Analysis of Manipulator in Consideration of Collision 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. Considering the collision between the link and object, and considering the active motion to absorb kinetic energy of the object, trajectories for saving energy are calculated by iterative dynamic programming. 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, DC Motor, Minimum Energy .

1 Introduction

For the purpose of enlarging the work space about carriage work, it is necessary for studying about the throwing motion and catching motion of the manipulator. In a previous report [1], a casting manipulator is introduced, and it has large work space compared with its simple mechanism. But, the consideration of energy consumption is not enough. And, evaluation of robotic mechanisms subjected to impact load are investigated [2]. But, energy consumption is not considered.

In previous report by the authors [3][4], trajectories for saving energy about the throwing motion of manipulator, were easily calculated by iterative dynamic programming. And, dynamic characteristics of the system were analyzed.

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. Considering the collision between the link and object, and considering the active motion to absorb the kinetic energy of the object, the trajectories for energy saving are calculated by iterative dynamic programming. 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 Figure 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

$$A_{11} = a_1 ,\quad A_{12} = a_3 \cos(\theta_1 - \theta_2),\quad A_{21} = A_{12} ,\quad A_{22} = a_2$$

$$A_{13} = \tau_1 - a_3\dot{\theta}_2^{\,2} \sin(\theta_1 - \theta_2) - a_4 \cos\theta_1 - Fl_1 \cos\theta_1$$

$$A_{23} = \tau_2 + a_3\dot{\theta}_1^{\,2} \sin(\theta_1 - \theta_2) - a_5 \cos\theta_2 - Fl_c$$

$$a_1 = m_1 l_{g1}{}^2 + I_{G1} + m_2 l_1^2 \quad , \quad a_2 = I_{G2} + m_2 l_{g2}{}^2$$

$$a_3 = m_2 l_1 l_{g2} ,\quad a_4 = (m_1 l_{g1} + m_2 l_1) g ,\quad a_5 = m_2 g l_{g2}$$

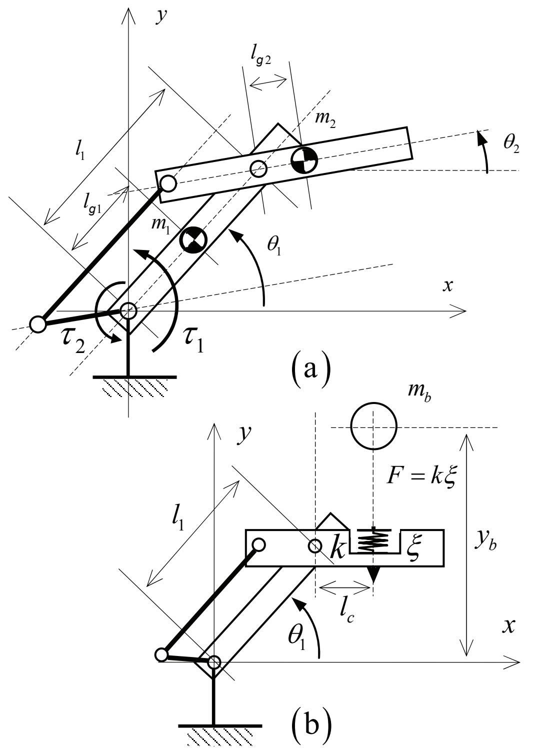


Fig.1 Mechanism of manipulator

The kinetic energy of the mechanism and object is

$$K=\frac{1}{2}a_1\dot{\theta}_1^{2}+\frac{1}{2}a_2\dot{\theta}_2^{2}+a_3\dot{\theta}_1\dot{\theta}_2\cos(\theta_1-\theta_2)+\frac{1}{2}m_b\dot{y}_b^{2}\ , \qquad (2)$$

and potential energy is

$$U=a_4\sin\theta_1+a_5\sin\theta_2+\frac{1}{2}k\xi^2+m_b\,g\,y_b\ . \qquad (3)$$

(ξ ; displacement of spring)

And, absorbed energy by motor is

$$E_{ab}=-\int\tau_1\cdot\dot{\theta}_1\,dt-\int\tau_2\cdot\dot{\theta}_2\,dt\ . \qquad (4)$$

The applied voltage of the servomotor is

$$e_j=b_{1j}\dot{\theta}_j+b_{2j}\ddot{\theta}_j+b_{3j}\tau_j+b_{3j}\tau_{fj}\,\mathrm{sign}(\dot{\theta}_j) \qquad (5)$$

where

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

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

$$i_{aj}=(e_j-k_{vj}\,\dot{\theta}_j)/R_{aj}\ . \qquad (6)$$

And, the consumed energy is

$$E=\sum_{j=1}^{2}\int(e_j\cdot i_{aj})dt\ . \qquad (7)$$

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 dynamic programming [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

$$\theta_j=\theta_{ij}+\frac{(\theta_{fj}-\theta_{ij})}{2}\left\{1-\cos\left(\frac{\pi}{t_f}t\right)\right\}\ . \qquad (8)$$

Figure 4 shows the motion of an object to fall free. Initial height is $y_b=0.15\ (\mathrm{m})$, and velocity is $\dot{y}_b=0$. When $t=0.128\,(\mathrm{s})$, the object contacts with the link. And then, $y_b'=0.069\,(\mathrm{m})$ and $\dot{y}_b=-1.25\,(\mathrm{m/s})$. Under the condition that $\theta_{1i}=0.1$ and $\theta_{1f}=0.05\,(\mathrm{rad})$, optimal trajectory is calculated by IDP method.

The performance criterion is

$$E'=\sum_{j=1}^{2}\int(e_j\cdot i_{aj})dt+C_1\int|F|\cdot dt+C_2\left|y_b-y_b'\right|\ . \qquad (9)$$

In Figure 4, the solid line shows the motion of object whose kinetic energy is absorbed by the motor.

Table 1 Parameters of the manipulator

Parameter	Value	Parameter	Value
l_1 (m)	0.10	I_{G1} (kgm^2)	1.7×10^{-5}
l_c (m)	0.01	I_{G2} (kgm^2)	1.7×10^{-5}
l_{g1} (m)	0.05	k (N/m)	500
l_{g2} (m)	0.01	k_{t1} (Nm/A)	0.046
m_1 (kg)	0.02	k_{v1} (Vs/rad)	0.046
m_2 (kg)	0.02	D_{m1} (Nms/rad)	7.9×10^{-5}
m_b (kg)	0.02	τ_{f1} (Nm)	0.0013
r_b (m)	0.01	R_{a1} (Ω)	3.5

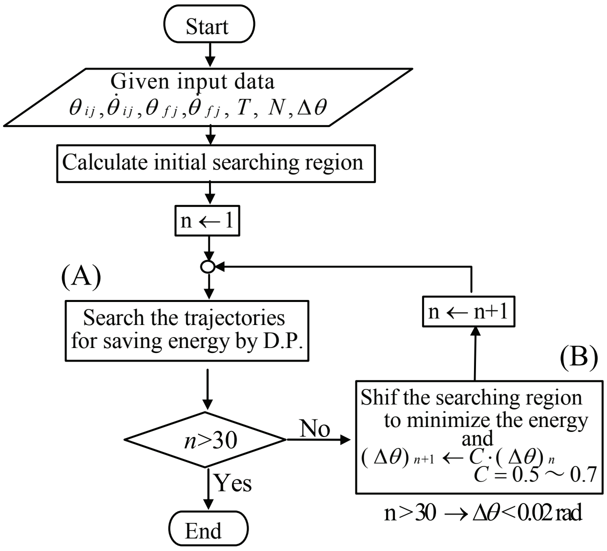


Fig.2 Flow chart for simulation

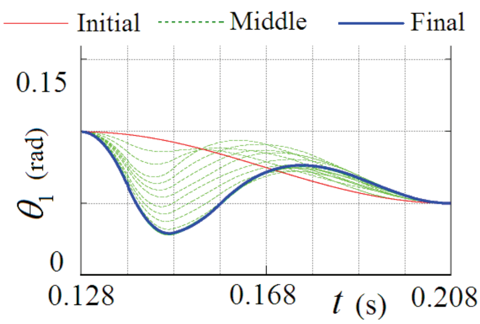


Fig.3 Trajectory for searching

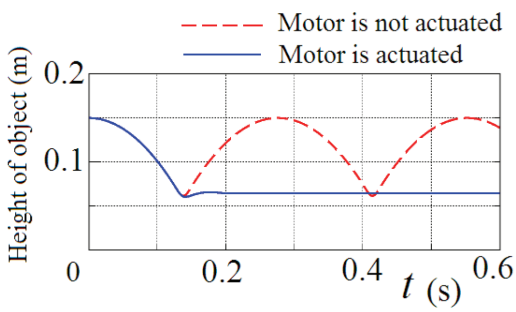
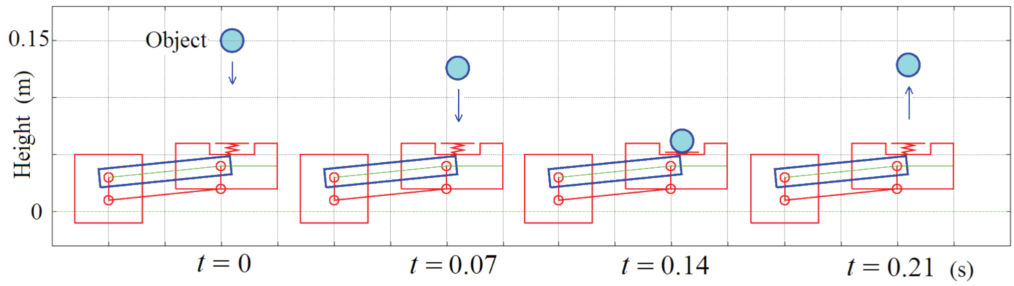
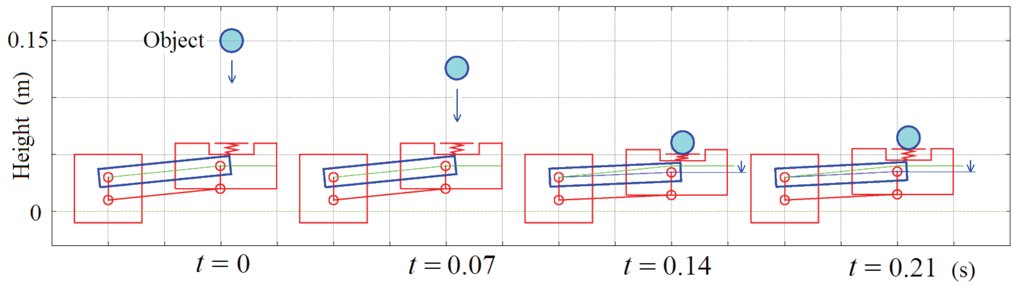


Fig.4 Motion of object to fall free



(a) Link is not actuated



(b) Link is actuated

Fig.5 Motion of the object and the mechanism

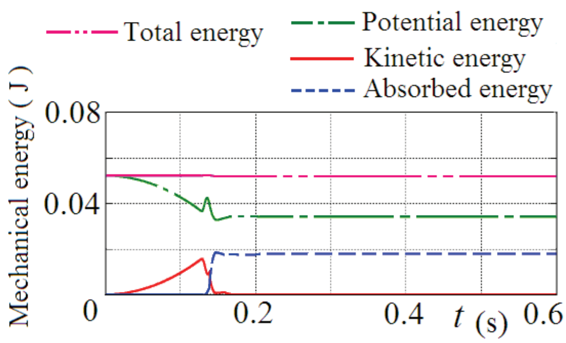
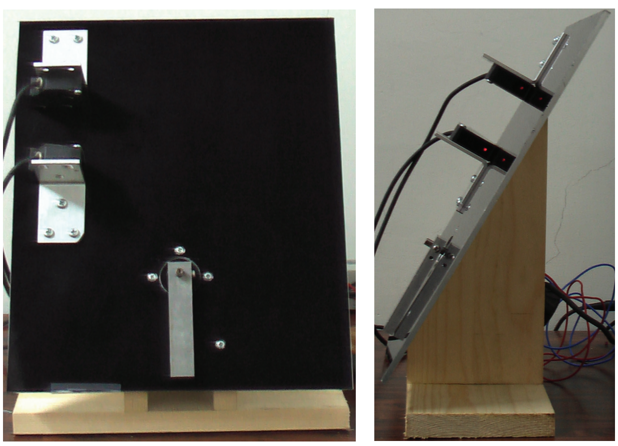


Fig.6 Mechanical energy



(a) Front view (b) Side view

Fig.7 Experimental apparatus

Figure 5 shows the motion of the object and the mechanism. In Figure (b), link 1 is actuated, and kinetic energy of the object is absorbed. And, the response about conservation of mechanical energy are shown in Fig.6.

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.

The parameter of the link 1 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 50 V/rad, and the feedback gain for angular velocity is 0.5 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 show are experimental results about the response of the link and motor. About the angular displacement and angular velocity, experimental results (blue line) are similar to the theoretical results (red 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 kinetic energy of object 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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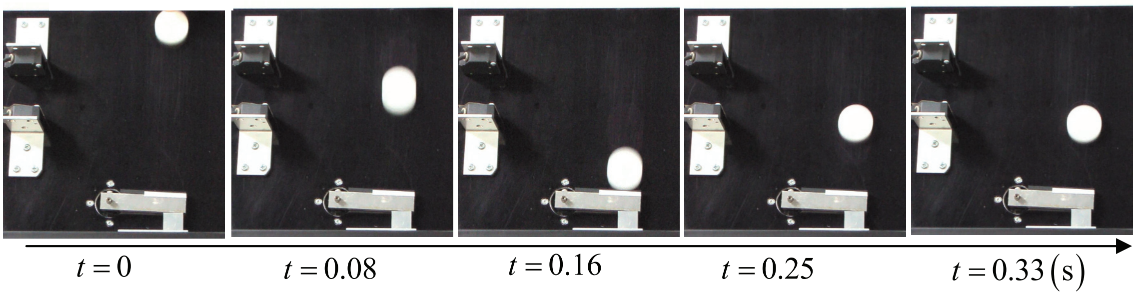
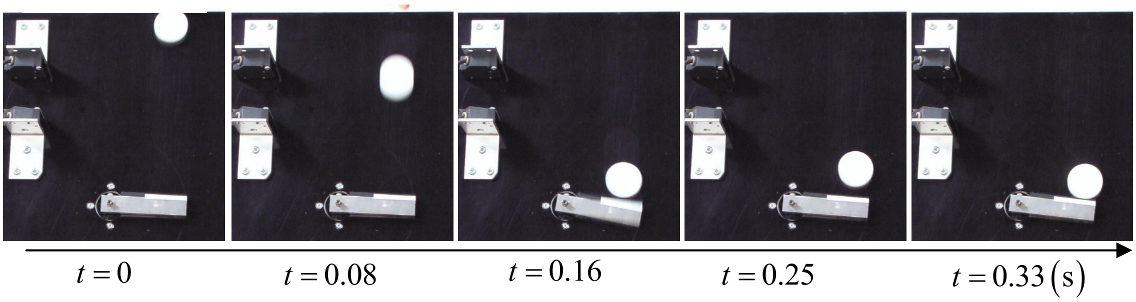


(a) Link is fixed at initial position



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

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

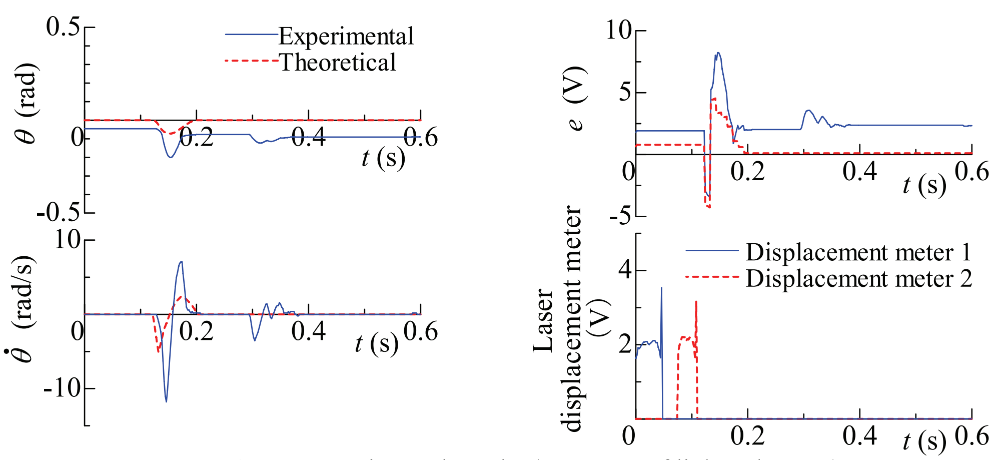


Fig.9 Experimental results (response of link and motor)