Forcefree Control with Independent Compensation for Articulated Robot Arms and Its Applications

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Abstract—In this paper, the forcefree control with independent compensation is described. The forcefree control with independent compensation, in which inertia, friction and gravity torque are compensated independently, can realize flexible motion of robot arms. The forcefree control with independent compensation is compared with other force control methods such as compliance control. Various applications of the forcefree control with independent compensation are also explained.

I. INTRODUCTION

Nowadays, a lot of robots are used in various fields. Especially, industrial articulated robot arms are operated for a long time in order to automatize monotonous works. Some robotic applications 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 of robot arms, impedance control [1], [2] and compliance control [3], [4] can be applied. These control methods realize 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 realize the flexible motion of the robot arm. Spring behavior generates potential force and the force is retraining force, hence the motion escaping from external force is hard to be realized.

Sensor-less flexible control is also proposed in order to realize flexible motion of industrial articulated robot arms [5], and it is already applied to actual industrial robot arms. The sensor-less flexible control realizes flexible motion by restricting torque input of servo motors or gain adjustment of position loop and velocity loop in the servo controller. The sensor-less flexible control can realize free motion because of no usage of potential force. However, the motion of the end-effector which escapes from an environment can not be realized.

On the other hand, the authors have proposed the forcefree control and it can realize the flexible motion in virtual circumstances of non-gravity and non-friction without any change of the built-in controller [6].

In this paper, advantages of the forcefree control over other flexible control methods such as impedance control and sensor-less flexible control are investigated, and applications of the forcefree control with independent compensation are expressed.

II. FORCEFREE CONTROL WITH INDEPENDENT COMPENSATION

A. Derivation of Forcefree Control with Independent Compensation

Forcefree control with independent compensation can realize flexible motion of articulated robot arms. Figure 1 shows the block diagram of forcefree control with independent compensation. Dynamics of an articulated robot arm is expressed by

\[ H(q) \ddot{q} + Dq + N_\phi \text{sgn}(\dot{q}) + h(q, \dot{q}) + g(q) = \tau_s + \tau_f \]  

where \( H(q) \) is the inertia matrix, \( Dq + N_\phi \text{sgn}(\dot{q}) \) 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, \( \tau_s \) is the torque input to the robot arm and \( \tau_f \) is the torque caused by external force [7].

In industrial robot arms, P and PI cascade type servo controller is adopted to control the motion of robot arm. The control loop of the servo controller is shown in the right side of Fig. 1, where \( K_p, K_s, K_g \) are position loop gain, velocity loop gain and torque constant, respectively [8], [9]. The servo controller generates a torque input \( \tau_s \) to the robot arm as

\[ \tau_s = K_s (K_p (q_d - q) - q) + \tau_d + \tau_g - \tau_f \]  

where \( q_d \) is the input of joint angle, \( \tau_d \) is the friction compensation torque and \( \tau_g \) 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. The friction and the gravity are assumed to be ideally compensated by the servo controller as

\[ \tau_d = Dq + N_\phi \text{sgn}(\dot{q}) \]  

\[ \tau_g = g(q) \]  

The torque caused by an external force \( \tau_f \) is also compensated by the servo controller because the servo controller of an industrial robot arm is designed such that the stiffness of the
Forcefree control with independent compensation means that the influences of inertia, friction and gravity to the robot arm motion can be assigned arbitrarily. The whole dynamics of the industrial robot arms controlled by the forcefree control with independent compensation is described by

\[ H(q) \ddot{q} + h(q, \dot{q}) = K_r \left( K_p \left( q_d - q \right) \right) + \tau_f/\tau_d - c_f \tau_d - c_g \tau_g. \]  

Here, \( c_f, c_d \) and \( c_g \) are the coefficients of the inertia, friction and gravity terms, respectively. The coefficients can be used to adjust 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 [6] and \( c_f = c_d = c_g = 0 \) corresponds to the perfect compensation of the inertia, friction and gravity.

The inputs of joint angle \( q_d \) for the forcefree control with independent compensation is obtained by substituting (6) for (5) and by solving for \( q_d \) as

\[ q_d = K_p^{-1} \left( K_r^{-1} \left( \left( \frac{1}{c_f} \right) \tau_f \right) - c_d \tau_d - c_g \tau_g \right) + q. \]  

where \( \tau_f \) is the joint torque corresponding to the external force \( f \) on the tip of robot arm and it is obtained by substituting (2) for (5) as

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

Here, \( \tau_s \) 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.

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 (\( H(q)\ddot{q} + h(q, \dot{q}) \approx 0 \)), and the external torque is approximately given by

\[ \tau_f = -\left( \tau_s - \tau_d - \tau_g \right). \]  

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

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**Fig. 1.** Block diagram of the forcefree control with independent compensation.

**Fig. 2.** Flowchart of forcefree control with independent compensation.
B. Algorithm of Forcefree Control with Independent Compensation

Figure 2 shows the flow of the forcefree control with independent compensation. 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 $K_T$ in the servo controller are obtained.
2) Friction term (3) and
3) Gravity model (4) are estimated. The control algorithm of the forcefree control with independent compensation has the following 9 items.
4) External force ($f$) is applied to the robot arm.
5) Torque monitor in the servo controller detects the external force ($f$).
6) The friction torque ($\tau_d$) is estimated,
7) The gravity torque ($\tau_g$) is estimated.
8) External torque ($\tau_f$) is calculated by eq. (9).
9) The inertia compensation torque ($1/c_f \tau_f$) is calculated.
10) The friction compensation torque ($c_d \tau_d$) is calculated.
11) The gravity compensation torque ($c_g \tau_g$) is calculated.
12) The position input ($q_d$) is generated by eq. (7).

Finally, the position input ($q_d$) is given to the servo controller. According to the above algorithm, the forcefree control with independent compensation is realized.

The inertia matrix $H(q)$ and the coupling nonlinear term $h(q,q)$ in the robot arm dynamics (5) are not required in order to realize the forcefree control with independent compensation.

The torque input to the robot arm $\tau_f$ is measured by the torque monitor, the friction term, $Dq + N_p \text{sgn}(\dot{q})$ and the gravity term, $g(q)$ are estimated, and the servo parameters $K_p$, $K_v$, $K_T$ in the servo controller are necessary in the algorithm whereas these parameters are known from the specifications of the servo controller.

III. APPLICATIONS OF FORCEFREE CONTROL WITH INDEPENDENT COMPENSATION

A. Direct Teaching

Most of all industrial robot arms in factory are teaching/playback type. The teaching/playback type robots require the teaching process for the operation in industry. In the teaching process, a operator brings the robot arm to the reference points, and the reference points are memorized in
the robot arm. Usually, teaching of industrial robot arms is carried out by using an operational equipment.

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. Smooth teaching can be achieved if direct teaching is realized.

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 \( l_1 = 0.25 \text{[m]} \), \( l_2 = 0.215 \text{[m]} \), and masses of the links are \( m_1 = 2.86 \text{[kg]} \), \( m_2 = 2.19 \text{[kg]} \), respectively. The position loop gain was \( K_p = \text{diag}(25, 25)[1/\text{s}] \), the velocity loop gain was \( K_v = \text{diag}(150, 150)[1/\text{s}] \), and the torque constant was \( K_T = \text{diag}(0.017426, 0.036952)[\text{Nm/(rad/s)}^2] \). The compensation coefficients of the forcefree control with independent compensation were \( c^f = 0.5 \), \( c^d = 1 \), \( c^g = 0 \). The operator grasped the tip of the robot arm and brought it to the reference position from \((0.3 \text{[m]}, 0.3 \text{[m]})\) to \((0.3 \text{[m]}, 0.1 \text{[m]})\).

Figure 4 shows the experimental result of direct teaching. In Fig. 4 (a) and (b) show the torques of link 1 and link 2, respectively, and (c) and (d) show the positions of the link 1 and link 2, respectively. In Fig. 4 (e), the dotted line shows the objective locus and the bold line shows the following locus of the tip of the robot arm. As shown in Fig. 4 (a) and (b), the maximal amplitude of the torque was about 4 [Nm], and the teaching was successfully done by the direct use of human hand.

**B. Rehabilitation Robot**

Forcefree control with independent compensation uses the torque monitor in order to detect the external force. Hence, 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. As a result, the forcefree control with independent compensation can also improve the safety of works with human operator. To utilize the feature, the forcefree control with independent compensation is applied to a rehabilitation robot.

Figure 5 shows the system configuration of a meal assistance orthosis for disabled persons. The structure of the robot arm which supports the human hand is five-degree-of freedom SCARA type robot. Three plates are installed in front of the user. The user selects the plate by his fixed gaze, the specified plate is detected from his EOG (electro-oculogram) signal. The meal assistance arm supports the user’s upper arm and bring it to the position of the specified plate.

The forcefree control with independent compensation is applied to the control of a meal assistance orthosis for disabled persons both of direct teaching of plates position and user’s mouth position, and safety operation against unexpected human motion. The teaching of the positions of the plates and the user’s mouth is done by the direct teaching as explained in III-A.

In ordinal operation of the meal assistance orthosis, contour control is adopted. The velocity vector \( \mathbf{v}^* \) of the meal assistance arm is calculated by

\[
\mathbf{v}^* = v_0 \frac{\mathbf{p}_d - \mathbf{p}_d^0}{|\mathbf{p}_d - \mathbf{p}_d^0|} \quad (11)
\]

where \( \mathbf{p}_d \) is the objective point vector such as the plate position and the user’s mouth position, \( \mathbf{p}_d^0 \) is the current meal assistance arm position, and \( v_0 \) is the assigned motion speed of the meal assistance arm. The position command \( \mathbf{p}_d^0 \) for the orthosis is
calculated by
\[ p_d^p = p^R + v^A \Delta t \]
\[ = p^R + v_0 \frac{p_d - p^R}{|p_d - p^R|} \Delta t \]  \hspace{1cm} (12)

where \( \Delta t \) is the sampling time.

In the meal assistance orthosis, the meal assistance arm supports the user’s upper arm, then the user’s upper arm contacts with the meal assistance arm all the time. With only the usage of the contour control, if the motion of the user’s upper arm is inconsistent with that of the meal assistance arm, the meal assistance arm brings the user’s upper arm by compulsion. It is very dangerous situation for the user. Hence, the forcefree control with independent compensation is adopted for the control of the meal assistance orthosis. When the torque of each link exceeds a threshold value, the control strategy is changed from the contour control to the forcefree control with independent compensation and the meal assistance arm moves to the direction of the user’s upper arm motion. The compensation coefficients are \( c_I = 1, c_d = 1, c_g = 1 \).

Figure 6 shows the experimental results of the meal assistance orthosis. At the time 20[s], the external force was applied to the X-axis direction, the values of the torque of the link 1 and link 2 exceed \( \alpha = 6[Nm] \) and the control strategy was changed from the contour control to the forcefree control with independent compensation. The meal assistance arm escaped to the X-axis direction from the external force. When the external force vanished, the control strategy was changed again from the forcefree control with independent compensation to the contour control, and the meal assistance arm supported the user’s upper arm and bring it to the position of the mouth. The result shows the effectiveness of the forcefree control with independent compensation for the safety operation of the meal assistance orthosis.

C. Comparison between Forcefree Control with Independent Compensation and Other Flexible Control

Original control system of the industrial robot arm is utilized without any change and meantime, the forcefree control can be realized as an optional function. Coexistence of original positioning and/or contouring control with the proposed forcefree control is possible. Moreover, switching between the positioning and/or 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 impedance control [1], [2], 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 comparison between forcefree control with independent compensation and impedance control is summarized in Table I. As shown in Table I, the forcefree control with independent compensation and the impedance control are different control strategy and it is impossible to realize the forcefree motion by using the impedance control.

Characteristics of the forcefree control and the sensor-less flexible control [5] is also compared in Table I. The contact force between the tip of the robot arm and the environment tends to be zero for the forcefree control with independent compensation, whereas it is set by the designer for the sensor-less flexible control. Hence, the sensor-less flexible control requires tuning set contact force. In other words, the role of the sensor-less flexible control is not to control the flexibility but the contact force. The forcefree control is sensitive to the external force. The sensor-less flexible control actuates when the external force of the robot arm exceeds the assigned
TABLE I

<table>
<thead>
<tr>
<th></th>
<th>Forcefree control</th>
<th>Impedance control</th>
<th>Sensor-less flexible control</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Objective</strong></td>
<td>Flexible motion by external force</td>
<td>Desirable mechanical impedance</td>
<td>Flexible motion by external force</td>
</tr>
<tr>
<td><strong>Model</strong></td>
<td>Dynamics of industrial articulated robot arm</td>
<td>Mechanical impedance between arm and object</td>
<td>Dynamics of two-mass model</td>
</tr>
<tr>
<td><strong>Motion</strong></td>
<td>Passive motion against external force</td>
<td>Active motion to realize assigned force</td>
<td>Passive motion against external force</td>
</tr>
<tr>
<td><strong>Rigidity</strong></td>
<td>Zero</td>
<td>Setting by virtual spring</td>
<td>Setting by torque limits</td>
</tr>
<tr>
<td><strong>Inertia</strong></td>
<td>Setting by the coefficient of inertia</td>
<td>Setting by virtual mass</td>
<td>-</td>
</tr>
<tr>
<td><strong>Friction</strong></td>
<td>Setting by the coefficient of friction</td>
<td>Setting by virtual damper</td>
<td>Compensation</td>
</tr>
<tr>
<td><strong>Gravity</strong></td>
<td>Setting by the coefficient of gravity</td>
<td>Compensation</td>
<td>Compensation</td>
</tr>
<tr>
<td><strong>Target</strong></td>
<td>Industrial articulated robot arm</td>
<td>Articulated robot arm</td>
<td>Industrial articulated robot arm</td>
</tr>
<tr>
<td><strong>Coordinates</strong></td>
<td>Joint coordinates</td>
<td>Cartesian coordinates</td>
<td>Cartesian coordinates, Joint coordinates</td>
</tr>
<tr>
<td><strong>Command</strong></td>
<td>Position command</td>
<td>Torque command, Position command</td>
<td>Position command</td>
</tr>
</tbody>
</table>

contact force. From such point of view, the property of the forcefree control is more suitable for flexible motion control as compared to the sensor-less flexible control.

IV. Conclusions

The forcefree control with independent compensation for inertia, friction and gravity of industrial articulated robot arms was presented. 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. Experiments of an actual industrial robot arm and a rehabilitation robot were successfully carried out by the forcefree control with independent compensation. The comparison of the forcefree control with other flexible control is expressed and the feature of the forcefree control with independent compensation is clarified. The proposed method requires no change in hardware of the robot arm and therefore easily acceptable to many applications.

References