# FORCEFREE CONTROL WITH INDEPENDENT COMPENSATION FOR INDUSTRIAL ARTICULATED ROBOT ARM

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Abstract: In this paper, the concept of forcefree control is extended to realize flexible motion of industrial articulated robot arms under the virtual operational circumstances such as free of inertia, friction and gravity through independent compensation of inertia, friction and gravity. The forcefree control with independent compensation was verified with an experimental study of an actual industrial robot arm.

Keywords: industrial robots, force control, inertia, friction, gravity, compensation

## 1. INTRODUCTION

A lot of industrial robot arms are operated in industry and some robotic applications in the industry such as pulling-out of products made by die casting requires flexible motion with a consideration to the external force. To realize the flexible motion, impedance control (Hogan, 1985; Chae, *et al.*, 1988; Sciavicco and Siciliano, 2000) and compliance control (Mason, 1981; Michael, *et al.*, 1982) were proposed. However, these methods are difficult to be applied in industrial robot arms because of the complexity of algorithms and the necessity to change the built-in controller of industrial robot arms. On the other hand, servo float method can realize the flexible motion of industrial robot arms and it has already applied in the industry (Nagata, *et al.*, 1998). The servo float method requires a mode change of the controller for the realization of flexible motion. Besides, switching between the positioning/contouring motion and the flexible motion in the same work cannot be realized with the servo float method. The authors have proposed the forcefree control (Kushida, *et al.*, 2001) and it can realize the flexible motion in virtual circumstances of non-gravity and non-friction without any change of the built-in controller.

In this paper, the previously proposed forcefree control is extended to realize flexible motion emulating the operational circumstances of arbitrary inertia, friction and gravity through independent compensation of inertia, friction and gravity. The property of the forcefree control with independent compensation was also investigated by an experimental study using an actual industrial robot arm.

## 2. FORCEFREE CONTROL WITH INDEPENDENT COMPENSATION

### 2.1 Concept of Forcefree Control

Industrial robot arms are difficult to be moved by an external force applied by a human being because servo

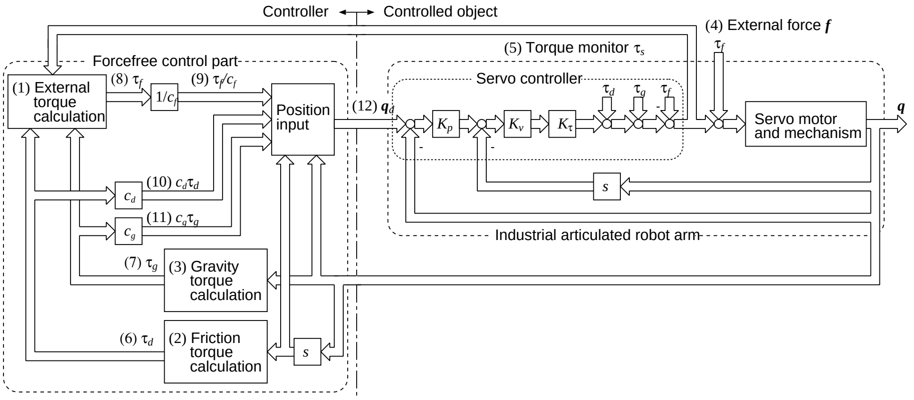


Fig. 1. Block diagram of forcefree control by independent compensation.

controller of industrial robot arm keeps its position excited by an input signal responsible for the motion. The torque generated by the external force is a kind of torque disturbance for the robot control system and it can be compensated by the servo controller.

The forcefree control can realize the motion of the industrial robot arm under non-friction and non-gravity circumstance (Kushida, *et al.*, 2001). By the use of the forcefree control, the robot arm moves according to the external force directly as if it were under the circumstances of non-friction and non-gravity. Previously proposed forcefree control realizes the non-friction and non-gravity condition, nevertheless, friction and/or gravity of the robot arm are useful for some operations. Moreover, a large force is required for huge robot arms even if the forcefree control is applied. In this paper, the forcefree control is extended to realize flexible motion under arbitrary assigned friction and gravity with arbitrary assigned inertia.

### 2.2 *Dynamics of Industrial Articulated Robot Arm*

Dynamics of an articulated robot arm is expressed by

$$H(\boldsymbol{q})\ddot{\boldsymbol{q}} + D\dot{\boldsymbol{q}} + \mu\mathrm{sgn}(\dot{\boldsymbol{q}}) + \boldsymbol{h}(\boldsymbol{q}\,\dot{\boldsymbol{q}}) + \boldsymbol{g}(\boldsymbol{q}) = \boldsymbol{\tau}_s + \boldsymbol{\tau}_f \quad (1)$$

where $H(\boldsymbol{q})$ is the inertia matrix, $D\dot{\boldsymbol{q}} + \mu\mathrm{sgn}(\dot{\boldsymbol{q}})$ is the friction term, $\boldsymbol{h}(\boldsymbol{q}\,\dot{\boldsymbol{q}})$ is the coupling nonlinear term, $\boldsymbol{g}(\boldsymbol{q})$ is the gravity term, $\boldsymbol{q}$ is the output of joint angle, $\boldsymbol{\tau}_s$ is the torque input to the robot arm and $\boldsymbol{\tau}_f$ is the torque caused by external force (Fu, *et al.*, 1987).

In industrial robot arms, servo controller (P and PI type cascade control) is adopted to control the motion of robot arm and the control loop of the servo controller is shown in the right hand side of Fig. 1, where $K_p$, $K_v$ and $K_\tau$ are position loop gain, velocity loop gain and torque constant, respectively (Nakamura, *et al.*, 2004; Kyura, 1996). The servo controller generates a torque input to the robot arm as

$$\boldsymbol{\tau}_s = K_\tau(K_v(K_p(\boldsymbol{q}_d - \boldsymbol{q}) - \dot{\boldsymbol{q}})) + \boldsymbol{\tau}_d + \boldsymbol{\tau}_g - \boldsymbol{\tau}_f \quad (2)$$

where $\boldsymbol{q}_d$ is the input of joint angle, $\boldsymbol{\tau}_d$ is the friction compensation torque and $\boldsymbol{\tau}_g$ 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 in the servo controller. The friction and the gravity are assumed to be ideally compensated by the servo controller as

$$\boldsymbol{\tau}_d = D\dot{\boldsymbol{q}} + \mu\mathrm{sgn}(\dot{\boldsymbol{q}}) \quad (3)$$

and

$$\boldsymbol{\tau}_g = \boldsymbol{g}(\boldsymbol{q}). \quad (4)$$

The torque caused by an external force $\boldsymbol{\tau}_f$ 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 external force never moves the robot arm.

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

$$H(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}\,\dot{\boldsymbol{q}}) = K_\tau(K_v(K_p(\boldsymbol{q}_d - \boldsymbol{q}) - \dot{\boldsymbol{q}})). \quad (5)$$

### 2.3 *Derivation of Forcefree Control with Independent Compensation*

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

$$H(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}\,\dot{\boldsymbol{q}}) = (1/c_f)\boldsymbol{\tau}_f - c_d\boldsymbol{\tau}_d - c_g\boldsymbol{\tau}_g. \quad (6)$$

Here, $c_f$, $c_d$ and $c_g$ are the coefficients of the inertia, friction and gravity terms, respectively. They can be adjusted to vary the effect of the inertia, friction and gravity, independently. For instance, $c_f = 1$, $c_d = 0$ and $c_g = 0$, corresponds to the original forcefree control (Kushida, *et al.*, 2001) and $c_f = c_d = c_g = 0$ 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. 1. The inputs of joint angle ($\boldsymbol{q}_d$) for the forcefree control is obtained by substituting (6) for (5) and solving for $\boldsymbol{q}_d$ as

$$\boldsymbol{q}_d = K_p^{-1}(K_v^{-1}K_\tau^{-1}((1/c_f)\boldsymbol{\tau}_f - c_d\boldsymbol{\tau}_d - c_g\boldsymbol{\tau}_g) + \dot{\boldsymbol{q}}) + \boldsymbol{q} \quad (7)$$

where $\boldsymbol{\tau}_f$ is the joint torque corresponding to the external force $\boldsymbol{f}$ on the tip of robot arm and it is obtained by substituting (2) for (5) as

$$\boldsymbol{\tau}_f = -(\boldsymbol{\tau}_s - \boldsymbol{\tau}_d - \boldsymbol{\tau}_g - (H(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}\,\dot{\boldsymbol{q}}))). \quad (8)$$

Here, $\boldsymbol{\tau}_s$ is measured by the torque monitor which is usually attached to the servo controller of the industrial robot arm and it is used to check the value of the torque. Generally, the speed of contouring control of an industrial robot arm is relatively slow, usually lesser than 1/5 of the rated speed. Hence, the inertia term and nonlinear term of the robot arm is negligibly small ($H(\boldsymbol{q})\ddot{\boldsymbol{q}} + \boldsymbol{h}(\boldsymbol{q}\,\dot{\boldsymbol{q}}) \approx 0$) and the external torque is approximately given by

$$\boldsymbol{\tau}_f = -(\boldsymbol{\tau}_s - \boldsymbol{\tau}_d - \boldsymbol{\tau}_g). \quad (9)$$

Finally, control law of the forcefree control with independent compensation is obtained by substituting (9), (3) and (4) for (7).

### 2.4 Estimation of Friction Term and Gravity Term

*Friction Term* Friction term $\boldsymbol{\tau}_d$ in (3) consists of viscous friction $D\dot{\boldsymbol{q}}$ and Coulomb friction $\mu\mathrm{sgn}(\dot{\boldsymbol{q}})$. The friction effect to the motion of robot arm is estimated by the torque output under constant velocity motion. Then, the friction term is obtained by using the following procedure; 1) To vanish the effect of the gravity, the robot arm moves around vertical position. 2) Various constant velocities are applied to each link of the robot arm, independently. 3) Respective torque outputs for applied velocities are measured by using the torque monitor. 4) Points of the torque outputs and the applied velocities are plotted in which the vertical axis is the torque output and the horizontal axis is the applied velocity. 5) Viscous friction coefficient $D$ and Coulomb friction coefficient $\mu$ in (3) are estimated by using the least square method from the above collected data.

*Gravity Term* The gravity term is modeled as

$$\boldsymbol{g}(\boldsymbol{q}) = C(\boldsymbol{q})\boldsymbol{a} + \boldsymbol{b} \quad (10)$$

where $C(\boldsymbol{q})$ is the position dependent matrix, e.g., $C(\boldsymbol{q}) = \begin{pmatrix} \cos q_1 & \cos(q_1+q_2) \\ 0 & \cos(q_1+q_2) \end{pmatrix}$ for two-degree-of-freedom robot arm. In (10), constant term $\boldsymbol{b}$ is zero in usual robot arm dynamics, however, it is introduced to represent the actual behavior of the robot arm. The parameters $\boldsymbol{a}$ and $\boldsymbol{b}$ are estimated by using the least square 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 $\boldsymbol{a}$ and $\boldsymbol{b}$ in (10), the steady-state torque monitor outputs are used because the torque monitor output contains transient term, which is caused by the integral action of the servo controller. Hence, the gravity compensation torque can be represented by

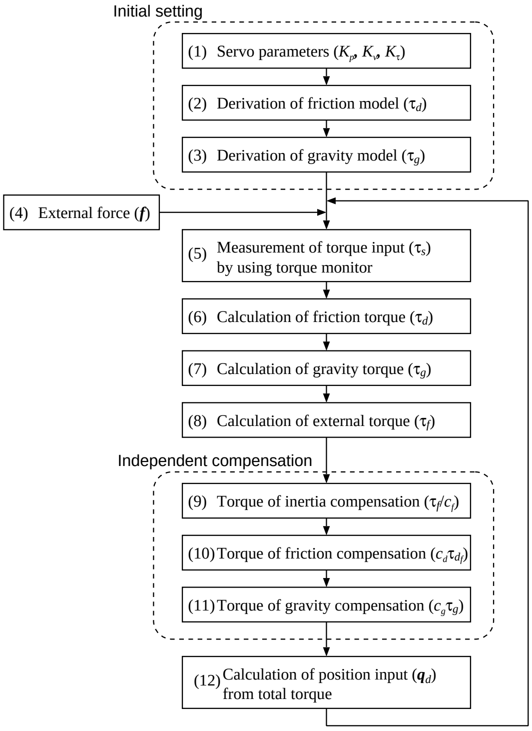


Fig. 2. Flowchart of forcefree control.

$$\boldsymbol{\tau}_g = (I - e^{At})\boldsymbol{g}(\boldsymbol{q}) \quad (11)$$

where

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

and $T_1, \cdots, T_n$ are time constants which are estimated from the actual torque monitor outputs.

### 2.5 Algorithm

The algorithm of the forcefree control with independent compensation is explained (see Fig. 2). Initial setting of the forcefree control with independent compensation is expressed in the following first 3 items. 1) Servo parameters $K_p$, $K_v$ and $K_\tau$ are obtained from the servo controller. 2) Friction model (3) and 3) Gravity model (11) are estimated as explained in 2.4. The main part has the following 9 items. 4) External force ($\boldsymbol{f}$) is added to the robot arm. 5) Torque

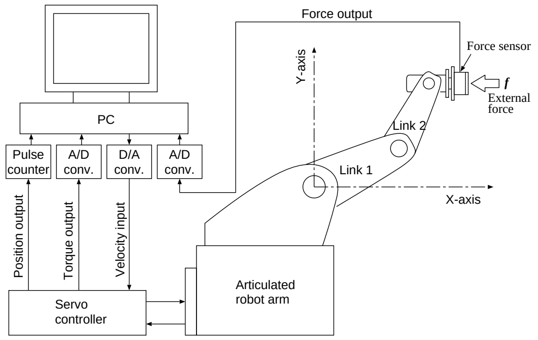


Fig. 3. Experimental equipment.

monitor detects the external force ($\boldsymbol{f}$). 6) The friction torque ($\boldsymbol{\tau}_d$) is estimated by eq. (3), 7) The gravity torque ($\boldsymbol{\tau}_g$) is estimated by eq. (11). 8) External torque ($\boldsymbol{\tau}_f$) is calculated by eq. (9). 9) Torque of inertia compensation ($(1/c_f)\boldsymbol{\tau}_f$) is calculated. 10) The friction compensation torque ($c_d\boldsymbol{\tau}_d$) is calculated. 11) The gravity compensation torque ($c_g\boldsymbol{\tau}_g$) is calculated. 12) The position input ($\boldsymbol{q}_d$) is generated by eq. (7). Finally, the position input ($\boldsymbol{q}_d$) is given to the servo controller. According to the above algorithm, the forcefree control with independent compensation is realized.

The inertia matrix $H(\boldsymbol{q})$ and the coupling nonlinear term $\boldsymbol{h}(\boldsymbol{q}, \dot{\boldsymbol{q}})$ in the robot arm dynamics are not required in the realization of the forcefree control with independent compensation. The friction term, $D\dot{\boldsymbol{q}} + \mu\mathrm{sgn}(\dot{\boldsymbol{q}})$ and the gravity term, $\boldsymbol{g}(\boldsymbol{q})$ are used in the algorithm as explained in the derivation of the terms under the section 2.4. Servo parameters $K_p$, $K_v$, $K_\tau$ in the servo controller are necessary in the algorithm whereas these parameters are determined by the servo controller.

## 3. VERIFICATION OF FORCEFREE CONTROL WITH INDEPENDENT COMPENSATION

### *3.1 Condition*

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. The structure of an experimental equipment is shown in Fig. 3. Two links of Performer-MK3S was 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 $K_\tau = \mathrm{diag}\{0.017426, 0.036952\}$[Nm/(rad/s$^2$)]. The initial end effector position of the robot arm was at (0.3, 0.3)[m]. The force sensor was used to measure the value of the external force.

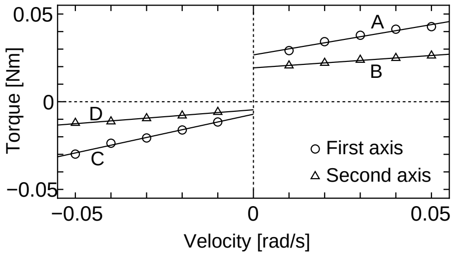
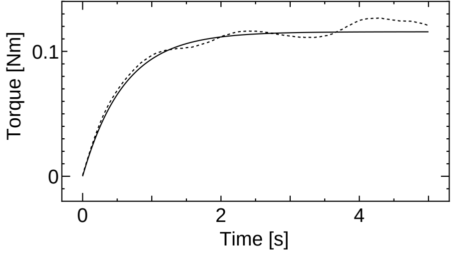


Fig. 4. Estimation of friction term.

(a) First axis



(b) Second axis

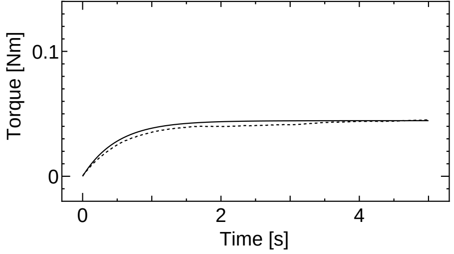


Fig. 5. Estimation of gravity term $(x, y) = (0.3, 0.3)$[m].

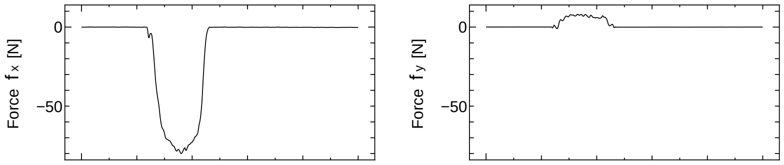
### *3.2 Estimation of Friction Term and Gravity Term*

The parameters in the friction term (3) are estimated by using the experimental data as $D = \mathrm{diag}\{0.345, 0.141\}$ and $\mu = (\,0.0046\ \ 0.0193\,)^T$, according to the procedure described in 2.4. Figure 4 shows the model output of the friction term and the actual data. A close proximity of the results shows the accuracy of friction model.

The parameters in gravity term (11) are estimated by using the experimental data as $\boldsymbol{a} = (\,0.114\ \ 0.041\,)^T$, $\boldsymbol{b} = (\,0.0012\ \ 0.0317\,)^T$ , $T_1 = 0.6$[s] and $T_2 = 0.5$[s] according to the procedure described in 2.4. Figure 5 shows the model output of the gravity term and the experimental data corresponding to the position $(x, y) =$ (0.3, 0.3)[m]. The results shows a good coincidence of the model output and the experimental data.

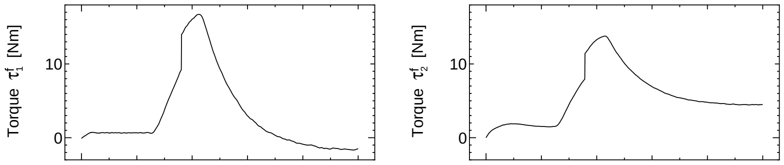
### *3.3 Simulation and Experimental Results*

Simulation and experimental results of the forcefree control with independent compensation of $(c_f, c_d, c_g) = (0.5, 0, 0), (1.0, 0, 0), (1.0, 0.5, 0)$ are shown in Fig. 6. As in Fig. 6, the experimental results and simulation ones are almost the same and thereby shows that the ideal forcefree control with independent compensation can be achieved practically. The robot arm was



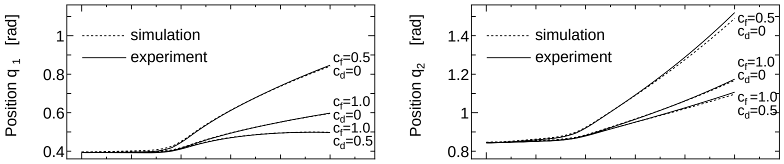
(a) Force along X−axis

(b) Force along Y−axis



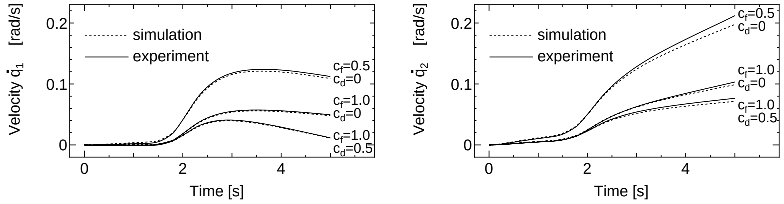
(c) Torque of link1

(d) Torque of link2



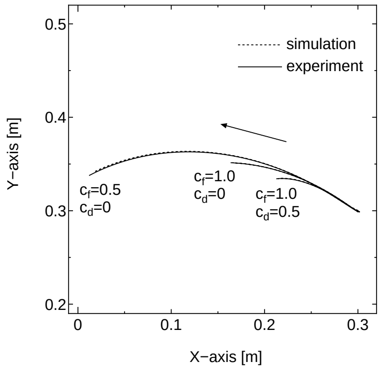
(e) Position of link 1

(f) Position of link 2



(g) Velcity of link 1

(h) Velcity of link 2



(i) Locus of tip of robot arm

Fig. 6. Experimental result of forcefree control with independent compensation in the addition of external force input under $(c_f, c_d, c_g) = (0.5, 0, 0), (1.0, 0, 0), (1.0, 0.5, 0)$.

moved by an external force of around −100 [N] when the masses of the links are $m_1 = 2.86$[kg] and $m_2 = 2.19$[kg]. Therefore, the absolute value of the external force is not so large and the result shows that the forcefree control with independent compensation was realized with an actual industrial robot arm.

## 4. DISCUSSION

### *4.1 Advantages of Forcefree Control with Independent Compensation*

Original control system of the industrial robot arm is utilized without any change and meantime, the forcefree control can be realized as an additional function. Coexistence of original positioning/contouring control with the proposed forcefree control is possible. Moreover, switching between the positioning/contouring control and the forcefree control for the same task execution is feasible.

Additional hardware such as force sensor and modification of the original control system are not required. Inclusion of the algorithm in control software is the only requirement to realize the forcefree control with independent compensation. Hence, the forcefree control with independent compensation is easy to be introduced in the existing industrial robot arms with a lower introduction cost.

The compliance control (Mason, 1981; Michael, *et al.*, 1982), which is famous and applicable to articulated robot arms, can realize desired mechanical impedance of mass-damper-spring system between the tip of the robot arm and the environment. The compliance control, however, requires a mathematical model of the robot arm dynamics, and it does not consider the servo controller of the industrial articulated robot arms. The proposed forcefree control with independent compensation is recommended for the industrial articulated robot arms, since the characteristics of the servo controller and the torque monitor are effectively used.

Characteristics of the forcefree control and the servo float method (Nagata, *et al.*, 1998) is compared as follows. (i) The contact force between the tip of the robot arm and the environment tends to be zero for the forcefree control, and it is set by the designer for the servo float method. Hence, the servo float method requires tuning set contact force. In other words, the role of the servo float method is not to control the flexibility but the contact force. (ii) The forcefree control is sensitive to the external force. The servo float method actuates when the external force of the robot arm exceeds the set contact force. (iii) In the forcefree control, the flexible motion can be realized even if an external force is applied to every part of the robot arm. The servo float method, however, depends on the set contact force to the tip of the robot arm. From such point of view, the property of the forcefree control is more suitable for flexible motion control as compared to the servo float method.

### *4.2 Applications of Forcefree Control with Independent Compensation*

Direct-teaching for teaching playback type robot arms is one of the 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 an operational equipment and smooth teaching can be achieved if direct-teaching is realized. Non-gravity and non-friction condition is desirable for the implementation of direct-teaching, and that can be realized by the proposed forcefree control with independent compensation. The forcefree control with independent compensation is also applicable to pull-out work, which is operated as follows; a) the hand of the robot arm grasps the workpiece, b) the workpiece is pushed out by the push-rod, c) the workpiece is released by the force from the cast. The third step motion requires flexibility in order to follow the pushed workpiece.

Further, each joint could 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. Under such circumstances, forcefree control mode can be invoked and thereby can assure the avoidance of damages. Hence, the forcefree control can also improve the safety of works with human operator. To utilize the feature, the forcefree control with independent compensation is applied to meal assistance orthosis for challenged persons.

## 5. CONCLUSION

The forcefree control with independent compensation for inertia, friction and gravity of industrial articulated robot arms was proposed. The corrective measures for inertia, friction and gravity of the robot arm was adjusted by selecting the appropriate coefficients of the respective compensation terms in the forcefree control. An experiment of an actual industrial robot arm was successfully carried out by the proposed method. The proposed method requires no change in hardware of the robot arm and therefore easily acceptable to many industrial applications.

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