Throwing Motion of Manipulator with Passive Revolute Joint

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Abstract

In this paper, equations of motion of a manipulator, whose mechanism has a passive revolute joint, are derived in consideration of characteristics of driving source. Considering the final condition about displacement and velocity, 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, Throwing Motion

1 Introduction

For the purpose of enlarging the work space, it is necessary for studying the optimal control of the manipulator in throwing motion. In a previous report [1], a casting manipulator is introduced, and the merit of this type is its large work space compared with its simple mechanism. But, the consideration of energy consumption of driving source is not enough. Also, the throwing motion of 2-DOF robot was studied to reduce the target error[2]. But, the consideration about trajectory of saving energy is not enough.

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

In rescue and agricultural field, it is considered that hand of tray type with passive joint is available for throwing the object which is various shape. In this paper, equations of motion of a manipulator, whose mechanism has a passive revolute joint, are derived in consideration of characteristics of the DC servomotors, and a performance criterion for saving energy is defined in consideration of energy consumption of 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 final condition about displacement and velocity, trajectories of velocity for saving energy are calculated by iterative dynamic programming. Initial searching region, which is surrounded by two sine-wave translated in parallel, is shifted to minimize the energy consumption of the motor. The dynamic characteristics of manipulator controlled based on above mentioned trajectory are analyzed theoretically.

2 Modeling of manipulator with passive joint

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.

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

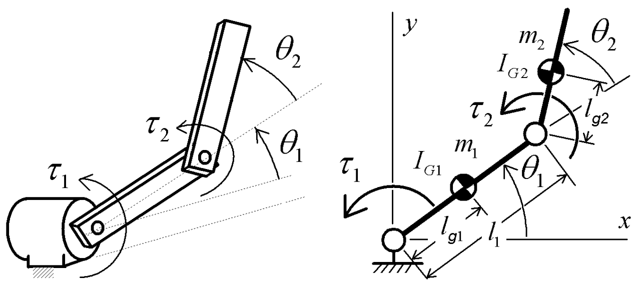
where

τ_1, τ_2 ; torque which acts on link 1 and 2 ,

θ_1, θ_2 ; angular displacement of link ,

$$a_{11} = I_{G1} + m_1 l_{g1}{}^2 + m_2 l_1{}^2 + m_2 l_1 l_{g2} \cos\theta_2$$
$$a_{12} = m_2 l_1 l_{g2} \cos\theta_2$$
$$a_{13} = \tau_1 - \tau_2 + m_2 l_1 l_{g2} (\dot{\theta}_1 + \dot{\theta}_2)^2 \sin\theta_2 - (m_1 l_{g1} + m_2 l_1) g \cos\theta_1$$
$$a_{21} = I_{G2} + m_2 l_{g2}{}^2 + m_2 l_{g2} l_1 \cos\theta_2$$
$$a_{22} = I_{G2} + m_2 l_{g2}{}^2$$
$$a_{23} = \tau_2 - m_2 l_{g2} l_1 \dot{\theta}_1^2 \sin\theta_2 - m_2 g l_{g2} \cos(\theta_1 + \theta_2)$$

Joint 2 is passive revolute joint, and $\tau_2 = 0$.



(a) (b)

Fig. 1 Mechanism of manipulator

Table 1 Parameters of the manipulator

Parameter	Value	Parameter	Value
l_1, l_2 (m)	0.1	m_1, m_2 (kg)	0.1
l_{g1}, l_{g2} (m)	0.05	A_1 (Nm)	0.04
I_{G1}, I_{G2} (kgm^2)	8.33×10^{-5}	T_1 (sec)	0.52

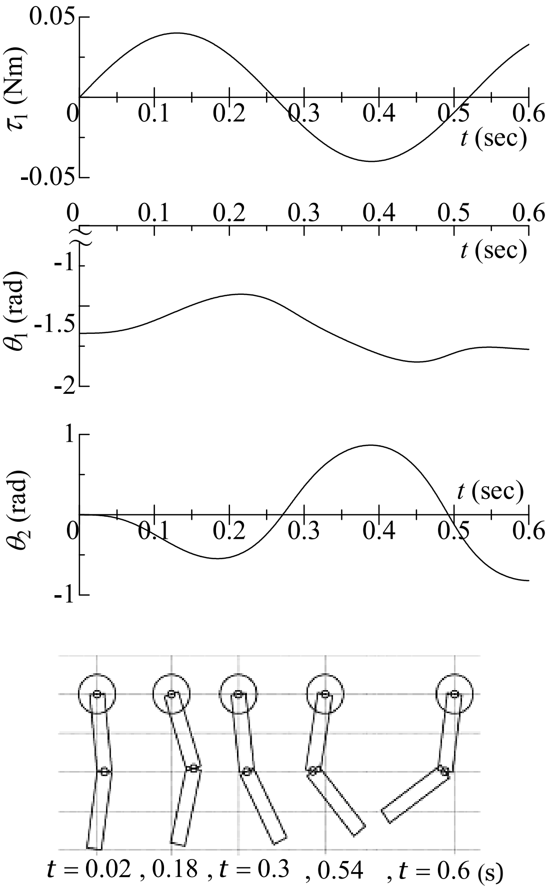


Fig. 2 Response of manipulator with a passive joint

We shall take the parameters of the system as shown in Table 1. The simulations of the system are done as follows. The period of pendulum movement of link 2 is approximated as

$$T_1 = 2\pi\sqrt{\frac{I_{G2} + m_2 l_{g2}^{\ 2}}{m_2 g l_{g2}}} \quad . \tag{2}$$

Then, output torques of the motor 1 and 2 are

$$\tau_1 = A_1 \sin\left(\frac{2\pi}{T_1}t\right) \quad , \quad \tau_2 = 0 \quad . \tag{3}$$

A response of the manipulator from initial position $(\theta_{1i} = -\pi/2\ , \theta_{2i} = 0)$ is shown in Figure 2. Amplitude of pendulum movement caused by inertia force increases as the response time increases.

3 Throwing motion of manipulator

The applied voltage of the servomotor is

$$e_1 = b_1\dot{\theta}_1 + b_2\ddot{\theta}_1 + b_3\tau_1 + b_3\tau_{f1}\mathrm{sign}(\dot{\theta}_1) \tag{4}$$

where

$$\tau_1 = \left(I_{G1} + m_1 l_{g1}^{\ 2} + m_L l_1^{\ 2}\right)\ddot{\theta}_1 + \left(m_1 l_{g1} + m_L l_1\right) g \cos\theta_1 \tag{5}$$

$b_1 = k_v + (R_a / k_t) D_m$, $b_2 = (R_a / k_t) I_m$, $b_3 = R_a / k_t$,

i_a : electric current of the armature ,
R_a : resistance of armature ,
I_m : moment of inertia of armature,
D_m : coefficient of viscous damping.

Then, the electric current is $i_a = (e - k_v\dot{\theta}) / R_a$. (6)

And, the consumed energy is $E = \int (e \cdot i_a) dt$. (7)

The velocity of object for throwing is expressed as

$$v = \frac{x_f - l_1 \cos\theta_{1f}}{\cos\phi}\sqrt{\frac{g}{2\left|x_f - l_1\cos\theta_{1f}\right|\tan\phi - 2\left(y_f - l_1 \sin\theta_{1f}\right)}}$$

where

(x_f, y_f) ; position of arrival
$(\theta_{1f}, \theta_{2f})$; angle of link 1 and 2 at release time .

Figure 3 shows a flow chart for iterative dynamic programming method. In frame (A), the trajectory for saving energy is searched by dynamic programming [4]. In frame (B), the searching region is shifted to minimize the consumed energy, and width of the region is changed smaller. Figure 4 shows the trajectory for searching, and the initial trajectory for searching is expressed as

$$\Theta_1(t) = \frac{v}{2 l_1 t_f} t^2 + \theta_{1i} + \frac{t_f}{2}\left(\frac{\theta_{1f} - \theta_{1i}}{t_f} - \frac{v}{2 l_1}\right)\left[1 - \cos\left(\frac{\pi}{t_f} t\right)\right].$$

This proposed trajectory is used as a center line of initial searching region of the iterative dynamic programming, and the region is shifted along the axis of coordinate to minimize the consumed energy of the motor.

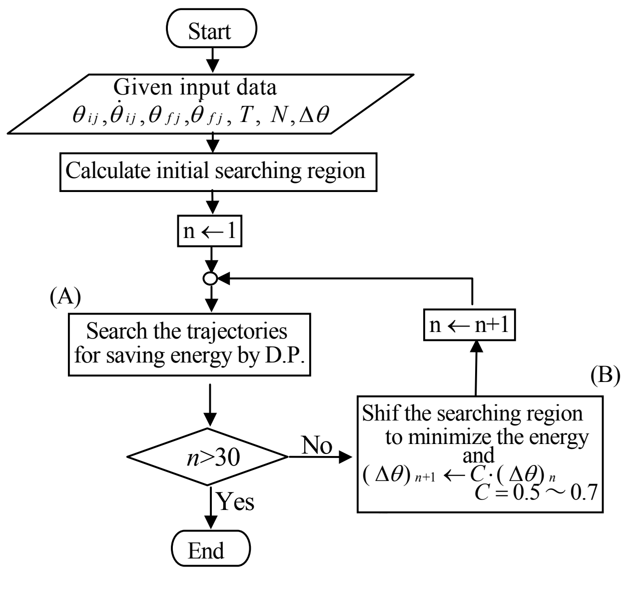


Fig. 3 Flow chart for simulation

Table 2 Parameters of the manipulator for throwing

Parameter	Value	Parameter	Value
l_1 (m)	0.080	k_{t1}, k_{t2} (Nm/A)	0.046
l_2 (m)	0.035	k_{v1}, k_{v2} (Vs/rad)	0.046
l_{g1} (m)	0.044	R_{a1}, R_{a2} (Ω)	3.5
l_{g2} (m)	0.031	D_{m2}, D_{m2} (Nms/rad)	7.9×10^{-5}
I_{G1} (kgm^2)	1.07×10^{-5}	τ_{f1}, τ_{f1} (Nm)	0.0013
I_{G2} (kgm^2)	0.36×10^{-5}	m_1 (kg)	0.020
I_{m1}, I_{m2} (kgm^2)	8.5×10^{-6}	m_2 (kg)	0.004
		m_L (kg)	0.005

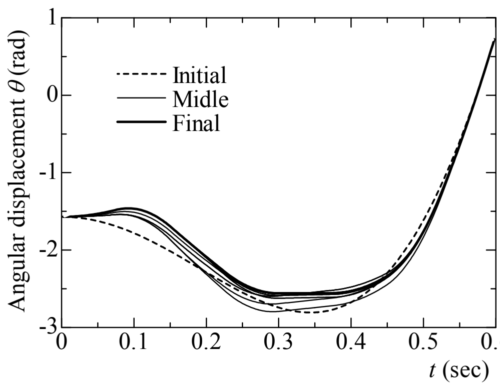


Fig. 4 Trajectory for searching

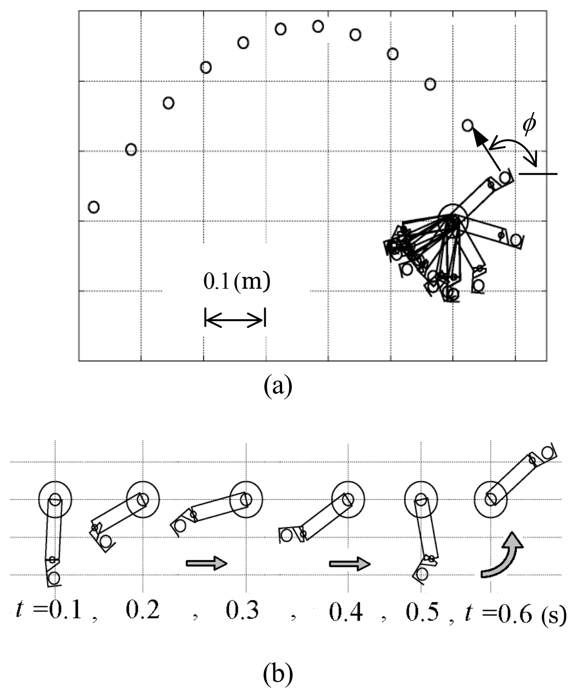


Fig. 5 Throwing motion of manipulator

We shall take the parameters of the system as shown in Table 2.

A response of the manipulator from initial position ($\theta_{1i} = -\pi/2,\ \theta_{2i} = 0$) to the position of release ($\theta_{1f} = \pi/4,\ \theta_{2f} = -\pi/10$) is shown in Fig.5, under the condition that distance from origin to the point of arrival is x=–0.6[m], release angle is $\phi = 3\pi/4$, and the working time is T=0.6. In Figure 5, it is shown that the locus of every sampling time (0.04 [s]) is like a pendulum movement, and circles are locus of object under the condition that link 1 and 2 are stopped at the time of release (0.6 [s]). They show the motion of object caused by kinetic energy at the time of release.

Figure 6 shows the response of angular displacement and angular velocity in throwing motion of Fig. 5. The angular velocity of links are $\dot{\theta}_1 = 28$ [rad/s] , $\dot{\theta}_2 = -18$ [rad/s] at the time of release (0.6 [s]). And, velocity of object,

$$v = \sqrt{(l_1 \cdot \dot{\theta}_1)^2 + \{l_O \cdot (\dot{\theta}_1 + \dot{\theta}_2)\}^2 + 2l_1 \cdot l_O \cdot \dot{\theta}_1(\dot{\theta}_1 + \dot{\theta}_2)\cos(\theta_2)}$$

$\cong 2.5\,[\mathrm{m/s}]$,

(l_O=0.027 [m] ; length between joint and center of object) is enough for throwing motion. The kinetic energy of object is 0.016[J], and on the other hand consumed energy of the motor is 0.79[J]. From these analysis, it is considered that the manipulator with a passive joint is available for throwing the object.

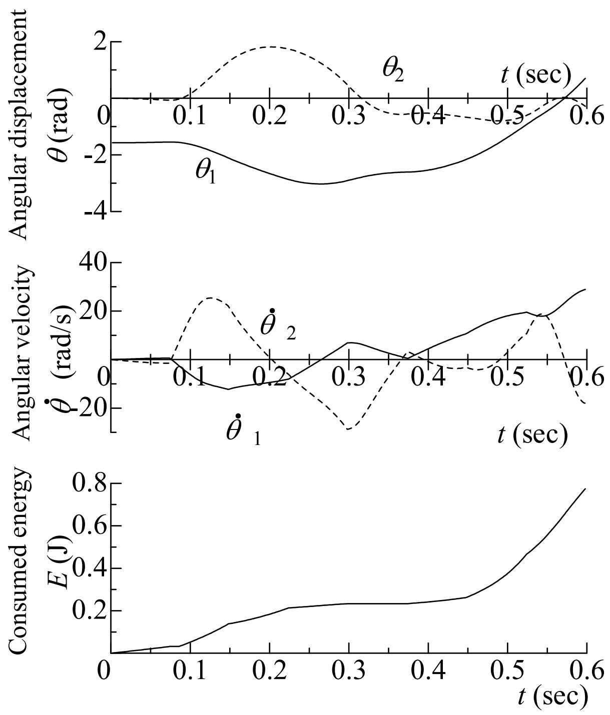


Fig. 6 Response of the manipulator with a passive joint

4 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, which is used in previous report by the authors [3]. A tray for holding the object is connected to link 2 by a passive revolute joint. It is able to use Equation (1) for calculating the motion of link 2 and the tray, under the condition that motion of link 1 (θ_1) is the same as link 2 (θ_2). And, the parameters of system are shown in Table 3. The motors 1 and 2 (rated 24 V, 60 W) are on the frame. Figure 8 shows a mechanism of manipulator.

Figure 9 shows the locus of every sampling time (0.05 [s]) , under the condition that initial position is ($\theta_{1i} = -\pi/4$, $\theta_{2i} = -\pi/2$), the finale position is ($\theta_{1f} = \pi/4$, $\theta_{2f} = 0$), and the working time is T=0.4 [s].

Figure 10 shows the experimental response under the condition that 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]. In Figure 10, the response of angular displacement θ_2 and θ_3 are measured by rotary encoder, and angular velocity $\dot{\theta}_3$ is calculated by angular displacement. Theoretical results (broken line) agree with experimental results (solid line).

From these results, it is confirmed that modeling for the simulations is effective.

5 Conclusions

The results obtained in this paper are summarized as follows.

(1) It is considered that manipulator with passive revolute joint is available for throwing motion.

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

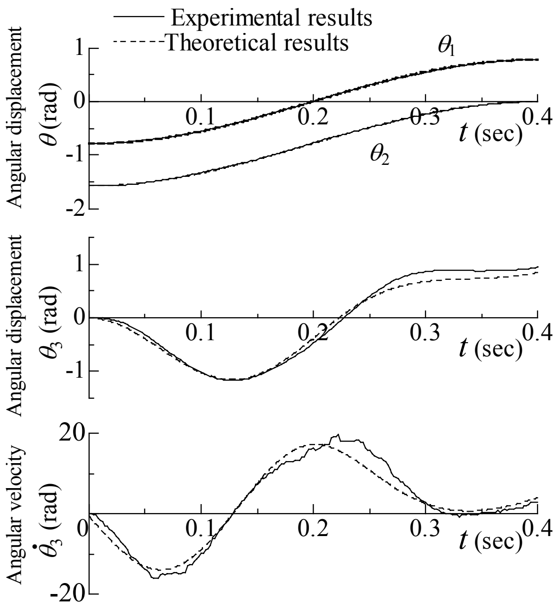


Fig. 10 Experimental results

References

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Table 3 Parameters of experimental apparatus

Parameter	Value	Parameter	Value
l_1 (m)	0.080	I_{G1} (kgm^2)	1.73×10^{-5}
l_2 (m)	0.115	I_{G2} (kgm^2)	8.42×10^{-5}
l_{g1} (m)	0.044	I_{G3} (kgm^2)	9.43×10^{-6}
l_{g2} (m)	0.078	m_1 (kg)	0.0202
l_{g3} (m)	0.030	m_2 (kg)	0.0468
D_3 (Nms/rad)	7.35×10^{-6}	m_3 (kg)	0.0218

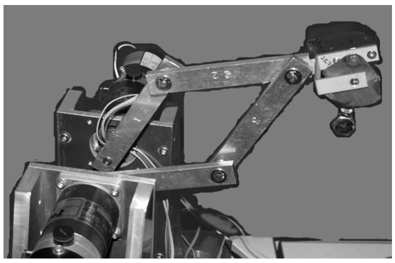

Fig. 7 Experimental apparatus

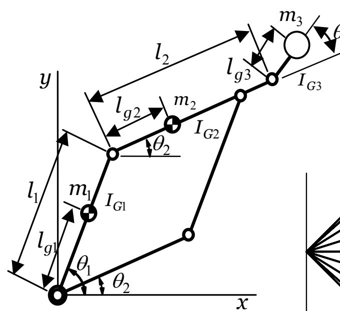

Fig. 8 Mechanism of manipulator

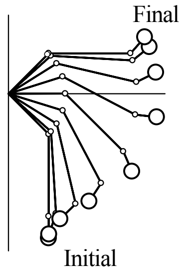

Fig. 9 Locus of manipulator