STUDY ON MODELING AND CONTROL OF EXCAVATOR

Le Quang Hoan[1], Chan Se Jeong[1], Hack Sun Kim[1], He Lim Yang[1], and Soon Yong Yang[2]*

[1] *Graduate School of Mechanical and Automotive Engineering, University of Ulsan, Ulsan, Korea*
[2] *Department of Mechanical and Automotive Engineering, University of Ulsan, Ulsan, Korea*
* Corresponding author (soonyy@ulsan.ac.kr)

ABSTRACT: An excavator is a typical hydraulic heavy-duty human-operated machine used in general versatile construction operations, such as digging, carrying loads, grounding and dumping loads. However, operating excavators in the hazard environment such as earthquake, nuclear decomposition etc is not suitable for human to operate on site. Therefore, automation in excavator has been investigated to protect the operators from the harmful environments. To find a feasible way to control excavator, firstly the Full Kinematic and dynamic model of the excavator's manipulator which three degrees of freedom were studied. The inverse kinematic equations are used to determine the joint angles and the actuator lengths corresponding to a specific position and orientation of the bucket, given in the base coordinate system. To control the excavator's manipulator, the computed torque control are using and some simulation results are given.

Keywords: Excavator, Modeling, Automation, Control, Manipulator

1. INTRODUCTION

Excavation is an importance work in mining, earth removal and general earthworks. Excavation productivity (amount of work done), efficiency (cost of work done in terms of labor and machinery) and operator safety, particularly in underground mining or during the removal of hazardous waste, are constantly under pressure from industry. After decades of increases in machine size and power, practical limits are now being approached and automation is being sought for further improvements. Furthermore, computing and sensing technologies have reached to a stage where they can be applied to automatic excavation. Nowadays, automation in excavators has been studied by several researchers and so on. Among the fundamental element used as a basis for developing complicated tasks, the Control of excavator's manipulator is an important and basic task in autonomous research of hydraulic excavator. To control an excavator's manipulator, firstly, the Full Kinematic and dynamic model of the excavator's manipulator which three degrees of freedom were studied in [1]. The trajectory of the bucket is designed and the desired angle joint of each links are determined by using Inverse Kinematic. The controller is designed to control the bucket tracking the desired trajectory. In this paper, the computed torque control and PID control are designed. Some simulations are proposed to verify the controller.

2. MODELING OF THE EXCAVATOR'S MAINIPULATIOR

2.1. Kinematic

The kinematic and dynamic models of the experimental D Company solar 105 hydraulic excavator will be presented. These models have been built to describe the experimental excavator as a robotic manipulator with 3 degrees of freedom. In computer-controlled motion, the bucket of the excavator follows a path specified by its position and angle, i.e. the pose of the bucket, which corresponds to specific values of angular positions of the joint shafts. The values of these joint variables are determined by the lengths of hydraulic actuators. The mathematical relations between these variables are given by the kinematic relations of the excavator arm.
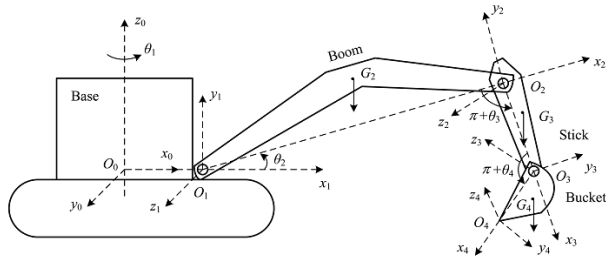
Fig. 1   Schematic diagram of an excavator

The forward kinematics is used to describe the positions and orientations of the points on the excavator in the Cartesian coordinate for the given joint positions during the digging operation. The problem can be summarized as below:

For the given $\theta = [\theta_1\ \theta_2\ \theta_3\ \theta_4]$, find the coordinate

$$P = [X\ Y\ Z]^T = \left[f_x(\theta)\ f_y(\theta)\ f_z(\theta) \right]^T$$

To determine the positions of the points on the excavator in the base Cartesian coordinate frame, the relations between the fixed coordinate system and other coordinate systems is necessary. Therefore, the transformation matrix relating two adjacent coordinate frames was studied by Koivo [2] as follows:

$$A_{i-1}^i = \begin{bmatrix} \cos\theta_i & -\cos\alpha_i\sin\theta_i & \sin\alpha_i\sin\theta_i & a_i\cos\theta_i \\ \sin\theta_i & \cos\alpha_i\cos\theta_i & -\sin\alpha_i\cos\theta_i & a_i\sin\theta_i \\ 0 & \sin\theta_i & \cos\theta_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{1}$$

Where α_i is the twist angle of link I, a_i is the length of link I, and d_i is the offset distance in link I, $I = 1, 2, 3, 4$.

By the given coordinates of the origin in each coordinate frame O_i, the coordinates of points O_i in the base coordinate frame can be described as follows using the equation (1):

$$P_0^{O_i} = A_0^i P_i^{O_i} \tag{2}$$

Where $P_0^{O_i} = [0\ 0\ 0\ 1]^T$ specifies point O_i in the ith coordinate frame. From equation (2) we can describe the origin of each coordinate frame O_i in the base coordinate frame as follows:

$$P_0^{O_1} = A_0^1 P_1^{O_1} = [a_1 c_1\ a_1 s_1\ 0\ 1]^T \tag{3}$$

$$P_0^{O_2} = A_0^1 A_1^2 P_2^{O_2} = \left[a_2 c_1 c_2 + a_1 c_1\ \ a_2 c_2 s_1 + a_1 s_1\ \ a_2 s_2\ \ 1 \right]^T \tag{4}$$

$$P_0^{O_3} = A_0^1 A_1^2 A_2^3 P_3^{O_3} = \begin{bmatrix} c_1\left(a_3 c_{23} + a_2 c_2 + a_1\right) \\ s_1\left(a_3 c_{23} + a_2 c_2 + a_1\right) \\ a_3 s_{23} + a_2 s_2 \\ 1 \end{bmatrix} \tag{5}$$

$$P_0^{O_4} = A_0^1 A_1^2 A_2^3 A_3^4 P_4^{O_4} = \begin{bmatrix} c_1\left(a_4 c_{234} + a_3 c_{23} + a_2 c_2 + a_1\right) \\ s_1\left(a_4 c_{234} + a_3 c_{23} + a_2 c_2 + a_1\right) \\ a_3 s_{23} + a_3 s_{23} + a_2 s_2 \\ 1 \end{bmatrix} \tag{6}$$

Where $c_i = \cos\theta_I$, $s_i = \sin\theta_I$, $\theta_{23} = \theta_2 + \theta_3$, $\theta_{234} = \theta_2 + \theta_3 + \theta_4$.
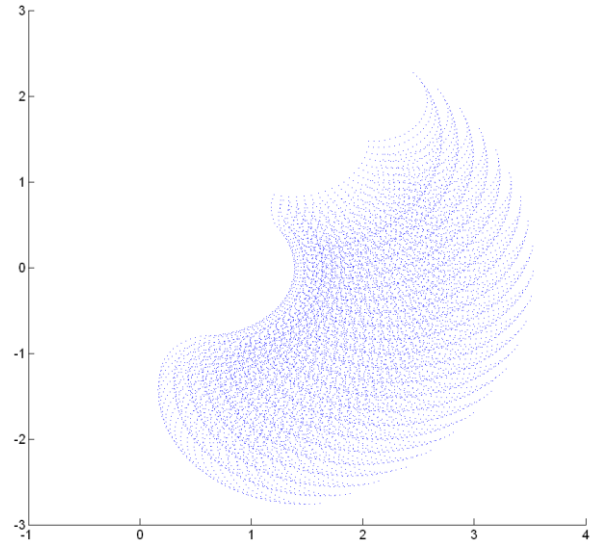

Fig. 2   The mainipulator's workspace of the Solar 105

2.2 Inverse kinematics

The inverse kinematic equations are used to determine the joint angles and the actuator lengths corresponding to a specific position and orientation of the bucket, given in the base coordinate system.
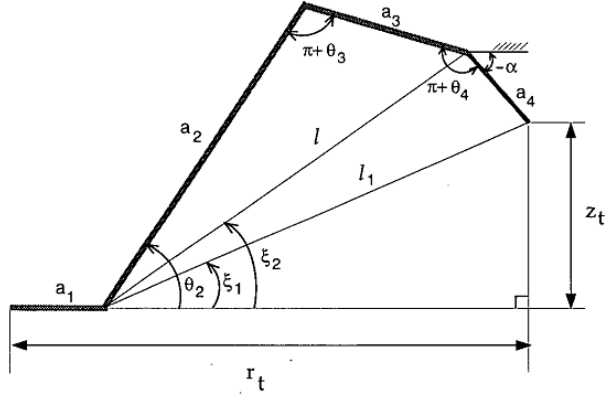
Fig. 3   Projection of the links onto the vertical plane

It is assumed that the coordinate of point $O_4 \equiv N$ are given in the coordinate system. According to Tafazoli [3], the inverse kinematic model of the excavator is given as follows:

$$\theta_1 = \theta_b \tag{7}$$

$$l_1 = \sqrt{(r_b - a_1)^2 + z_b^2} \tag{8}$$

$$\xi_1 = a\tan\left[z_b / (r_b - a_1) \right] \tag{9}$$

$$l = \sqrt{l_1^2 + a_4^2 - 2la_4 \cos(\xi_1 - \alpha)} \tag{10}$$

$$\xi_2 = a\sin\left[(z_b - a_4 \sin\alpha_4) / l \right] \tag{11}$$

$$\theta_2 = \xi_2 + a\cos\left[\left(a_2^2 + l^2 - a_3^2 \right) / \left(2a_2 l \right) \right] \tag{12}$$

$$\theta_3 = -\pi + a\cos\left[\left(a_2^2 + a_3^2 - l^2 \right) / \left(2a_2 a_3 \right) \right] \tag{13}$$

$$\theta_4 = \alpha - \theta_{23} \tag{14}$$

2.3 Modeling of the Excavator's manipulator

The Dynamic model of excavator can be expressed concisely using the form of the well-known rigid-link manipulator equations of motion:

$$D_\alpha(\theta)\ddot{\theta} + C_\alpha\left(\theta,\dot{\theta}\right) + G_\alpha(\theta) + B_\alpha\left(\dot{\theta}\right) = \Gamma\tau_\alpha - F_L \tag{15}$$

Where

$\theta = [\theta_1\, \theta_2\, \theta_3\, \theta_4]$ is the vector of measured joint angles as defined in Fig.2

$D_\alpha(\theta)$ represents inertia

$C_\alpha(\theta,\dot{\theta})$ represents Coriolis and centripetal effects

$G_\alpha(\theta)$ represents gravity forces

$B_\alpha(\dot{\theta})$ represents frictions

Γ is the corresponding input matrix

$\tau_\alpha = [\tau_1\, \tau_2\, \tau_3\, \tau_4]^T$ specifies the torques acting on the joint shafts

F_L represents the interactive torques between the bucket and the environment during the digging operation.

3. CONTROL OF EXCAVATOR

The control system shown in figure 4 is designed to make the end of effecter track desired trajectory. Using the dynamic model of excavator in (15), the primary controller is given below:

$$U_d = \hat{D}(\theta)\ddot{\theta}_v + \hat{C}\left(\theta,\dot{\theta}\right)\dot{\theta} + \hat{G}(\theta) + \hat{B}\left(\dot{\theta}\right) \tag{15}$$

Where

$\dot{\theta}_v = \ddot{\theta}_d - k_v\, \dot{e} - k_p e$; $e = \theta - \theta_d$ is the error k_v and k_p are the linear gains to be determined.

$\hat{D}(\theta)$ is the estimated inertia, $\hat{C}\left(\theta,\dot{\theta}\right)$ is the estimated Coriolis and centripetal effects, $\hat{G}(\theta)$ is the estimated gravity forces; $\hat{B}\left(\dot{\theta}\right)$ is the estimated friction effects; U_d is the desired torque provided to the system; $\theta_d, \dot{\theta}_d, \ddot{\theta}_d$ are the desired joint link angle, angular velocity and angular acceleration.

A secondary controller is designed to compensate for derivations of the actual motion from the desired
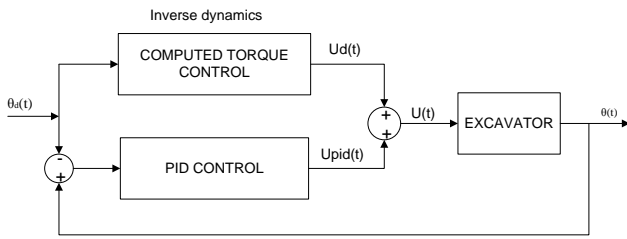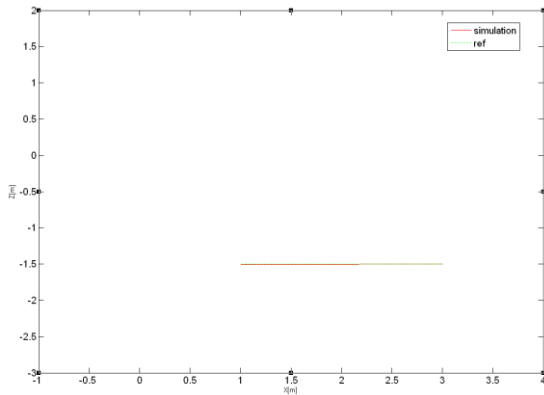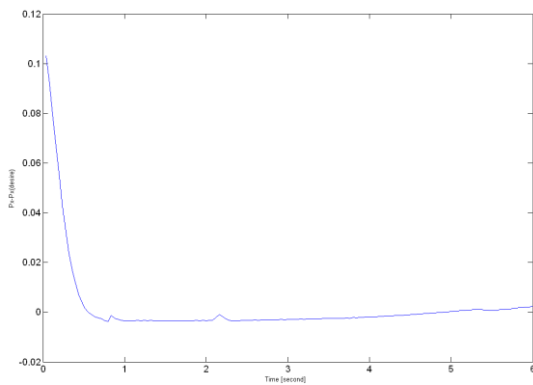
trajectory [2].

Fig.4   Control architecture

4. SIMULATION

A simulation study on an excavator was performed in Matlab/Simulink. A desired trajectory is first designed in the Casterian space. The joint angles of the boom, arm and bucket are determined by using Inverse Kinematic.
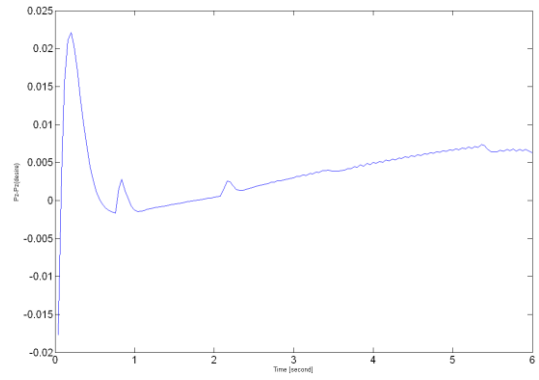
In figure 5 shows the result of the simulation when the trajectory of the bucket is moving horizontal.
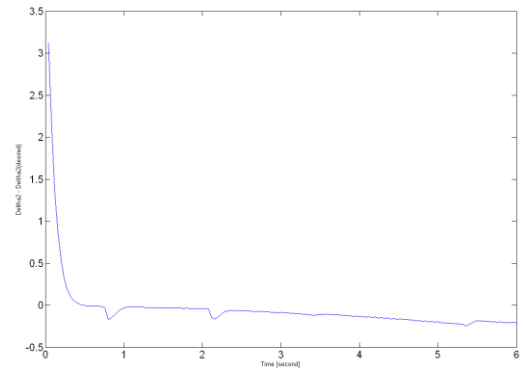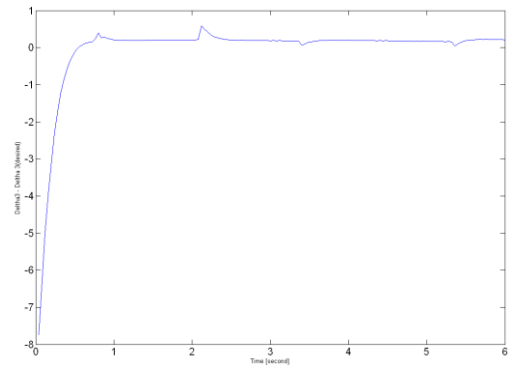

(c)

Fig.5   Horizontal movement (m): (a) Trajectory of the bucket; (b) x-coordinate Error of bucket Position versus time; (c) z-coordinate Error of bucket Position versus time.

The error of the angular joint of boom, arm and bucket are shown in the figure 6. The errors of all the links of system when the bucket is moving are less than 1 degree.
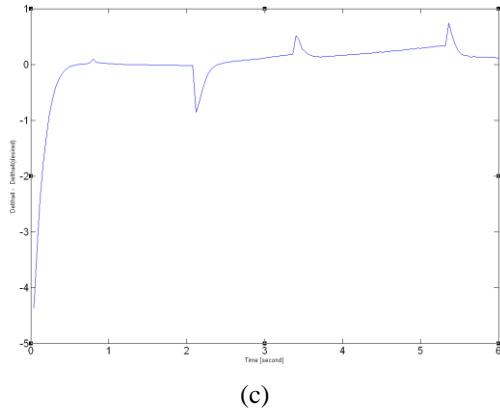

(a)

(b)

(a)

(b)

(c)

Fig. 6   The error of the angular joint
(a) Boom; (b) Arm; (c) Bucket (degree)

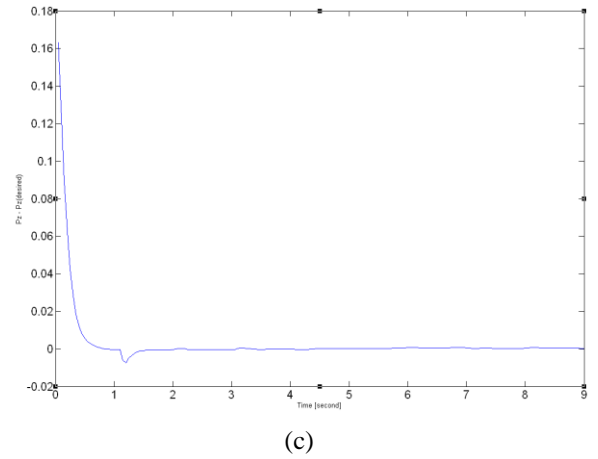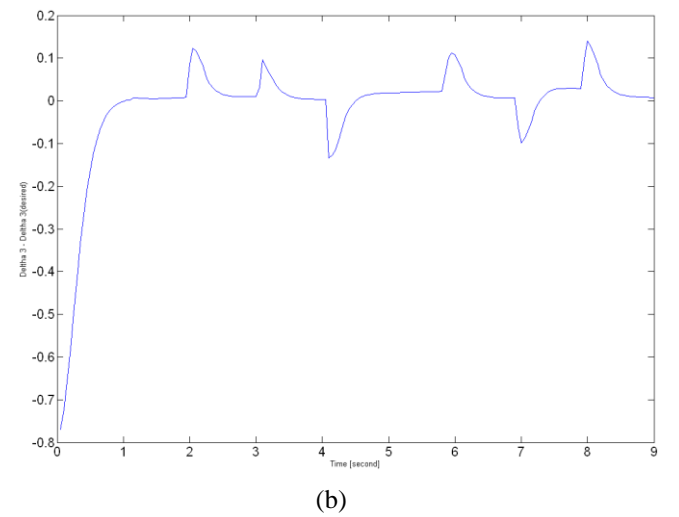Another simulation is shown in the figure 7 when the end of effecter is moving vertical.
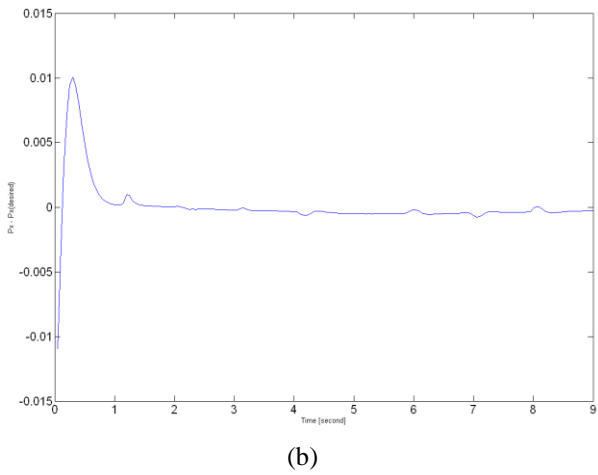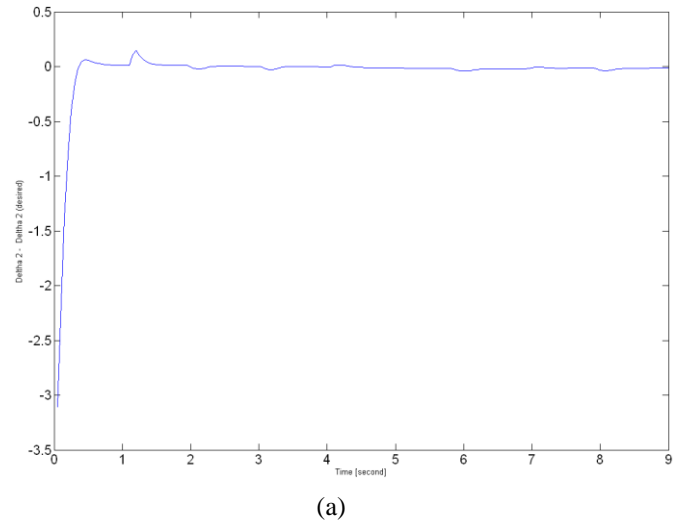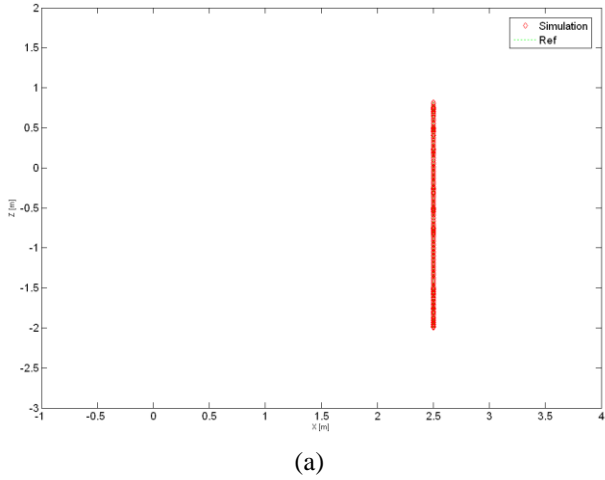

(c)

Fig.7   Vertical movement (m): (a) Trajectory of the bucket; (b) x-coordinate Error of bucket Position versus time; (c) z-coordinate Error of bucket Position versus time.
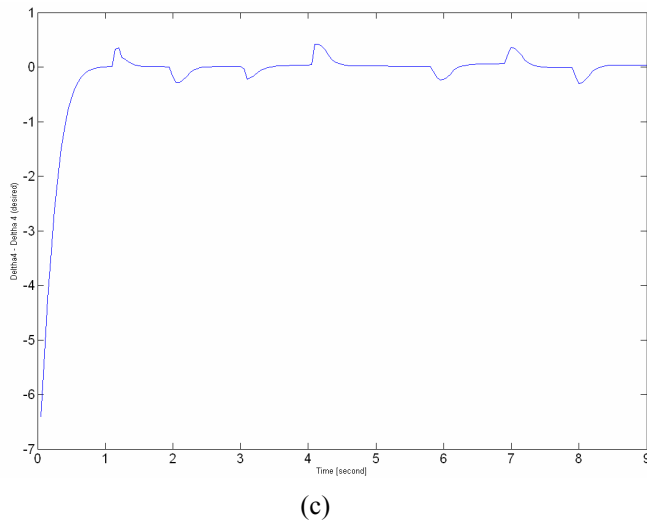

(a)

(a)

(b)

(b)

973

(c)

Fig. 8   The error of the angular joint (a) Boom; (b) Arm; (c) Bucket (degree)

The error of the angular joint of the boom, arm and bucket when the trajectory of the end of effecter is moving vertical is shown in figure 8. The errors of all the links of system when the bucket is moving are less than 0.5 degree. The simulations illustrate that the controller performs very well during the system is operating.

5. CONCLUSION

The paper has reported the review of the Kinematic and modeling of the Excavator's Manipulator. The basic controller is computed torque control and PID control are applied to the system and some simulations are proposed to test the controller.

References

[1] Koivo, A.J. (1994) 'Kinematics of excavators (backhoes) for transferring surface material', *J. Aerosp*. Eng., Vol. 7, No. 1, pp.17–32.

[2] Koivo, A.J., Thoma, M., Kocaoglan, E. and Andrade-Cetto, J. (1996) 'Modeling and control of excavator dynamics during digging operation', *J. Aerosp*. Eng., January, Vol. 9, No. 1, pp.10–18.

[3] Tafazoli. S, P. D. Lawrence, S. E. Salcudean. 'Identification of inertial and friction parameters for excavator arms'. *IEEE Transactions on Robotics and Automation*, vol. 15, no.5, pp.996-971, 1999.

[4]Tafazoli, S., Salcudean, S.E., Hashtrudi-Zaad, K. and Lawrence, P.D. (2002) 'Impedance control of a teleoperated excavator', *IEEE Trans. on Control Systems Technology*, May, Vol. 10, No. 3, pp.355–367.

[5] Hongnian Yu*, Yang Liu and Mohammad Shahidul Hasan, 'Review of modelling and remote control for Excavators', *Int. J. Advanced Mechatronic Systems*, Vol. 2, Nos. 1/2, 2010.

[6] Yang Liu, Mohammad Shahidul Hassan, Hong-Nian Yu, Modeling and remote control of an Excavator', *International Journal of Automation and Computing*, 7(3), August 2010, 349-358.

[7] Ha, Q., Santos, M., Nguyen, Q., Rye, D. and Durrant-Whyte, H. (2002) 'Robotic excavation in construction automation', *IEEE Robotics & Automation Magazine*, March, Vol. 9, No. 1, pp.20–28.

[8] Ha, Q.P., Nguyen, Q.H., Rye, D.C. and Durrant-Whyte, H.F. (2000) 'Impedance control of a hydraulically-actuated robotic excavator', *Automat. Construction*, Vol. 9, No. 5, pp.421–435.

[9] ZHANG Da-qing, HE Qing-hua, HAO Peng. Trajectory tracking control of hydraulic excavator bucket [J]. *Journal of Jilin University: Engineering and Technology Edition*, 2005, 35(5): 490-494.