Energy Saving Motion of Multi-Joint Robots Through Stiffness Adaptation and DFC

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Abstract: This paper presents a new energy saving control method for multi-joint robots. The purpose of the proposed control method is to generate periodic motions without using actuator torque as much as possible. To solve this problem, stiffness adaptation(SA) and delayed feedback control(DFC) are simultaneously used. Even though the original DFC requires priori knowledge of objective systems, the proposed control method works without using parameters of the objective systems. Numerical simulation shows that the proposed control method can generate a periodical motion requiring almost no actuator torque in a steady state.

Keywords: multi-joint robots, stiffness adaptation, time-delayed feedback

1. Introduction

It seems that energy saving becomes dramatically important nowadays due to environmental and resource problems. However, energy saving control method of multi-joint robotic systems are not widely established in industrial field. For example, though industrial robot arms commonly used to do periodic task in process line, kinetic energy is not stored as potential energy for periodic motions generation. One solution is to use mechanical elastic elements to store potential energy for energy saving purpose. However, the problem is that such kind of multi-joint robots generally generate chaotic motions because of their dynamics nonlinearity.

In 1992, K.Pyragos proposed the delayed feedback control (DFC) for dynamic chaos control. The DFC do not require precise priori knowledge of the system dynamics and can be particularly convenient for an experimental application [1]. Unfortunately, the DFC still has a disadvantage that the cycle time of passive periodic motions, which require no input, should be known [2,3].

In robotics field, Y. Sugimoto and K. Osaka applied the DFC to a walking robot [4]. For the walking robot, the DFC enables that actuator torque will be almost zero while generating walking motions in steady states. In this case, the cycle time of the periodic motions, which is needed for the DFC, can be fortunately found owing to impact phenomenon. However, the cycle time of periodic motions of multi-joint robots is difficult to find due to the problems of multi degree-of-freedom and non-linearity. Furthermore, careful selection of physical parameters and initial conditions seems to be required for the walking robots with the DFC.

On the other hand, in our previous work, we studied energy saving control method using stiffness adaptation for robotic systems [5,6]. The stiffness adaptation method can effectively reduce actuator torque while generating desired periodic motions. This means that the natural frequency of the robotic systems is adjusted to frequency of desired motions.

This paper proposes a new control method by combining the DFC and the stiffness adaptation to generate periodic motions requiring less actuator torque. Section 4 gives four typical simulation cases, and the simulation results demonstrate the effectiveness of the new controller.

2. Problem Formulation

This section formulates the problem of this study.

2.1 Dynamics

The dynamic equation of multi-joint robots with elastic elements as shown in Fig.1 can be described as:

\[ R(q)\ddot{q} + \{\frac{1}{2} \dot{R}(q) + S(q, \dot{q})\} \dot{q} = -Kq + \tau \]  (1)

where \( R(q) \in \mathbb{R}^{n \times n} \) is a positive definite inertia matrix, \( S(q, \dot{q}) \in \mathbb{R}^{n \times n} \) is a skew symmetric matrix, \( g(q) \in \mathbb{R}^{n} \) is a vector of gravitational torque, \( K = \text{diag}(k_1, k_2, \ldots, k_n) \) is a stiffness matrix, \( k_1, k_2, \ldots, k_n \) are adjustable stiffness of elastic elements installed in each joints, \( q = (q_1, q_2, \ldots, q_n)^T \) is a vector of joint angles, and \( \tau = (\tau_1, \tau_2, \ldots, \tau_n)^T \) is a vector of torque of actuators.
2.2 Control Objective

Control objective is to generate periodic motions requiring less actuator torque as much as possible. Cycle time of the period motions $T$ is specified.

3. Controller

This paper proposes the controller using the DFC and the stiffness adaptation as follows:

$$\tau = -K_v(\dot{q} - \dot{q}_d)$$  \hspace{1cm} (2)

$$\dot{k} = \Gamma_s Q(\dot{q} - \dot{q}_d)$$  \hspace{1cm} (3)

where $K_v = \text{diag}(k_{v1}, k_{v2}, \ldots, k_{vn})$ is a feedback gain matrix, $\Gamma_s = \text{diag}(\gamma_{s1}, \gamma_{s2}, \ldots, \gamma_{sn})$ is an adaptive gain matrix, $k = (k_1, k_2, \ldots, k_n)^T$, and $Q = \text{diag}(q_1, q_2, \ldots, q_n)$.

The desired motion $q_d$ after the first cycle $t > T$ is updated by the following law:

$$q_d(t + T) = (1 - \alpha)q_d(t) + \alpha q(t)$$  \hspace{1cm} (4)

where $\alpha$ is a gain which is set from 0 to 1. If $\alpha$ is set to 1, Eq.2 and 4 will be the same as the conventional DFC.

4. Simulation

This section presents simulation results of a two-joint robot with elastic elements as shown in Fig.2, to show the validity of the proposed controller from Eq.2 to Eq.4.

4.1 Model

In this model, we ignore the effect of gravity, the first and second links are denoted by link 1 and link 2 and, the links are confined in a horizontal plane. The length of two links is denoted by $l_1$ and $l_2$. The mass of two links is denoted by $m_1$ and $m_2$. The length from mass center to joint of the two links is denoted by $s_1$ and $s_2$. The stiffness of two elastic elements is denoted by $k_1$ and $k_2$. Tip position of the robot is denoted by $(x, y)$.

As shown in Fig.2, tip position of the robot is described as follows:

$$x = l_1 \sin(q_1) + l_2 \sin(q_1 + q_2)$$ \hspace{1cm} (5)

$$y = l_1 \cos(q_1) + l_2 \cos(q_1 + q_2)$$ \hspace{1cm} (6)

4.2 Condition

The physical parameters were set as shown in Table 1.

The initial conditions were set as $q_{d1}(t) = 1.8 \sin(2\pi t)$, $(0 < t < T)$, $q_{d2}(t) = 1.2 \sin(2\pi t)$, $(0 < t < T)$, $q_1(0) = 0$ [rad], $q_2(0) = 0.25\pi$ [rad], $k_1(0)=10$ [Nm/rad], $k_2(0)=10$ [Nm/rad].

The cycle $T$ was set to 1 [s]. The gains were set as shown in Table 2.

As shown in Table 1, the case 1 did not use the DFC and the stiffness adaptation. Therefore, the desired motions $q_{d1}, q_{d2}$ and the stiffness $k_1, k_2$ keep the initial ones. This is the same as usual velocity feedback control (VFC). In the case 2, the controller is the same as the conventional DFC. Then, the desired motion $q_{d1}$ and $q_{d2}$ would be changed after the first cycle. In the case 3, we only used the stiffness adaptation. This controller is almost the same as our previous energy saving controller [6]. In the case 4, we simultaneously used the DFC and the stiffness adaptation, and this is the proposed controller in this paper.

4.3 Results

Fig.3 was the simulation result of case 1 (velocity feedback control). Fig.3 (a) and (b) showed that the angle $q_1$ and $q_2$ almost converged to the desired motion $q_{d1}$ and $q_{d2}$. This controller generated desired motion.

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<thead>
<tr>
<th>Table 1: Physical Parameters</th>
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<td>parameters [unit]</td>
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<tr>
<td>-----------------------------</td>
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<tr>
<td>length[m]</td>
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<tr>
<td>mass[kg]</td>
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<tr>
<td>inertia moment[kg.m²]</td>
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<td>length from mass center to joint [m]</td>
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<th>Table 2: Gain Setting</th>
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<tr>
<td>Case \quad \alpha \quad k_{v1} \quad k_{v2} \quad \gamma_1 \quad \gamma_2 \quad Type</td>
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<tr>
<td>Case 1 \quad 0 \quad 6 \quad 8 \quad 0 \quad 0 \quad VFC</td>
</tr>
<tr>
<td>Case 2 \quad 1 \quad 6 \quad 0.7 \quad 0 \quad 0 \quad DFC</td>
</tr>
<tr>
<td>Case 3 \quad 0 \quad 6 \quad 8 \quad 3 \quad 2 \quad SA</td>
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<tr>
<td>Case 4 \quad 0.2 \quad 0.8 \quad 0.2 \quad 1 \quad 0.5 \quad DFC and SA</td>
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Figure 2: Simulation Model
Figure 3: Case 1 (Velocity Feedback Control)

Figure 5: Case 3 (Using Stiffness Adaptation)

Figure 4: Case 2 (Using DFC)

Figure 6: Case 4 (Using DFC and Stiffness Adaptation)
4.4 Evaluation of energy saving

We used the following equation to evaluate energy saving effect of the proposed controller.

\[ J = \int_{20}^{30} r^T \tau dt \]  \hspace{1cm} (7)

The simulation result of \( J \) is shown in Table 3. This result showed that simultaneous use of the DFC and the stiffness adaptation (case 4) was effective for energy saving purpose.

<table>
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<tr>
<th>( J [N^2 m^2 s] )</th>
<th>Case 1</th>
<th>Case 2</th>
<th>Case 3</th>
<th>Case 4</th>
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<tr>
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<td>223.95</td>
<td>57.36</td>
<td>77.99</td>
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5. Conclusion

This paper proposes a new energy saving control method utilizing the stiffness adaptation and the DFC simultaneously for multi-joint robots. The proposed control method can generate periodic motions, which require less torque of actuator. Though the original DFC needs the knowledge of cycle time of periodic motions, the proposed method works without using parameters of the objective systems. Simulation results demonstrated that the proposed method could generate a periodic motion, which requires almost no actuator torque.

In the future, we will try to prove stability of the proposed control method, and to improve the control method to specify the final desired motions.

References