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The Performance Validation of an Actuator Fault Detection of a Nonlinear Model Predictive Controller in using Approximate Differentiation

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***Abstract*— Adaptive Nonlinear Model Predictive Controller (ANMPC) can estimate system's parameters and detect a fault of actuators based on relationship between past control inputs and states variables of systems, and estimated parameters are need for calculating a control input in next step. In this paper, for applying this ANMPC to real systems, performance verification of ANMPC using an approximated differentiation as an angular velocity and an angular acceleration is verified.**

I. INTRODUCTION

Model Predictive Control (MPC) decides a control input by an optimal calculation as the system output tracks a reference trajectory which is an ideal trajectory for the system output to converge on the desired value[1]. MPC is widely adopted in industry because this method solves an optimal control problem with some constrains, especially, it has been popular in process control where system dynamic is moving slow[2], [3]. MPC already has been extended to nonlinear systems (NMPC), and many NMPC controllers have been proposed[4], [5], [6], [7].

In the optimal calculating of the control input, parameters of a controlled system are needed and these parameters are treated as well-known and invariable parameters. However, parameters of the controlled systems in real systems are commonly unknown and may secularly change, that is, parameters have possibilities to change by various causes, and a changed parameter is a cause of deterioration in the control performance.

On the other hand, an actuator in the real system has risk of fault, and the fault of the actuator causes several disadvantages for safety and economy of controlled systems. Thus, detecting some fault about the actuator is important task for safety controlling.

For these problems, our group already proposed an adaptive controller for a two-link planar manipulator on the horizontal space via Adaptive Nonlinear Model Predictive Control (ANMPC)[8]. This controller can estimate the system's parameters by using past states of systems and control inputs, and the estimated parameters are used in calculating of control inputs. Moreover, in this method, fault gain of actuators are defined as new system parameter and a fault detection of actuators can be realized by estimating these error parameters as same as another system's parameters[8].

Effectiveness of this method is proved by a numerical simulation under the condition that angular velocity and angular acceleration are useable. However, in real system, there are some cases data of the angular velocity and the angular acceleration can not be measured and can not be used for controller. In this case, we must use an approximate differentiation of angular position instead of the angular velocity and the angular acceleration.

In this study, the performance validation of an actuator fault detection of ANMPC in using approximate differentiation is discussed. A new idea used the mode values is proposed for the actuator fault detection in case of using approximate differentiation and effectiveness of proposed idea is verified using numerical simulations.

II. DYNAMICS OF THE TWO-LINK PLANAR MANIPULATOR

In this section, dynamics of a two-link planar manipulator as controlled system is discussed. Using Lagrange method, the dynamics of the two-link planar manipulator on the horizontal space as depicted in Fig. 1 is obtained by

$$L_{11}\ddot{\theta}_1 + L_{21}\ddot{\theta}_2 + \phi_1 + \psi_1 = h_1\tau_1 \quad (1)$$
$$L_{12}\ddot{\theta}_2 + L_{22}\ddot{\theta}_2 + \phi_2 + \psi_2 = h_2\tau_2 \quad (2)$$

where, $\ddot{\theta}$=$[\ddot{\theta}_1, \ddot{\theta}_2]^T$ and τ=$[\tau_1, \tau_2]^T$ are angler position of each links and control input torque for each actuators, respectively. And functions in dynamics are

$$\begin{aligned}
L_{11} &= c_1 + 2c_3\cos\theta_2 \\
L_{12} &= c_2 + c_3\cos\theta_2 \\
L_{21} &= c_2 + c_3\cos\theta_2 \\
L_{22} &= c_2 \\
\phi_1 &= -2c_3\dot{\theta}_1\dot{\theta}_2\sin\theta_2 - c_3\dot{\theta}_2{}^2\sin\theta_2 \\
\phi_2 &= c_3\dot{\theta}_1^2\sin\theta_2 \\
\psi_1 &= \mu_1\dot{\theta}_1 \\
\psi_2 &= \mu_2\dot{\theta}_2 \\
c_1 &= m_1lc_1^2 + m_2l_2^2 + m_2lc_2^2 + I_1 + I_2 \\
c_2 &= m_2lc_2^2 + I_2 \\
c_3 &= m_2l_1lc_2.
\end{aligned}$$

The parameters of the two-link planar manipulator are defined in TABLE I, especially, h_i is defined new parameter

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of actuators of systems as fault gain, and means being in 0 when actuator is fault.

In this paper, we assume that h_i has in 1(not fault) or 0(fault) , and propose an idea of fault detection($h_i = 0$) with tracking control using ANMPC.

For designing control method, we assume that θ_i is measurable, and $\dot{\theta}_i$ and $\ddot{\theta}_i$ are approximated by θ_i as follow as

$$\dot{\theta}_i(k) = \frac{\theta_i(k) - \theta_i(k-1)}{\Delta} \quad (3)$$

$$\ddot{\theta}_i(k) = \frac{\dot{\theta}_i(k) - \dot{\theta}_i(k-1)}{\Delta}. \quad (4)$$

Measured or approximated data at $t = k\Delta$ are shown as $\theta_i^d(k)$, $\dot{\theta}_i^d(k)$ and $\ddot{\theta}_i^d(k)$.

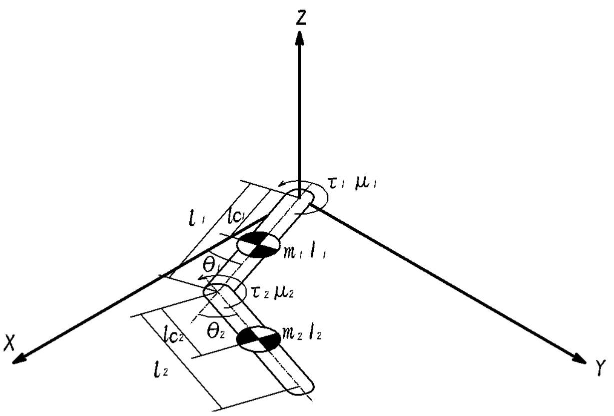

Fig. 1. The model of the two-link planar manipulator on the horizontal space

TABLE I
DEFINITIONS OF PARAMETERS $(i = 1, 2)$

h_i	Fault gain of the ith actuator
m_i	Mass of the ith link
l_i	Length of the ith link
l_{ci}	Length from joint to the center of the gravity of the ith link
I_i	Inertia moment around the center of gravity of the ith link
μ_i	Viscosity of the ith joint

III. ANMPC WITH FAULT DETECTION OF ACTUATORS

In this section, Adaptive Nonlinear Model Predictive Control(ANMPC) which is used as fault detection is introduced. Proposed ANMPC is constructed by four units, approximating angular velocity and angular acceleration, designing reference trajectory, deciding control input and estimation of system's parameters. The block diagram of a control system is shown in Fig. 2.

A. Reference trajectory with variable time-coefficient

The reference trajectory of MPC means an ideal trajectory for controlled values to track a desired value and is commonly designed as first-order lag element in order to decrease a control error in exponential (as depicted in Fig. 3).

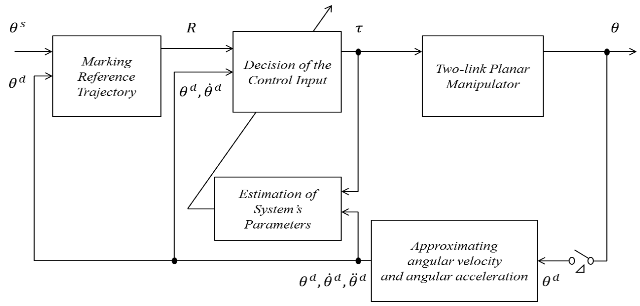

Fig. 2. Block diagram of ANMPC

A function of the reference trajectory of ith link at $t = (k+1)\Delta$ by using the first-order lag element is obtained as

$$R_i(k+1) = \theta_i^s(k) - \exp(-\Delta/T_i^{old})\varepsilon_i(k) \quad (5)$$

where, $\theta_i^s(k+1)$ is the desired value of ith link at $t = (k+1)\Delta$, T_i^{old} is time-constant of first order lag element, and $\varepsilon_i(k)$ is control error of ith link at $t = k\Delta$ as follow as

$$\varepsilon_i(k) = \theta_i^s(k) - \theta_i^d(k). \quad (6)$$

In case of the previous method[1], the performance of the control system depends on fixed the time-constant T_i^{old} of the reference trajectory. That is, if T_i^{old} is chosen in a large value, then the speed of response may be slow. On the other hand, if T_i^{old} is chosen in a small value, then the speed of response may be quick but the control input may be large. From the above relationship between the values of time constant and the performance of the control system, when MPC is applied to a control of the process system, the time-constant T_i^{old} is set in a fixed constant value, and is decided based on trade-off between the upper bound value of control inputs and needs of speed of response.

However, in case of the tracking control of a servo system like a fast moving manipulator, the desired trajectory is an unknown time-variant function, and the performance of the tracking controller cannot be guaranteed by a fixed time-constant.

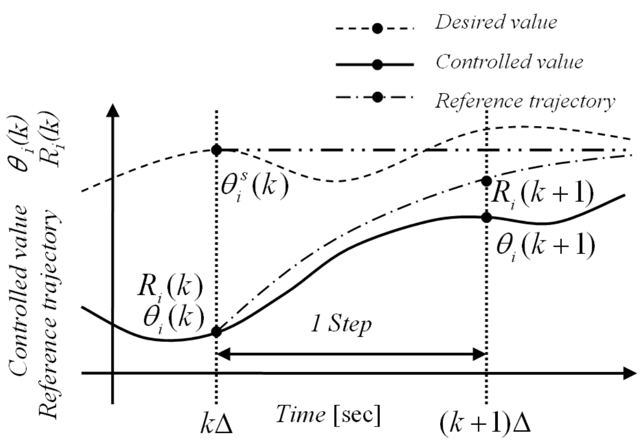

Fig. 3. Reference trajectory

For this problem, we have proposed a new reference trajectory using time-variant time-coefficient T_i^{new} instead of time-constant T_i^{old}[7], [8]. This time-coefficient is tuned based on the control error between the controlled value and the desired value which is shown in Fig.5.

The time-variant type time- coefficient $T_i^{new}$is obtained by

$$T_i^{new} = (T_i^{max} - T_i^{min})\sigma(|\varepsilon_i(k)|) + T_i^{min} \quad (i = 1,2) \qquad (7)$$

where, $\sigma(\cdot)$ is the sigmoid function. T_i^{new} is decided between upper value T_i^{max} and lower value T_i^{min} based on the control error ε_i and overshoot and tracking delays between controlled value and desired value are reduced using the proposed reference trajectory.

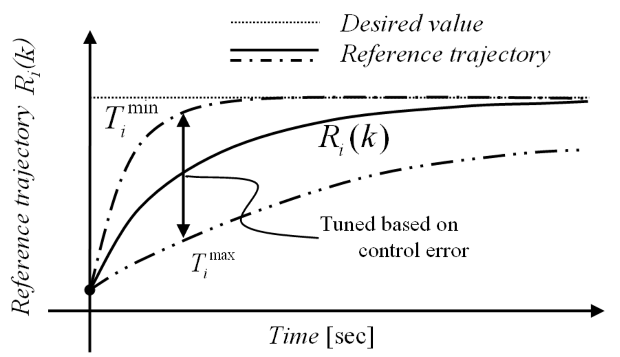

Fig. 4. Reference trajectory using Time-variant type time-coefficient

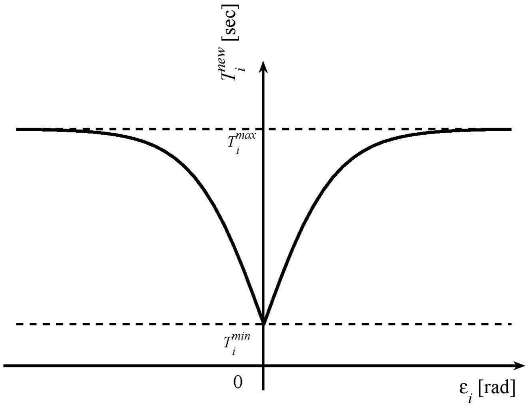

Fig. 5. Time-variant type time-coefficient

B. Calculation of the Control Input

In this section, a calculation of control input for the two-link planar manipulator is introduced. Control inputs realizing the system to track the proposed reference trajectory in the next step are decided. To calculate the control input, we use a predicted angles of the next step with assuming that angular acceleration $\ddot{\theta}_i(k)$ at $t = k\Delta$ is constant in one sampling interval.

Now, an angle of next step $\theta_i(k+1)$ can be predicted as a following 2^{nd} order systems by using Newton's formula with assuming $\ddot{\theta}_i(k)$ is constant in $\{t | k\Delta \le t < (k+1)\Delta\}$.

$$\theta_i(k+1) = \frac{1}{2}\ddot{\theta}_i(k)\Delta^2 + \dot{\theta}_i^{\,d}(k)\Delta + \theta_i^d(k), \qquad (i = 1,2). \ (8)$$

where, $\dot{\theta}_i^{\,d}(k)$ and $\theta_i^d(k)$ are measured angular velocity and angle at $t = k\Delta$, respectively.

From (8), an angular acceleration $\ddot{\theta}_i(k)$ is necessary to satisfy the following equation so that $\theta_i(k+1)$ may track to reference trajectories $R_i(k+1)$ in the next step.

$$\ddot{\theta}_i(k) = \frac{2}{\Delta^2}\left\{R_i(k+1) - \dot{\theta}_i^{\,d}(k)\Delta - \theta_i^d(k)\right\}, \quad (i = 1,2). \ (9)$$

Then substituting (9) into (1), we obtain the following the control inputs for two link manipulator tracking the proposed reference trajectory in the next step.

$$\begin{aligned} \tau_i \ = \ & \frac{2}{\Delta^2}\Big(L_{i1}(R_1(k+1) - \dot{\theta}_1^d(k)\Delta - \theta_1^d(k)) \\ & - L_{i2}(R_2(k+1) - \dot{\theta}_2^d(k)\Delta - \theta_2^d(k))\Big) + \phi_i + \psi_i, \\ & \qquad (i = 1,2). \ (10) \end{aligned}$$

C. Estimation of system's parameter

From (10), system's parameters c_1, c_2, c_3, μ_1 and μ_2 are needed for calculating the control inputs τ_i. However, these parameters are commonly unknown and may secularly change. Therefore, this section explains algorithm of estimating system's parameters using system's state and past control inputs.

Now, dynamics of systems (1) and (2) can be changed to

$$\ddot{\theta}_1 c_1 + \ddot{\theta}_2 c_2 + d_1 c_3 + \dot{\theta}_1 \mu_1 = \tau_1 \qquad (11)$$

$$d_2 c_2 + d_3 c_3 + \dot{\theta}_2 \mu_2 = \tau_2 \qquad (12)$$

where, d_1, d_2 and d_3 are obtained by

$$\begin{aligned} d_1 &= (2\ddot{\theta}_1 + \ddot{\theta}_2)\cos\theta_2 - (2\dot{\theta}_1\dot{\theta}_2 + \dot{\theta}_2^2)\sin\theta_2 \\ d_2 &= \ddot{\theta}_1 + \ddot{\theta}_2 \\ d_3 &= \ddot{\theta}_1\cos\theta_2 + \dot{\theta}_1^2\sin\theta_2. \end{aligned}$$

If c_1, c_2, c_3 and μ_1 are constant in 4 steps, (11) in $(t = k-3, k-2, k-1, k)$ can be shown by

$$\begin{cases} \ddot{\theta}_1(k)c_1 + \ddot{\theta}_2(k)c_2 + d_1(k)c_3 + \dot{\theta}_1(k)\mu_1 = h_1\tau_1(k) \\ \ddot{\theta}_1(k-1)c_1 + \ddot{\theta}_2(k-1)c_2 + d_1(k-1)c_3 + \dot{\theta}_1(k-1)\mu_1 \\ \qquad = h_1\tau_1(k-1) \\ \ddot{\theta}_1(k-2)c_1 + \ddot{\theta}_2(k-2)c_2 + d_1(k-2)c_3 + \dot{\theta}_1(k-2)\mu_1 \\ \qquad = h_1\tau_1(k-2) \\ \ddot{\theta}_1(k-3)c_1 + \ddot{\theta}_2(k-3)c_2 + d_1(k-3)c_3 + \dot{\theta}_1(k-3)\mu_1 \\ \qquad = h_1\tau_1(k-3) \end{cases}$$

Thus, by using matrix, these equations are shown as

$$\begin{pmatrix} D_1(k) \\ D_1(k-1) \\ D_1(k-2) \\ D_1(k-3) \end{pmatrix} \begin{pmatrix} c_1(k) \\ c_2(k) \\ c_3(k) \\ \mu_1(k) \end{pmatrix} = h_1 \begin{pmatrix} \tau_1(k) \\ \tau_1(k-1) \\ \tau_1(k-2) \\ \tau_1(k-3) \end{pmatrix} \qquad (13)$$

where,

$$D_1(k) = (\ddot{\theta}_1(k), \ddot{\theta}_2(k), d_1(k), \dot{\theta}_1(k)). \qquad (14)$$

Then, we can obtain parameters c_1/h_1,c_2/h_1,c_2/h_1 and μ_1/h_1 as following equations by deforming eq.(13).

$$P_1(k) = \frac{1}{h_1}\begin{pmatrix} c_1(k) \\ c_2(k) \\ c_3(k) \\ \mu_1(k) \end{pmatrix} = \begin{pmatrix} D_1(k) \\ D_1(k-1) \\ D_1(k-2) \\ D_1(k-3) \end{pmatrix}^{-1} \begin{pmatrix} \tau_1(k) \\ \tau_1(k-1) \\ \tau_1(k-2) \\ \tau_1(k-3) \end{pmatrix} \tag{15}$$

Therefore, when the actuator of the first link is not fault($h_1 = 1$), c_1, c_2, c_3 and μ_1 can be estimated by using systems state and past control input.

In a same way, c_2, c_3 and μ_2 can be estimated by using (12). If c_2, c_3 and μ_2 are constant in 3 steps, (12) in ($t = k-2, k-1, k$) can be shown by

$$\begin{cases} d_2(k)c_2+d_3(k)c_3+\dot{\theta}_2(k)\mu_2 = h_2\tau_2(k) \\ d_2(k-1)c_2+d_3(k-1)c_3+\dot{\theta}_2(k-1)\mu_2 = h_2\tau_2(k-1) \\ d_2(k-2)c_2+d_3(k-2)c_3+\dot{\theta}_2(k-2)\mu_2 = h_2\tau_2(k-2) \end{cases}$$

By using matrix, these equations are shown as

$$\begin{pmatrix} D_2(k) \\ D_2(k-1) \\ D_2(k-2) \end{pmatrix} \begin{pmatrix} c_2(k) \\ c_3(k) \\ \mu_2(k) \end{pmatrix} = h_2 \begin{pmatrix} \tau_2(k) \\ \tau_2(k-1) \\ \tau_2(k-2) \end{pmatrix} \tag{16}$$

where, $D_2(k)$ is defined as

$$D_2(k) = (d_2(k), d_3(k), \dot{\theta}_2(k)) \tag{17}$$

Therefore, we can obtain parameters c_2/h_2,c_3/h_3 and μ_2/h_2 and c_2, c_3 and μ_2 can be estimated, when the actuator of the second link is not fault ($h_2 = 1$).

$$P_2(k) = \frac{1}{h_2}\begin{pmatrix} c_2(k) \\ c_3(k) \\ \mu_2(k) \end{pmatrix} = \begin{pmatrix} D_2(k) \\ D_2(k-1) \\ D_2(k-2) \end{pmatrix}^{-1} \begin{pmatrix} \tau_2(k) \\ \tau_2(k-1) \\ \tau_2(k-2) \end{pmatrix} \tag{18}$$

From (15) and (18), if $[\tau_1(k), \tau_1(k-1), \tau_1(k-2), \tau_1(k-3)]^T$ and $[\tau_2(k), \tau_2(k-1), \tau_2(k-2)]^T$ are zero, then P_1 and P_2 are calculated in zero and estimated parameters are not true. Therefore, in this case, parameters are not estimated.

D. Elimination of Estimate Error

In this section, the elimination of estimate error method are discussed.

Since proposed algorithm needs that parameters are constant in a few steps as the estimating condition, after changing parameters, the estimation of several steps is not correct. Moreover, because the estimation process uses the approximated angular velocity and angular acceleration, estimated parameters might contain approximation error.

In contrast, the estimation results of the past few between steps are a tendency to have a distribution similar to the normal distribution. So for this problem, we use mode of the data, which is most frequently occurring value. Specifically, the estimated result between the few steps of the past is sampled, and a mode is calculated using the data.

Moreover when parameter variations exceed the tolerance of variation, controlled variables diverge by control input calculated by using wrong estimated parameters in ANMPC.

To prevent this problem, when controlled variables exceed the threshold, the calculation method of a control input is changed from ANMPC to for interpolation calculating as follow as

$$\tau_1(k) = -10\sin 5t \tag{19}$$

$$\tau_2(k) = -6\sin 5t. \tag{20}$$

The flow of decision of control input is shown in Fig. 6.

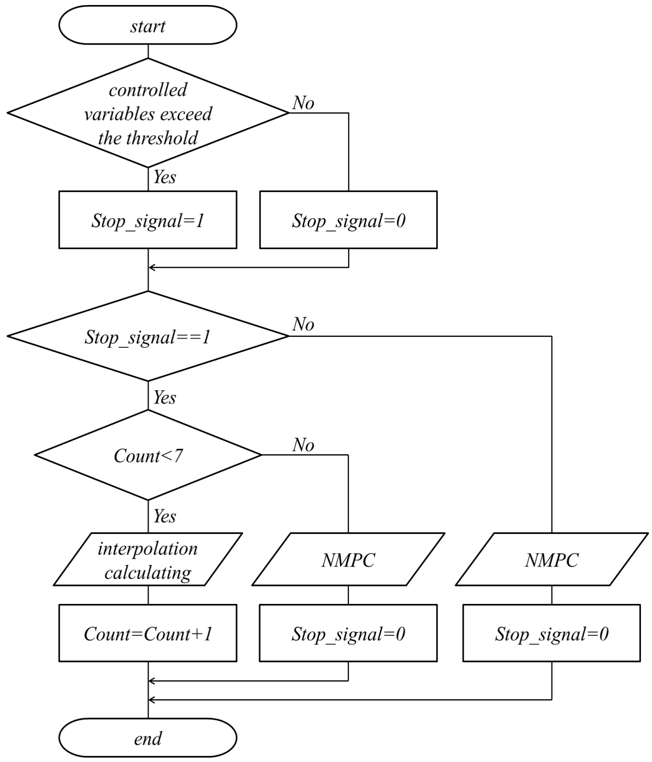

Fig. 6. The flow of decision of control input

E. Fault Detection using Estimated Parameters

In this section, we show the fault detection method using estimated parameters. Using (15) and (18) in section III-C, we can estimate $P_1(k)$ and $P_2(k)$ and these parameter vectors have h_i at denominator. Thus, we can easily detect a fault of actuator using following conditions.

The ith actuator is

$$\begin{cases} \text{Fault} & \text{if } V_i > V_i^s \\ \text{Not fault} & \text{otherwise.} \end{cases} \tag{21}$$

where

$$V_1(k) = \left|\frac{c_1(k)}{h_1(k)}\right| + \left|\frac{c_2(k)}{h_1(k)}\right| + \left|\frac{c_3(k)}{h_1(k)}\right| + \left|\frac{\mu_1(k)}{h_1(k)}\right| \tag{22}$$

$$V_2(k) = \left|\frac{c_2(k)}{h_2(k)}\right| + \left|\frac{c_3(k)}{h_2(k)}\right| + \left|\frac{\mu_2(k)}{h_2(k)}\right| \tag{23}$$

and V_i^s are threshold of detection which is decided in trial and error based on several required condition e.g., nominal values of parameters, sampling rate of controller, bounded maximum value of control input, necessary robustness, etc..

IV. NUMERICAL SIMULATIONS

In order to show an effectiveness of the proposed ANMPC with the fault detection function using approximated an angular velocity and an angular acceleration in this paper. In order to verify the estimating functions and the fault detection functions of proposed method, in simulation, parameters of the two link planar manipulator are changed at between $t = 10$[sec] and $t = 20$[sec] assuming that a object of 1[kg] is gripped by edge of the second link.

Nominal parameters given in TABLE II are used at the beginning of simulation and the system's parameters used in calculating control input are changed to following.

$$\begin{cases} c_1 \ : \ 0.0711 \ \rightarrow \ 0.1502, \quad c_2 \ : \ 0.0173 \ \rightarrow \ 0.0374 \\ c_3 \ : \ 0.0152 \ \rightarrow \ 0.0483, \\ \mu_1 \ : \ 0.0390 \ \rightarrow \ 0.0390, \quad \mu_2 \ : \ 0.0350 \ \rightarrow \ 0.0400 \end{cases}$$

Moreover, the fault actuators are happened only the second link at $t = 25$[sec], that is, $h_2 = 1$ changes to 0 at $t = 25$[sec]. After failure occurs, a control input is set to 0 in order to prevent emission of a controlled variable.

Results of tracking control are shown in Fig.7 and estimating results of systems parameter is shown in Fig. 8 and Fig. 9. Solid lines shown behavior of measured output and broken lines show behavior of desired values in Fig.7. The parameters of the controller are given in TABLE III.

From Fig.7, tracking control for the planar manipulator which has time-variant parameters is achieved until failure occurs. And Fig.8 and Fig.9 shows estimating parameters using proposed algorithm is succeed. Moreover, successful of fault detection can be achieved using estimated parameters of system.

TABLE II

NOMINAL PARAMETERS OF THE TWO-LINK PLANAR MANIPULATOR

m_1	9.90×10^{-1}[kg]	m_2	6.87×10^{-1}[kg]
l_1	2.43×10^{-1}[m]	l_2	2.66×10^{-1}[m]
l_{c1}	4.04×10^{-2}[m]	l_{c2}	9.11×10^{-2}[m]
I_1	1.16×10^{-2}[kg·m^2]	I_2	1.16×10^{-2}[kg·m^2]
μ_1	3.90×10^{-2}	μ_1	3.50×10^{-2}

TABLE III

PARAMETER OF THE PROPOSED NMPC CONTROLLER

T_1^{max}	10 [sec]	T_2^{max}	10 [sec]
T_1^{min}	0 [sec]	T_2^{min}	0 [sec]
β_1	0.1	β_2	0.1
V_1^s	1.0	V_2^s	0.5

V. CONCLUSIONS

In this paper, an adaptive NMCP controller with fault detection function of actuators for the two-link planar manipulator using approximate differentiation is proposed. In proposed method, NMPC is redesigned using approximating an angular velocity and an angular acceleration so as to close the simulation condition to real system's conditions. Although the influence of an approximation error had arisen greatly in the estimation of system's parameter, it become removable an estimated error by using the mode values, and fault detection of actuators is realized by using estimate system's parameter. From numerical simulations, the effectiveness of the proposed method can be proved.

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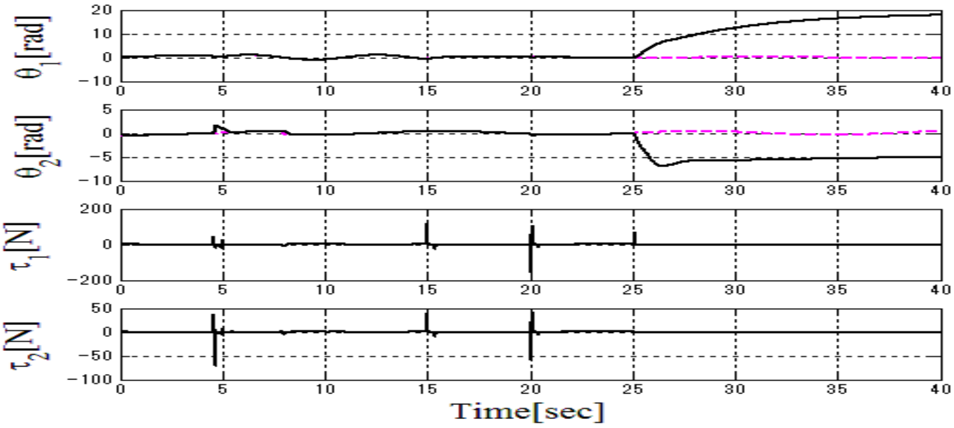

Fig. 7. Simulation results of Proposed method

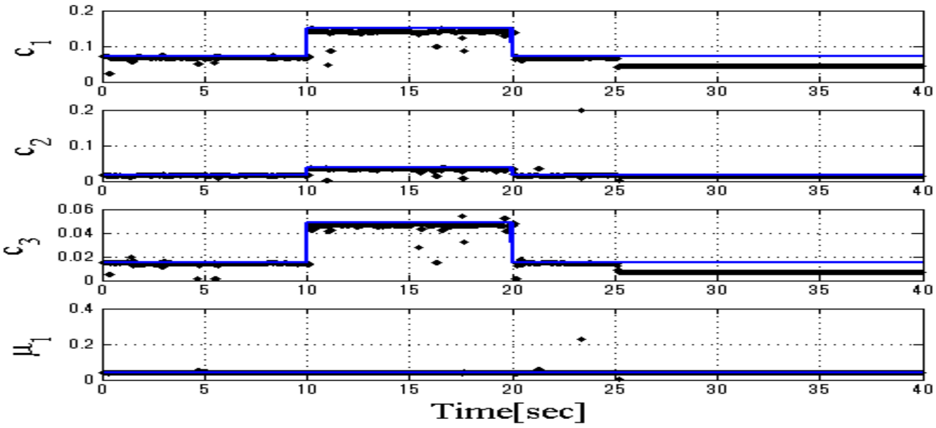

Fig. 8. Estimation result of h_1

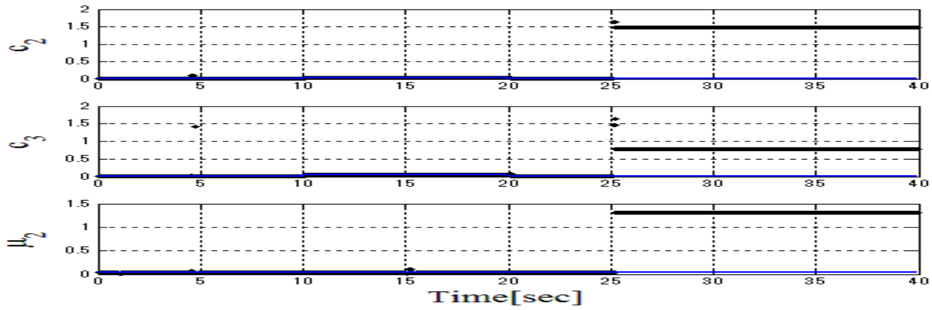

Fig. 9. Estimation result of h_1

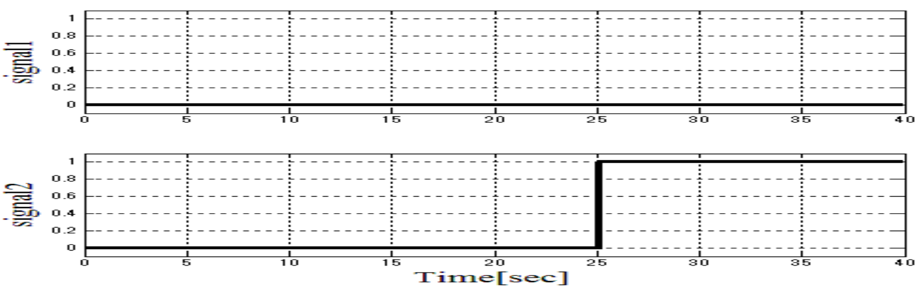

Fig. 10. Estimation result of the failure signal