The Fifteenth International Symposium on Artificial Life and Robotics 2010 (AROB 15th '10),
B-Con Plaza, Beppu,Oita, Japan, February 4-6, 2010

Analysis of Manipulator in Consideration of Relative Motion between Tray and Object

Asaji SATO[1] , Osamu SATO[2] , Nobuya TAKAHASHI[2] , Akira UEKUBO[2] and Michio KONO[2]

[1]*Dept. of Mechanical Engineering, Miyakonojo National college of Technology, Miyakonojo 885-8567, Japan.*
[2]*Dept. of Computer Science and Systems Engineering, Faculty of Engineering, University of Miyazaki, Miyazaki 889-219, Japan.*

***Abstract*:** In this paper, equations of motion of a manipulator, whose mechanism has a tray installed by passive revolute joint, are derived in consideration of characteristics of driving source. Considering the relative motion between the tray and object, trajectories of velocity 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.

***Keywords*:** Manipulator, Trajectory, Dynamic Programming, DC Motor, Minimum Energy, Passive joint.

1 Introduction

For the purpose of enlarging the work space, it is necessary for studying the optimal control of the manipulator whose mechanism has a passive joint. 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. In horizontal plane, obstacle avoidance motion planning for a three-axis planar manipulator with a passive joint is investigated [2]. But, energy consumption is not considered.

In previous report by the authors [3][4], trajectories for saving energy of manipulator, whose mechanism has two active joints, were easily calculated by iterative dynamic programming. And, dynamic characteristics of the system were analyzed.

In this paper, equations of motion of a manipulator, whose mechanism has a passive revolute joint, 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 relative motion between the tray and the object, the trajectories of velocity 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 with passive joint

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

$$\begin{bmatrix} A_{11} & A_{12} & A_{13} & A_{14} \\ A_{21} & A_{22} & A_{23} & A_{24} \\ A_{31} & A_{32} & A_{33} & A_{34} \\ A_{41} & A_{42} & A_{43} & A_{44} \end{bmatrix} \begin{bmatrix} \ddot{\theta}_1 \\ \ddot{\theta}_2 \\ \ddot{\theta}_3 \\ \ddot{\theta}_4 \end{bmatrix} = \begin{bmatrix} \tau_1 - \tau_2 + A_{15} \\ \tau_2 - \tau_3 + A_{25} \\ \tau_3 - \tau_4 + A_{35} \\ \tau_4 + A_{45} \end{bmatrix} \quad (1)$$

where

$A_{11}=a_1+a_6C_2+a_8C_{23}+a_9C_{234}$, $A_{12}=a_6C_2+a_8C_{23}+a_9C_{234}$,
$A_{13}=a_8C_{23}+a_9C_{234}$, $A_{14}=a_9C_{234}$, $A_{21}=a_2+a_6C_2+a_7C_3+a_{10}C_{34}$,
$A_{22}=a_2+a_7C_3+a_{10}C_{34}$, $A_{23}=a_7C_3+a_{10}C_{34}$, $A_{24}=a_{10}C_{34}$,
$A_{31}=a_3+a_7C_3+a_8C_{23}+a_{11}C_4$, $A_{32}=a_3+a_7C_3+a_{11}C_4$,
$A_{33}=a_3+a_{11}C_4$, $A_{34}=-a_5+a_{11}C_4$, $A_{43}=a_4+a_{11}C_4$, $A_{44}=a_4+a_5$,
$A_{41}=a_4+a_9C_{234}+a_{10}C_{34}+a_{11}C_4$, $A_{42}=a_4+a_{10}C_{34}+a_{11}C_4$,
$A_{15}=a_6(\dot{\theta}_1+\dot{\theta}_2)^2S_2+a_8(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2S_{23}+a_9(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2S_{234}-a_{12}C_1$,
$A_{25}=-a_6\dot{\theta}_1^2S_2+a_7(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2S_3+a_{10}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2S_{34}-a_{13}C_{12}$,
$A_{35}=-a_7(\dot{\theta}_1+\dot{\theta}_2)^2S_3-a_8\dot{\theta}_1^2S_{23}+a_{11}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2S_4-a_{14}C_{123}$,
$A_{45}=-a_9\dot{\theta}_1^2S_{234}-a_{10}(\dot{\theta}_1+\dot{\theta}_2)^2S_{34}-a_{11}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2S_4-a_{15}C_{1234}$,

$a_1=I_{G1}+m_1r_1^2+(m_2+m_3+m_4)l_1^2$, $a_2=I_{G2}+m_2r_2^2+(m_3+m_4)l_2^2$,
$a_3=I_{G3}+m_3r_3^2+m_4r_3'^2$, $a_4=m_4r_4^2$, $a_5=I_{Gb}\left(r_4^2/r_b^2\right)$,
$a_6=\{m_2r_2+(m_3+m_4)l_2\}l_1$, $a_7=(m_3r_3+m_4r_3')l_2$, $a_8=(m_3r_3+m_4r_3')l_1$,
$a_9=m_4l_1r_4$, $a_{10}=m_4l_2r_4$, $a_{11}=m_4r_3'r_4$, $a_{12}=(m_1r_1+m_2l_1+m_3l_1+m_4l_1)g$,
$a_{13}=(m_2r_2+m_3l_2+m_4l_2)g$, $a_{14}=(m_3r_3+m_4r_3')g$, $a_{15}=m_4gr_4$,

$C_j=\cos\theta_j$, $S_j=\sin\theta_j$, $C_{jk}=\cos(\theta_j+\theta_k)$, $S_{jk}=\sin(\theta_j+\theta_k)$,
$C_{jkn}=\cos(\theta_j+\theta_k+\theta_n)$, $S_{jkn}=\sin(\theta_j+\theta_k+\theta_n)$,
$C_{jknp}=\cos(\theta_j+\theta_k+\theta_n+\theta_p)$, $S_{jknp}=\sin(\theta_j+\theta_k+\theta_n+\theta_p)$,
$(j=1\sim4, k=1\sim4, n=1\sim4, p=1\sim4)$

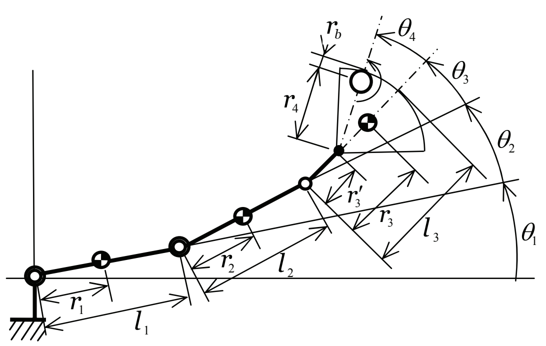
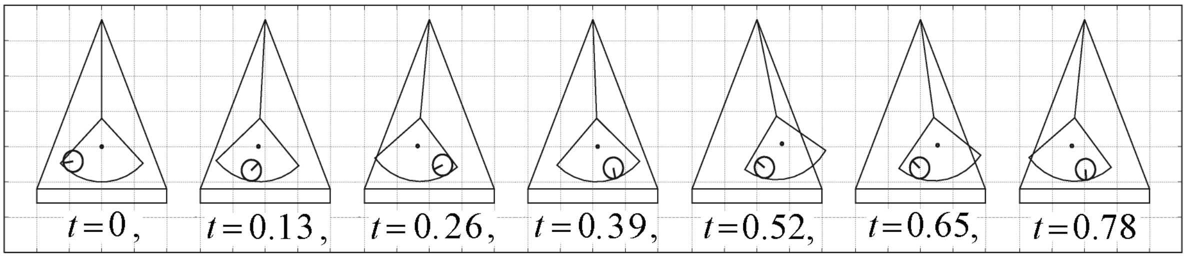
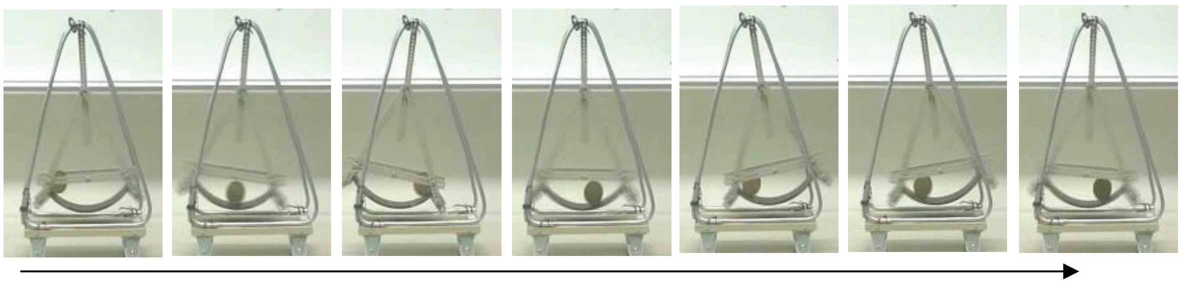


Fig.1 Mechanism of manipulator



(a) Simulation of pendulum movement about the tray and the object



(b) Experimental results of pendulum movement (every 0.13 s)

Fig.2 Pendulum movement about the tray and the object

And, the relation between $\dot{\phi}$ and $\dot{\theta}_4$ is

$$r_b\dot{\phi} = -r_4\dot{\theta}_4 \quad . \tag{2}$$

($\dot{\phi}$; rotational speed of the object)

The kinetic energy of the mechanism is

$$\begin{aligned} K = & \frac{a_1}{2}\dot{\theta}_1^2 + \frac{a_2}{2}(\dot{\theta}_1+\dot{\theta}_2)^2 + \frac{a_3}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)^2 \\ & + \frac{a_4}{2}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)^2 + \frac{a_5}{2}\dot{\theta}_4^2 \\ & + a_6\dot{\theta}_1(\dot{\theta}_1+\dot{\theta}_2)C_2 + a_7(\dot{\theta}_1+\dot{\theta}_2)(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)C_3 \\ & + a_8\dot{\theta}_1(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)C_{23} + a_9\dot{\theta}_1(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)C_{234} \\ & + a_{10}(\dot{\theta}_1+\dot{\theta}_2)(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)C_{34} \\ & + a_{11}(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3)(\dot{\theta}_1+\dot{\theta}_2+\dot{\theta}_3+\dot{\theta}_4)C_4 \quad , \end{aligned} \tag{3}$$

and potential energy of the mechanism is

$$U = a_{12}S_1 + a_{13}S_{12} + a_{14}S_{123} + a_{15}S_{234} \quad . \tag{4}$$

The applied voltage of the servomotor is

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

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

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

And, the consumed energy is

$$E = \sum_{j=1}^{3} \int (e_j \cdot i_{aj})dt \; . \tag{7}$$

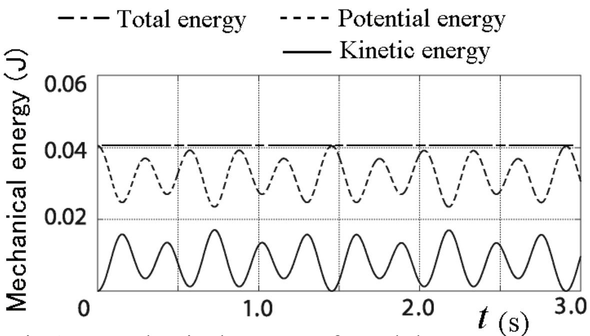


Fig.3 Mechanical energy of pendulum movement

3 Simulation of the pendulum movement

Under the condition that joint 1 and 2 are fixed, simulations of the system are shown in Fig.2 and 3.

We shall take the parameters of the system as $m_3 = 0.109, m_4 = 0.122(\mathrm{kg}), r_4 = 0.075, r_b = 0.015(\mathrm{m})$. And, initial conditions are $\theta_{3i} = -(\pi/2)$, $\theta_{4i} = -(\pi/5)$, $\dot{\theta}_{3i} = \dot{\theta}_{4i} = 0$. Figure 2 shows the motion of the system like a pendulum movement, and Figure 3 shows the response about the conservation of mechanical energy of the pendulum movement.

4 Simulation of the manipulator

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

Figure 4 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 5 shows the trajectory for searching, and initial trajectory for searching is expressed as

$$\dot{\theta}_j = \dot{\theta}_{ij} + \left(\frac{\dot{\theta}_{fj} - \dot{\theta}_{ij}}{t_f}\right)t + \frac{\pi}{2}\left(\frac{\theta_{fj} - \theta_{ij}}{t_f} - \frac{\dot{\theta}_{fj} + \dot{\theta}_{ij}}{2}\right)\sin\left(\frac{\pi t}{t_f}\right). \quad (8)$$

The tray and the object are shown in Figure 6. Considering the relative motion between the tray and the object, the performance criterion is changed as

$$E' = \sum_{j=1}^{3} \int_0^T (e_j \cdot i_{aj})\ dt + k\{|\theta_4| - (\lambda/2)\} \quad . \quad (9)$$

A response of the manipulator from the initial position ($\theta_{1i} = -\pi/4$, $\theta_{2i} = -\pi/4$, $\theta_{3i} = 0$, $\dot{\theta}_{1i} = 0$, $\dot{\theta}_{2i} = \dot{\theta}_{3i} = 0$) to the release position ($\theta_{1f} = 13\pi/36$, $\theta_{2f} = -7\pi/36$, $\theta_{3f} = -7\pi/24$, $\dot{\theta}_{1f} = 13.9$ rad/s, $\dot{\theta}_{2f} = -1.1$ rad/s) is shown in Figure 7, under the condition that working time $t_f = 0.8$ (s). In this case, joint 3 is passive, and joint 1, 2 are actuated. In order to prevent the object falling from the tray at turning point 2, and not to prevent the object releasing from the tray at point 3, the center of gravity of the tray is adjusted in consideration of the analysis about the relative motion between the object and the tray.

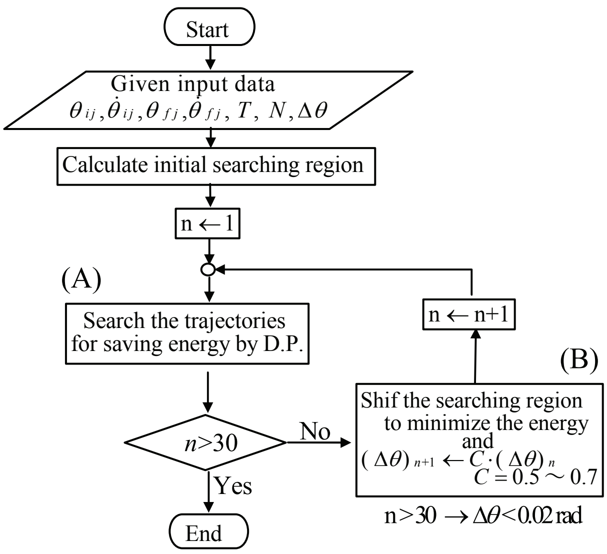


Fig.4 Flow chart for simulation

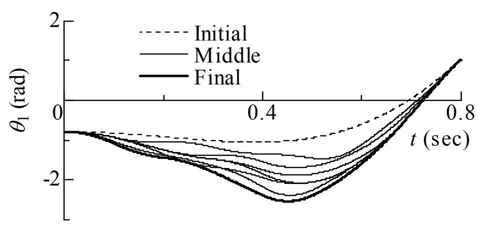


Fig.5 Trajectory for searching

Table 1 Parameters of the manipulator

Parameter	Value	Parameter	Value
l_1 (m)	0.080	I_{G1} (kgm^2)	1.7×10^{-5}
l_2 (m)	0.115	I_{G2} (kgm^2)	8.4×10^{-5}
l_3 (m)	0.015	I_{G3} (kgm^2)	1.2×10^{-6}
r_1 (m)	0.044	I_{Gb} (kgm^2)	4.8×10^{-7}
r_2 (m)	0.078	k_{t1}, k_{t2} (Nm/A)	0.046
r_3 (m)	0.028	k_{v1}, k_{v2} (Vs/rad)	0.046
r_3' (m)	0.000	D_{m1}, D_{m2}(Nms/rad)	7.9×10^{-5}
r_4 (m)	0.005	τ_{f1}, τ_{f2} (Nm)	0.0013
r_b (m)	0.010	R_{a1}, R_{a2} (Ω)	3.5
m_1 (kg)	0.020	m_3 (kg)	0.018
m_2 (kg)	0.047	m_4 (kg)	0.012

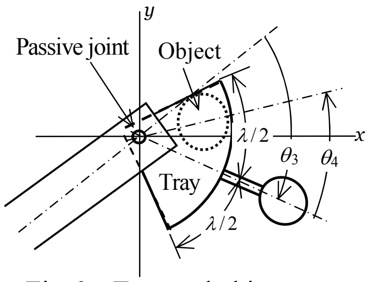


Fig.6 Tray and object

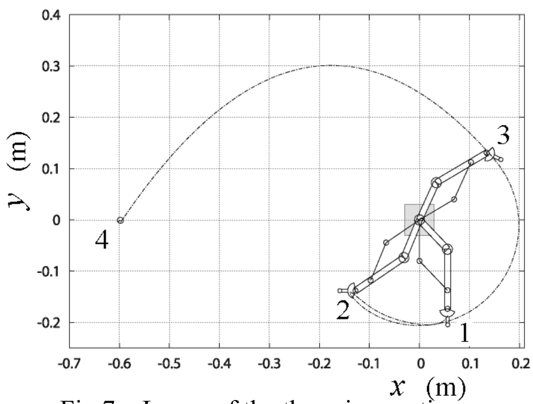


Fig.7 Locus of the throwing motion

5 Experimental results

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

Figure 8(a) shows the experimental results of the manipulator in throwing motion, under the same condition as Fig.7. This apparatus is used in previous report by the authors [4]. A mechanism of manipulator is a closed type and a tray (link 3) is connected to link 2 by a passive revolute joint. Under the condition that the torque of joint 3 is zero, the angular acceleration of joint 1 and 2 are given in iterative dynamic programming method, and the acceleration of link 3 and torques of joint 1, 2 are calculated simultaneously. The parameters of the system are shown in Table 1. The motors 1 and 2 (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(b) shows the theoretical results which is similar to the experimental one.

Figure 9 (a) and (b) show the experimental response of angular velocity of the motor which are calculated by angular displacement measured by rotary encoder. And, Figure (c) shows the angular displacement of the tray. From initial position to release position, the theoretical results (broken line) are similar to the experimental results (solid line). From these results, it is considered that modeling for simulation is effective.

From experimental results, it is clear that the holding and releasing of the object are possible by analyzing the relative motion between the object and the tray.

6 Conclusions

The results obtained in this paper are summarized as follows.

(1) It is considered that the holding and releasing of the object is possible by analyzing the relative motion between the object and the tray.

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

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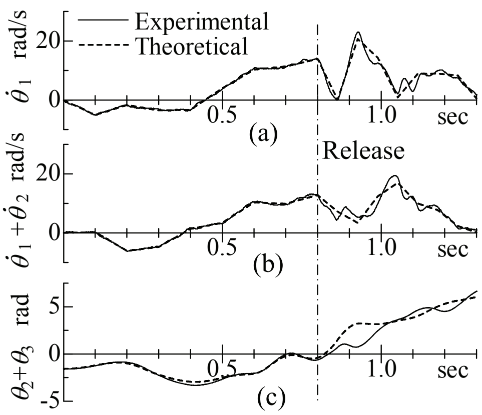
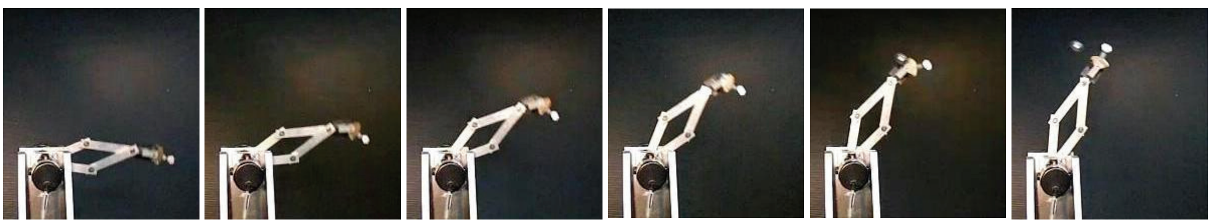
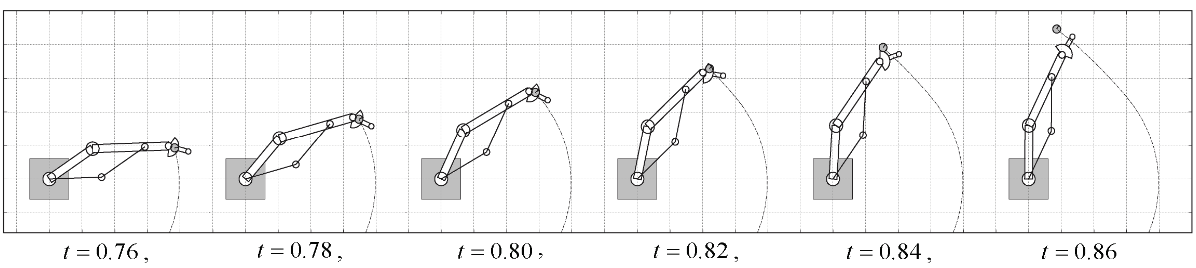


Fig.9 Experimental results



(a) Experimental results



(b) Theoretical results

Fig.8 Throwing motion of the manipulator