Robust Adaptive Controller Design for Excavator Arm

Nga Thi-Thuy Vu
School of Electrical Engineering, Hanoi University of Science and Technology
Email: nga.vuthithuy@hust.edu.vn

Abstract—Working in the dynamic environment makes the operation of excavator arm be affected by many factors. This leads to the unexpected operation of the automated arm. In order to overcome this problem, in this paper a robust adaptive controller that does not depend on the system parameters is presented for an excavator arm. Firstly, the model of the excavator arm is demonstrated in the Euler-Lagrange form considering with overall excavator system. Next, a robust adaptive controller has been constructed from information of state error to calculate the unknown factors. In this paper, the stability of overall system as well as the convergence of the adaptive components is mathematically proven by using Lyapunov stability theory. Also, the proposed controller is model free then the closed loop system is not affected by disturbances and uncertainties. Finally, the simulation is executed in Matlab/Simulink to compare the performances of the presented scheme and the PD controller under some conditions (i.e. no load, full load, rated parameters, varying parameters). The simulation results show that the proposed algorithm given the better performances (fast response, small steady state error) for all cases.

Index Terms—adaptive, excavator, Euler-Lagrange system, robust control

I. INTRODUCTION

Nowadays, robots are used commonly in the industries because of their versatility and efficiency [1]-[3]. The automatic remote control of the robot plays a significant role in real-life application, such as nuclear field, construction, rescue missions,… For the excavator robot, in order to perform a specific duty, it needs to complete at least two tasks: determining a feasible path from its initial location to the destination and then executing the task through control algorithm that has to be designed. According to these requirements, the tracking control problem for the excavator robot system is constantly receiving the interest of scientists.

The earlier research work mainly focused on modelling work including kinematic and dynamic model, modelling of interaction between the machine and the environment, and parameter identification [4]-[10]. Modelling and parameter identification during the operation of machine is very helpful for the real-time monitoring and remote control.

About the control design, during the earlier stage of study on excavator, impedance control is considered as a popular control. In [11], a position-based impedance controller is presented on mini-excavator. In [12]-[13], authors present detail of robust impedance control for hydraulic excavator. The impedance control suits to apply for excavator because it can deal with both free and constrain motion [13]. However, the algorithm is quite complicated. Recently, many modern control techniques are used in trajectory control of excavator arm. In [14], an adaptive controller is presented in controlling excavator arm. The stability of system is ensured through mathematical proof and verified by simulation results. However, the simulation as well as the explanation of simulation results is quite poor. In [15]-[16], the fuzzy controllers are employed to solve the tracking control problem of the excavator. In these type of controllers, the information about the system does not require. However, the stability of the overall system is not shown in the mathematic. Nowadays, the PID controller still being used widely in the practice because of its simplify. However, tuning of the PID gains to adapt with the change of working conditions is difficult and depending on the personal experiences. In recent times, in order to deal with this problem, some optimization techniques such as artificial neural network (ANN), ant colony optimization (ACO), etc., have been applied to optimize the PID parameters. In [17], an genetic algorithm (GA) is used to determine the PID gains for trajectory tracking control of robotic excavator. The presented scheme gave the good performances in comparison with some given methods. However, the gotten results still have problems needed to be discussed.

In this paper, a robust adaptive controller is proposed for excavator arm system. The structure of controller consists of two parts: the first part is responsible for keeping the stability of the system and the second part is used for adapting with the unknown parameters. Therefore, the proposed controller has ability to cancel the effect of the uncertainties as well as to keep the tracking error go to zero. Also, the presented controller is simple so it is easy to implement. The feasible of the algorithms is demonstrated by Lyapunov stability theory and verified through simulation models. The simulation is executed in Matlab/Simulink for both presented scheme and the PD controller under some conditions to ensure
that the proposed algorithm given the good performances for all cases.

II. CONTROLLER DESIGN FOR EXCAVATOR ARM

A. Modelling of Excavator Arm

Consider an excavator system with structure as Fig. 1. The system consists of two subsystems: the base is used to move the entire system on the $x_0O_0y_0$ plane and the arm is used for movement in the $z_0O_0y_0$ and $z_0O_0x_0$ planes. This paper concern mainly on the motion control of excavator arm, so the base part and the rotation around $O_0z_0$ axis are consider unchanged.

![Figure 1. Schematic diagram of an excavator.](image)

The Euler-Lagrange model of excavator arm during the digging process corresponding to the coordinates of each joint as shown in Fig. 1 is as follow [18]:

$$ D(\theta) \ddot{\theta} + C(\theta, \dot{\theta}) \dot{\theta} + G(\theta) + B(\dot{\theta}) = \Gamma \tau - F_L $$

where $\theta = [\theta_1, \theta_2, \theta_3]$ is the position of each joint in the joint space, $D(\theta)$ represents inertial part, $C(\theta, \dot{\theta})$ is the Coriolis and centripetal effects, $G(\theta)$ is the gravity part, $B(\dot{\theta})$ represents frictions; $\Gamma$ is the corresponding input matrix, $\tau = [\tau_1, \tau_2, \tau_3]$ specifies the torques acting on the shaft of 3 joints, $F_L$ represents the interactive torques. The formulas of above parts are given by the following expressions:

$$ D(\theta) = \begin{bmatrix} D_{11} & D_{12} & D_{13} \\ D_{21} & D_{22} & D_{23} \\ D_{31} & D_{32} & D_{33} \end{bmatrix}, $$

$$ C(\theta, \dot{\theta}) = \begin{bmatrix} C_{11} & C_{12} & C_{13} \\ C_{21} & C_{22} & C_{23} \\ C_{31} & C_{32} & C_{33} \end{bmatrix}, \quad \Gamma = \begin{bmatrix} 1 & -1 & 0 \\ 0 & 1 & -1 \\ 0 & 0 & 1 \end{bmatrix}, $$

$$ G(\theta) = \begin{bmatrix} G_2 \\ G_3 \\ G_4 \end{bmatrix}, $$

$$ B(\dot{\theta}) = \begin{bmatrix} B_{1u} \dot{\theta}_2 \\ B_{2u} \dot{\theta}_3 \\ B_{3u} \dot{\theta}_4 \end{bmatrix}, $$

where:

$$ D_{11} = I_{1u} + M_{1u} r_2^2 $$

$$ D_{12} = D_{13} + I_{1u} + M_{1u} r_3^2 + M_{1u} [a_1^2 + 2a_1 r_4 \cos(\theta_3 + \alpha_4)] $$

$$ D_{13} = D_{23} + I_{1u} + M_{1u} r_3^2 + M_{1u} [a_1^2 + 2a_1 r_4 \cos(\theta_3 + \alpha_4)] + M_{1u} [a_2^2 + 2a_2 r_4 c_3 + 2a_4 r_4 \cos(\theta_4 + \alpha_4)] $$

$$ D_{21} = D_{32} = D_{33} + M_{1u} a_1 r_3 \cos(\theta_4 + \alpha_4) $$

$$ D_{31} = D_{23} + M_{1u} a_2 r_3 \cos(\theta_4 + \alpha_4) $$

$$ D_{12} = D_{21} = D_{13} + I_{1u} + M_{1u} [a_2^2 + 2a_2 r_3 \cos(\theta_3 + \alpha_3)] + M_{1u} [a_3^2 + 2a_3 c_3 + 2a_4 r_4 \cos(\theta_4 + \alpha_4)] $$

$$ C_{11} = -M_{1u} a_1 r_3 \sin(\theta_3 + \alpha_3) - M_{1u} a_1 \dot{\theta}_3 s_3 $$

$$ -M_{1u} a_1 r_3 \dot{\theta}_3 s_3 $$

$$ C_{12} = -M_{1u} a_2 r_3 \sin(\theta_3 + \alpha_3) - M_{1u} a_3 \dot{\theta}_3 s_3 $$

$$ -M_{1u} a_2 r_3 \dot{\theta}_3 s_3 $$

$$ C_{13} = -M_{1u} a_3 r_3 \sin(\theta_3 + \alpha_4) $$

$$ -M_{1u} a_3 r_3 \dot{\theta}_3 s_3 $$

$$ C_{21} = a_2 \dot{\theta}_3 [M_{1u} a_3 s_3 + M_{1u} a_3 \sin(\theta_3 + \alpha_3)] $$

$$ -M_{1u} a_2 r_3 \dot{\theta}_3 s_3 $$

$$ C_{22} = -M_{1u} a_2 r_3 \dot{\theta}_3 s_3 $$

$$ C_{23} = -M_{1u} a_3 r_3 \dot{\theta}_3 s_3 $$

\[ C_{11} = M_{a_b} a_t \dot{\theta}_d \left[ a_1 \sin (\theta_d + \alpha_1) + a_4 \sin (\theta_d + \alpha_4) \right] \]
\[ + M_{a_b} a_t r \dot{\theta}_d \sin (\theta_d + \alpha_4) \]
\[ C_{12} = M_{a_b} a_t r \sin (\theta_d + \alpha_4) \]
\[ C_{33} = 0 \]
\[ G_i = M_{a_b} \left[ a_{g_i} c_i + M_{a_b} g_i \cos (\theta_d + \alpha_4) \right] \]
\[ G_2 = M_{a_b} a_{g_2} c_i + M_{a_b} g_i \cos (\theta_d + \alpha_4) \]
\[ G_3 = M_{a_b} g_i \cos (\theta_d + \alpha_4) \]

**B. Robust Adaptive Controller Design**

Define the error signal:
\[ e = \theta_d - \theta \]
where \( \theta_d \) is desired value of \( \theta \). The filtered error surface is chosen as

\[ \Phi_n = \left[ \left\| D(\theta) \right\| \right. \left\| C(\theta, \dot{\theta}) \right\| \left\| B(\theta) \right\| \left\| G(\theta) \right\| \left\| F_i \right\| \]

and \( \rho_i \) \((i = 1, 2, 3, 4, 6)\) are unknown positive constants.

Consider the following theorem.

\[ \Phi_n = \left[ \left\| D(\theta) \right\| \right. \left\| C(\theta, \dot{\theta}) \right\| \left\| B(\theta) \right\| \left\| G(\theta) \right\| \left\| F_i \right\| \]

then the following controller and adaptation law can make the dynamic error go to zero.

\[ \dot{\rho}_i = -\eta_k \rho_i \varphi_{\rho_i}^2 - \rho_i \hat{\rho}_i, k = 1, \ldots, 6 \]

where \( K = \text{diag}(k_1, k_2, k_3) \) with \( k_i > 0 \) \((i = 1, 2, 3)\), \( \eta_k > 0, \eta_i > 0 \) are constant, \( \zeta = \text{diag} (\zeta_1, \zeta_2, \zeta_3) > 0 \), \( \varphi = \left[ 1 \right] \left[ 1 \right] \left[ \rho_1 \rho_2 \rho_3 \rho_4 \rho_5 \rho_6 \right] \]

**Proof:** Choose the Lyapunov function:
\[ V = \frac{1}{2} x^T D(\theta) x + \sum_{k=1}^{6} \frac{1}{2 \eta_k} \hat{\rho}_i^2 \]

where \( \hat{\rho}_i = \rho_i - \dot{\hat{\rho}}_i \), \( \dot{\hat{\rho}}_i \) are estimated values of \( \rho_i \), \( \eta_k \) positive constant.

The time derivative of Lyapunov function using (4) is as follow:

\[ \dot{V}_i = -x^T \left[ C(\theta, \dot{\theta}) - \frac{1}{2} D(\theta) \right] x + \sum_{k=1}^{6} \frac{1}{2 \eta_k} \hat{\rho}_i \dot{\rho}_i + \]
\[ + x^T \left[ -D(\theta) \dot{\theta} - C(\theta, \dot{\theta}) \dot{\theta} \right] \]
\[ -G(\theta) - B(\theta) - F_i + \Gamma \]

\[ = x^T \left( -\Phi_n x + \Gamma \right) - \sum_{k=1}^{6} \frac{1}{2 \eta_k} \hat{\rho}_i \dot{\rho}_i \]

Substituting (5) into (7), it is obtained:

\[ \dot{V} = \dot{\theta} - \dot{\hat{\theta}}_d + Ye \]
\[ \dot{x} = \dot{\theta} - \dot{\hat{\theta}}_d + Y \dot{e} \]

where \( Y = \text{diag}(Y_1, Y_2, Y_3) > 0 \).

Based on (3), (1) can be written as

\[ D(\theta) \dot{\theta} = -C(\theta, \dot{\theta}) - M(\theta) \dot{\theta} - (C(\theta, \dot{\theta}) \dot{\theta} - G(\theta) - B(\theta) - F_i + \Gamma \]

where \( \dot{\gamma} = \dot{\theta} - Ye \), \( \Phi_n = \left[ D(\theta) \right] C(\theta, \dot{\theta}) B(\theta) G(\theta) F_i \]

**Theorem:** If there exist the scalars \( \rho_i \) \((i = 1, 2, 3, 4, 6)\) so that

\[ \dot{V} = -x^T K x - x^T \rho^T \rho \sum_{k=1}^{6} \frac{x^T \rho_i \rho_i}{2 \eta_k} \]

\[ - \sum_{i=1}^{6} \left[ \frac{4}{\eta_k^2} \rho_i \dot{\rho}_i \right] + \sum_{i=1}^{6} \frac{4}{\eta_k^2} \rho_i \dot{\rho}_i \sum_{i=1}^{6} \frac{4}{\eta_k^2} \rho_i \dot{\rho}_i \]

\[ \leq -x^T \left( K x + \rho \rho^T \rho \right) - \mu V + \delta \]

where \( \mu = \min[\lambda_{\text{max}}(K), \frac{2 \eta_1}{\eta_1} / \text{max} (\left\| D(\theta) \right\|, 1 / \eta_1)] > 0 \)

\[ \Phi = \left[ \rho_1 \rho_2 \rho_3 \rho_4 \rho_5 \rho_6 \right] \]

\[ \delta = \sum_{i=1}^{6} \frac{4}{\eta_k^2} \rho_i \dot{\rho}_i \]

Multiplying (8) by \( e^{\mu t} \) gives:

\[ \frac{d}{dt} (Ve^{\mu t}) \leq \delta e^{\mu t} \]

Integrating (9) leads to the following inequality:

\[ 0 < V(t) < \left( V(0) + \frac{d}{\mu} \right) e^{\mu t} + \frac{\delta}{\mu} V(0) + \frac{\delta}{\mu} \]

\[ \text{International Journal of Mechanical Engineering and Robotics Research Vol. 9, No. 1, January 2020} \]

Based on above results and Barbalat’s lemma, all error signals will go to zero when time goes to infinite-time.

III. SIMULATION RESULTS

Based on above results and Barbalat’s lemma, all error signals will go to zero when time goes to infinite-time.

To evaluate the correctness and suitability of the proposed robust adaptive controller, the algorithm was set and simulated in Simulink software with an excavator system given parameters as the following [18]:

\[ \begin{align*}
M_{bo} &= 1566; \quad M_{st} = 735; \quad M_{bu} = 432; \quad M_{load} = 500; \\
I_{bo} &= 14250.6; \quad I_{st} = 727.7; \quad I_{bu} = 224.6; \\
a_2 &= 5.16; \quad a_3 = 2.59; \quad r_2 = 0.64; \quad r_4 = 0.65; \\
B_{bo} &= 0.02; \quad B_{st} = 0.02; \quad B_{bu} = 0.02;
\end{align*} \]

The parameters for the control law is chosen by practical method (trial – and – error):

\[ 
\Gamma = \text{diag}(1), \quad K = \text{diag}(2 \times 10^6, 1.5 \times 10^6, 10^5), \quad \eta_k = 1, \quad \alpha = 0.01, \quad \varepsilon_k = 0.1
\]

With the purpose of comparison, the simulation is executed for both proposed controller and PD controller [15]. The simulation has been conducted for three cases:

- **Case 1**: The parameters of system are rated, the machine works without payload.
- **Case 2**: The parameters of system are rated, the machine works with full payload.
- **Case 3**: The parameters of model change, the machine works will full payload.

In each case, the results were compared with the response of PD controller which was mentioned in [18]. Simulation results for Case 1, Case 2, and Case 3 are shown in Figs. 2, 3 and 4, respectively. In these figures, the solid line (Theta_d) represents the reference value of and dashed line (Theta) is for real value of \( \theta \).

![Image 1](image1.png)

**Figure 2.** System responses under condition of without payload and rated system parameters

![Image 2](image2.png)

**Figure 3.** System responses under condition of full payload and rated system parameters.
In Fig. 2, when system works without load and the parameters of model is rated, the position response of joints by using proposed controller and PD controller is absolutely tracked to desired value, and the tracking error is trivial. In the second case (Fig. 3), the system parameters remain unchanged but the excavator work with full payload. The adaptive controller gives the position response of joints almost no deviation from desired trajectory, while the PD controller gives a tracking error about 0.05 rad. In case system works with full payload and the parameter of system change (figure 4), the results obtained for the adaptive controller are still relatively good. The PD controller give a maximal tracking error about 0.15 rad.

From the simulation results, it can be seen that the PD controller can make the system only work well when the elements of system are determined. When the system has load disturbance, the tracking error appears (0.05 rad) and will increase to 0.15 rad if the system is affected by addition disturbances. This prove that the PD controller will increase tracking error when system has disturbance. Meanwhile, for adaptive controller, the responses of system under condition of system uncertainties as well as payload noise are so good.

IV. CONCLUSIONS

This paper has presented the robust adaptive controller that does not depend on the system model for excavator arm. The controller includes two parts, the state feedback part for system stability and the adaptive part for compensation. The controller has simple structure, easy to implement but still guarantees good performances to the uncertainty of the system. The stability and suitability of the overall system as well as the convergence of the adaptive component were demonstrated by Lyapunov stability theory and examined through simulation. Also, the PD controller was setup to evaluate the effectiveness of the two control schemes. The simulation results show that in comparison with PD controller, the proposed algorithm guarantees the better characteristics under all conditions, i.e. all joints of excavator arm absolutely track to desired value even if there is the effect of the load disturbance and the impact of the uncertainties of system model.

REFERENCES


Nga Thi -Thuy Vu received the B.S. and M.S. degrees in electrical engineering from Hanoi University of Science and Technology, Hanoi, Vietnam, in 2005 and 2008, respectively, and the Ph.D. degree in electronics and electrical engineering from Dongguk University, Seoul, Korea, in 2013. She is currently with the Department of Automatic Control, Hanoi University of Science and Technology, Hanoi, Vietnam, as a Full Lecturer. Her research interests include control theory, robot control, motion control, and renewable energy system.