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Original Paper

# A Study of a Throwing Motion of a 2-DOF Robot with Adaptive Control

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Abstract

A throwing motion control for a 2 degree of freedom robot is studied. Our control objective is to reduce the target error that is the distance between the mark and the position where the object hit. We design a trajectory of the robot in consideration of the torque limit, the maximum angular velocity, the sensitivity of the target error and the time required, from the beginning of the throwing motion to hitting a mark. We apply nonlinear dynamic compensation with parameter estimation for a trajectory control. Furthermore, our controller predicts the target error by using the estimated parameters, then it modifies the time when an object is released from hand to reduce the predicted target error. The effectiveness of this method is examined. The result shows that this method provides satisfactory performance for a reduction of target error.

Key Words : Robotics, Motion Control, Adaptive Control, Parameter Estimation, On-line Modification

## 1. Introduction

In this paper, the throwing motion control is studied as an application of the robot manipulator control as shown in Fig.1. Our control objective is to reduce the target error that is the distance between the mark and the position where the thrown object hit. It is necessary to think about the problem of the trajectory planning and the tracking control of the robot to do such throwing motion.

There is a lot of literature on the trajectory planning and the tracking control of the robot, and numerous methods have been developed so far. Among the tracking control schemes, the adaptive control of robot proposed by Slotine[1], which contains the nonlinear compensation and the parameter estimation, seems to be relatively efficient. However, the robot's parameters are not settled to true values and the tracking error is caused when the operation time is short or when the discrete time controller is used. The target error occurs due to the tracking error.

In order to reduce the target error for the throwing motion control, we propose an adaptive nonlinear compensation for a robot manipulator with a modification of time when the object is released from hand. In Sec.2, we derive this control scheme. In Sec.3, we design a trajectory of the robot in consideration of the maximum angular velocity and the sensitivity of the target error for the time required, from the beginning of the throwing motion to hitting a mark. In Sec.4, we explain the method of the modification of the release time. In Sec.5, an experimental result is shown in order to prove that the proposed method provides satisfactory performance for a reduction of the target error.

## 2. Control scheme

We consider a 2 degree of freedom SCARA robot, which moves in the vertical plane, as shown in Fig.1. The shoulder and the elbow are driven by actuators while the wrist is fixed with respect to the base coordinates. The dynamic equation of this robot manipulator is described as follows.

$$M(q)\ddot{q} + C(q,\dot{q})\dot{q} + d(\dot{q}) + g(q) = \tau \tag{1}$$

with

$$M(q) = \begin{bmatrix} M_{11} & M_{12}\cos(\theta_2-\theta_1) \\ M_{12}\cos(\theta_2-\theta_1) & M_{22} \end{bmatrix}, \qquad d(\dot{q}) = \begin{bmatrix} D_1\dot{\theta}_1 + F_1\mathrm{sgn}(\dot{\theta}_1) \\ D_2(\dot{\theta}_2-\dot{\theta}_1) + F_2\mathrm{sgn}(\dot{\theta}_2-\dot{\theta}_1) \end{bmatrix}$$

$$C(q,\dot{q}) = \begin{bmatrix} 0 & -M_{12}\sin(\theta_2-\theta_1)\dot{\theta}_2 \\ M_{12}\sin(\theta_2-\theta_1)\dot{\theta}_1 & 0 \end{bmatrix}, \quad g(q) = \begin{bmatrix} M_{g1}\cos\theta_1 \\ M_{g2}\cos\theta_2 \end{bmatrix}$$

where $q = [\theta_1, \theta_2]^T$ is the robot arm angle vector, $\tau = [\tau_1, \tau_2]^T$ is the torque vector. In Eq.(1), $M(q)\ddot{q}$ represents the inertia torque and $M(q)$ is the symmetric positive definite matrix. $C(q,\dot{q})\dot{q}$ is the nonlinear term of Coriolis and centrifugal torque and $\dot{M}(q) - 2C(q,\dot{q})$ is the skey-symmetric matrix. $d(\dot{q})$ is the viscous friction and Coulomb friction torque, and $g(q)$ is the gravitational torque.

In the above dynamic equations of the manipulator system, we assume that the physical parameters $M_{11}$, $M_{12}$, $M_{22}$, $M_{g1}$, $M_{g2}$, $D_1$, $D_2$, $F_1$, $F_2$ appearing in Eq.(1) are unknown, because the physical parameters of a robot arm are usually difficult to know a priori and they vary with the wrist arm angle. Using these unknown parameters, Eq.(1) can be expressed in the compact matrix form

$$\tau = Y(q,\dot{q},\ddot{q})\, a \tag{2}$$

with

$$a = [M_{12}\ M_{11}\ M_{g1}\ D_1\ F_1\ M_{22}\ M_{g2}\ D_2\ F_2]^T$$

where $a$ is the unknown parameter vector and matrix $Y(q,\dot{q},\ddot{q})$ is the nonlinear function with respect to $q$, $\dot{q}$ and $\ddot{q}$. By substituting the arm reference angle, $q_d$, for $q$ in Eq.(2), the perfect nonlinear dynamic compensation becomes Eq.(3).

$$\tau = Y(q_d,\dot{q}_d,\ddot{q}_d)\, a \tag{3}$$

However, these parameters are not known a priori. This implies that these parameters should be estimated on-line with input and output data from the robot system.

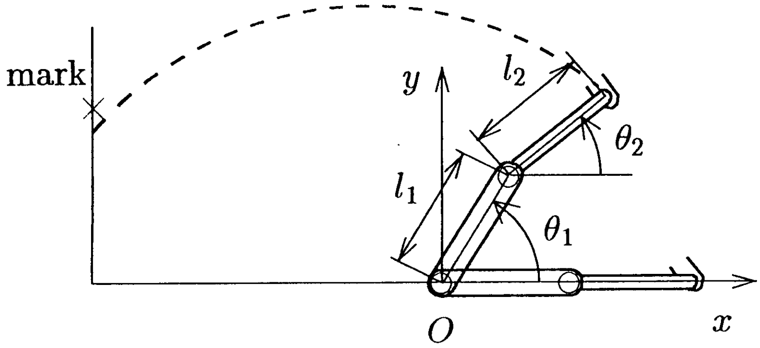



Fig.1 Throwing motion of SCARA robot

Our controller consists of feedback nonlinear dynamic compensation with parameter estimation and controller shown in Fig.2, which is a little similar to the one proposed in Ref.[2]. In this block diagram, the ID block is an "estimated" inverse dynamics model defined as

$$\hat{\tau} = Y(q, \dot{q}, \ddot{q}_r)\,\hat{a} \tag{4}$$

where

$$\ddot{q}_r = \ddot{q}_d + \Lambda \dot{e}$$

$e = q_d - q$ is the arm angle error and $\hat{a}$ is estimated vector of $a$. The element K in Fig.2 is the PD controller.

$$\tau_f = K_D(\dot{e} + \Lambda e) \tag{5}$$

where $\Lambda$ and $K_D$ are positive definite diagonal matrices. Thus the control law becomes

$$\tau = \hat{\tau} + \tau_f = Y(q, \dot{q}, \ddot{q}_r)\,\hat{a} + K_D(\dot{e} + \Lambda e) \tag{6}$$

By using the output of the PD controller, $\tau_f$, the parameter $a$ is estimated as follows.

$$\dot{\hat{a}} = \Gamma\, Y^T(q, \dot{q}, \ddot{q}_r) K_D^{-1} \tau_f \tag{7}$$

where $\Gamma$ is a positive definite diagonal matrix.

Now we show the stability condition from a Lyapunov stability analysis. Let the Lyapunov function candidate

$$V = \tfrac{1}{2}\,[\tau_f^T K_D^{-1} M(q) K_D^{-1} \tau_f + \tilde{a}^T \Gamma^{-1} \tilde{a}] \tag{8}$$

where $\tilde{a} = \hat{a} - a$ denotes the parameter estimation error vector. Using from Eq.(1) to Eq.(7), differentiating $V$ yields

$$\begin{aligned}
\dot{V} &= \tau_f^T K_D^{-1}[\tfrac{1}{2}\,\dot{M}(q) K_D^{-1}\tau_f + M(q)(\ddot{q}_d - \ddot{q} + \Lambda\dot{e})] + \tilde{a}^T Y^T(q, \dot{q}, \ddot{q}_r) K_D^{-1}\tau_f \\
&= \tau_f^T K_D^{-1}[\tfrac{1}{2}\,\dot{M}(q) K_D^{-1}\tau_f + M(q)\ddot{q}_r - M(q)\ddot{q} + Y(q, \dot{q}, \ddot{q}_r)\tilde{a}] \\
&= \tau_f^T K_D^{-1}[\tfrac{1}{2}\,\dot{M}(q) K_D^{-1}\tau_f + M(q)\ddot{q}_r + C(q, \dot{q})\dot{q} + d(\dot{q}) + g(q) - (Y(q, \dot{q}, \ddot{q}_r)\hat{a} + \tau_f) + Y(q, \dot{q}, \ddot{q}_r)\tilde{a}] \\
&= \tau_f^T K_D^{-1}[\tfrac{1}{2}\,\dot{M}(q) - K_D] K_D^{-1}\tau_f
\end{aligned} \tag{9}$$

Therefore, the stability of this adaptive controller is guaranteed as long as $K_D$ is chosen large enough to satisfy $K_D > \frac{1}{2}\,\dot{M}(q)$.

In Eq.(6) and Eq.(7), matrix $Y$ has many zero elements. Therefore, we slightly modify the controller to reduce the computation time. It is very important because the operation time of our robot is very short.

The dynamic equation of this robot, Eq.(2), can be rewritten for each joint (j=1,2).

$$\tau_j = \zeta_j(q, \dot{q}, \ddot{q})\,\phi_j \tag{10}$$

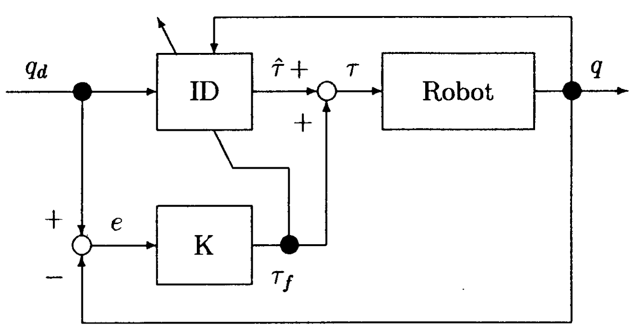



Fig.2 Whole block diagram of a robot system with the proposed controller

with

$$\phi_1 = [\ M_{12}\ M_{11}\ M_{g1}\ D_1\ F_1\ ]^T$$
$$\phi_2 = [\ M_{12}\ M_{22}\ M_{g2}\ D_2\ F_2\ ]^T$$

where $\phi_j$'s are vectors containing the unknown parameters and $\zeta_j(q,\dot{q},\ddot{q})$'s are vectors containing the nonlinear function with respect to $q$, $\dot{q}$ and $\ddot{q}$. The physical parameter, $M_{12}$, exists in both $\phi_1$ and $\phi_2$ because of the interaction between the joints. This relation is very important for the parameter estimation described later. Similarly, Eq.(4), Eq.(5) and Eq.(6) become

$$\hat{\tau}_j = \zeta_j(q,\dot{q},\ddot{q}_r)\,\hat{\phi}_j \tag{11}$$
$$\tau_{fj} = K_{Dj}(\dot{e}_j + \Lambda_j e_j) \tag{12}$$
$$\tau_j = \hat{\tau}_j + \tau_{fj} = \zeta_j(q,\dot{q},\ddot{q}_r)\,\hat{\phi}_j + K_{Dj}(\dot{e}_j + \Lambda_j e_j) \tag{13}$$

Next we show the parameter estimation scheme for each joint. The parameter estimation law, Eq.(7), can be regarded as the estimation method to minimize the square of the generalized errors, $\tau_f^T\tau_f$. Therefore, the parameter vectors are estimated for each joint to minimize $\tau_{fj}^2$. However, the parameter $\phi_1$ and $\phi_2$ have same physical parameter $M_{12}$, that is $\phi_{11} = \phi_{21} = M_{12}$ as mentioned above. Taking account of this constraint, it is attempted to minimize the generalized errors of arm angles. By solving the minimization problems via the penalty method, we can derive a recursive estimation algorithm for $\phi_j$'s as follows[2],

$$\hat{\phi}_{ji}(k) = \hat{\phi}_{ji}(k-1) - \Gamma_{ji}\frac{\partial J_j(k)}{\partial\hat{\phi}_{ji}(k)} \quad \text{for} \quad j=1,2\,, \quad i=1,\cdots,5 \tag{14}$$

In this equation, $\Gamma_{ji}$ is a constant gain, and $J_j$ is defined as

$$J_j = \tau_{fj}^2 + \lambda_j\Delta_j^2\,, \;\; \Delta_j = \hat{\phi}_{j1} - (\hat{\phi}_{11} + \hat{\phi}_{21})/2$$

and $\lambda_j$ are very large constants. The partial differential in Eq.(14) is actually calculated as follows;
(first term)

$$\frac{\partial\tau_{fj}^2}{\partial\hat{\phi}_{ji}} = 2\tau_{fj}\frac{\partial\tau_{fj}}{\partial\hat{\phi}_{ji}} = -2\zeta_{ji}(q,\dot{q},\ddot{q}_r)\tau_{fj} \quad \text{for} \quad j=1,2\,, \quad i=1,\cdots,5$$

where the last equality follows from Eq.(13). The corresponding term of Eq.(14) is similar to Eq.(7).
(second term)

$$\frac{\partial\Delta_j^2}{\partial\hat{\phi}_{ji}} = \begin{cases} +(\hat{\phi}_{11} - \hat{\phi}_{21})/2 & \text{for} \;\; i=1,\; j=1 \\ -(\hat{\phi}_{11} - \hat{\phi}_{21})/2 & \text{for} \;\; i=1,\; j=2 \\ 0 & \text{for} \;\; i\neq 1,\; j=1,2 \end{cases}$$

Notice that for the calculation of the second terms of $\partial J_j(k)/\partial\hat{\phi}_{ji}(k)$ in Eq.(14), $\hat{\phi}_{ji}(k-1)$'s must be used instead of $\hat{\phi}_{ji}(k)$'s because $\hat{\phi}_{ji}(k)$'s are still not determined on the right hand side of Eq.(14). This term is very simple and it is calculated for only 2 elements.

## 3. Trajectory Planning

Now we show how to plan a trajectory of the robot manipulator and a release time when an object is released from the robot's hand. We assume that the initial state of the robot and the position of the mark are given, then we design the trajectory to satisfy the time required for the task, from the beginning of the throwing motion to the hitting on the mark, in consideration of the incident angle on the mark, the torque limit and the maximum angular velocity.

The trajectory has three stages: acceleration stage, release stage, deceleration stage as shown in Fig.3. In the release stage, the angular velocities of joints are constant before and behind the release time, while joint accelerations in the acceleration stage and the deceleration stage are given by quadratic function with respect to time in order for the joint accelerations to be continuous. The origin of the base coordinates is coincident at the origin of the first arm coordinates. Let us define the following variables:

$q_0 = [\theta_{01}\ \theta_{02}]^T$: initial arm angle : given
$p_e = [x_e\ y_e]^T$ : position of the mark : given
$q_r = [\theta_{r1}\ \theta_{r2}]^T$: arm angle at the release time
$p_r = [x_r\ y_r]^T$ : position of the robot's hand at the release time
$t_{S1}$ : time at the end of the acceleration stage
$t_{S2}$ : time at the end of the release stage
$t_{S3}$ : time at the end of the deceleration stage
$t_r$ : time when the object is released (the release time)
$t_f$ : time takes from release of the object to hit on the mark (the flying time of the object)
$t_t$ : time required to do the task (the total time), $t_t = t_r + t_f$ : given

At the release time, a following kinematic relationship is held.

$$\begin{bmatrix} x_r \\ y_r \end{bmatrix} = \begin{bmatrix} l_1\cos\theta_{r1} + l_2\cos\theta_{r2} \\ l_1\sin\theta_{r1} + l_2\sin\theta_{r2} \end{bmatrix}, \quad \begin{bmatrix} \dot{x}_r \\ \dot{y}_r \end{bmatrix} = J\begin{bmatrix} \dot{\theta}_{r1} \\ \dot{\theta}_{r2} \end{bmatrix} \tag{15}$$

where $J$ is jacobian. The motion of the flying object that was released from robot's hand is assumed to be ideal without air resistance and disturbance by wind as follows.

$$m\ddot{x} = 0, \quad m\ddot{y} = -mg \tag{16}$$

where $m$ is mass of the object. Then the velocities of the robot's hand at the release time are yield.

$$\dot{x}_r = \frac{1}{t_f}(x_e - x_r)\ , \quad \dot{y}_r = \frac{1}{t_f}(y_e - y_r + \frac{1}{2}gt_f^2) \tag{17}$$

The total time $t_t$ is expressed as

$$t_t = t_f + 2\max\{(\theta_{r1} - \theta_{01})/\dot{\theta}_{r1}, (\theta_{r2} - \theta_{02})/\dot{\theta}_{r2}\} - t_c \tag{18}$$

where $t_c = t_r - t_{S1}$ is given.

The release time $t_r$ is determined as following manner.
(1) Substitute Eq.(15) and (17) in Eq.(18).
(2) Solve the resultant cubic equation with respect to $t_f$ for the given $p_e$ and $t_t$.
(3) Determine $t_f$ so as not to contradict the relation of time.
(4) Get $t_r$ from $t_r = t_t - t_f$.

Figure 4 shows an example of the domain in which the object can be thrown when $l1 = l2 = 0.304$m, $m = 0.01$kg, $p_e = [-2\ 0.5]^T$m, $t_t = 0.7$s. The position of the hand at release time was limited within the range that $y_r > 0$ and the arm configuration under the throwing motion was decided so that $\theta_1 \geq \theta_2$. Only within the white domain like the wing section shape in Fig.4, the object can be thrown. In the light gray domain, there is no valid real-solution of Eq.(18) for the given condition. While, in the dark gray domain, there exist solutions but the contradiction of time occurs, for example, negative acceleration

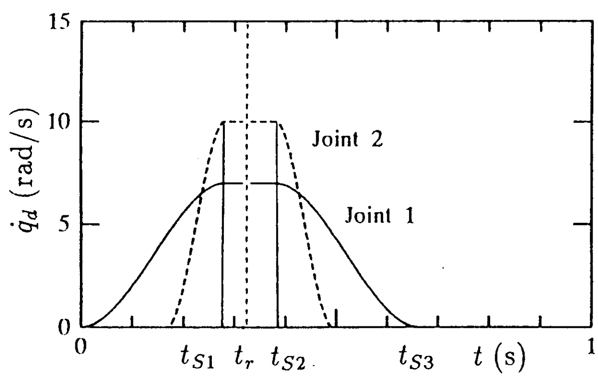



Fig.3 Trajectories of reference angular velocities

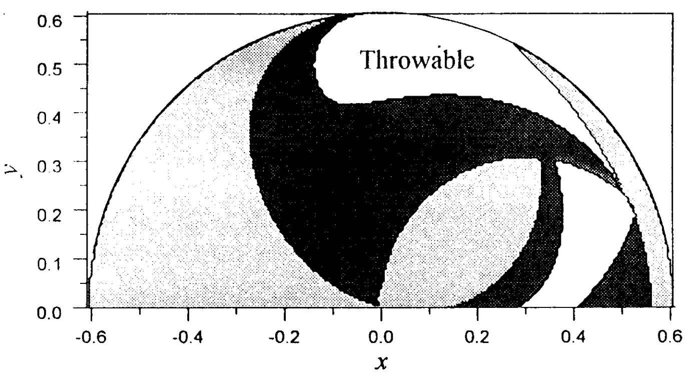



Fig.4 Throwable domain
$([x_e\ y_e]^T = [-2\ 0.5]^T,\ t_t = 0.7\text{s})$

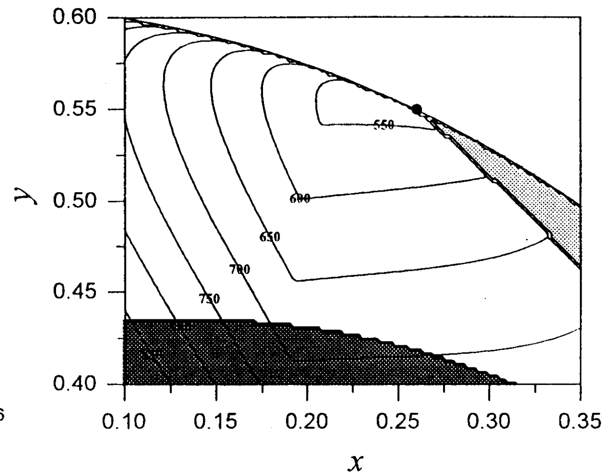
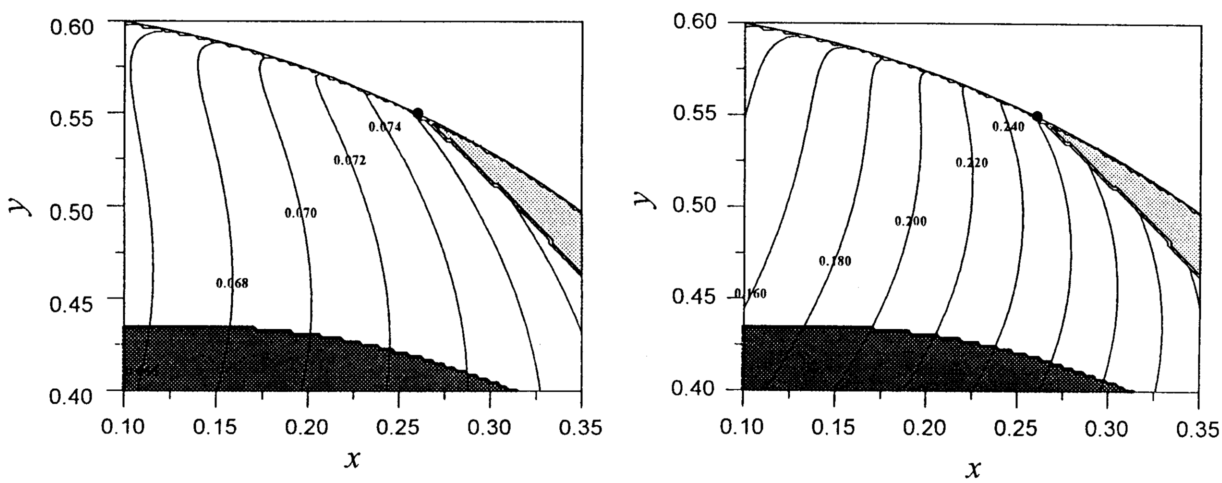
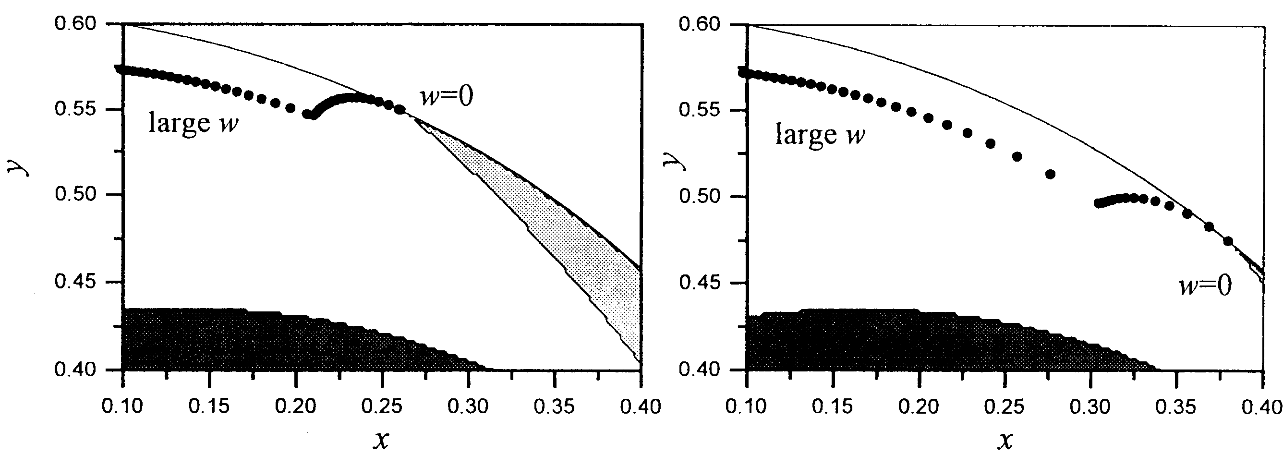



Fig.5 Contour map of maximum value of angular velocities




(a) When the released position shifts by ±0.05m (b) When the velocity shifts by ±10%

Fig.6 Contour map of the target error




(a) $t_t = 0.7\text{s}$ (b) $t_t = 0.8\text{s}$

Fig.7 Examples of released position for some weight factors time. Figure 5 shows the contour map of maximum value of angular velocities of joints, $\max\{\dot{\theta}_1, \dot{\theta}_2\}$. The mark "•" represents the position at which this value is minimum. We made it the first candidate of the release time. At this minimum position, the arms become straight and the object is thrown in the tangential direction because each arm length is equal.

Next we investigate the influence that the position error and velocity error at the release time exert the target error. Figure 6(a) shows the contour map of the target error when the released position shifts by $\pm 0.05$m and Fig.6(b) shows one when the velocity shifts by $\pm 10\%$. From these figures, it is found that the error becomes large when the release position parts from the target and outside in the radial direction near the minimum position. Therefore, taking account of these results, we decided the release position and the release time by weighted mean of the maximum value of angular velocity and the target error. Examples of the release position are shown in Fig.7(a) and (b) with several weight factors. From these figures, the release position shifts inside the domain and approaches the mark when weight factor for the target error becomes large.

## 4. Modification of release time

Thus, the tracking error causes the target error. In order to reduce the target error, we can use several methods, change to another controller, on-line planning of the trajectory[3], dynamic programming[4], on-line modification of the release time. In this paper, we use the on-line modification of the release time.

We explain this method. If above-mentioned controller, Eq.(13) and (14), is used, the equation of the arm angle error is expressed as

$$\hat{M}(q)(\ddot{e} + \Lambda\dot{e}) + K_D(\dot{e} + \Lambda e) = -\begin{bmatrix} \zeta_1(q, \dot{q}, \ddot{q})\,\tilde{\phi}_1 \\ \zeta_2(q, \dot{q}, \ddot{q})\,\tilde{\phi}_2 \end{bmatrix} \tag{19}$$

where $e$ is the arm angle error, $\tilde{\phi}_j = \hat{\phi}_j - \phi_j$ denotes the parameter estimation error. These parameters are estimated until several sampling times before the predetermined (off-line determined) release time. If these parameters are estimated well, the right hand side of Eq.(19) is negligible. Then the future arm angle, $\hat{q}(t)$, can be approximated by Eq.(20).

$$\left.\begin{array}{l} \hat{M}(q)(\ddot{\hat{e}} + \Lambda\dot{\hat{e}}) + K_D(\dot{\hat{e}} + \Lambda\hat{e}) = 0 \\ \hat{q} = q_d - \hat{e}, \quad \dot{\hat{q}} = \dot{q}_d - \dot{\hat{e}} \\ \hat{e}(t_0) = e(t_0)\,, \quad \dot{\hat{e}}(t_0) = \dot{e}(t_0) \end{array}\right\} \quad \text{for} \quad t > t_0 \tag{20}$$

Using kinematics of robot and the dynamics of ideal flying object, the target error, $\hat{e}_y$, is predicted from this $\hat{q}(t)$.

$$\hat{e}_y = y_e - (\hat{y} + \dot{\hat{y}}\hat{t}_f - \frac{1}{2}g\hat{t}_f^2)\,, \quad \hat{t}_f = \frac{1}{\dot{\hat{x}}}(x_e - \hat{x}) \tag{21}$$

$$\begin{bmatrix} \hat{x} \\ \hat{y} \end{bmatrix} = \begin{bmatrix} l_1\cos\hat{\theta}_1 + l_2\cos\hat{\theta}_2 \\ l_1\sin\hat{\theta}_1 + l_2\sin\hat{\theta}_2 \end{bmatrix}, \quad \begin{bmatrix} \dot{\hat{x}} \\ \dot{\hat{y}} \end{bmatrix} = J\begin{bmatrix} \dot{\hat{\theta}}_1 \\ \dot{\hat{\theta}}_2 \end{bmatrix}$$

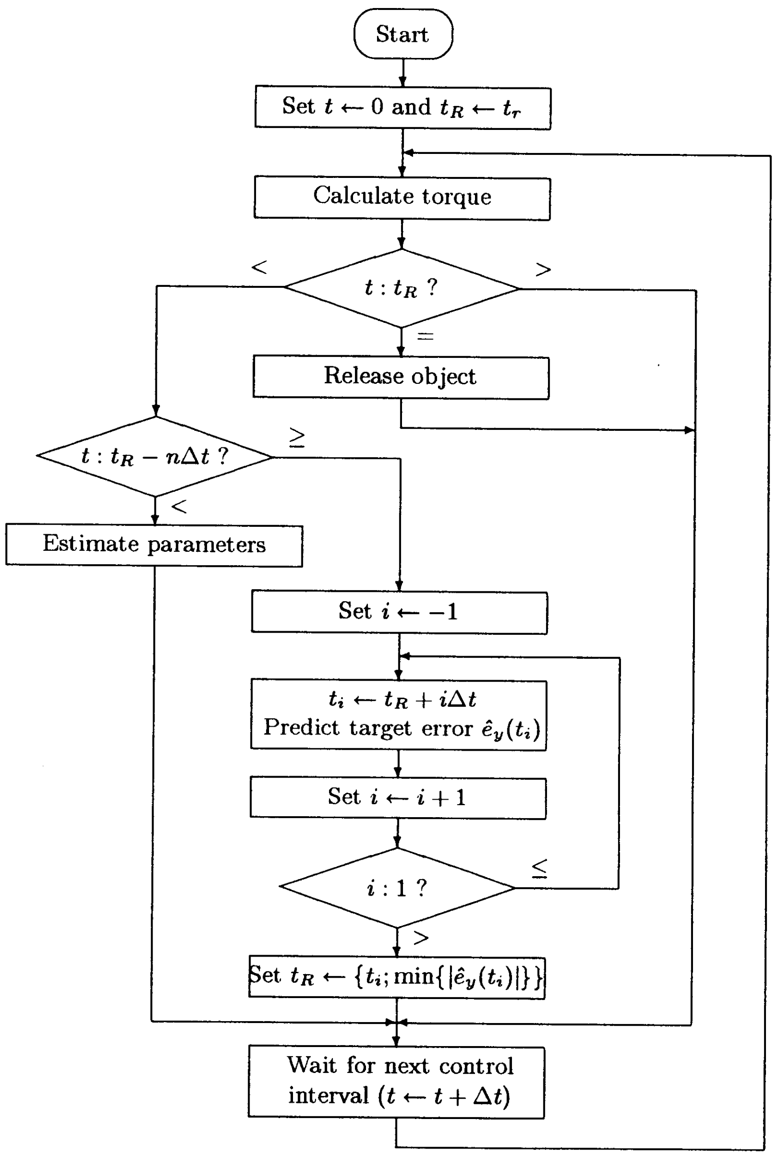
For the calculation of Eq.(eqn:estimatederror), the value of $\hat{M}(q)$ is given from the last estimated parameters and it is assumed to be constant because the predict time is short. The flowchart of the modification of the release time is shown in Fig.8.

## 5. Experimental results

The experiment is carried out in order to compare the proposed controller with nonlinear compensator based nominal model. The first arm is driven by NSK-made DD motor directly, and the second arm is driven by DD motor through a timing-belt of which reductional ratio is 1. A hand to throw an object is attached on the tip of the second arm. It keeps a fixed angle with respect to the base coordinates and holds the object with springs and is opened by solenoid. Each arm is 0.304m and about 1kg, and the object is 0.01kg. The mark is located at $[-2.0\,0.5]^T$ from the origin of the base coordinates. The sampling period is 6ms. We make experiments on these conditions.

Table 1 shows the predicted value and measured value of the target error for the proposed controller and nominal compensator. The experiment was done 10 times for each controller. The PD gain was adjusted in order to reduce the arm angle error and not to occur the vibration at the release time. The same gain was used in the proposed controller. The position at the predetermined release time is located at $[0.265\,0.54]^T$ and the predetermined release time is 0.324s. From this result, it is found that by using the proposed controller, the target error becomes smaller in comparison with the nominal compensator and diviation is also small. In the proposed controller, the difference between the predicted target error and the measured target error become small while the trial because the parameters estimated well.

Figure 9(a) shows the trajectories of arm reference angles $q_d$ and arm angles $q$. The former is shown by a dotted line and the latter is shown by a solid line. The vertical lines in this figure indicate the predetermined release time and the actual release time. The former is shown by a dotted line and the latter is shown by a solid line. The arm configuration under the throwing motion was decided so that




$t_r$ : predetermined release time, $\Delta t$ : sampling period

Fig.8 Algorithm of modification of release time

Table 1 Experimental result

| No. | Nominal compensator | | Proposed controller | | |
|---|---|---|---|---|---|
| | Release Time(s) | Target Error(m) Measured | Release Time(s) | Target Error(m) Predicted | Target Error(m) Measured |
| 1 | 0.324 | −0.210 | 0.312 | −0.305 | −0.085 |
| 2 | 0.324 | −0.375 | 0.312 | −0.108 | −0.120 |
| 3 | 0.324 | −0.185 | 0.312 | −0.161 | −0.085 |
| 4 | 0.324 | −0.185 | 0.312 | −0.123 | −0.133 |
| 5 | 0.324 | −0.255 | 0.312 | −0.295 | −0.065 |
| 6 | 0.324 | −0.335 | 0.312 | −0.046 | −0.165 |
| 7 | 0.324 | −0.250 | 0.312 | −0.175 | −0.165 |
| 8 | 0.324 | −0.265 | 0.312 | −0.206 | −0.250 |
| 9 | 0.324 | −0.373 | 0.312 | −0.201 | −0.150 |
| 10 | 0.324 | −0.455 | 0.312 | −0.250 | −0.235 |
| aver-age | 0.324 | $-0.29 \pm 0.09$ | 0.312 | $-0.19 \pm 0.08$ | $-0.15 \pm 0.06$ |

$\theta_1 \geq \theta_2$. As shown in Fig.9(a), the first arm begins to move earlier than the second arm, and the second arm moves quickly than the first arm because the initial arm angle is $[0\,0]^T$. There is a time lag between the predetermined release time and the actual release time because there exists the arm angle error. In this throwing motion, it is most important that the real velocity and position of arms agree with the planned them at the release time. The arm angle error after the release time is not important. Figure 9(b) shows some estimated parameters, $\hat{\phi}_j$, normalized by the initial values. The parameter estimation is taken until the time that is a little before the predetermined release time and isn't taken when the release time is modified. Figure 9(c) shows the modification of the release time. The abscissa is real time and the ordinate is the release time, $t_R$. The modification started at the time that is a little before the predetermined release time, and in this case, the mark "•" indicates the actual release time.

## 6. Conclusions

In order to reduce the target error for throwing motion control of the robot manipulator, we proposed an adaptive nonlinear compensation scheme with the modification of the release time. The trajectories of the robot arms are designed for the required time in consideration of the maximum angular velocity and the sensitivity of the target error. The characteristics of this controller are; (1) the unknown parameters of the inverse dynamics are estimated in an adaptive way, (2) the target error is predicted by using the estimated parameters, and (3) the release time is modified with the predicted target error. The experiment showed that the proposed controller could improve the target error. We will study the on-line planning of the trajectory and the control of the robot manipulator with wrist.

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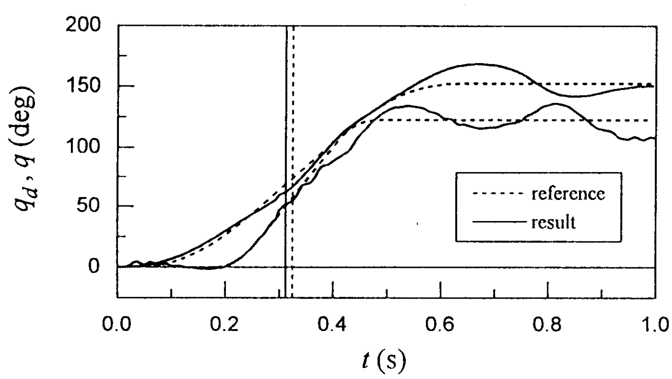
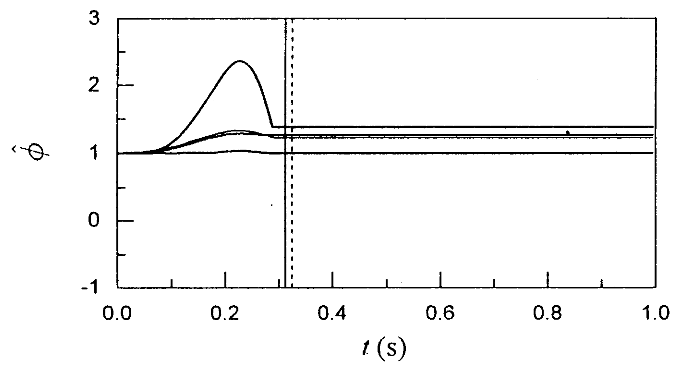
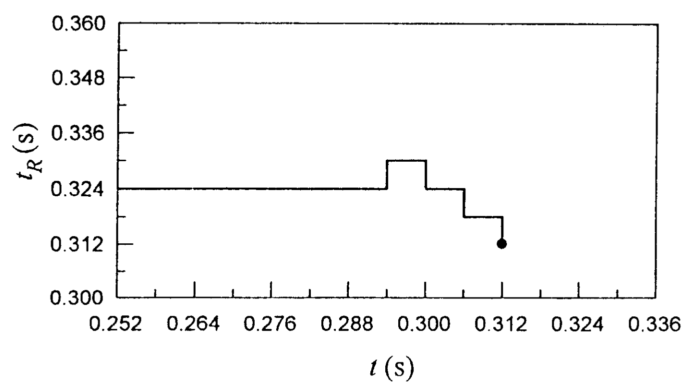



(a) Trajectories of arm reference angles and arm angles




(b) Some estimated parameters




(c) Modified release time

Fig.9 Experimental result of proposed controller