DESIGN OF HAPTIC DEVICE FOR EXCAVATOR WITH PRESSURE TRANSMITTER

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Abstract

The number of dismantling sites for buildings has been rapidly increased and these processes are very dangerous. So many research papers have been published addressing the development of a remote controller for the dismantling equipments. In this paper, a novel concept of applying haptic control is proposed for the remote control of excavator-like dismantling equipment. As a haptic device system, this controller is designed to improve the operability of the excavator. This paper also includes all the dynamic analysis of excavator to design the haptic device. Then, the hydraulic system of excavator which uses the proportional valve and pressure transmitter is also studied briefly. And parameter estimation of excavator is carried out with least square method. Last simulation result which is about the parameter estimation will be shown. And operator can control the real excavator intuitively with this new model of haptic device.

KEYWORDS: Excavator Control, Haptic Device, Dynamics, Parameter Estimation.

INTRODUCTION

The construction technology has been developed for thousands of years, so the latest buildings are about several hundred meters high. Furthermore, how tall buildings can be stably constructed has been a main theme in architecture. Recently, however, how to dismantle an old high-rise building has also been focused by many researchers. Dismantling methods have been also developed for centuries, and among these methods, mechanical dismantling has been very common. For example, the excavator which is used to construct a new designed building is also utilized for the heavy equipment for dismantling processes. Especially crusher and breaker are the attachments for the excavator to crack the building to pieces. This excavator which is equipped with the attachment can be easily seen at dismantling sites. However dismantling processes are very dangerous, so many safety-related accidents happen in many sites. Furthermore, operator has to ride on the excavator and this makes the dismantling process more dangerous. Therefore, remote control device is necessary to guarantee an operator’s safety.

There have been some recent researches related to the tele-operation of the excavator. First, basic research is tracking control of excavator equipped with electrical proportional valve. For this trajectory control, kinematics and dynamics analysis should be carried out. Koivo

(1996) formulated the dynamics model, and some methods are studied to estimate the parameter which is used in dynamic formulation (Atkeson et al., 1986)(Ma et al., 1996)(Tafazoli et al., 1999). With these basic researches, PID, Fuzzy and another control algorithms are developed to control the excavator. After, some devices are developed to control the excavator at remote site. Frankel (2004) studied remote control of excavator with commercial haptic device, Phantom. And last, new joystick devices are studied. So, Operator can control the excavator with one's arm and hand.

However, there are few researches about force feedback device. So in this paper, haptic device for excavator is newly designed and introduced. The shape of this haptic device is almost same with the links of excavator. And operator can control this device with one's finger, wrist and arm. So this developed device is very intuitive and comfortable. And next, to estimate the external force exerted to the bucket tip, dynamic of excavator will be shown briefly. And parameter estimation will be conducted with the nonlinear least square method. With these estimated value, information about the external force at bucket tip can be transferred to the haptic device. Finally, experiment setup to estimate the dynamic parameters and simulation results will be explained.

HAPTIC DEVICE

Hardware Design of Haptic Device

The haptic device which is newly designed is shown in figure 1. Like the figure, motion of finger controls the bucket angle. Second the rotation of wrist controls the angle of arm, and last arm controls the angle of boom. Traditional method to move the excavator is two joystick levers which move in all directions. But this is very difficult to control the excavator for beginner. To solve this problem, haptic device is designed like the shape of excavator, so operator can understand the motion of excavator with haptic device easily. This is a big advantage of this device. In this haptic device, three DC motors (Maxon) are installed at each joint. So operator can feel the force which is external force at bucket tip. To control the motion of motors, functions which are supported from Maxon corporation are used. So, in this paper, explanation of this control method will be skipped.

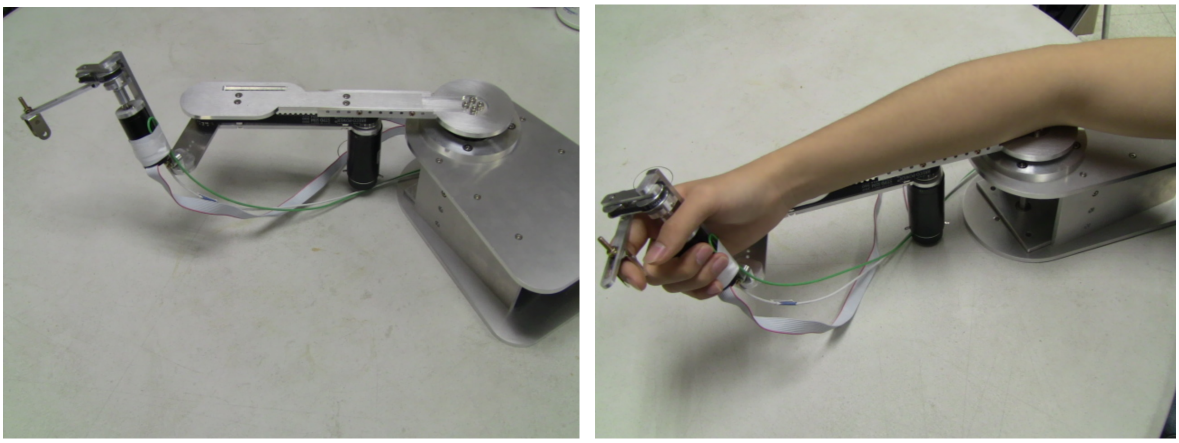


Figure 1: Newly Designed Haptic Device for Excavator

KINEMATICS AND DYNAMICS OF EXCAVATOR

Kinematics of Excavator

To control the trajectory of excavator, kinematics analysis is a basic research. With this kinematics, angles of boom, arm and bucket can be calculated from the stroke length of hydraulic cylinder. And from the angle of each link, position of bucket tip can be acquired. This is forward kinematics. There are so many researches about this kinematics(Frankel, 2004), so skipped in this paper.

Dynamics of Excavator

There are also many studies about dynamics of excavator. But parameters which are used in dynamics formulation are difficult to know: inertia of link, friction of joint and cylinder, etc. So some methods, for example least square method or Newton's methods(Zweiri et al., 2004), are proposed to estimate the values of parameters. First dynamics formulation is shown like following equation.

$$M(\theta)\ddot{\theta}+V(\theta,\dot{\theta})+G(\theta)+F_{friction}(\dot{\theta})=\Gamma(\theta)F \tag{1}$$

M is inertia matrix, V is velocity coupling vector, G is the vector of gravitational torques, and $F_{friction}$ is the friction of joint. Last, Γ is moment arm which is used to calculate the joint torques from the cylinder forces and F is the vector of cylinder force.

Formulation of Gravitational Torques and Friction

Vector of gravitational torques G and friction forces are important to get the information of force which is exerted to the bucket at stationary pose or slow motion. So in this case, dynamic formulation can be simplified like following equation.

$$G(\theta)+F_{friction}(\dot{\theta})=\Gamma(\theta)F \tag{2}$$

The components of vector G are calculated like following equations.

$$\begin{aligned} G_1 = m_1 g L_{O1G1}\cos(\theta_1 + A_{mc\_boom}) + m_2 g[l_1 c_1 + L_{O2G2}\cos(\theta_{12} + A_{mc\_arm})] \\ + m_3 g[l_1 c_1 + l_2 c_{12} + L_{O3G3}\cos(\theta_{123} + A_{mc\_bucket})] \end{aligned} \tag{3}$$

$$G_2 = m_2 g L_{O2G2}\cos(\theta_{12} + A_{mc\_arm}) + m_3 g[l_2 c_{12} + L_{O3G3}\cos(\theta_{123} + A_{mc\_bucket})] \tag{4}$$

$$G_3 = m_3 g L_{O3G3}\cos(\theta_{123} + A_{mc\_bucket}) \tag{5}$$

So to calculate the G with angles of each link ($\theta_1, \theta_2, \theta_3$), m_i, L_{OiGi}, A_{mc} should be known parameters. However the mass of link and the position of COG are not given. So components of vector G are nonlinear equation. And viscous friction effect is considered like following equation in this paper. μ_i is the coefficient of viscous friction.

$$F_{friction\ i} = \mu_i \cdot \dot{\theta}_i \quad (i = 1,2,3) \tag{6}$$

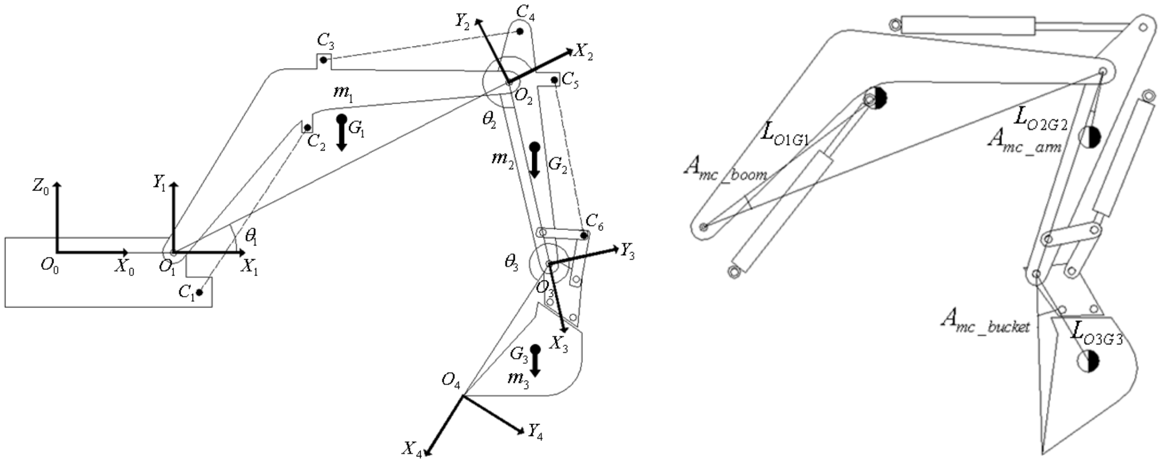


Figure 2: (a) Coordinate frame of excavator; (b) Position of COG

SIMULATION RESULTS

Experiments Setup

In this paper, Solar 015 Super (Doosan Infracore, Co., Ltd.) is used to make the testbed for haptic device. Proportional valves and wire-encoders are installed in this mini excavator. This setup is shown in figure 3. So excavator can be controlled with PC through proportional valve. And angle of link can be acquired from the length of cylinder stroke with wire-encoder. After all, trajectory control of boom, arm and bucket link can be carried out. Additionally, to estimate the external force, pressure transmitters are setup on the cylinder. 6 transmitters which can measure up to 400bar are installed at the inlet and outlet of boom, arm and bucket cylinder. Visual C++ is used to make the control program and sampling time is 15ms. Figure 4~6 are the graph of each joint angle. And the right side of figure is the graph of pressure at the inlet and outlet of each cylinder. Inlet and outlet area of cylinders are known parameter, so cylinder force and joint torque can be acquired with some kinematic analysis. These torque and joint angle data will be used to estimate the dynamic parameters.

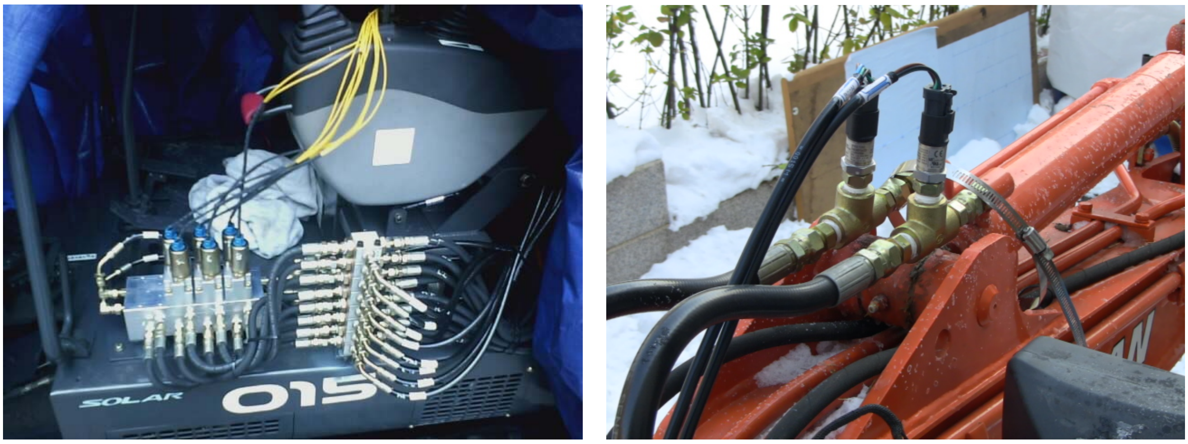


Figure 3: (a) Proportional valves on excavator; (b) Pressure transmitters at arm link

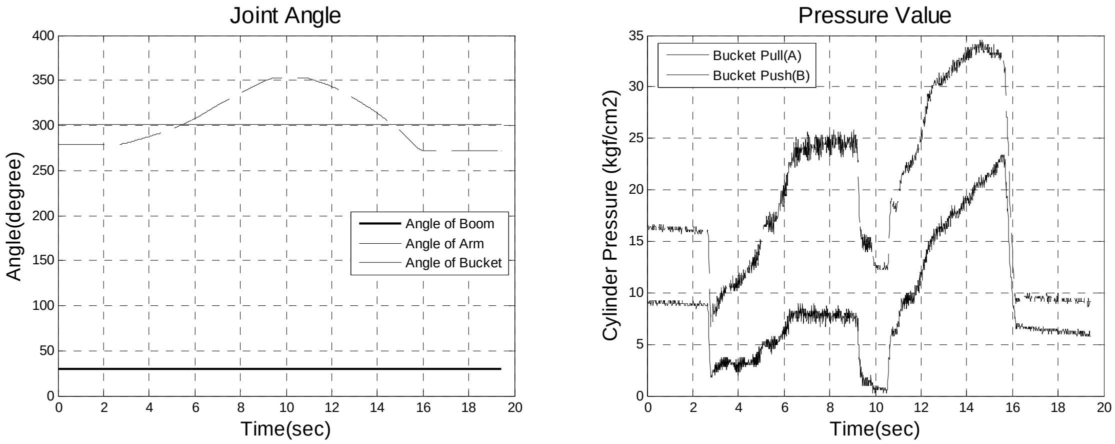


Figure 4: Pressure of bucket cylinder when the bucket moves

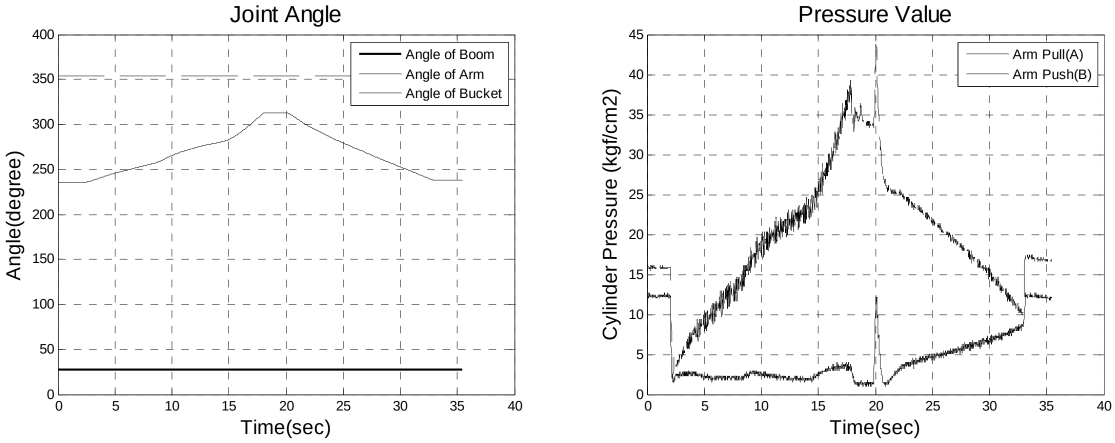


Figure 5: Pressure of arm cylinder when the arm moves

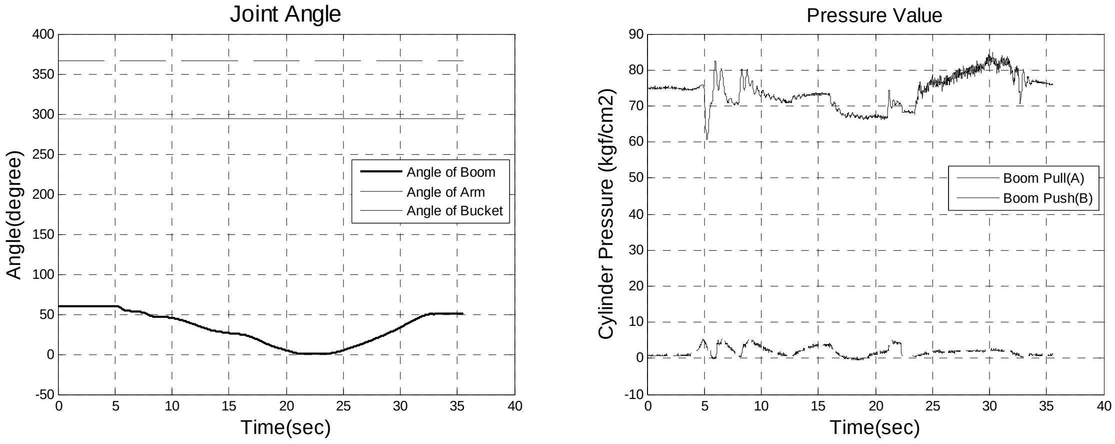


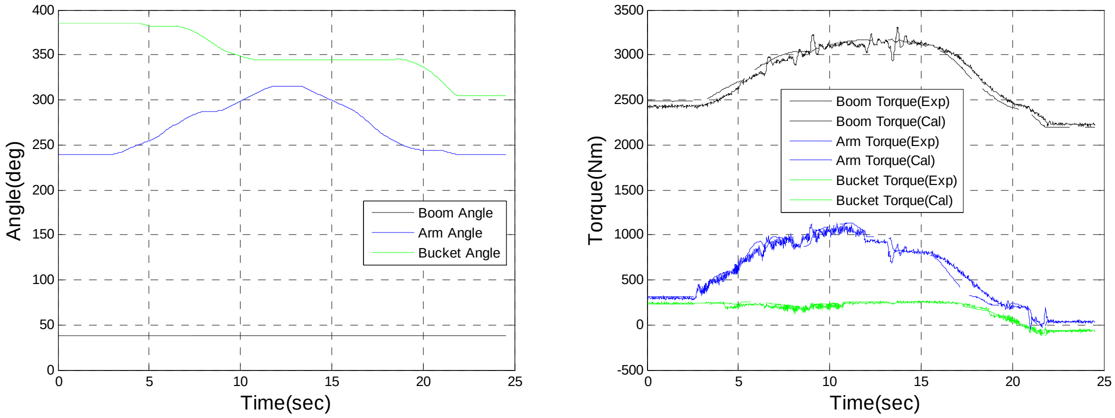
Figure 6: Pressure of boom cylinder when the arm moves

Estimation Results

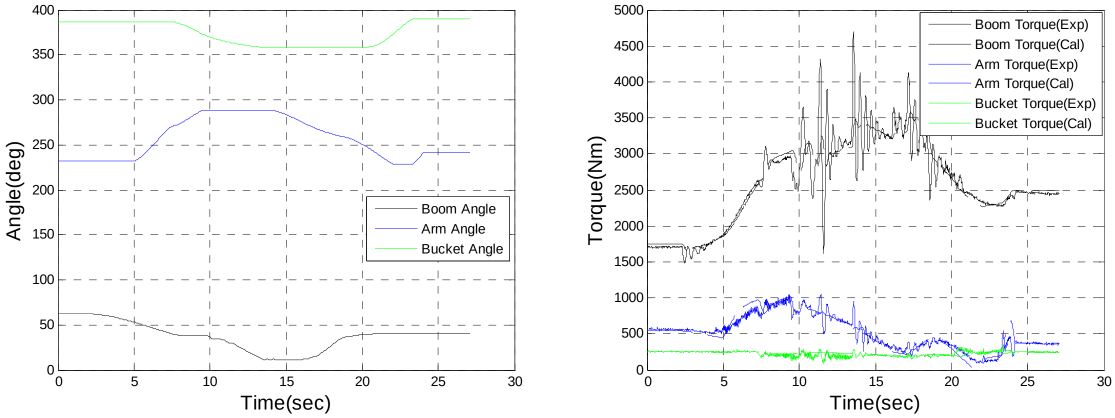
Pressure values are measured at slow motion. Then these values are used to estimate the gravity parameter of each link and friction coefficient with Matlab-toolbox (nonlinear least square method). And Estimation results are shown in table 1. So these estimated values can be used to haptic device for force feedback mechanism. We can also prove these values with another two experiments and these verification data are shown in figure 7. Figure 7 (a) is the experiment result when the bucket and arm links move. And Figure 7 (b) is when the all links move. Like this figure, estimated torque data is almost same with the measured torque data. However, in the figure 7 (b), this experiment is carried out with boom accelerating and decelerating motion, so inertia affects the result of estimation. There is vibrating motion.

Table 1: Estimation results of dynamic parameter

Links	$m_i \cdot L_{OiGi}$	A_{mc_i}	μ_i
Boom	98.65 kg m	11.48 degree	37.19 Nm/(deg/sec)
Arm	28.30 kg m	-2.67 degree	15.60 Nm/(deg/sec)
Bucket	26.01 kg m	31.82 degree	3.57 Nm/(deg/sec)



(a) Verification test 1



(b) Verification test 2

Figure 7: Estimated and calculated torque of each joint

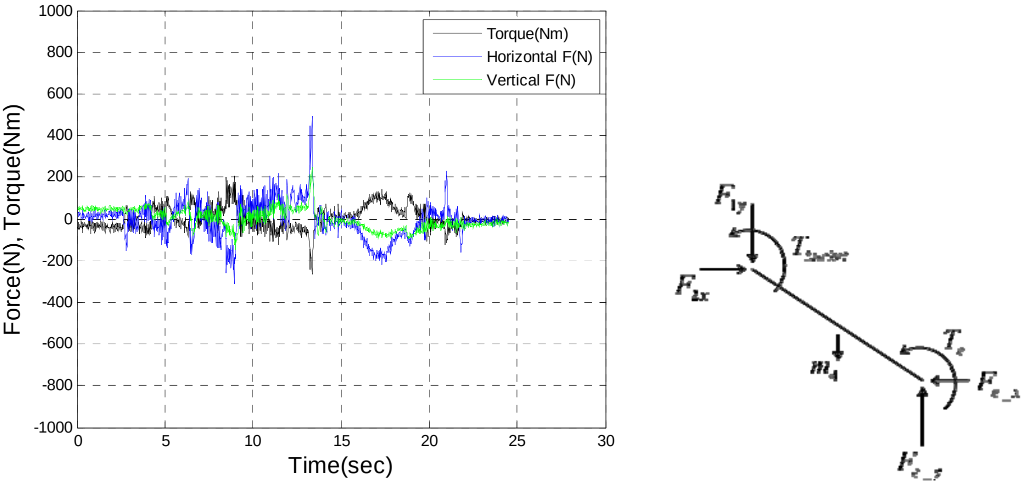


Figure 8: Estimation result of no payload

Figure 8 is about the load estimation result and free body diagram of bucket link. Horizontal, vertical forces and Torque at the bucket tip are shown in this figure. These forces can be calculated straightforwardly with matrix inversion. This is the simulation of no payload. So if the estimated parameter can exactly represent the dynamics, there is no force at bucket tip. However, there are horizontal and vertical forces which are under 200N in this experiment. These forces are very small as compared with real process of excavation. So this value is reasonable. If the weight whose mass is known is installed on bucket link, the pressure can be changed and also estimated. So from the pressure of cylinder, additional mass of bucket can be acquired. This information will be transferred to the haptic device and operator can feel the force exerted to the bucket tip.

CONCLUSIONS

In this paper, a newly designed haptic device is proposed for the remote control of excavator-like dismantling equipment. And to make the force feedback algorithm, first, external forces should be acquired. So pressure transmitters are used to estimate the values of gravitational vector in dynamics. And nonlinear least square method is applied to estimate. After all, gravity and friction parameters of links are estimated and these values can be used to find the external force. In the future, applying the force feedback mechanism, new haptic device will be used for many novice operators. So operator can control the excavator at the remote site safely and comfortably.

REFERENCES

A. J. Koivo, M. Thoma, E. Kocaoglan, and J. Andrade-Cetto (1996) Modeling and control of excavator dynamics during digging operation. Journal of Aerospace Engineering, 9(1), 10-18.

D. Ma and J. M. Hollerbach (1996) Identifying mass parameters for gravity compensation and automatic torque sensor calibration. Proceeding IEEE International Conference Robotics and Automation, Minneapolis, MN, 661-666.

J. G. Frankle (2004) Development of a Haptic Backhoe Testbed. A Thesis for the Degree of Master of Science, School of Mechanical Engineering, Georgia Institute of Technology.

S. Tafazoli, P. D. Lawrence, and S. E. Salcudean (1999) Identification of inertial and friction parameters for excavator arms. IEEE Transactions Robotics and Automation, 15, 966-971.

Y. H. Zweiri, L. D. Seneviratne, and K. Althoefer (2004) Parameter estimation for excavator arm using generalized newton method. IEEE Transactions on Robotics, 20(4), 762-767.

C. G. Atkeson, C. H. An, and J. M. Hollerbach (1986) Estimation of inertial parameters of manipulator. Int. J. of Robotics Research, 5(3), 101-119.