ADAPTIVE MOTION CONTROL OF A TWO-LINK DIRECT DRIVE MANIPULATOR USING DISTURBANCE OBSERVER

Phornsuk RATIROCH-ANANT*, Masatoshi ANABUKI** and Hiroshi HIRATA**

* Faculty of Engineering, King Mongkut's Institute of Technology, Ladkrabang, THAILAND

E-mail: ktphorns@kmitl.ac.th

** School of Information Technology and Electronics, Tokai University, JAPAN

E-mail: hirata@keyaki.cc.u-tokai.ac.jp

Abstract: The proposed system is realized by appending the disturbance observer to the type-2 servo in order to reduce the tracking error of trajectory control. Furthermore, the adaptive control is applied to control the deterioration of the tracking performance by the variation of payload. It is verified by the practical experiment that the adaptive control is very useful in the case of the nonlinear torque has small effect compared to the friction torque.

Key words: direct drive manipulator adaptive motion control disturbance observer

1. Introduction

This paper reports the result of the adaptive motion control based on both type-2 servo and the disturbance observer on a two-link D.D manipulator shown in Figure 1. The recursive estimation occupies an important part to realize the adaptive control system [1],[2]. The estimated value is efficiently updated by means of the recursive algorithm of the scalar type effectively selected from linear relation of the vector type.

Both links of the SICE standard D.D manipulator have the same length of 200[mm]. They are driven by the outer rotor type direct drive A.C motors in torque control mode. The maximum voltage of the torque command to both joints are ± 8 volts and the maximum torque to the actuators of first and second joint are 70 [Nm] and 15 [Nm] respectively. The resolution of the optical position encoders for the first and second link is 614400 and 507904 [pulse/rev] respectively. The variations of the payload is provided by changing the weight of steel disk on the second link. The adaptive controller is implemented by using DELL Dimension V400c (Intel celeron processor 400MHz) with interface board providing 2-channel 12 bits D/A for torque command, 2-channel 24 bits 2-phase encoder pulse counter for position detection and 4-channel 12 bits A/D for current and velocity detection.

2. Manipulator dynamics

The vector equation of motion of such manipulator can be written in the general form

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + F(\dot{\boldsymbol{q}}) + G(\boldsymbol{q}) = \boldsymbol{t}\ , \quad \boldsymbol{q} \in R^n , \qquad (1)$$

where $\boldsymbol{t}$ is the vector of joint torques by the actuators, $M(\boldsymbol{q}) \in R^{n\times n}$ is the inertia matrix, and $\boldsymbol{q}$, $\dot{\boldsymbol{q}}$ and $\ddot{\boldsymbol{q}}$ are the joint angles, velocities and accelerations, respectively. The vector $C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}}$ represents torques arising from centrifugal and Coriolis forces. The vectors $F(\dot{\boldsymbol{q}})$ and $G(\boldsymbol{q})$ represent the friction torques acting at rotational joints, and the gravitational torques respectively. In the case of neglecting the friction term of (1), the dynamic equation can be usually separated with respect to the link parameters by the property of linear parameterize as

$$M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + G(\boldsymbol{q}) = \Phi(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\mathbf{s}\ , \qquad (2)$$

where $\Phi(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}}) \in R^{n\times p}$ is a signal matrix called the regressor and $\mathbf{s} \in R^p$ is the vector of link parameters.

2.1 Dynamics of the SICE D.D arm

Figure 2 shows the schematic drawing of D.D arm. In the case of horizontal plane arm setting, the gravitational term $G(\boldsymbol{q})$ in (2) is identically zero. When the momentums of inertia concerning the links are symbolized as I_1, I_2, the terms in the dynamic equation can be obtained by means of the Euler-Lagrange dynamic equation as follows:

$$M(\boldsymbol{q}) = \begin{bmatrix} J_1 + J_2 + 2rC_2 & J_2 + rC_2 \\ J_2 + rC_2 & J_2 \end{bmatrix}, \qquad (3)$$

where $J_1 = I_1 + m_1 a_1{}^2 + m_2 \ell_1{}^2$, $J_2 = I_2 + m_2 a_2{}^2$, $r = m_2 \ell_1 a_2$, $C_2 = \cos q_2$, $\boldsymbol{q} = [q_1 \quad q_2]^T$,

Figure 1 Two-link direct drive manipulator "SR-402DD".

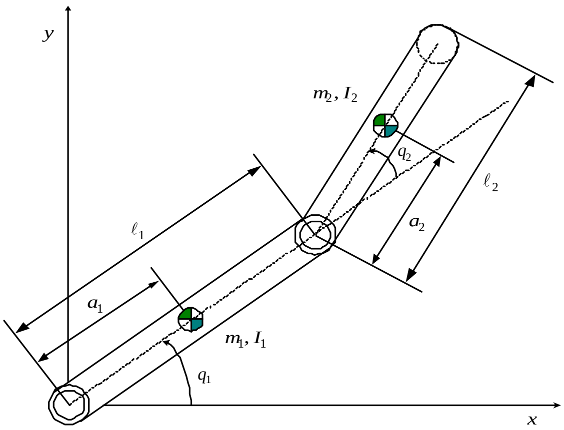

Figure 2 Schematic drawing of two-link D.D manipulator.

and $C(\boldsymbol{q},\dot{\boldsymbol{q}}) = \begin{bmatrix} -rS_2\dot{q}_2 & -rS_2(\dot{q}_1+\dot{q}_2) \\ rS_2\dot{q}_1 & 0 \end{bmatrix}$, $S_2 = \sin q_2$. (4)

Here, even though the characteristic of friction is very complicated, the approximation of friction torque is usually assumed by the following form:

$$F(\dot{\boldsymbol{q}}) = B\dot{\boldsymbol{q}} + D(\dot{\boldsymbol{q}}) \quad , \tag{5}$$

where $B\dot{\boldsymbol{q}}$ and $D(\dot{\boldsymbol{q}})$ represent the viscous friction and Coulomb friction, respectively, as follows:

$$B\dot{\boldsymbol{q}} = \begin{bmatrix} b_1\dot{q}_1 \\ b_2\dot{q}_2 \end{bmatrix} , \qquad D(\dot{\boldsymbol{q}}) = \begin{bmatrix} d_1 \operatorname{sgn}(\dot{q}_1) \\ d_2 \operatorname{sgn}(\dot{q}_2) \end{bmatrix} . \tag{6}$$

Therefore, the dynamic equation can be described by the linear parameterize form

$$\boldsymbol{t} = M(\boldsymbol{q})\ddot{\boldsymbol{q}} + C(\boldsymbol{q},\dot{\boldsymbol{q}})\dot{\boldsymbol{q}} + B\dot{\boldsymbol{q}} + D(\dot{\boldsymbol{q}}) = \Phi(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})\mathbf{s} \quad , \tag{7}$$

where joint torque is $\boldsymbol{t} = [\tau_1 \quad \tau_2]^T$ and the regressor $\Phi(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}})$ and basic parameter $\mathbf{s}$ are given by

$$\begin{aligned} \Phi(\boldsymbol{q},\dot{\boldsymbol{q}},\ddot{\boldsymbol{q}}) &:= [F_1 \quad F_2]^T \\ &= \begin{bmatrix} \ddot{q}_1 & \ddot{q}_1+\ddot{q}_2 & f_{13} & \dot{q}_1 & 0 & \operatorname{sgn}(\dot{q}_1) & 0 \\ 0 & \ddot{q}_1+\ddot{q}_2 & f_{23} & 0 & \dot{q}_2 & 0 & \operatorname{sgn}(\dot{q}_2) \end{bmatrix} , \end{aligned} \tag{8}$$

$\phi_{13} = C_2(2\ddot{q}_1 + \ddot{q}_2) - S_2(2\dot{q}_1\dot{q}_2 + \dot{q}_2{}^2)$, $\phi_{23} = C_2\ddot{q}_1 + S_2\dot{q}_1{}^2$, and

$$\begin{aligned} \mathbf{s} &:= [s_1 \quad s_2 \quad s_3 \quad s_4 \quad s_5 \quad s_6 \quad s_7]^T \\ &= [J_1 \quad J_2 \quad r \quad b_1 \quad b_2 \quad d_1 \quad d_2]^T . \end{aligned} \tag{9}$$

3. Manipulator identification

Here, in order to apply the update law of a scalar type, the linear parameterization (7) of vector type is appropriately separated to the following scalar forms

$$t_i = j_i{}^T q_i \quad , \quad (i = 1, 2) \quad , \tag{10}$$

where the vector $j_i \in R^{k_i}$ $(k_i < p)$ is selected from the i^{th} row vector in the regressor and the parameter vector $q_i \in R^{k_i}$ is properly picked up from the basic parameter $\boldsymbol{s}$. The estimate model is also defined as

$$y_i(t) = j_i{}^T(t)\,\hat{q}_i(t) \ , \ (i = 1, 2) \ , \tag{11}$$

where the vector $\hat{q}_i(t) \in R^{k_i}$ is the estimated value and $y_i(t)$ is the output of the estimate model. The condition of the recursive estimation is completed in every sampling interval by filling the motion data

$$\{\, q_i(t),\ \dot{q}_i(t),\ \ddot{q}_i(t),\ t_i(t) \,\} \ , \quad (i = 1,2) \ . \tag{12}$$

When the condition in signal to noise ratio of the dynamical system is good, the following least-squares estimation has small bias with respect to the estimated value.

Recursive least-squares algorithm:

$$\hat{q}_i(t) = \hat{q}_i(t-1) + \frac{P_i(t-1)j_i(t)}{l_i(t) + j_i{}^T(t)P_i(t-1)j_i(t)} e_i(t) \ ,$$

$$P_i(t) = \frac{1}{l_i(t)} \left\{ P_i(t-1) - \frac{P_i(t-1)j_i(t)j_i{}^T(t)P_i(t-1)}{l_i(t) + j_i{}^T(t)P_i(t-1)j_i(t)} \right\} ,$$

$$e_i(t) = t_i(t) - F_i{}^T(t)\,\hat{\sigma}(t-1) \ ,$$

$$l_i(t) = (1 - m_i)\,l_i(t-1) + m_i \ , \quad (i = 1, 2) \ , \tag{13}$$

where weighting sequences $l_i(t)$ is usually chosen within $0.98 < l_i(t) \le 1$ and m_i is the constant for adjusting (13).

3.1 The regressor for identifying D.D arm

There are some ways for separating the regressor vector in identifying basic parameters of D.D arm. It is necessary to arrange these parameters so that a separated system does not mutually have an influence upon the apriori error $e_i(t)$. The pairs of identification model with respect to regressor and estimate vector satisfying such conditions are given by

$$\begin{cases} \boldsymbol{j_1{}^T(t) = [\ddot{q}_1(t) \quad \dot{q}_1(t) \quad \operatorname{sgn}(\dot{q}_1(t))]} \\ \boldsymbol{\hat{q}_1{}^T(t) = [\hat{s}_1(t) \quad \hat{s}_4(t) \quad \hat{s}_6(t)]} \\ \boldsymbol{j_2{}^T(t) = [\ddot{q}_1(t) + \ddot{q}_2(t) \quad f_{23}(t) \quad \dot{q}_2(t) \quad \operatorname{sgn}(\dot{q}_2(t))]} \\ \boldsymbol{\hat{q}_2{}^T(t) = [\hat{s}_2(t) \quad \hat{s}_3(t) \quad \hat{s}_5(t) \quad \hat{s}_7(t)]} \ . \end{cases} \tag{14}$$

4. Acquisition of regressor

When the system identification has different sensor dynamics, the accuracy of estimation deteriorates. The availability of the filter for compensating the difference of sensor characteristics was proposed in[3] . However, the consideration of observation noise was not fully verified. When the estimation accuracy is considered on data acquisition, the compensation scheme [4] of sensor dynamics shown in Figure 3 is profitable compared to the accessible case of only joint torque and position. The link acceleration is calculated by using the derivation filter to the information of the velocity sensor. The motion data of the estimated acceleration, torque, position and velocity, etc. is given, respectively, by the filters as follows:

$$\begin{cases} t_a = G_0 t \ , \ q_a = G_0 q \ , \ \operatorname{sgn}(\dot{q}_a) = G_0 \operatorname{sgn}(\dot{q}) \\ \dot{q}_a = G_0\dot{q} \ , \ \ddot{q}_a = G_1\dot{q} \end{cases} \tag{15}$$

$$G_0 = \frac{1}{(1 + t_f s)^2} \ , \qquad G_1 = sG_0 \ . \tag{16}$$

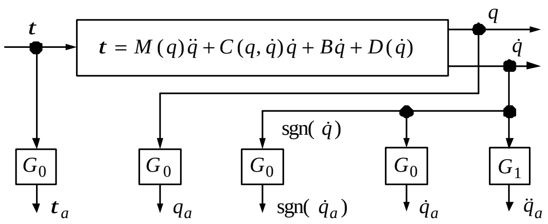

Figure 3 Compensation of sensor dynamics.

The operation of these filters is also calculated in discrete form using the bilinear transformation:

$$s = \frac{2}{T}\left(\frac{z-1}{z+1}\right), \quad T: \textit{sampling period.} \tag{17}$$

5. Control system for D.D arm

The friction torque and Coulomb torque of the SICE standard D.D manipulator are large compared to the nonlinear torque. The effect of the centrifugal and Coriolis torque does not appear so much during trajectory control.

5.1 Type-2 servo system

Neglecting the non-diagonal element of inertia matrix, type-2 servo shown in Fig.4 is designed by using the approximate model of the scalar system as

$$J\ddot{q} + B\dot{q} = t\ . \tag{18}$$

D.D manipulator P_n is described as

$$P_n = PG_s\ , \quad P = 1/(Js+B)\ , \quad G_s = K_c/s\ , \tag{19}$$

where K_c is the conversion constant of radian to degree. Furthermore, G_d represents the servo driver

$$G_d = K_1/(1+T_1 s)\ , \tag{20}$$

where K_1 and T_1 represent the gain and time constant of torque amplifier, respectively. Then, the resultant transfer function $G_d P_n$ is described as

$$G_d P_n = b/s(s^2 + a_1 s + a_2)\ , \tag{21}$$

$$a_1 = (J + T_1 B)/JT_1\ ,\ a_2 = B/JT_1\ ,\ b = K_1 K_c/JT_1\ .$$

When the characteristic polynomial is specified by $(s+w)^6$, type-2 servo controller G_c is given by

$$G_c = (b_0 s^3 + b_1 s^2 + b_2 s + b_3)/s(s^2 + d_1 s + d_2)\ , \tag{22}$$

$$\begin{cases} d_1 = 6w - a_1, \quad d_2 = 15w^2 - a_2 - a_1 d_1 \\ b_0 = (20w^3 - a_1 d_2 - a_2 d_1)/b, \quad b_1 = (15w^4 - a_2 d_2)/b \\ b_2 = 6w^5/b, \quad b_3 = w^6/b, \quad t_b = 6/w \quad . \end{cases}$$

The reference and disturbance characteristics are given, respectively, by following:

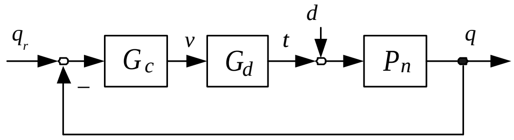

Figure 4 Block diagram of type-2 servo system.

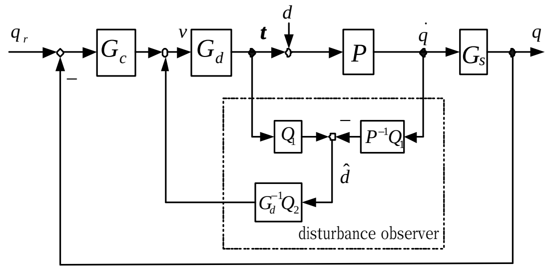

Figure 5 Control system with disturbance observer.

$$q = Gq_r\ ,\ G = G_c G_d P_n/(1 + G_c G_d P_n)\ ,\ q = \{(1-G)P_n\}d\ . \tag{23}$$

5.2 Disturbance observer

The modeling error is compensated by appending the disturbance observer to type-2 servo. The disturbance observer shown in Figure5 estimates the modeling error and parameter variation, etc. as one disturbance variable. If the payload variation is not to large, the control system by the feedback of this variable has robustness and is one of useful methods. The low-pass filter Q_1 and Q_2 are specified by

$$Q_1 = 1/(1 + t_{d1}s)\ ,\ Q_2 = 1/(1 + t_{d2}s)^2\ . \tag{24}$$

Then, the reference characteristic is similar to (24), the disturbance characteristic is given by

$$q = \{(1 - Q_1 Q_2)(1 - G)P_n\}d\ . \tag{25}$$

Therefore, the sensitivity is reduced to $(1 - Q_1 Q_2)$ times as compared with type-2 servo.

5.3 Adaptive control system

The control performance deteriorates in the case of operating with the variation of payload, because the servo controller and the disturbance observer depend on the manipulator payload. The proposed adaptive control system shown in Figure 6 is proposed by appending the recursive estimation to disturbance observer system. This system updates both servo controller and disturbance observer by estimating the payload variation of D.D manipulator.

6. Trajectory control results of D.D arm

The nominal parameter shown in Table 1 is obtained by off-line identification. Each gain K_1 of joint is, respectively, 12.5 and 3.75 [Nm/V].

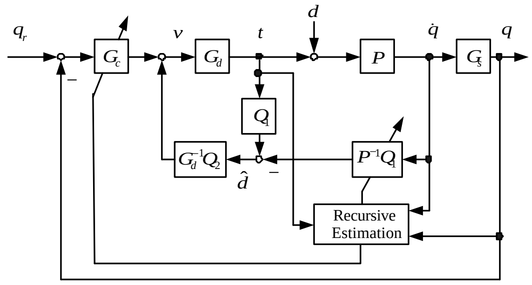

Figure 6 Proposed adaptive control system.

Table1: Nominal parameter for controller design.

Parameter / Payload	J_1 $[kgm^2]$	J_2 $[kgm^2]$	r $[kgm^2]$	b_1 $[Nms]$	b_2 $[Nms]$	d_1 $[Nm]$	d_2 $[Nm]$
light [1kg]	0.434	0.061	0.105	5.162	0.994	3.243	0.885
heavy [3kg]	0.514	0.161	0.232	5.044	0.959	3.441	0.926

The time constant of torque amplifier is $T_1 = 0.009$. Type-2 servo controllers for each joint are designed by selecting the specified pole of $t_b = 0.1$. The circular orbit of diameter 100$[mm]$ is given as reference trajectory. A period of movement is 2[sec], since sampling period is 1$[ms]$ and also data of reference angle to each joint is selected as 2000. The tracking error from a circular orbit by trajectory control experiments with a light payload is shown in Figure 7. The large errors due to disturbance torque appear periodically. When the time constants of low-pass filter for disturbance observer and the pole of servo controller are selected, respectively, as $t_{d1} = 1, t_{d2} = 2.5[ms]$ and $t_b = 0.07$, the error with same condition is shown in Figures 8 and 9. The error is effectively decreased by using the disturbance observer.

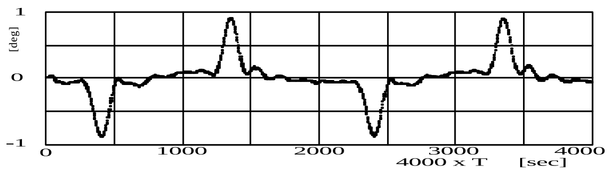

Figure 7 Tracking error by type-2 servo (Joint 1).

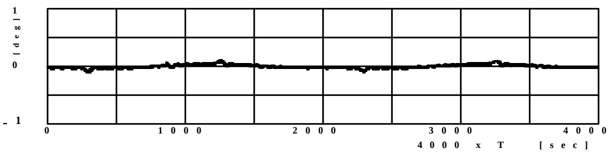

Figure 8 Tracking error by disturbance observer (Joint 1).

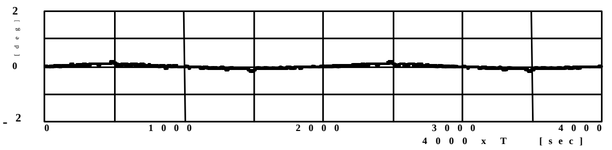

Figure 9 Tracking error by disturbance observer (Joint 2).

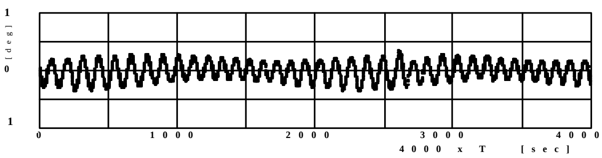

Figure 10 Tracking error with payload variation (Joint 1).

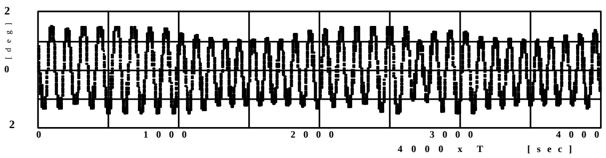

Figure 11 Tracking error with payload variation (Joint 2).

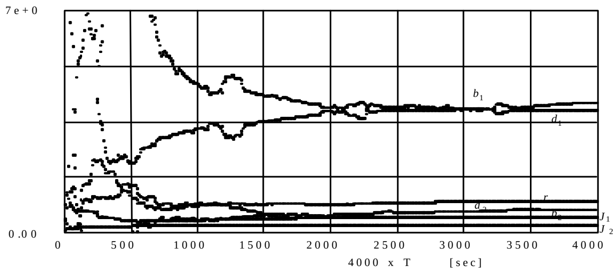

Figure 12 Transition process of estimated parameter.

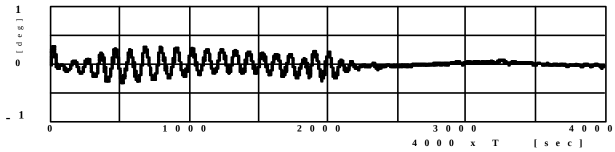

Figure 13 Tracking error by adaptive control (Joint 1).

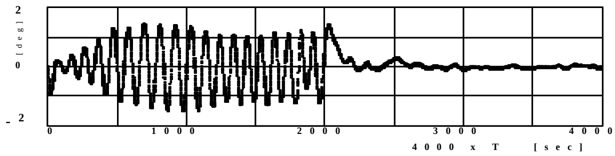

Figure 14 Tracking error by adaptive control (Joint 2).

However, when same experiment is repeated by changing only payload to 3[kg], Figures 10 and 11 reveal that the control system is not satisfactory and loses the robustness. Therefore, it is shown in Figures 12 through 14 that the adaptive control is very useful. Figure 12 is the transition process of recursively estimated parameter with filter time constant of $t_f = 6$ $[ms]$ and the parameter estimation completes after passing 2[sec]. The adaptive system starts the adjusting of both controller and disturbance observer after passing 2 [sec]. After starting the parameter adjusting, the vibration of D.D robot disappears and the tracking error is simultaneously decreased as shown in Figures 13 and 14.

7. Conclusions

The adaptive control system appending the disturbance observer to the type-2 servo in order to reduce the tracking error of the trajectory control was proposed. The validity of the proposed method was confirmed by applying to the SICE D.D robot.

References

1. K.J.Åström & B.Wittenmark, *Adaptive Control*, Addison Wesley, 1989.
2. J. J. Craig, *Adaptive Control of Mechanical Manipulators*, Addison Wesley, 1988.
3. K. Osuka, *"Identification for Mechanical systems"*, J.SICE, vol.33, No.6, June 1994, pp.487-493.
4. R.Phornsuk, N.Jongkol, M.Anabuki & H. Hirata, *"Recursive Simultaneous Estimation of a Two-link Direct Drive Manipulator with Great Variation of Payload"*, IEEE ISCIT, 2001, pp.713-716.