The Seventeenth International Symposium on Artificial Life and Robotics 2012 (AROB 17th '12),
B-Con Plaza, Beppu, Oita, Japan, January 19-21, 2012

Analysis of Manipulator in Consideration of Impact Absorption between Link and Object

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Abstract: In this paper, equations of motion of a manipulator are derived in consideration of characteristics of driving source. By considering impact force absorption between a link and an object, trajectories for saving energy are calculated by the iterative dynamic programming (IDP) method. And, the dynamic characteristics of manipulator controlled based on the trajectory for saving energy are analyzed theoretically and investigated experimentally.

Keywords: Manipulator, Trajectory, Dynamic Programming, Impact force, Minimum Energy.

1 Introduction

For the purpose of enlarging the work space in carriage work, it is necessary to study the throwing motion of a manipulator. In a previous report [1], a casting manipulator is introduced, and it has large work space compared with its simple mechanism. However, considerations of energy consumption are not enough. Evaluations of robotic mechanisms subjected to impact load are investigated [2], but energy consumption is not considered.

In previous report [3], trajectories for saving energy about the throwing motion of manipulator were easily calculated by IDP method. And, dynamic characteristics of the system were analyzed. In previous report [4], considering the collision between the link and the object, and considering the active motion which absorbs kinetic energy from the object, the trajectories for saving energy are calculated by the IDP method.

In this paper, equations of motion of a manipulator are derived in consideration of the characteristics of DC servomotors, and a performance criterion for saving energy is defined in consideration of energy consumption of the driving source. When the manipulator is operated in a vertical plane, the system is highly non-linear due to gravity, and an analytical solution can not be found. Then, a numerical approach is necessary. By considering impact force absorption between a link and an object, trajectories for saving energy are calculated by IDP method. The dynamic characteristics of manipulator controlled based on above-mentioned trajectory are analyzed theoretically and investigated experimentally.

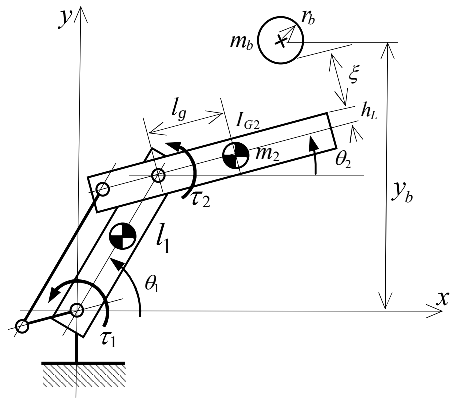
2 Modeling of manipulator

The dynamic equations of the manipulator with two degrees of freedom, as shown in Fig. 1, which is able to move in a vertical plane, are as follows.

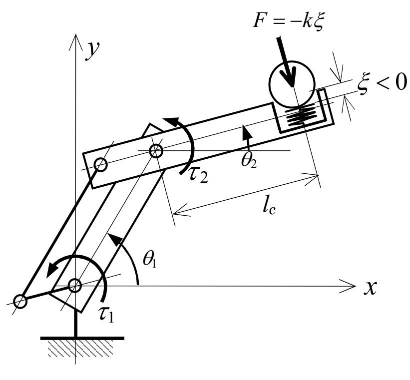
$$\begin{bmatrix} A_{11} & A_{12} \\ A_{21} & A_{22} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \end{bmatrix} = \begin{bmatrix} A_{13} \\ A_{23} \end{bmatrix} \tag{1}$$

where

$$A_{11} = a_1 \,, A_{12} = a_3 \cos(\theta_1 - \theta_2) \,, A_{21} = A_{12} \,, A_{22} = a_2$$
$$A_{13} = \tau_1 - a_3 \dot{\theta}_2^2 \sin(\theta_1 - \theta_2) - a_4 \cos\theta_1 - F l_1 \cos\theta_1$$
$$A_{23} = \tau_2 + a_3 \dot{\theta}_1^2 \sin(\theta_1 - \theta_2) - a_5 \cos\theta_2 - F l_c$$



(a) Link is out of contact with object.



(b) Link is in contact with object.

Fig.1 Mechanism of manipulator

$$a_1 = m_1 l_{g1}^{\ 2} + I_{G1} + m_2 l_1^2 \ , a_2 = I_{G2} + m_2 l_{g2}^{\ 2}$$
$$a_3 = m_2 l_1 l_{g2} \ , a_4 = \left(m_1 l_{g1} + m_2 l_1\right) g \ , a_5 = m_2 g l_{g2} \ .$$

When the link is in contact with an object, the contact force is

$$F = -k\xi \quad , \quad (\xi < 0) \ . \tag{2}$$

Where ξ is displacement of spring, and

$$\xi = \frac{y_b - (l_1 \sin\theta_1 + l_c \sin\theta_2)}{\cos\theta_2} - (h_L + r_b) \ . \tag{3}$$

The applied voltage of the servomotor is

$$e_j = b_{1j}\dot{\theta}_j + b_{2j}\ddot{\theta}_j + b_{3j}\tau_j + b_{3j}\tau_{f_j}\,\mathrm{sign}(\dot{\theta}_j) \tag{4}$$
$$(j = 1, 2) \quad ,$$

where

$b_{1j} = k_{vj} + (R_{aj}/k_{tj})D_{mj}$, $b_{2j} = (R_{aj}/k_{tj})I_{mj}$, $b_{3j} = R_{aj}/k_{tj}$,

i_{aj} : electric current of the armature ,
R_{aj} : resistance of armature ,
I_{mj} : moment of inertia of armature,
D_{mj} : coefficient of viscous damping.

Then, the electric current is

$$i_{aj} = (e_j - k_{vj}\dot{\theta}_j)/R_{aj} \ . \tag{5}$$

And, the consumed energy is

$$E_j = \int (e_j \cdot i_{aj}) dt \ . \tag{6}$$

3 Simulation of the manipulator

We shall take the parameters of the system as shown in Table 1.

Figure 2 shows a flow chart for iterative dynamic programming method. In frame (A), the trajectory for saving energy is searched by IDP method [3]. In frame (B), the searching region is shifted to minimize the consumed energy, and width of the region is changed smaller.

Figure 3 shows the trajectory for searching, and initial trajectory for searching is expressed as

$$\theta_j = \theta_{ji} + \frac{(\theta_{jf} - \theta_{ji})}{2}\left\{1 - \cos\left(\frac{\pi}{t_f}t\right)\right\} \ . \tag{7}$$

The performance criterion is

$$E' = \int (e \cdot i_a) dt + C_1 \int |F| \cdot dt + C_2 |y_b'| \ . \tag{8}$$

The simulations of the system are done as follows.

Figure 4 and 5 show the response of the manipulator. The motion of an object is free-fall from initial height y_b=0.18(m). When t=0.206(s), the object is in contact with the link. And then, position and velocity are y_b'=0.03 (m), $\dot{y}_b$=−1.75 (m/s). Under the condition that $\theta_{2i} = \theta_{2f}$=0, an optimal trajectory is calculated by IDP method.

Table 1 Parameters of the manipulator

Parameter	Value	Parameter	Value
l_2 (m)	0.10	I_{G2} (kgm^2)	4.8×10^{-5}
l_{g2} (m)	0.057	I_{m2} (kgm^2)	8.5×10^{-5}
m_2 (kg)	0.045	D_{m2} (Nms/rad)	7.9×10^{-5}
m_b (kg)	0.017	k_{t2} (Nm/A)	0.046
R_{a2} (Ω)	3.5	k_{v2} (Vs/rad)	0.046
k (N/m)	9000	τ_{f2} (Nm)	0.013
c (Ns/m)	2.0		

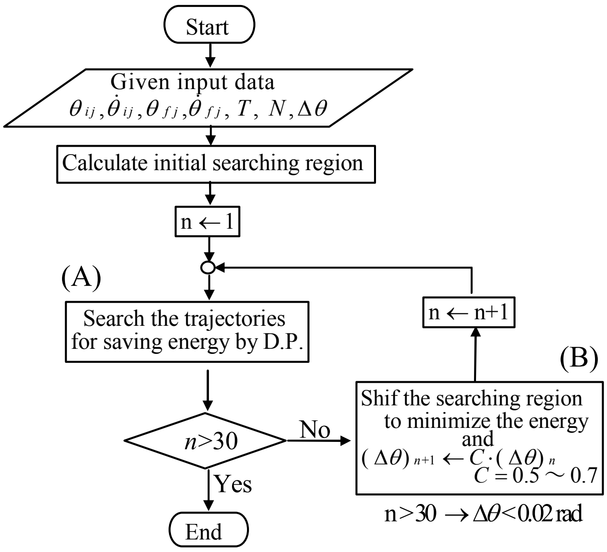


Fig.2 Flow chart for simulation

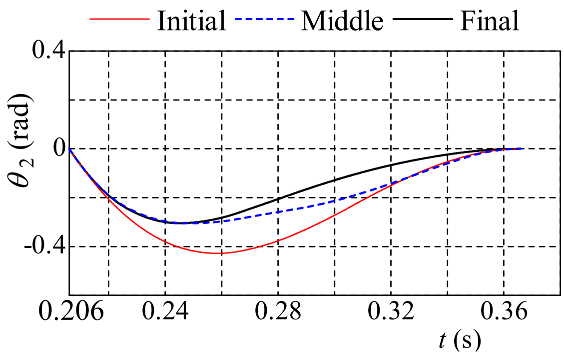


Fig.3 Trajectory for searching

In Figure 4, under the condition that $\dot{\theta}_{1i}$=0, $\dot{\theta}_{2i}$=−17.5 (rad/s), the solid lines show the response of manipulator which is actuated along the optimal trajectory. And broken lines show the response of manipulator which is fixed at the initial position. Impact force F about actuated case (solid line) becomes smaller than one of fixed case (broken line). And, consumed energy of motor is increases gradually.

In Figure 5, under the condition that $\dot{\theta}_{1i} = \dot{\theta}_{2i}$=0, the solid lines show the response of manipulator which is actuated along the optimal trajectory. But, the impact force is not reduced.

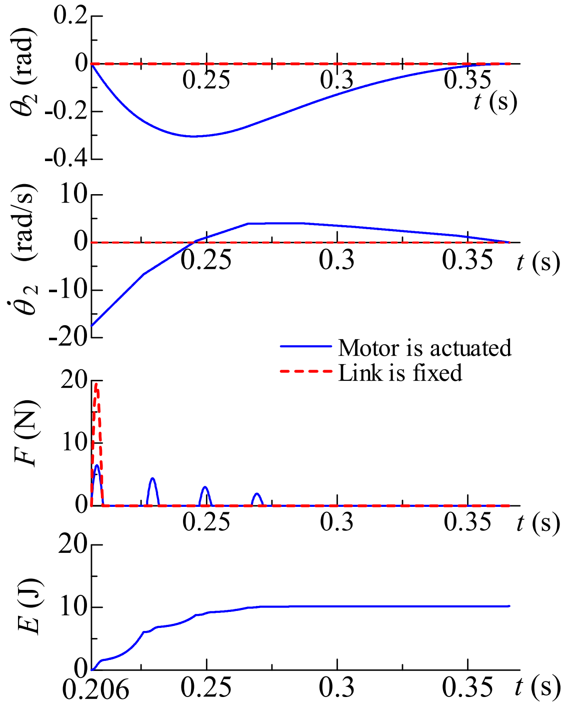


Fig.4 Theoretical results ($\dot{\theta}_{2i} = -17.5$ rad/s)

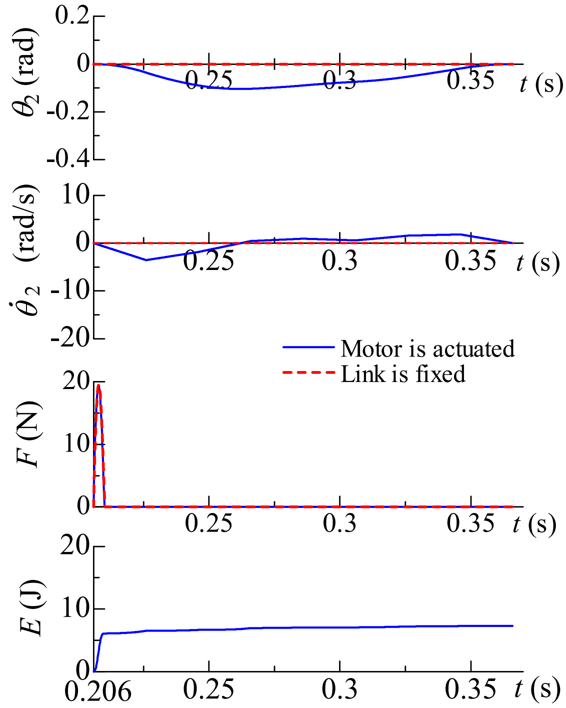
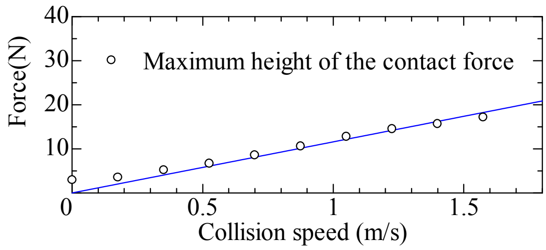


Fig.5 Theoretical results ($\dot{\theta}_{2i} = 0$)

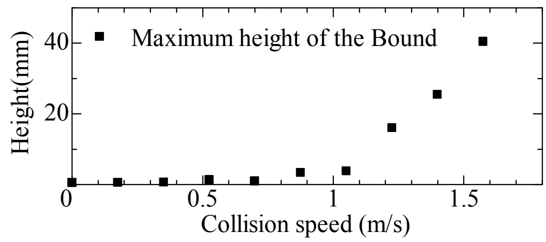
5 Experimental results

In this section, the results of fundamental experiment are shown to examine the effectiveness of modeling for the simulations.

Figure 7 shows an experimental apparatus. Slide board is tilted ($\pi/3$) measured from the level surface. And, two Laser displacement meters are installed for measuring the passing time of the object.

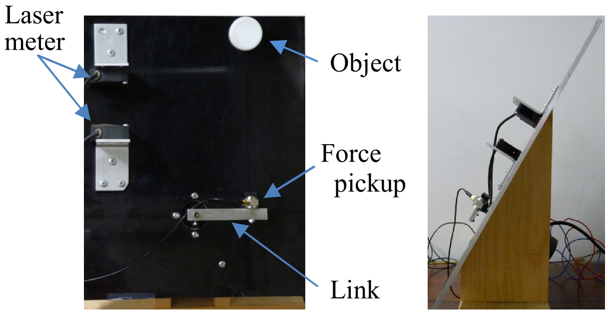


(a) Relation between collision speed and impact force



(b)Relation between collision speed and height of bound

Fig.6 Impact force and height of bound



(a) Front view (b) Side view

Fig.7 Experimental apparatus

The parameter of the link and the motor are shown in Table 1, and the motor (rated 24 V, 60W) are on the frame, and sampling time of the control is 0.002 s. The feedback gain for angular displacement is 100 V/rad, and the feedback gain for angular velocity is 1.0 Vs/rad.

Figure 8 (a) and (b) show experimental results about motion of the link and object. In Figure (a), the link is fixed at initial position, and the object bounds high. In Figure (b), the link is actuated along the trajectory calculated by IDP method, and the object bounds low.

Figure 9 shows the experimental results about the response of the link and motor after the passing time of Laser meter. Impact force F about optimal case (b) becomes smaller than one of supported case (a). The experimental results (solid line) are similar to the theoretical results (broken line).

From these results, it is considered that modeling for simulation is effective.

6 Conclusions

The results obtained in this paper are summarized as follows.

(1) It is considered that the active motion to absorb the impact force is possible by analyzing the relative motion about the collision between the link and object.

(2) From experimental results, it is considered that modeling for simulation is effective.

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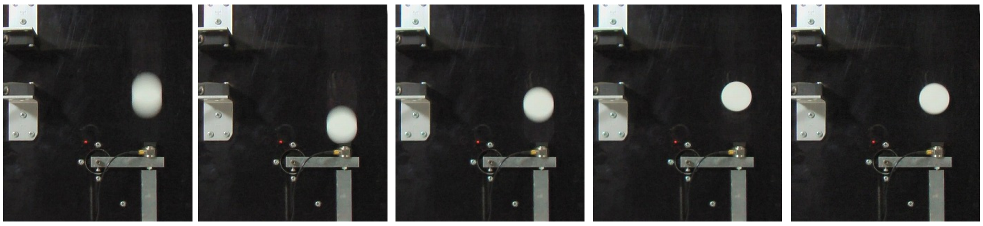
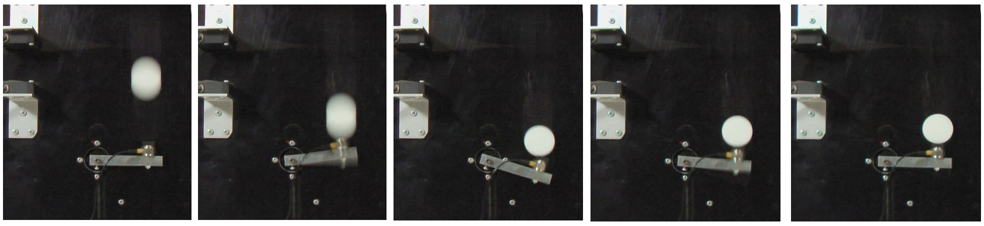
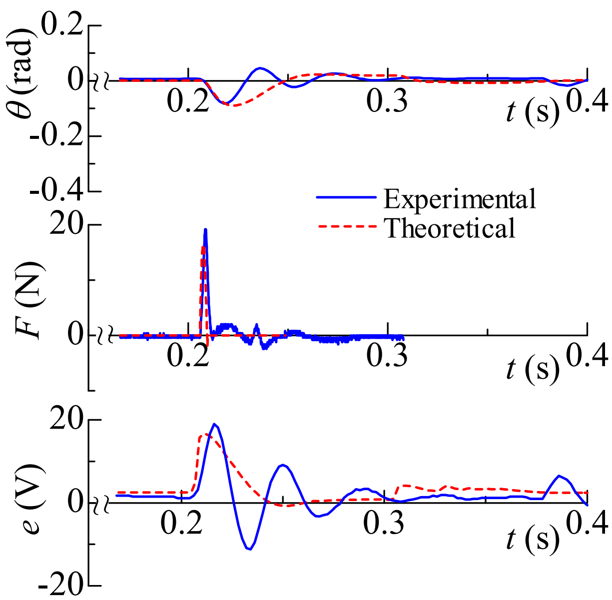


(a) Link is fixed at initial position.

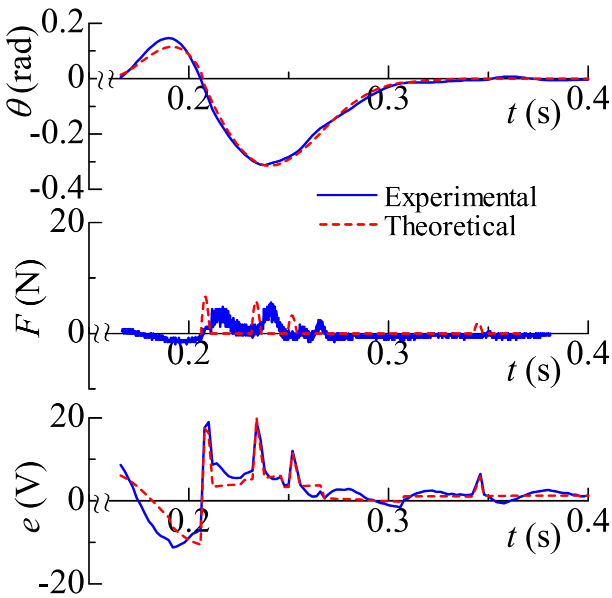


(b) Link is actuated along the trajectory calculated by IDP method.

Fig.8 Experimental results (motion about the link and object)



(a) Link is supported at horizontal.



(b) Link is controlled by the optimal trajectory.

Fig.9 Experimental results (response of link and motor)