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**Forcefree Control for Flexible Motion
of Industrial Articulated Robot Arms**

Satoru Goto

1. Introduction

Many industrial robot arms are operated in industry, and some robotic applications in the industry, such as a pulling-out of products made by die casting, require the flexible motion excited by an external force. Here, the flexible motion means that the robot arm moves passively according to the external force. Industrial robot arms, however, are difficult to be moved by the external force because the servo controller of the industrial robot arm controls the motion of the robot arm excited by an input signal responsible for the motion. The torque generated by the external force is a kind of disturbance for the robot control system and it can be compensated by the servo controller.

Impedance control (Hogan 1985; Scivicco & Siciliano, 2000) and compliance control (Mason, 1981; Micheal et al., 1982) were proposed in order to achieve the flexible motion, and these methods have been applied to industrial robots (Ciro et al., 2000). Most of these control methods impose desired dynamic characteristics between an end-effector and an environment by setting inertia, friction and stiffness. Usually an elastic spring behavior is introduced in order to achieve the flexible motion of the robot arm. The potential force of the elastic spring behavior is a conservative force, and it is impossible to achieve the passive motion away from the environment caused by the external force is impossible to be achieved by using these control methods.

In this research, the forcefree control, which achieves the passive motion of the robot arm according to the external force, is proposed. Moreover, the forcefree control is extended to the forcefree control with independent compensation, the forcefree control with assigned locus and the position information based forcefree control. The effectiveness of the proposed forcefree control is assured by comparing the experimental results with simulation results. Comparison between the forcefree control and other force control methods such as impedance control are also described. Finally, applications of the forcefree control of pull-out work, direct teaching and rehabilitation robot are demonstrated.

2. Forcefree Control

2.1 Necessity of Forcefree Control

Operations such as cutting and welding can be easily achieved by using industrial robot arms. These operations are carried out through contour control in that the tip of the robot arm moves along a given path, and point-to-point (PTP) control in that the tip moves between previously assigned points. These operations are tractable as the rigidity of the robot arm advances. Therefore, the industrial robot arms are designed with high rigidity.

Recently, control of a contact force is required in order to carry out assembling, handling, inlaying, pull-out work and grinder operations. On the contrary, it is difficult to control the contact force if the robot arm possesses high rigidity. In view of this, the property of low rigidity for the industrial robot arms is required to control the contact force.

On the other hand, flexible motion is also required for the safety operation such as contact between the robot and human operator. Generally, an emergency shutdown switch is built in to the servo controller. When the operator is sandwiched between the tip of the robot arm and the environment, the emergency halt becomes more dangerous. If the robot arm can be actuated with flexibility, the operator is released from the sandwiched situation.

Some of the problems have been solved by particularly designed robots or by remodeling of robots. However, a number of industrial robot arms are manufactured for general purpose, and such robot arms have a lower cost compared with that of special purpose robots. In this view, flexible motion by general purpose industrial robot arms is required in industry.

A servo controller of industrial robot arm includes a position loop and a velocity loop. Input to the industrial robot arm is usually the joint position of each link. Hence, the industrial robot arms should be considered as the combination of the mechanism of the robot arm and the servo controller.

Recently, a study of force control of industrial robots has developed rapidly and the achievement of such force control has been the major concern. A number of force control methods for the change of rigidity of robot arms such as impedance control (Hogan 1985; Scivicco & Siciliano, 2000) and compliance control (Mason, 1981; Mecheal et al., 1982) have been proposed. These methods are apparently good enough to achieve the requirement of force control. However, to apply these methods in industry, there are difficult problems to be solved. For general purpose robots including the servo controller, these methods require changes in the control strategy in the servo controller.

Modification of the servo controller is almost impossible from the user side, and modification by the maker is very expensive even upon request from the user side. Presently, available methods for the achievement of flexible contact

between the tip of the robot arm and the environment are almost achieved by attaching a flexible device on the tip of the robot arm.

The forcefree control can achieve the flexible motion of the industrial robot arms under virtual circumstances of non-gravity and non-friction without any change of the built-in controller. By use of the forcefree control, the robot arm moves passively according to the external force directly as if it were under the circumstances of non-friction and non-gravity. The mathematical explanation of the forcefree control is described below.

2.2 Derivation of Forcefree Control

Dynamics of an articulated robot arm is expressed by

$$H(q)\ddot{q} + D\dot{q} + N_{\mu}\mathrm{sgn}(\dot{q}) + h(q,\dot{q}) + g(q) = \tau_s + \tau_f \tag{1}$$

where $H(q)$ is the inertia matrix, $D\dot{q} + N_{\mu}\mathrm{sgn}(\dot{q})$ is the friction term, $h(q,\dot{q})$ is the coupling nonlinear term, $g(q)$ is the gravity term, q is the output of joint angle, τ_s is the torque input to the robot arm and τ_f is the joint torque corresponding to the external force f acting on the tip of the robot arm (Fu et al., 1987).
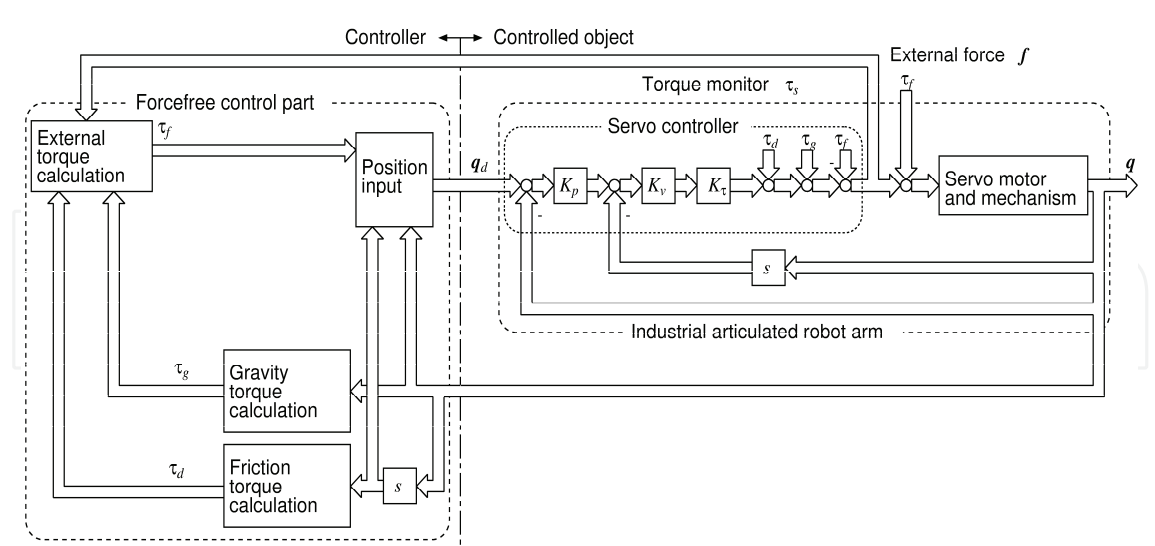

Figure 1. Block diagram of forcefree control

In industrial robot arms, the servo controller is adapted to control the motion of the robot arm. The control loop of the servo controller is shown on the right side of Fig. 1, where K_p, K_v and K_τ are position loop gain, velocity loop gain and torque constant, respectively (Nakamura et al., 2004; Kyura, 1996). The

servo controller adopts P and PI type cascade control, the P controller is used for the position loop control and the PI controller is used for the velocity loop control. The velocity control loop has the role of the derivative action. The servo controller generates the torque input to the robot arm as described by

$$\tau_s = K_\tau \left(K_v \left(K_p (q_d - q) - \dot{q} \right) \right) + \tau_d + \tau_g - \tau_f \tag{2}$$

where q_d is the input of joint angle, τ_d is the friction compensation torque and τ_g is the gravity compensation torque. As expressed in (2), the servo controller includes the friction compensation and the gravity compensation through integral action of PI control. The friction and the gravity are assumed to be exactly compensated by the servo controller as

$$\tau_d = D\dot{q} + N_\mu \mathrm{sgn}(\dot{q}) \tag{3}$$

$$\tau_g = g(q). \tag{4}$$

The torque caused by an external force τ_f is also compensated by the servo controller because the servo controller of an industrial robot arm is designed such that the stiffness of the robot arm is high enough and the robot arm will never be moved by the external force.

The total dynamic equation of an industrial articulated robot arm including the servo controller is given by substituting (2), (3) and (4) for (1) as

$$H(q)\ddot{q} + h(q,\dot{q}) = K_\tau \left(K_v \left(K_p (q_d - q) - \dot{q} \right) \right). \tag{5}$$

Forcefree control means that the influences of friction and gravity on the robot arm motion can be compensated. The entire dynamics of the industrial robot arms controlled by the forcefree control is described by

$$H(q)\ddot{q} + h(q,\dot{q}) = \tau_f \tag{6}$$

where τ_f is obtained by substituting (2) for (5) as

$$\tau_f = -\left(\tau_s - \tau_d - \tau_g - \left(H(q)\ddot{q} + h(q,\dot{q}) \right) \right). \tag{7}$$

Generally, the speed of the flexible motion of an industrial robot arm is relatively slow, usually less than 1/5 of the rated speed. Hence, the inertia and nonlinear terms of the robot arm is negligibly small $\left(H(q)\ddot{q} + h(q,\dot{q}) \approx 0 \right)$, and the external torque is approximately given by

$$\tau_f = -(\tau_s - \tau_d - \tau_g).$$ (8)

Finally, the control law of the forcefree control with independent compensation is obtained by substituting (6) and (8) for (5) and by solving for q_d as

$$q_d = K_p^{-1}\left(K_v^{-1}K_\tau^{-1}\left(-\tau_s + \tau_d + \tau_g\right) + \dot{q}\right) + q.$$ (9)

Here, τ_s is measured by the torque monitor which is usually attached to the servo controller of the industrial robot arm and is used to check the value of the torque.

2.2.1 Estimation of Friction Term

Friction term τ_d consists of Viscous friction $D\dot{q}$ and Coulomb friction $N_\mu \text{sgn}(\dot{q})$ as in (3). The friction effect to the motion of the robot arm is estimated by the torque output under constant velocity motion. The friction term is obtained through the following procedure;

1. To cancel the effect of the gravity, the robot arm sets around its vertical position;
2. Various constant velocity inputs are applied to each link of the robot arm;
3. Respective torque outputs corresponding to the applied velocities are measured by using the torque monitor;
4. The torque output vs. applied velocities are plotted;
5. Viscous friction coefficient D and magnitude of Coulomb friction N_μ in (3) are estimated by using the least squares method from the collected data.

In order to smoothen the Coulomb friction effect, the Sigmoid function is introduced in the friction term as

$$\tau_d = D\dot{q} + N_\mu f_d(\dot{q})$$ (10)

where

$$f_d(\dot{q}) = \begin{pmatrix} \left(1 - e^{-\gamma\dot{q}_1}\right)/\left(1 + e^{-\gamma\dot{q}_1}\right) \\ \left(1 - e^{-\gamma\dot{q}_2}\right)/\left(1 + e^{-\gamma\dot{q}_2}\right) \\ \vdots \\ \left(1 - e^{-\gamma\dot{q}_n}\right)/\left(1 + e^{-\gamma\dot{q}_n}\right) \end{pmatrix}$$ (11)

and the parameter γ is introduced for adjusting the effect of smoothness.

2.2.2 Estimation of Gravity Term

The gravity term is a function of the robot arm position q as (4). Here, the gravity term is modelled by

$$g(q) = U(q)a + V(\dot{q})b \tag{12}$$

where the function

$$V(\dot{q}) = \begin{pmatrix} e^{-\lambda(\dot{q}_1)^2} & 0 & \cdots & 0 \\ 0 & e^{-\lambda(\dot{q}_2)^2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & e^{-\lambda(\dot{q}_n)^2} \end{pmatrix} \tag{13}$$

is introduced in order to smoothen the effect of static friction b. In (13), the parameter λ is introduced for adjusting the effect of smoothness.

The parameters a and b are estimated by using the least squares method from the experimental data of the steady-state torque monitor outputs for various postures of the robot arm. For the estimation of the parameters a and b in (12), the steady-state torque monitor outputs are used because the torque monitor output contains a transient component, which is caused by the integral action of the servo controller. Hence, the gravity compensation torque can be represented by

$$\tau_g = \left(I - e^{At}\right)g(q) \tag{14}$$

where

$$e^{At} = \begin{pmatrix} e^{-t/T_1} & 0 & \cdots & 0 \\ 0 & e^{-t/T_2} & \ddots & \vdots \\ \vdots & \ddots & \ddots & 0 \\ 0 & \cdots & 0 & e^{-t/T_n} \end{pmatrix} \tag{15}$$

and $T_i \, (i = 1, \cdots, n)$ are the time constants.

2.3 Alogrithm of Forcefree Control

The algorithm of the forcefree control is explained here. Initial setting of the forcefree control is expressed in the following first 3 items.

1. Servo parameters K_p, K_v and K_τ are obtained from the servo controller;
2. Friction term (10) is estimated as explained in the above section;
3. Gravity term (12) is estimated as explained in the above section.

The execution of the forcefree control has summarized by the following 6 items.

1. External force f is added to the robot arm;
2. Torque monitor detects the external force f;
3. The friction torque τ_d is estimated by (10);
4. The gravity torque τ_g is estimated by (12);
5. External torque τ_f is calculated by (8);
6. The position input q_d is generated by (9).

Finally, the reference position input q_d is given to the servo controller according to the above algorithm and the forcefree control is achieved.

2.4 Verification

Robot arm motion by using the forcefree control was verified by a simulation study and experiments. The simulation study shows an ideal motion of the forcefree control. An industrial articulated robot arm (Performer-MK3S, YAHATA Electric Machinery Mfg., Co., Ltd) was used for the experiment on the forcefree control with independent compensation. Two links of Performer-MK3S were used for the experiment. The link lengths of the robot arm are $l_1 = 0.25$ [m], $l_2 = 0.215$ [m], and masses of the links are $m_1 = 2.86$ [kg], $m_2 = 2.19$ [kg], respectively. The position loop gain was $K_p = \mathrm{diag}(25,25)$ [1/s], the velocity loop gain was $K_v = \mathrm{diag}(150,150)$ [1/s], and the torque constant was $K_\tau = \mathrm{diag}(0.017426,0.036952)$ [$\mathrm{Nm}/(\mathrm{rad}/\mathrm{s}^2)$].

Fig. 2 shows the experimental results of the estimation of friction term. The bold lines show the results of (10) for $\gamma = 120$ and the dotted lines show the results of $D\dot{q} + N_\mu \mathrm{sgn}(\dot{q})$. The step change of the results of $D\dot{q} + N_\mu \mathrm{sgn}(\dot{q})$ can be smoothened using the sigmoid function.
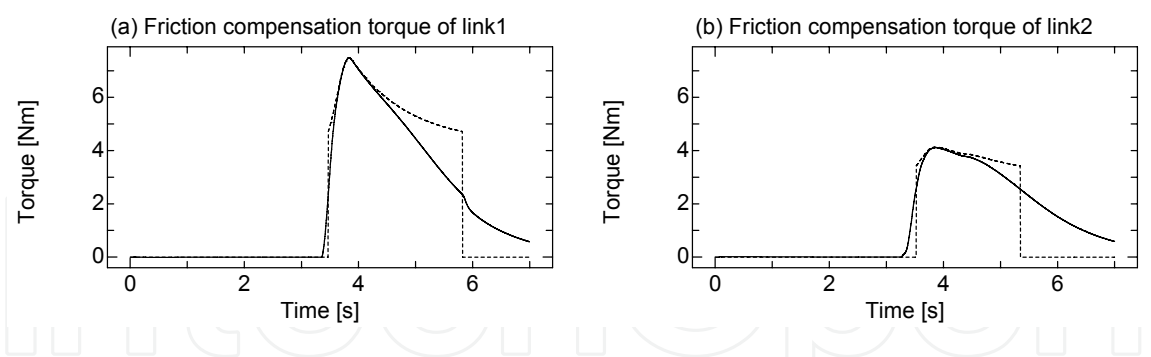
Figure 2. Estimation of friction term

Fig. 3 shows the experimental results of the estimation of gravity term. The bold lines show the results of (12) for $\lambda = 150$ and the dotted lines show the results of $U(q)a + b$. The alternate long and short lines show the result of $U(q)a$. The estimated friction approximately gives the static friction effect.
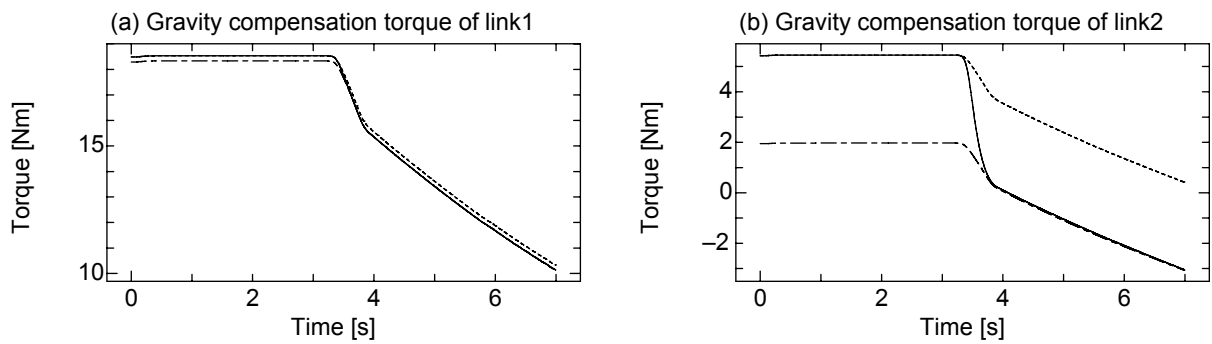

Figure 3. Estimation of gravity term

Fig. 4 shows the simulation results and the experimental results where the external force f is $(-88.9, 6.1)$ [N]. The dotted lines show the simulation results and the bold lines show the experimental results. As in Fig. 4, the experimental results and theoretical response are almost the same and thereby shows that the exact forcefree control can be achieved in practice. The result shows that the forcefree control was achieved with an actual industrial robot arm.
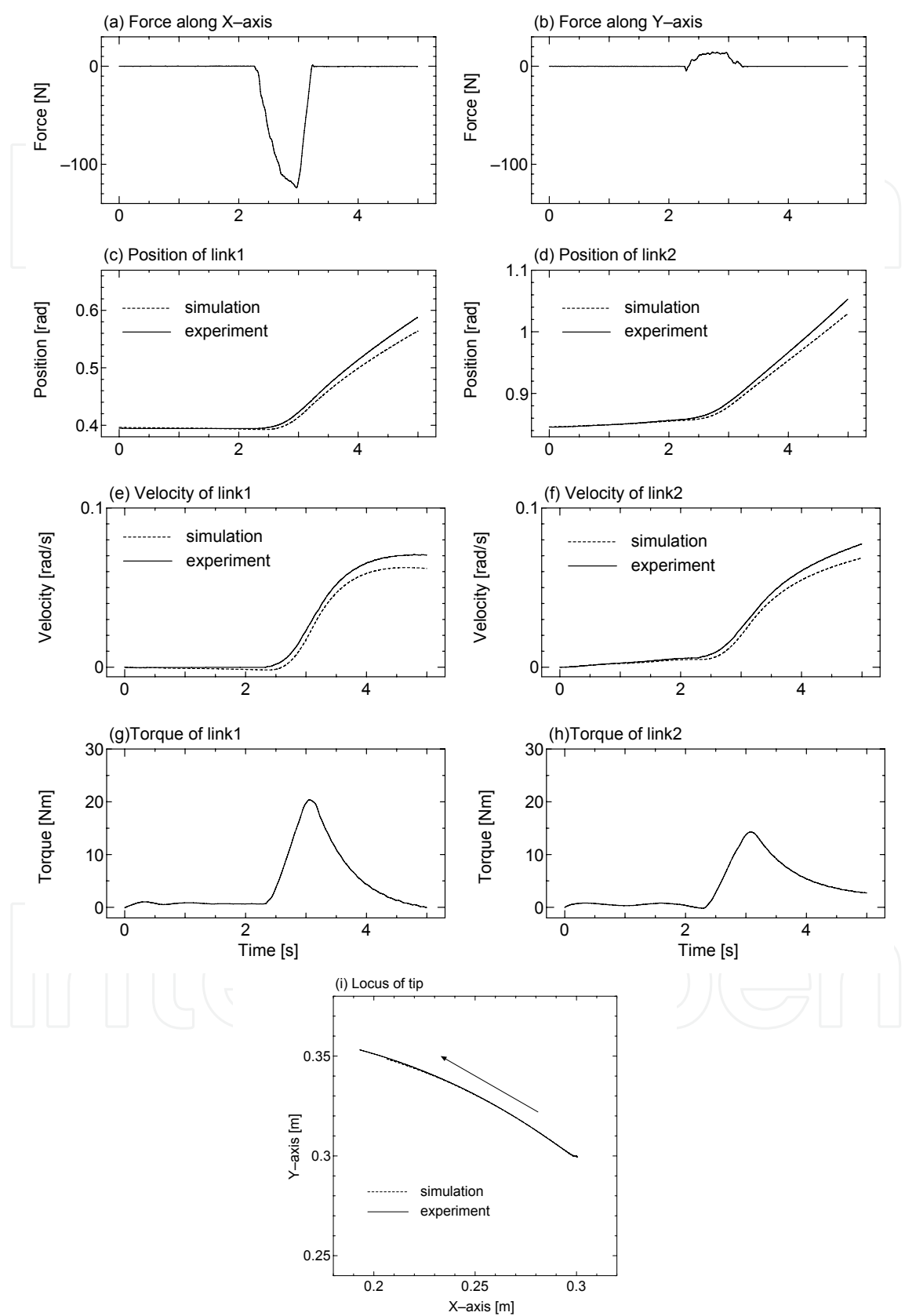
Figure 4. Simulation and experimental results of forcefree control

3. Expansion of Forcefree Control

3.1 Forcefree Control with Independent Compensation

The forcefree control is achieved in the non-friction and non-gravity condition. Nevertheless, in some operation of industrial robot arms, friction and/or gravity of the robot arm is useful. Moreover, a large force is required in order to achieve flexible motion of huge robot arms because of their huge inertia, even if the forcefree control is applied. The forcefree control is extended to realize flexible motion emulating the operational circumstances of arbitrary inertia, arbitrary friction and arbitrary gravity through independent compensation of inertia, friction and gravity.

3.1.1 Derivation of Forcefree Control with Independent Compensation

Forcefree control with independent compensation means that the influences of inertia, friction and gravity to the robot arm motion can be assigned arbitrarily. The entire dynamics of an industrial robot arm working on the forcefree control with independent compensation is described by

$$H(q)\ddot{q} + h(q,\dot{q}) = C_f \tau_f - C_d \tau_d - C_g \tau_g \qquad (16)$$

where C_f, C_d and C_g are the coefficients of the inertia, friction and gravity terms, respectively. They can be tuned to adjust the effect of the inertia, friction and gravity, independently. For instance, $C_f = E$, $C_d = 0$ and $C_g = 0$, corresponds to the forcefree control and $C_f \rightarrow \infty$, $C_d = C_g = 0$ corresponds to the perfect compensation of the inertia, friction and gravity.

The block diagram of the forcefree control with independent compensation is shown in Fig. 5. The inputs of joint angle q_d for the forcefree control with independent compensation is obtained by substituting (14) for (5) and by solving for q_d as

$$q_d = K_p^{-1}\left(K_v^{-1}K_\tau^{-1}\left(C_f \tau_f - C_d \tau_d - C_g \tau_g\right) + \dot{q}\right) + q. \qquad (17)$$

Finally, the control law of the forcefree control with independent compensation is obtained by substituting (8) for (17) as

$$q_d = K_p^{-1}\left(K_v^{-1}K_\tau^{-1}\left(-C_f \tau_s + \left(C_f - C_d\right)\tau_d + \left(C_f - C_g\right)\tau_g\right) + \dot{q}\right) + q \qquad (18)$$
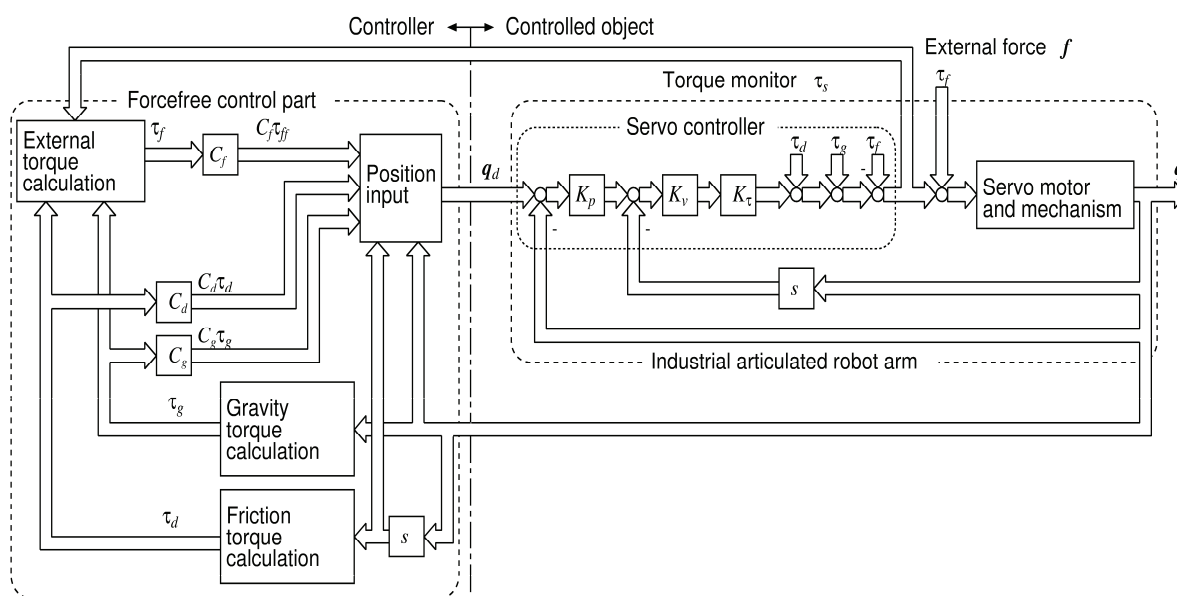
Figure 5. Block diagram of forcefree control with independent compensation

3.1.2 Verification

Step input of 10[N] to X-axis direction was applied to the tip of the robot arm. A force sensor was used to measure the value of external force. The initial end-effector position of the robot arm was at (0.3, 0.3)[m].

Experimental results of the forcefree control with independent compensation are shown in Fig. 6, where the coefficients of compensation are $c^f = 2E$, $C^d = E$, $C^g = 0$. In Fig. 6, the dotted lines show the theoretical responses obtained through simulation and the bold lines show the experimental results.

As in Fig. 6, the experimental results and theoretical response are almost the same and thereby shows that the exact forcefree control with independent compensation can be achieved in practice. The result shows that the forcefree control with independent compensation was realized with an actual industrial robot arm.
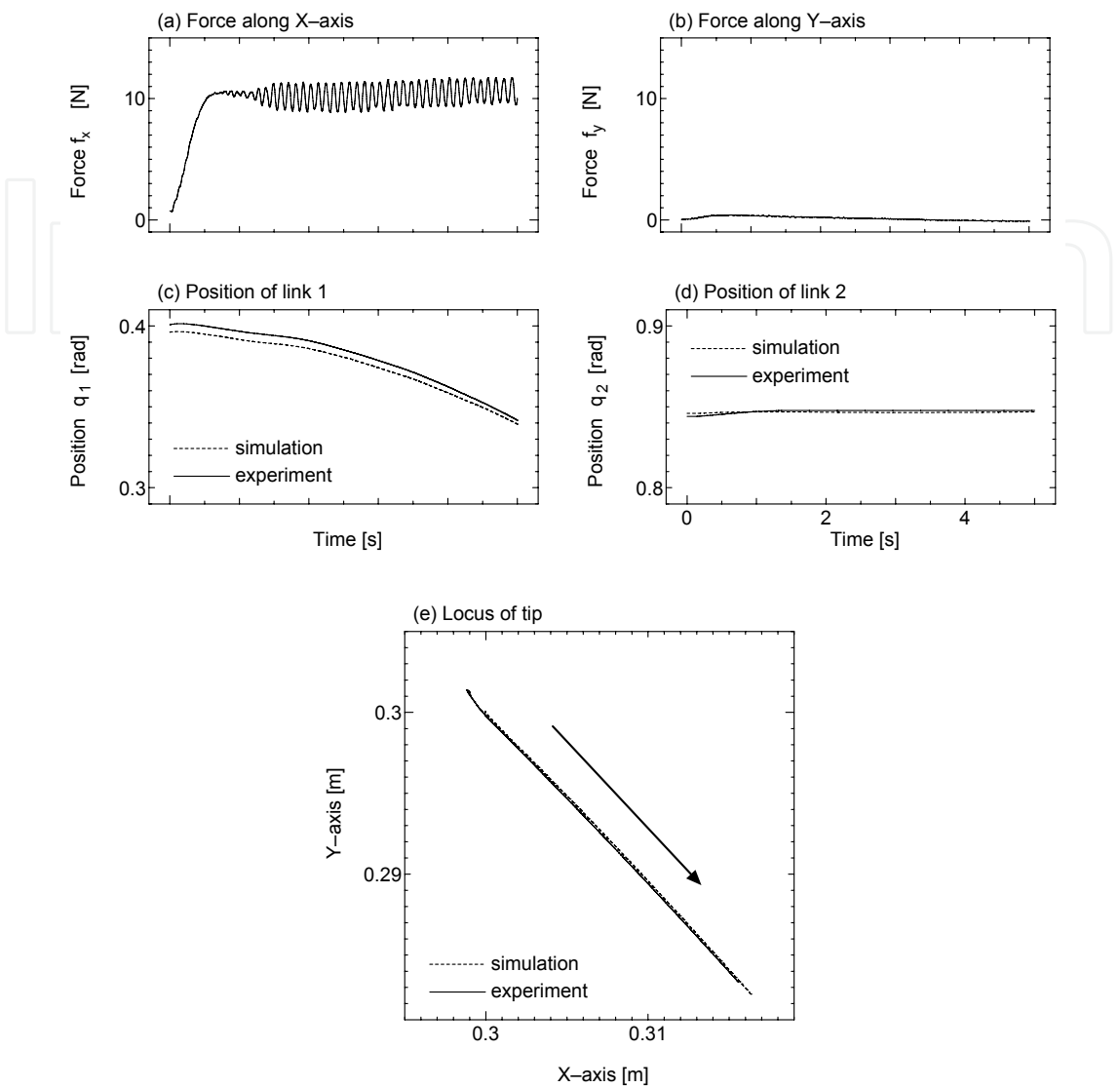
Figure 6. Simulation and experimental results of forcefree control with independent compensation

3.2 Forcefree Control with Assigned Locus

3.2.1 Necessity of Forcefree Control with Assigned Locus

By use of the forcefree control, the robot arm moves according to the external force. The direction of the motion depends on the direction of the external force. When the motion of the robot arm was restricted, the original forcefree control can not be applied. In such a case, the flexible motion with assigned locus is required. In this section, the forcefree control with assigned locus is introduced. The forcefree control with assigned locus makes the tip of the robot arm to follow the assigned locus, and the tip velocity depends on the external force.

3.2.2 Derivation of Forcefree Control with Assigned Locus

The forcefree control with assigned locus is based on mass point type forcefree control. Mass point type forcefree control is constructed from a mass point which is assumed to be the tip of the robot arm. Therefore, the motion of the mass point and the tip of the robot arm are the same. The mass point moves according to the velocity v caused by the external force f, when an external force f is applied on the mass point.

The direction of the motion is the same as the external force f. Besides, the absolute value of the velocity v depends on the external force f. Therefore, the mass point could not follow the assigned locus. In order to follow the assigned locus, the direction of the generated velocity v has to be changed to the tangential direction of the assigned locus. By continuing the above processes, the direction of the velocity v of the mass point is always the same as the tangential direction on the assigned locus. Hence, the tip of the robot arm follows the assigned locus with the velocity which is determined by the external force f.

Fig. 7 shows the block diagram of the forcefree control with assigned locus. Under the non-gravity condition, the equation of the motion of the mass point by the external force f

$$m\ddot{r} + d\dot{r} = f \tag{19}$$

where r is the position of the mass point, m is the mass of the mass point and d is the friction coefficient.

In order to realize the flexible motion with assigned locus according to the external force f, the mass point obeys the equation (19) only for the component in (x, y, z) which gives the maximal amplitude of the external force f.

Figure 7. Block diagram of the forcefree control with assigned locus

The other components of the position of the mass point are determined by the assigned locus $h(r_d) = 0$. As a result, the position of the tip of the robot arm r_d under the forcefree control with assigned locus is determined by

$$\begin{cases} m\ddot{r}_d^i + d\dot{r}_d^i = f^i, \ i = \mathrm{argmax}_{j=x,y,z} \left| f^j \right|. \\ h(r_d) = 0 \end{cases} \tag{20}$$

The algorithm of forcefree control can be described as follows.

1. The external force f is measured by a force sensor.
2. The component having the maximum amplitude of the external force $i = \mathrm{argmax}_{j=x,y,z} \left| f^j \right|$ is determined.
3. The i th component of the position of the tip of the robot arm r_d^i is determined by using the equation of motion.
4. The other components of the position of the tip of robot arm is determined by the assigned locus $h(r_d) = 0$.
5. The input of the servo controller q_d is calculated from the tip position r_d by using inverse kinematics.

3.2.3 Verification

Verification of the forcefree control with assigned locus was carried out by simulation and experiment. Besides, simulation and experiment were carried out under non-friction conditions which mean the coefficient of friction d was zero.

Simulation and experimental results are shown in Fig. 8. In Fig. 8, (a) and (b) illustrate the components of the external force f along the direction of X-axis and Y-axis, respectively, (c) and (d) show the joint trajectories of link1 and link2, respectively, (e) and (f) show the velocity v of X-axis and Y-axis, respectively, and (g) shows the locus of the tip of the robot arm. In Fig. 8, the dotted line denotes the simulation result and the bold line denotes the experimental results. In Fig. 8(g), dash line shows the assigned locus. It can be verified that simulation and experimental results are comparable, and both results have realized the exact assigned locus. This phenomenon illustrates the realization of the proposed forcefree control with assigned locus.
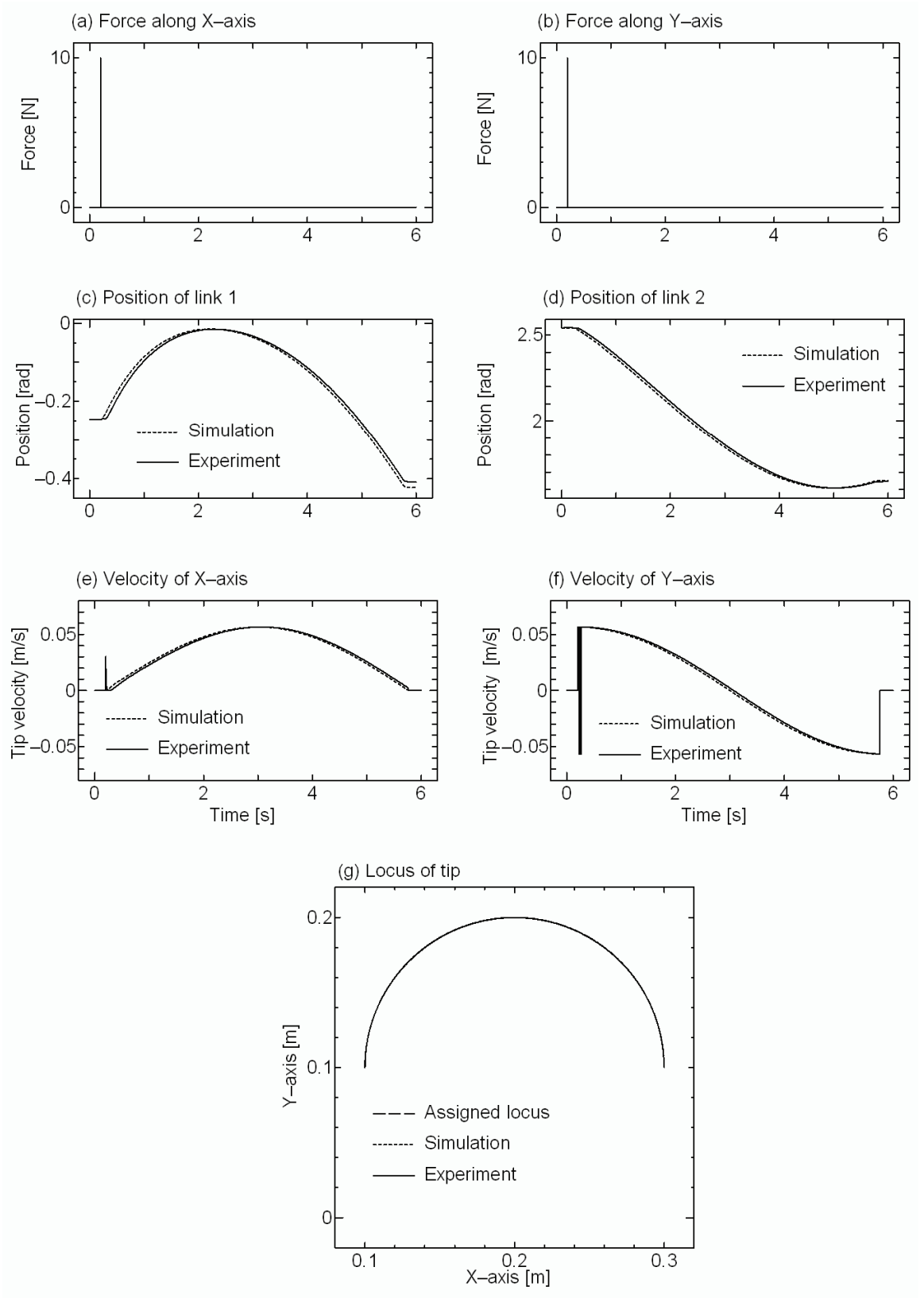
Figure 8. Simulation and experimental results of forcefree control with assigned locus

3.3 Position Information Based Forcefree Control

3.3.1 Necessity of Position Information Based Forcefree Control

The above explained forcefree control requires a force sensor or a torque monitor for the detection of the external force. In order to apply more general industrial robot arms, the forcefree control is extended, where the external force is estimated only by the position information.

In the servo controller of the industrial robot arms, a PI controller is used for the velocity loop and the torque disturbance is compensated by the integral action of the PI controller so that the robot arm is not moved by the external force. On the other hand, the torque information required for the forcefree control must be estimated by the change of position caused by the external force. Hence, the P controller must be used for the velocity loop. By changing the velocity controller from PI controller to P controller, the compensation of the torque disturbance vanishes and the torque information can be estimated from the change of position caused by the external force.

3.3.2 Derivation of Position Information Based Forcefree Control

Fig. 9 shows the block diagram of the position information based forcefree control. As in Fig. 9, the velocity loop in the servo controller is the P controller and the friction compensation τ_d, the gravity compensation τ_g and the external torque compensation τ_f are not included in the servo controller compared with the servo controller in Fig. 1.
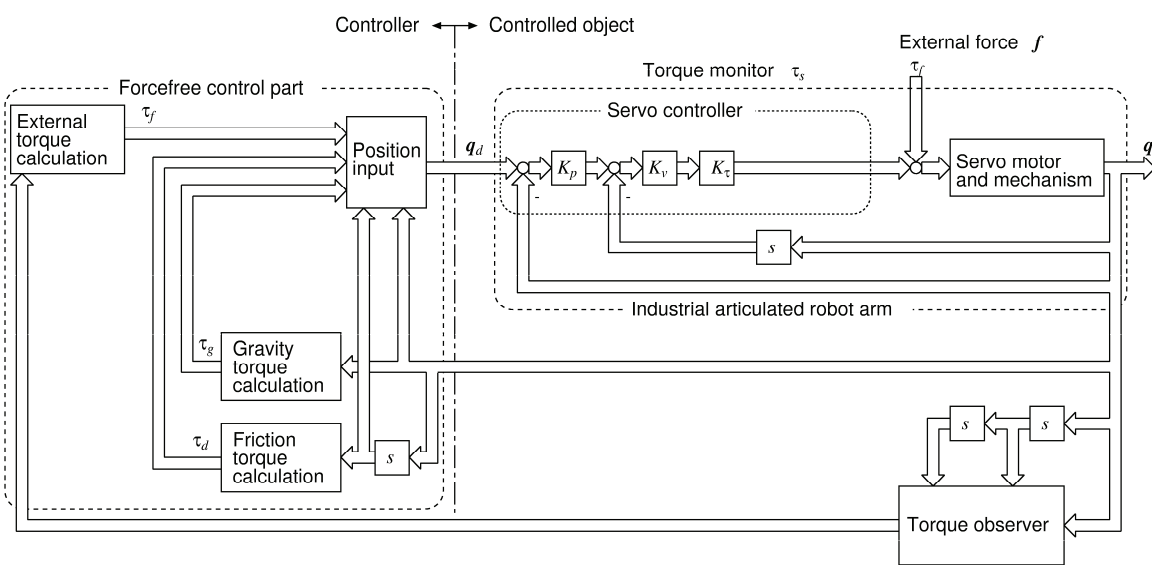

Figure 9. Block diagram of position information based forcefree control

The control input q_d is calculated by

$$q_d = K_p^{-1}\left(K_v^{-1}K_\tau^{-1}\left(\tau_f + \tau_d + \tau_g\right) + \dot{q}\right) + q \tag{21}$$

where the friction compensation torque τ_d and the gravity compensation torque τ_g are calculated by (8) and (12), respectively.

The external force compensation torque τ_f can be estimated by using the position information q and the velocity information $\dot{q}$ as

$$\tau_f = H(q)\ddot{q} + h(q,\dot{q}). \tag{22}$$

3.3.3 Verification

Verification of the position information based forcefree control was carried out by a simulation study and an experiment. Simulation and experimental results are shown in Fig. 10. In Fig. 10, (a) and (b) illustrate the components of the external force f in the directions of X-axis and Y-axis, respectively, (c) and (d) show the joint trajectories of link1 and link2, respectively, (e) and (f) show the velocity v of X-axis and Y-axis, respectively, (g) and (h) show the estimated torque by using the torque observer and the torque calculated by the force sensor, respectively, and (i) shows the locus of the tip of the robot arm. In Fig. 10, the dotted line denotes the simulation result and the bold line shows the experimental result. In (g) and (h), the estimated torque coincides with the actual torque. It can be verified that the simulation and experimental results are comparable, and the forcefree control can be achieved only by the usage of the position information.
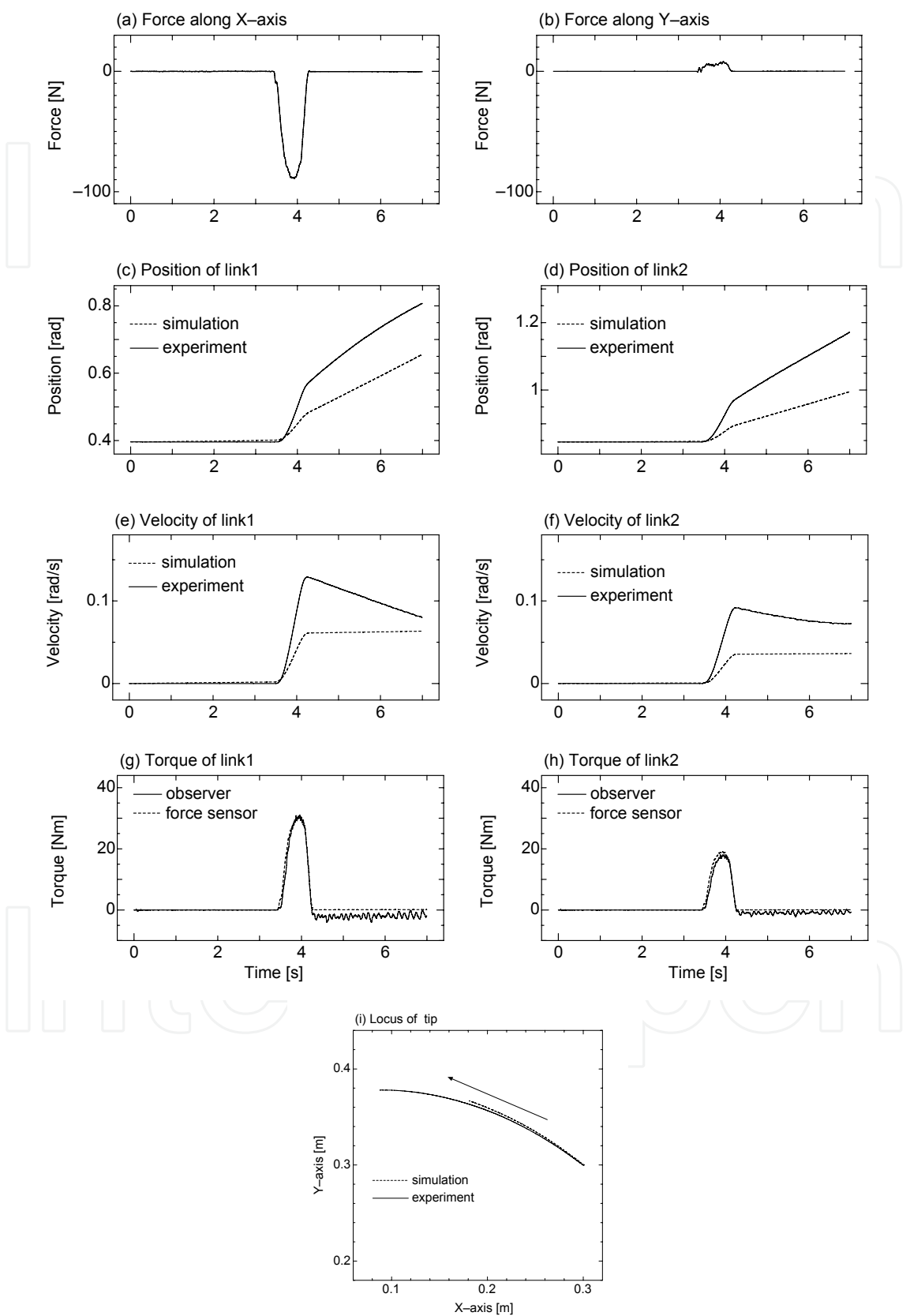
Figure 10. Simulation and experimental results of position information based forcefree control

4. Comparison between Forcefree Control and Force Control

4.1 Comparison between Forcefree Control with Independent Control and Inpedance Control

In order to illustrate the feature of the forcefree control, the forccefree control with independent compensation is compared with the impedance control (Hogan 1985; Scivicco & Siciliano, 2000). The impedance control is the typical force control, which enables the contact force between the tip of the robot arm and the object as assigned inertia, friction and stiffness. The impedance characteristics are expressed by

$$M_d \ddot{r} + D_d (\dot{r} - \dot{r}_d) + K_d (r - r_d) = F \tag{23}$$

where F is the assigned force between the tip of the robot arm and the object, M_d, D_d and K_d are the assigned inertia, friction and stiffness, respectively, and r_d, $\dot{r}_d$ are the objective position and the objective velocity in working coordinates, respectively. The dynamics of the robot arm in joint coordinates is expressed by

$$H(q)\ddot{q} + h(q,\dot{q}) + D\dot{q} + N_\mu \mathrm{sgn}(\dot{q}) + g(q) = \tau + J^T F \tag{24}$$

and the dynamics in working coordinates is expressed by

$$H_r(q)\ddot{r} + h_r(q,\dot{q}) + D_r \dot{r} + N_{\mu r} \mathrm{sgn}(\dot{r}) + g_r(q) = (J^T)^{-1} \tau + F. \tag{25}$$

By substituting (23) for (25), the torque input for the impedance control is obtained by

$$\begin{aligned} \tau = J^T \big[H_r(q)M_d^{-1}\{-D_d(\dot{r}-\dot{r}_d) - K_d(r-r_d)\} \\ + h_r(q,\dot{q}) + (H_r(q)M_d^{-1} - I)F + D_r\dot{r} + N_{\mu r}\mathrm{sgn}(\dot{r}) + g_r(q) \big] \end{aligned} \tag{26}$$

The torque input of the forcefree control with independent compensation is derived as the same format of the impedance control. The dynamics of the forcefree control with independent compensation in joint coordinates (16) is transformed into working coordinates as

$$H_r(q)\ddot{r} + h_r(q,\dot{q}) = C^f F - C^d (D_r\dot{r} + N_{\mu r}\mathrm{sgn}(\dot{r})) - C^g g_r(q). \tag{27}$$

By substituting (27) for (24), the torque input for the forcefree control with independent compensation is obtained by

$$\tau = J^T \left[\left(C^f - I \right) F + \left(I - C^d \right) \left(D_r \dot{r} + N_{\mu r} \mathrm{sgn}(\dot{r}) \right) + \left(I - C^g \right) g_r(q) \right] \qquad (28)$$

By comparing the torque input of the impedance control (26) and that of the forcefree control with independent compensation (28), the following relationship is fulfilled.

$$H_r(q) M_d^{-1} \left\{ -D_d (\dot{r} - \dot{r}_d) - K_d (r - r_d) \right\} + h_r(q, \dot{q}) = 0 \qquad (29)$$

$$M_d = \left(C^f \right)^{-1} H_r(q) \qquad (30)$$

$$D_d = O \qquad (31)$$

$$K_d = O \qquad (32)$$

$$h_r(q, \dot{q}) = 0 \qquad (33)$$

$$C^d = C^g = O \qquad (34)$$

The difference between the forcefree control with independent compensation and the impedance control is as follows;

1. In impedance control, the objective trajectory r_d is defined whereas no objective trajectory exists in the forcefree control with independent compensation.
2. The forcefree control with independent compensation can tune the effects of the friction and the gravity whereas the impedance compensation do perfect compensation.

As a result, the forcefree control with independent compensation is completely different control strategy from the impedance control.

4.2 Comparison between Forcefree Control with Assigned Locus and Impedance Control

In the case of forcefree control with assigned locus and the impedance control, the tip of the robot arm is related to joint motion, but actually, joint coordinate is not necessary to consider because generalized coordinates are defined in working coordinate.

In case of impedance control, inertia is compensated by adjusting a compliance matrix. On the contrary to the forcefree control with assigned locus, inertia can be adjusted through independent setting of the value of the mass point.

Moreover, in case of impedance control, identification of coefficients of viscous friction and calculation of gravity term must be done a priori for the friction compensation and the gravity compensation. On the contrary to the forcefree control with assigned locus, these compensations are not required because a dynamic equation of the mass point is defined in non-friction and non-gravity space.

Although forcefree control with assigned locus is capable of following the assigned locus, impedance control is not thus capable. Therefore, forcefree control with assigned locus has the many advantages over impedance control counterparts. Other general force control methods have same problems as impedance control.

The impedance control is expressed by

$$M_d \ddot{r} + D_d (\dot{r} - \dot{r}_d) + K_d (r - r_d) = f \tag{35}$$

where f is the assigned force between the tip of the robot arm and the object, M_d, D_d and K_d are the assigned inertia, friction and stiffness, and r_d, $\dot{r}_d$ are the objective position and the objective velocity in working coordinates, respectively.

The mass point type forcefree control is expressed by

$$m \ddot{r} = f \tag{36}$$

where m is the assigned mass of the mass point. By comparing (35) and (36), the mass point type forcefree control is achieved by

$$M_d = m \tag{37}$$

$$D_d = 0 \tag{38}$$

$$K_d = 0 \tag{39}$$

After achieving the mass point type forcefree control by the impedance control, the forcefree control with assigned locus is accomplished in exactly the same way explained in section 3.2.2.

Table 1 summarized the comparison of the forcefree control with independent compensation, the forcefree control with assigned locus and the impedance control.

	Forcefree control with independent compensation	Forcefree control with assigned locus	Impedance control
Objective	Free motion by external force	Free motion by external force with assigned locus	Desirable mechanical impedance
Model	Dynamics of industrial articulated robot arm	Dynamics of industrial articulated robot arm	Mechanical impedance between tip arm and object
Motion	Passive motion against external force	Passive motion against external force	Active motion to realize assigned force
Rigidity	Zero	Zero	Setting by virtual spring
Inertia	Setting by coefficient of inertia	Setting by virtual mass	Setting by virtual mass
Friction	Setting by coefficient of friction	Setting by virtual friction	Setting by virtual damper
Gravity	Setting by the coefficient of gravity	Zero	Compensation
Target	Industrial articulated robot arm	Industrial articulated robot arm	Articulated robot arm
Coordinates	Joint coordinates	Cartesian coordinates	Cartesian coordinates
Locus following	Impossible	Possible	Impossible
Command	Position	Position	Torque, Position

Table 1. Comparison among forcefree control with independent compensation, forcefree control with assigned locus and impedance control

5. Applications of Forcefree Control

5.1 Pull-Out Work

Pull-out work means that the workpiece is pulled out by the push-rod, where the workpiece is held by the robot arm, and it is usually used in aluminum casting in industry. The operation follows the sequence, a) the hand of the robot arm grasps the workpiece, b) the workpiece is pushed out by the push-rod, and c) the workpiece is released by the force from the push-rod. The motion of the robot arm requires flexibility in order to follow the pushed workpiece.

Experimental results of pull-out work by the force-free control is shown in Fig. 11. Fig. 11(a) and (b) show the torque monitor outputs of link 1 and link 2 caused by the push-rod, respectively, (c) and (d) show the position of link 1 and link 2, respectively, and Fig. 11(e) shows the locus of the tip of the robot arm.

It guarantees the realization of pull-out work with industrial articulated robot arm based on the forcefree control.

5.2 Direct Teaching

In general, the industrial robot arms carry out operations based on teaching-playback method. The teaching-playback method is separated into two parts, i.e., teaching part and playback part. In the teaching part, the robot arm is taught the data of operational positions and velocities. In the playback part, the robot arm carries out the operation according to the taught data.

The teaching of industrial articulated robot arms is categorized into two methods, i.e., on-line teaching and off-line teaching. Off-line teaching requires another space for teaching. Therefore, on-line teaching is used for industrial articulated robot arms. On-line teaching is also categorized into remote teaching and direct teaching. Here, the remote teaching means that the teaching is carried out by use of a teach-pendant, i.e., a special equipment for teaching, and direct teaching means that the robot arm is moved by human direct force.

Usually, the teaching of industrial articulated robot arms is carried out by remote teaching. Remote teaching by use of teach-pendant, however, requires human skill because there exists a difference between operator coordinates and robot arm coordinates. Besides, the operation method of teach-pendant is not unique, thus depends on the robot arm manufacturer.

Direct teaching is useful for industrial articulated robot arms against remote teaching. The process of direct teaching is as follows; 1) the operator grasps the

tip of the robot arm, 2) the operator brings the tip of the robot arm to the teaching points by his hands, directly, and 3) teaching points are stored in memory. Operational velocities between teaching points are set after the position teaching process. In other words, anyone can easily carry out teaching. In direct teaching, operational positions of the industrial articulated robot arm are taught by human hands directly. The proposed forcefree control can be applied to realize the direct teaching of the industrial articulated robot arm. Forcefree control can realize non-gravity and non-friction motion of the industrial articulated robot arm under the given external force. In other words, an industrial articulated robot arm is actuated by human hands, directly. Here, position control of the tip of the robot arm is the important factor in direct teaching. Position control of the tip of the robot arm is carried out by the operator in direct teaching.

Direct-teaching for teaching-playback type robot arms is an application of the forcefree control with independent compensation, where the robot arm is manually moved by the human operator's hand. Usually, teaching of industrial articulated robot arms is carried out by using operational equipment and smooth teaching can be achieved if direct-teaching is realized.

Fig. 12 shows the experimental result of direct-teaching where the compensation coefficients are $C_f = 0.5E$, $C_d = E$, $C_g = 0$. As shown in Fig. 12, teaching was successfully done by the direct use of human hand. The forcefree control with independent compensation does not use the force sensors and any part of the robot arm can be used for motion of the robot arm.
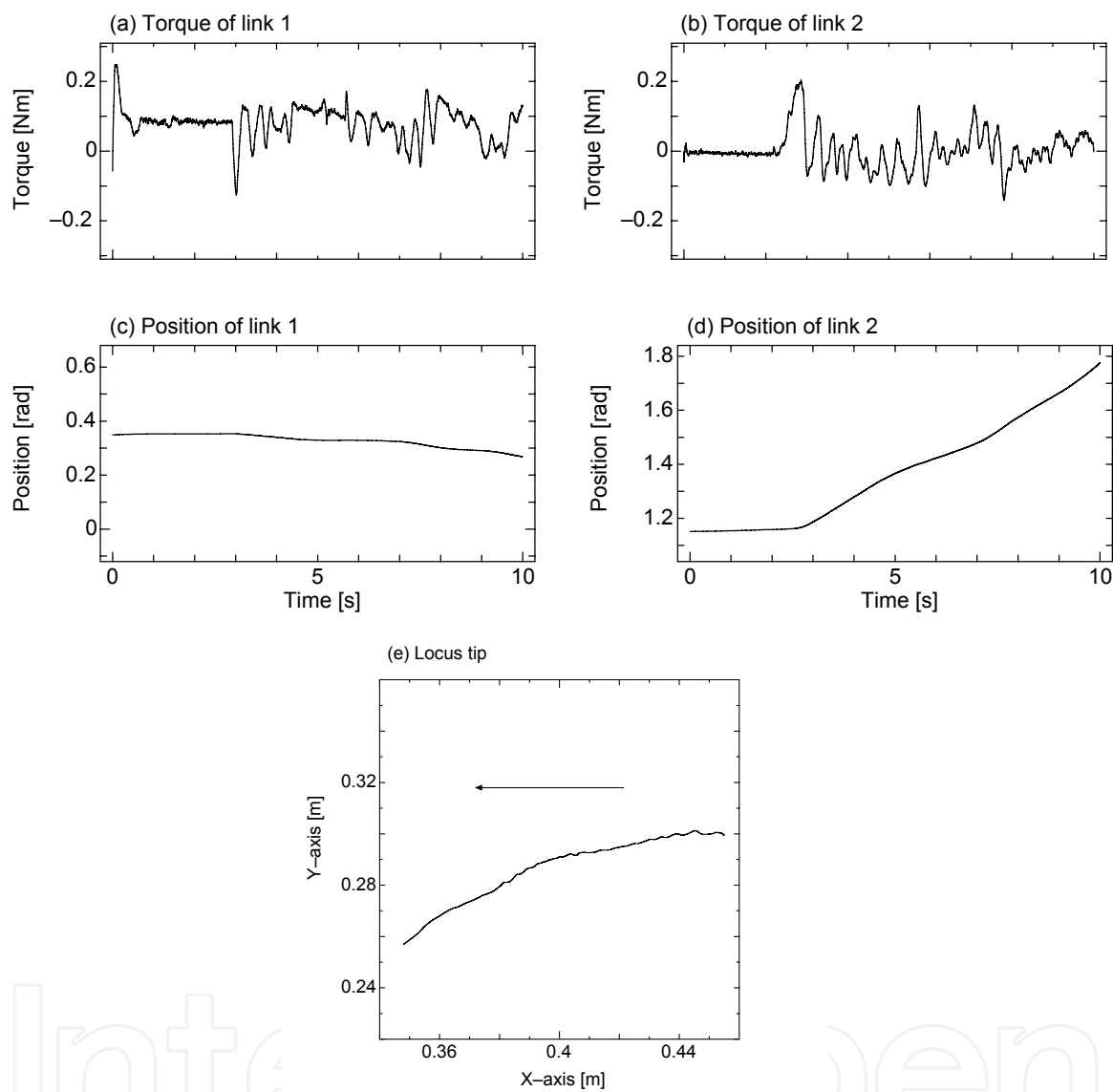
Figure 11. Experimental result of pull-out work by using the forcefree control with independent compensation ($C_f = 0.2E$, $C_d = C_g = 0$)
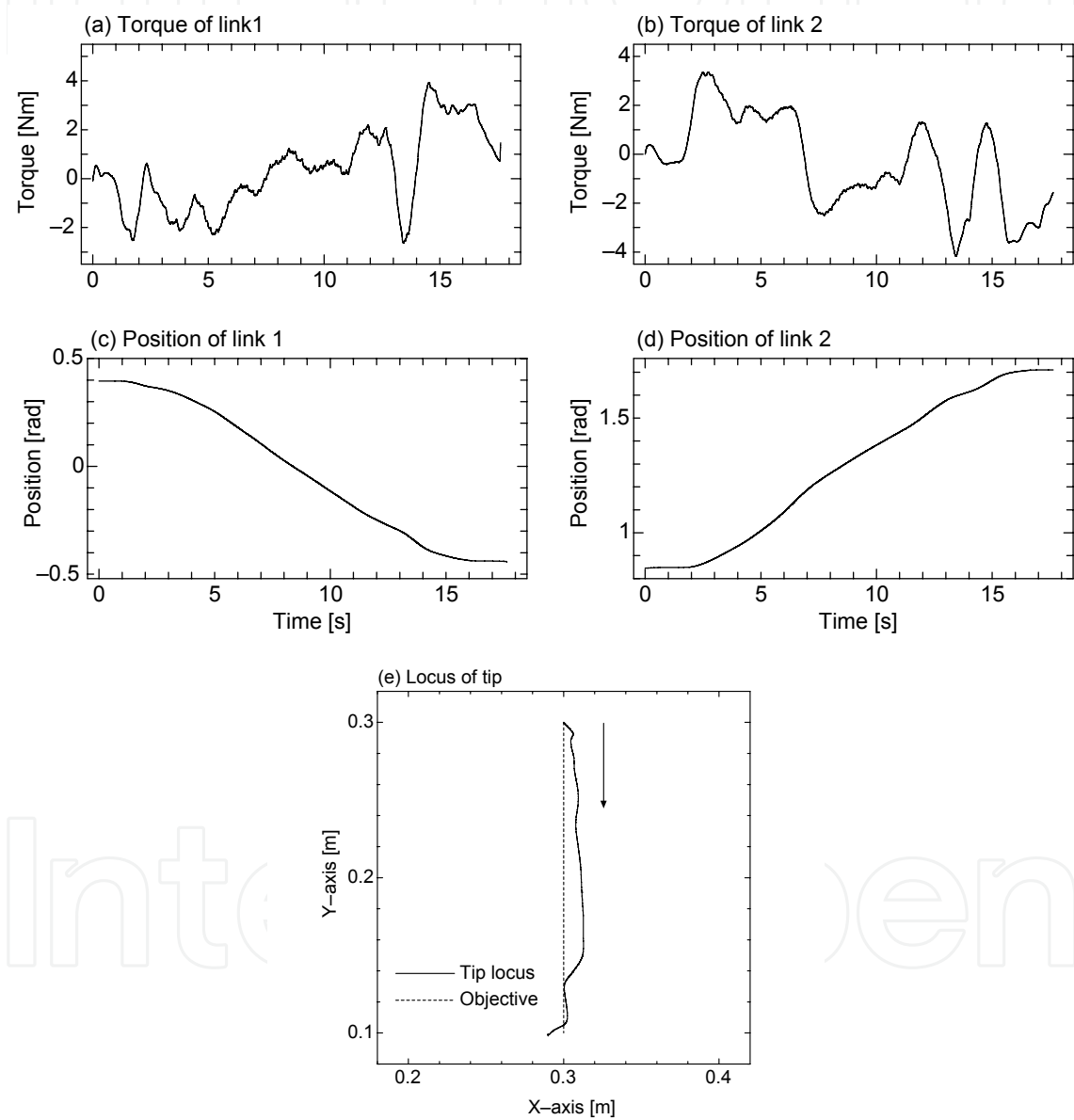
Figure 12. Experimental result of direct teaching by using the forcefree control with independent compensation ($C_f = 0.5E$, $C_d = E$, $C_g = 0$)

5.3 Rehabilitation Robot

The forcefree control with independent compensation uses the torque monitor in order to detect the external force. Hence, each joint can be monitored for unexpected torque deviation from the desired torque profile as a result of unplanned circumstances such as accidental contact with an object or human being. As a result, the forcefree control with independent compensation can also improve the safety of work with human operator. To utilize this feature, the forcefree control with independent compensation is applied to rehabilitation robots.

The forcefree control with independent compensation is applied to the control of a meal assistance orthosis for disabled persons both of direct-teaching of plate position and mouth position and safety operation against unexpected human motion.

If the forcefree control with independent compensation is installed in such systems, the safety will be improved because when the unexpected contact between the operator and the robot occurs, the escape motion of the robot arm can be invoked by the forcefree control method.

6. Conclusions

The proposed forcefree control realizes the passive motion of the robot arm according to the external force. Moreover, the forcefree control is extended to the forcefree control with independent compensation, the forcefree control with assigned locus and the position information based forcefree control. Experiments on an actual industrial robot arm were successfully carried out by the proposed methods. The comparison between the forcefree control and other force control is expressed and the features of the forcefree control are clarified. The proposed method requires no change in hardware of the robot arm and therefore is easily acceptable to many industrial applications.

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Industrial Robotics: Theory, Modelling and Control

Edited by Sam Cubero

This book covers a wide range of topics relating to advanced industrial robotics, sensors and automation technologies. Although being highly technical and complex in nature, the papers presented in this book represent some of the latest cutting edge technologies and advancements in industrial robotics technology. This book covers topics such as networking, properties of manipulators, forward and inverse robot arm kinematics, motion path-planning, machine vision and many other practical topics too numerous to list here. The authors and editor of this book wish to inspire people, especially young ones, to get involved with robotic and mechatronic engineering technology and to develop new and exciting practical applications, perhaps using the ideas and concepts presented herein.

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