They are measured by the inner sensors, and the whole dynamics of the system is defined as follows:

$$M'' = M + M',\ B'' = B + B',\ K'' = K + K' \tag{19}$$

Therefore,

$$M''(\ddot{X} - \ddot{X}e) + B''(\dot{X} - \dot{X}e) + K''(X - Xe) = 0 \tag{20}$$

The error from the unified motion, $(\ddot{X}e, \dot{X}e, Xe)$, is considered.

$$e_1 = X - Xe \tag{21}$$

The error, e_1, is also a six dimensional vector.

Therefore, the whole system dynamics is shown as follows:

$$M''\ddot{e}_1 + B''\dot{e}_1 + K''e_1 = 0 \tag{22}$$

If the real part of the roots in the characteristic equation of the whole system (M'', B'', K'') are negative values, then the error, e_1, converges to zero asymptotically, and also the whole system motion asymptotically converges to the motion, $(\ddot{X}e, \dot{X}e, Xe)$.

On the other hand, the manipulator may become unstable when performing a contact task, if the whole system impedance does not satisfy the stable condition. In this case, the strategy to regulate the target impedance of the manipulator is necessary. First, the target impedance is predetermined in considering that the arm is asymptotically stable in contact with the unknown object impedance; for example relatively large values for the virtual viscous friction coefficients of matrix B, and relatively small values for the virtual inertial coefficients of matrix M from equation (22). And it allows the whole system to converge to the *asymptotically stable* motion. Second, the whole system motion and the target impedance of the manipulator derive the object impedance. From equations (18), if the unified motion $(\ddot{X}e, \dot{X}e, Xe)$ are measured by the inner sensors, the object dynamics is calculated as follows. We can derive the next equations by equations (17), (18).

$$\begin{aligned} M'(\ddot{X}_1 - \ddot{X}e) &= M(\ddot{X}e - \ddot{X}o) \\ B'(\dot{X}_1 - \dot{X}e) &= B(\dot{X}e - \dot{X}o) \\ K'(X_1 - Xe) &= K(Xe - Xo) \end{aligned} \tag{23}$$

In general, these are indeterminate equations, but we can know the object impedance (M', B', K'), if the matrices M', B', K' are n-order diagonal matrices which order is equal to that of coordinates X_1, Xo, Xe. Define the next components:

$$X_1 = [x_{11}, \dots, x_{1i}, \dots x_{1n}]^T$$
$$Xo = [xo_1, \dots, xo_i, \dots xo_n]^T \qquad (24)$$
$$Xe = [xe_1, \dots, xe_i, \dots xe_n]^T$$

$$M\,(\ddot{X}e - \ddot{X}o) = [\,M_1 \dots M_i \dots M_n\,]^T$$
$$B\,(\dot{X}e - \dot{X}o) = [\,B_1 \dots B_i \dots B_n\,]^T \qquad (25)$$
$$K\,(Xe - Xo) = [\,K_1 \dots K_i \dots K_n\,]^T$$

And define the i-th components of diagonal matrices M', B', K' as M_i', B_i', K_i'. Therefore, by equations (23), (24), and (25),

$$M_i' = Mi\,/\,(\ddot{x}_{1i} - \ddot{x}e_i)$$
$$B_i' = Bi\,/\,(\dot{x}_{1i} - \dot{x}e_i), \quad \text{for all } i \qquad (26)$$
$$K_i' = Ki\,/\,(x_{1i} - xe_i)$$

The estimation of the object dynamics (M', B', K') allows to optimize the target impedance (M, B, K); for example the whole system converges to the motion $(\ddot{X}e, \dot{X}e, Xe)$ under *critical damping* by satisfying the next equation (27) and setting the real parts of the roots of the characteristic equation (28) sufficiently large and negative.

$$(\,M''^{-1}B''\,)^2 = 4M''^{-1}K'' \qquad (27)$$
$$|\; s\,I + M''^{-1}B''/2\;| = 0 \qquad (28)$$

If it is necessary that the error, e, between the desired motion of the manipulator and the actual movement of the whole system converges to zero when the manipulator contacts the object , another technique is considered as follows. Assume the object dynamics (M', B', K') and the motion $(\ddot{X}_1, \dot{X}_1, X_1)$ of the object are known. The manipulator output force, Fa, is regulated to converge the error, e, to zero.

$$Fa = M\,(\ddot{X} - \ddot{X}o) + B\,(\dot{X} - \dot{X}o) + K\,(X - Xo)$$
$$+\, M'(\ddot{X} - \ddot{X}_1) + B'(\dot{X} - \dot{X}_1) + K'(X - X_1) \qquad (29)$$

Remark that the impedance parameters regulated for stable contact should be limited to keep the actual manipulator stability. The reasonable range of the target impedance parameters has been discussed by D.A.Lawrence[24].

III. MANIPULATOR STRUCTURE

A. Hardware and Control System

A three d.o.f. vertically articulated DD manipulator is used for the experiments. Fig.2 shows its structure. Direct drive manipulators are suitable for precise control because of the accurate estimation of an internal model[13]. A DC torque motor (Inland Co.) is used at each joint.

Fig.3 shows the schematic diagram of the control system. The signal from the rotary encoder of each joint is fed into a computer(Intel 80386 + 80387). After the measurement of rotational angle, angular velocity and angular acceleration are estimated and the necessary motor torque is calculated and output to the servo amplifier.

The control algorithm (8) shows that the accuracy of this impedance control method is due to the accuracy of each joint sensor and its sampling period. Especially, the estimation of angular acceleration is most important to regulate the apparent inertia. When a contact task is executed with a small desired inertia --- low impedance, the controller needs to estimate a high angular acceleration. It is necessary to get a wide frequency range of desired impedance to deal with a variety of contact tasks. Therefore, the *pulse width measurement circuits* and the *second-order digital low-pass filter* are applied to the estimation of angular acceleration and angular velocity (APPENDIX).

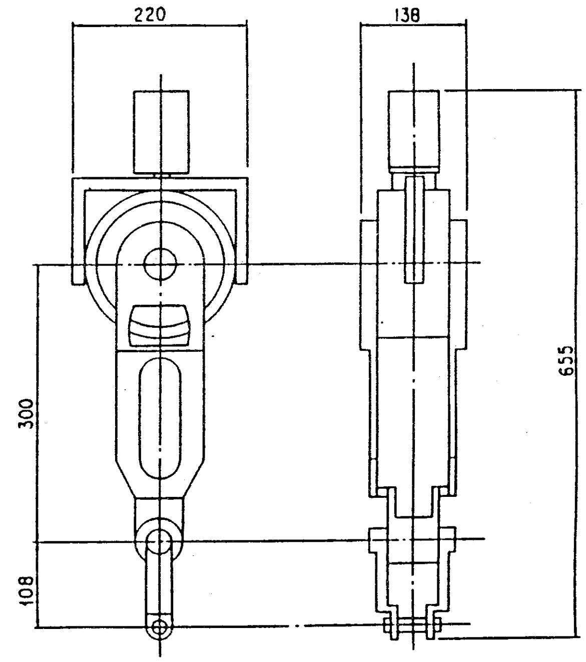

Fig.2 Configuration of the DD manipulator

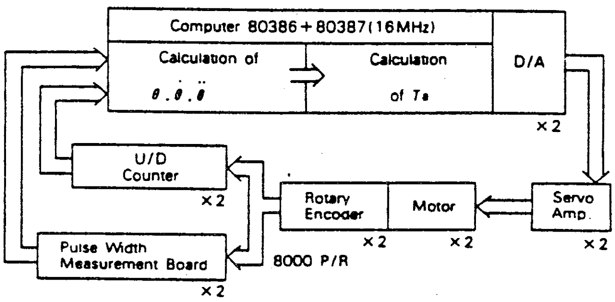

Fig.3 Control system of the manipulator

B. Derivation of the Equation of Motion and Identification of Control Parameters

Although it is not easy to get the accurate model of a conventional manipulator with gear reduction system and to compensate the value of its non-linear friction, the model of the DD manipulator is easily identified. A DD manipulator is a system that each axis has neither friction nor backlash, and ideally stiff bodies are linked freely at each joint. Therefore, each axis can be considered as the fulcrum of a pendulum, and the model parameters are estimated from the motion of each link which separately performs damped oscillation. The derived parameters are the moment of inertia matrix I, viscous friction coefficient matrix Dv, and Coulomb friction vector Cr. The Lagrange's equation is used to derive the equation of motion with the parameters.

IV. CONTROL EXPERIMENTS

1) *Compliance control*. The compliance of the target impedance for the horizontal and vertical orientations is assigned to the arm, and the end-effector is pushed by a human hand. The reaction force to the manipulator along both orientations is generated. Their results are shown in Fig.4.

2) *Obstacle avoidance*. The same three d.o.f manipulator performs obstacle avoidance during a contact task. The cylindrical coordinate system is constructed on the axis 1 as a center of the system (Fig.5). The target impedance is assigned in the vertical, horizontal and rotational orientations. The trajectory is set that the end-effector travels along the cylinder surface. The rigid ball-shaped object made of steel is placed in the trajectory as an obstacle. The end-effector performs a contact task with the object. Fig.6 shows the force applied to each orientation during the surface following.

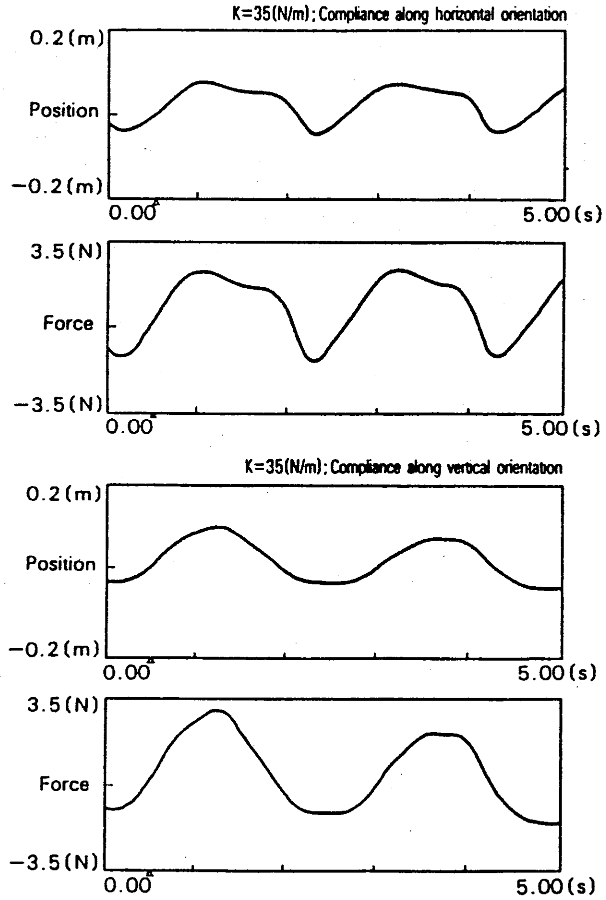

Fig.4 Experimental results of the compliance control

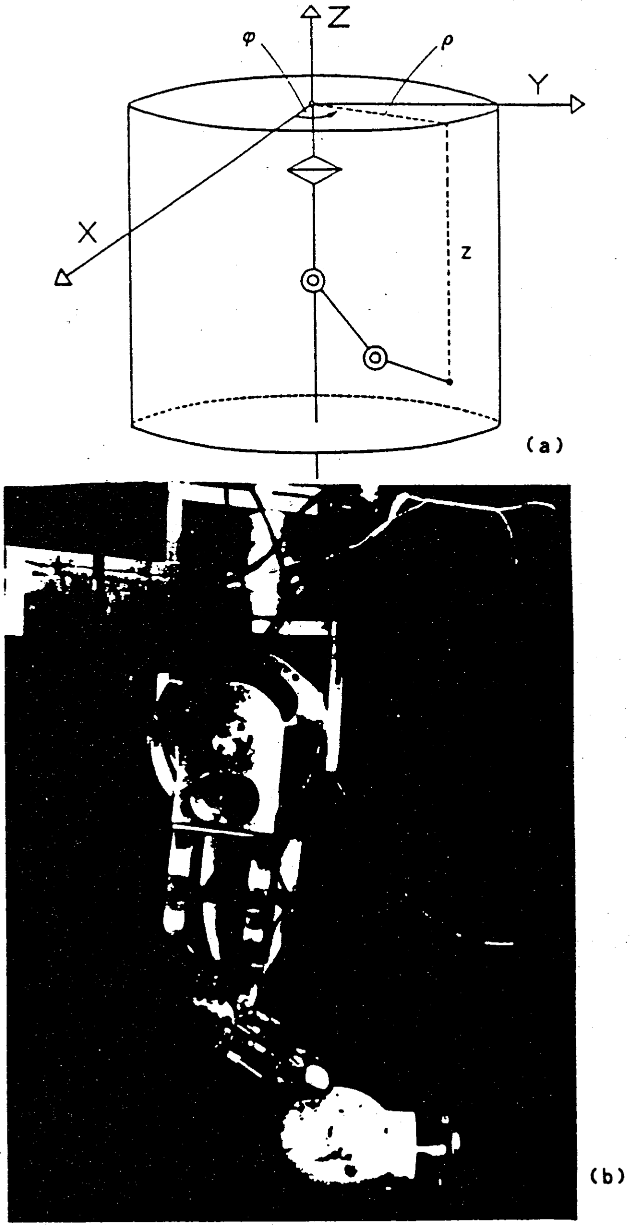

Fig.5 Cylindrical coordinate system (a) for the three d.o.f. arm (b)

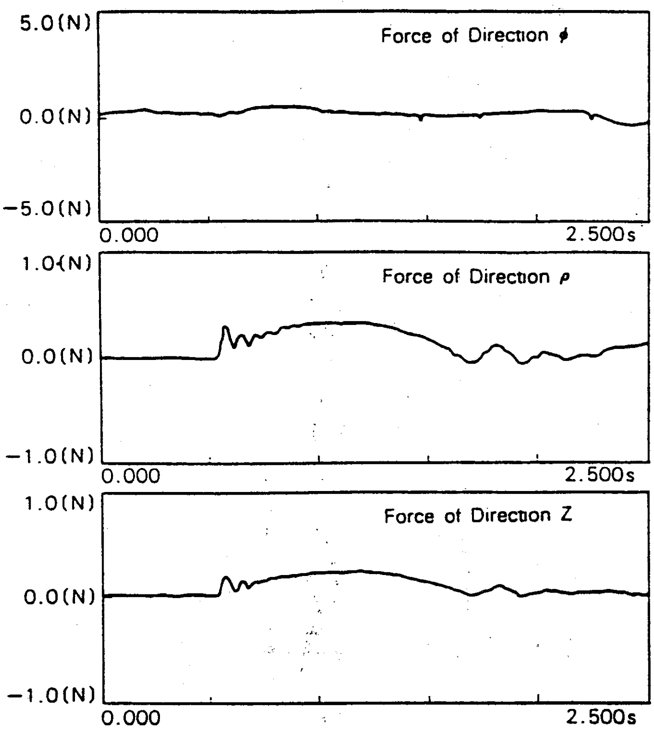

Fig.6 Experimental results of the surface following

3) *Transient response* in a collision. The effect of the apparently reduced inertia when the manipulator collides to an unexpected object is verified in this experiment. Shown in Fig.7, the end-effector is collided to a pendulum as an object at a constant velocity, V. The momentum, M*V is from the apparent inertia, M and the constant velocity, V, then the motion of the pendulum is observed to estimate the practical inertia of the manipulator. To prevent the destruction of the manipulator and to guarantee the regulation of the impedance, a tennis ball is put on the pendulum. The experimental result is shown in Fig.8.

V. DISCUSSION

1) A DD manipulator is a robot manipulator which links are jointed each other with no backlash or friction. These specifications are ideal to get a simplified manipulator dynamics model. Therefore, the simple impedance control algorithm could be derived. The model of the DD manipulator is simple, and the external force is estimated by using the inner model and the angular acceleration. It allows the calculation amount of actuator torque very little.

In general the control algorithm of multi d.o.f. over three d.o.f. manipulator is very complex. Thus the amount of the calculation to control is much more compared with that of the two d.o.f. one, and it limits precise impedance regulation. There are two solutions for this problem. One is to use a high performance CPU or DSP. Another is to brush up the calculation algorithm. The purpose of this paper is to create a simple control method without complex hardware. Thus the coordinate system is changed to cylindrical one without any DSPs or other CPUs. In the case of two d.o.f., the control period is 3.0 [ms], and in the case of three d.o.f., the control period is 3.5 [ms] with little in-

Fig.7 Collision experiment system

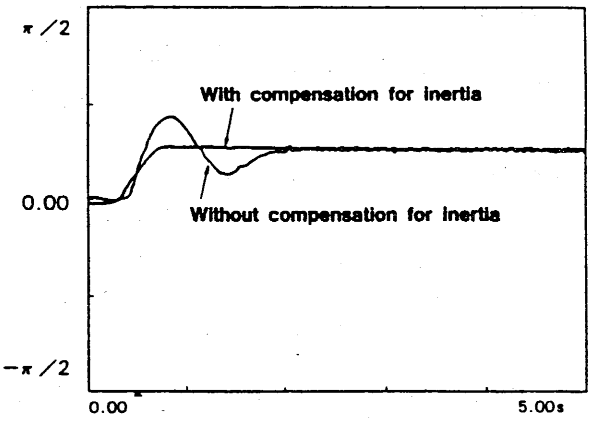

Fig.8 Results of the collision experiment

crease in the experiment III.2). Therefore the sampling period to control the three d.o.f. manipulator remains short with a single processor.

2) The *unified but compact* control strategy from free space motion to contact tasks was verified in the experiments III.2) and III.3). The strategy regulates the target impedance both to satisfy the stable conditions of trajectory control in free space and to perform stable contact tasks.

In the experiment III.1), Fig.4 shows the position displacement and reaction force for horizontal and vertical orientations. The reaction force is proportional to the position displacement from the virtual equilibrium point. The hand should be considered as a *soft* object, and the impedance control is regarded as compliance control.

The experiment III.2) shows trajectory control, stable contact task and obstacle avoidance. In Fig.6, force proportional to the positional variation from the virtual equilibrium point is applied to the obstacle. It shows the manipulator can perform stable contact tasks while maintaining a desired target impedance.
The experiment III.3) performs the dynamic effect of the apparently reduced inertia in the collision to an unexpected object. While the static contact task is controlled by compliance control in the experiment 1), dynamic interaction is controlled by changing the apparent inertia, M, in impedance control. Therefore, impedance control reduces the impact on an object by changing the *momentum*, M*V, at a same velocity, V. For example, if the inertia, M, is assigned sufficiently small as a low impedance, the danger to destroy a manipulator and an object is reduced when the manipulator travels at a high velocity and collides to the unexpected object. In this experiment, the case of the inertia reduced apparently by *acceleration feedback --- low impedance* --- is compared with the case of the actual inertia kept without acceleration feedback. The pendulum oscillates in response to the momentum given by the manipulator. The experimental result in Fig.8 shows the dynamic effect of the apparently reduced impedance that the impact of a low impedance is smaller than a high impedance. Therefore, impedance control reduces the impact on an object by changing the momentum even at a high velocity.

It is possible to set the trajectory controlled manipulator in free space the apparent low impedance which reduces the impact to the *unexpected* object. Another method to reduce the impact is to change a manipulator velocity[27]. But the manipulator controller has to know the position of the environment.

3) *Robustness* to the object with varieties of impedance is shown by the experiment III.1) for contact tasks with a low impedance object and the experiments III.2) and III.3) for collision to a high impedance object. The manipulator is regulated as high impedance for the soft object and low impedance for the stiff object, and it remains stable in the contact tasks.

VI. CONCLUSIONS

A new and compact implementation of impedance control by internal model of manipulator and angular acceleration feedback without using force sensors was proposed. This method was verified in the experiments with a three d.o.f. DD manipulator. This method has an advantage that the motion of a manipulator is controlled stably with a same low impedance, when it moves from a trajectory in free space to a contact task. Also, the manufacturing cost of the manipulator is reduced, and the control algorithm is simplified.

ACKNOWLEDGEMENT

The authors would like to express their sincere thanks to Shoichiro Nishizawa of the Mechanical Engineering Lab. and Jose Felipe Pelaez-Polo of the National Univ. of Mexico who helped to design the DD arm.

REFERENCES

[1]Whitney,D.E.,"Historical Perspective and State of the Art in Robot Force Control," Proc. of IEEE Int. Conf. on Rob. & Autom., p.262-268, 1985.
[2]Raibert,M.H. and Craig,J.J.,"Hybrid Position/Force Control of Manipulators," ASME J. of DSMC, Vol.102, pp.126-133, 1981.
[3]Salisbury,J.K.,"Active Stiffness Control of a Manipulators," Proc. of IEEE Int. Conf.on Decision and Control,Vol.102, 1980.
[4]Paul,R.P. and Shimano,B.,"Compliance and Control",Proc. of the JACC,pp.694-699,1976.
[5]Whitney,D.E.,"Force Feedback Control of Manipulator Fine Motions," ASME J. DSMC, pp.91-97, 1977.
[6]Hogan,N.,"Impedance Control : An Approach to Manipulation : Part I,II,III," J. DSMC, pp.1-24, 1985.
[7]Hogan,N.,"Stable Execution of Contact Tasks using Impedance Control," Proc. of IEEE Int. Conf. on Rob. & Autom.,pp.1047-1054, 1987.
[8]An,C.H. and Hollerbach,J.M.,"Dynamic Stability Issues in Force Control of Manipulators," Proc. of IEEE Int. Conf. on Rob. & Autom., pp.890-896, 1987.
[9]Uchiyama,M.,"Study on dynamic control of an artificial hand (coordination motion control with a mathematical model)," Trans. JSME, vol.45, no.391, pp.323-335,1979.
[10]Arai,H. and Tachi,S. "Force detection and active power assistance of a direct-drive manipulator," Advanced Robotics, vol.2, no.3, pp.241-257, 1987.

[11]Paul,R.P.,"Robot Manipulators : Mathematics, Programming, and Control," M.I.T. Press, Cambridge, MA, 1981.
[12]Craig,J.J.," Introduction to Robotics Mechanics & Control," Addison-Wesley, 1986.
[13]Asada,H.,"Direct-Drive Robots : Theory andPractice,"M.I.T.Press,Cambridge,MA,1987.
[14]Tachi,S., Arai,H. and Maeda,T.,"Development of an Anthropomorphic Tele-existence Slave Robot," Int. Conf. on Advanced Mechatronics, pp.385-390, 1989.
[15]Shimano,B. and Routh,B.,"On Force Sensing Information and its Use in Controlling Manipulators," Proc. of the 8th. Industrial Symp.on Industrial Robots, pp.119-126.
[16]Wu,C.H. and Paul,R.P.,"Resolved Motion Force Control of Robot Manipulators," IEEE Trans. Syst.,Man,Cybern., Vol.12, No.3, pp.266-275, 1982.
[17]Khatib,O. and Burdick,J.,"Motion and Force Control of Robot Manipulators," Proc. of IEEE Int. Conf. on Rob. & Autom., 1986.
[18]Khatib,O.,"A Unified Approach for Motion and Force Control of Robot Manipulators : The Operational Space Formulation," IEEE J. of Rob. & Autom., Vol.RA-3, No.1, pp.43-53, 1987.
[19]Kazerooni,H Houpt,P.K. and Sheridan, T.B.,"Robust Compliant Motion for Manipulators, Part I & II," IEEE J. of Rob. and Autom., Vol.RA-2, June, 1986.
[20]Kazerooni,H.,"Robust, Non-Linear Impedance Control for Robot Manipulators," Proc. of IEEE Int. Conf. on Rob. & Autom., pp.741-749, 1987.
[21]Asada,H. and Ogawa,K.,"On the Dynamic Analysis of a Manipulator and its End Effector Interacting with the Environment," Proc. of IEEE Int.Conf.on Rob.& Autom., pp.751-756, 1987.
[22]Goldenberg,A.A., "Implementation of Force and Impedance Control in Robot Manipulators," Proc. of IEEE Int. Conf. on Rob. & Autom., pp.1626-1632, 1988.
[23]Anderson,R.J. and Spong,M.,"Hybrid Impedance Control of Robotic Manipulators," IEEE J. of Rob. & Autom.,Vol.4,No.5,1988.
[24]Lawrence,D.A.,"Impedance Control Stability Properties in Common Implementations," Proc. of IEEE Int. Conf. on Rob. & Autom., pp.1185-1190, 1988.
[25]Hogan,N.,"Control Strategies for Complex Movements Derived from Physical Systems Theory," in Complex Systems -- Operational Approaches in Neurobiology Physics and Computers, H.Haken, Ed. New York, NY:Springer-Verlag,pp.156-168,1985.
[26]Hogan,N.,"On the Stability of Manipulators Performing Contact Tasks," IEEE J. of Rob.& Autom.,Vol.4,No.6,pp.677-686, 1988.
[27]Kitagaki,K. and Uchiyama,M.,"Generating Appropriate Approach Velocities to the Environment in Robot Tele-operation," Proc. of IEEE Int. Workshop on Intelligent Robots and Systems, pp.731-736, October, 1988.
[28]Murakami,T. and Ohnishi,K.,"An Advanced Approach of Servo Control in Industrial Robot," Proc. of IEEE Int. Workshop on Intelligent Robots and Systems,1988.

APPENDIX : Estimation of Angular Velocity and Angular Acceleration

The conventional method for estimating angular velocity and acceleration is to calculate the difference,

$$\dot{\theta} = (\theta_n - \theta_{n-1}) \; / \; T \qquad \text{(A-1)}$$

where θ_n, θ_{n-1} are angles in sampling time n,n-1, and T is the sampling period. However the encoder for a DD motor may have a trouble that the pulse number per a rotation is less than that of a reduction drive motor, and figure canceling makes the accuracy of the angular velocity very poor at low angular velocity. Pulse width measurement circuit that measures the pulse interval at 1 M Hz standard clock is mounted on the control system, and the reciprocal number is taken as the angular velocity,

$$\dot{\theta} = \hat{\theta} \; (T_n - T_{n-1}) \qquad \text{(A-2)}$$

where $\hat{\theta}$ is the rotational angle per one pulse, and T_n,T_{n-1} are pulse input time. This method makes no figure canceling at low rotation and generates small sampling delay[14]. Also, the last estimated value is reduced exponentially when no pulse is measured at each sampling time, and second order digital low pass filter is applied to the estimation. The estimated value is quite smooth as shown in Fig.A-1 in *sin* wave joint rotation.

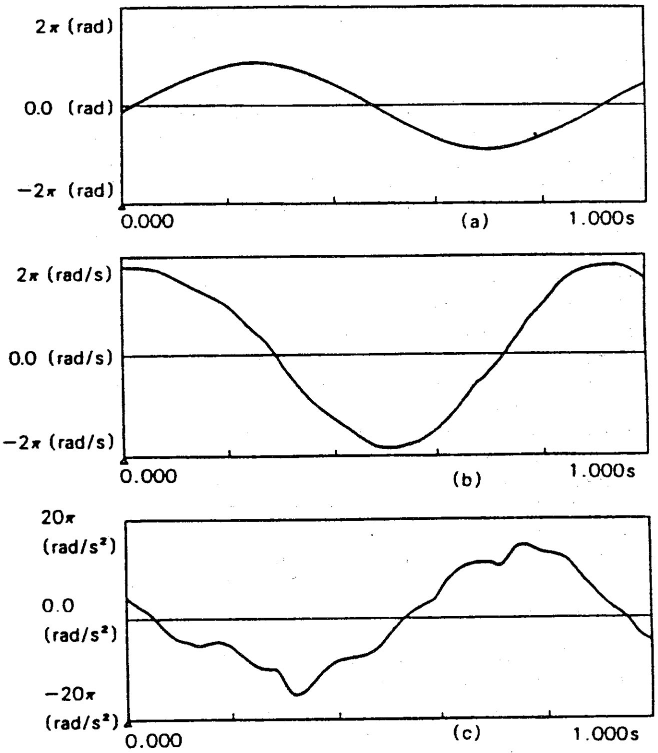

Fig.A-1 Estimated rotational angle (a), angular velocity (b), and angular acceleration (c)