Parameter Estimation and Actuator Friction Analysis for a Mini Excavator

S. Tafazoli, P.D. Lawrence, S.E. Salcudean, D. Chan, S. Bachmann and C.W. de Silva†
Departments of Electrical and Mechanical† Engineering
University of British Columbia
Vancouver, B.C. V6T 1Z4, Canada
shahram@ee.ubc.ca

Abstract- Gravitational and friction terms play an important role in achieving high performance control of heavy-duty hydraulic machines, such as excavators. In this paper, a new approach for decoupled estimation of the gravitational parameters is presented. Static experiments are carried out with an instrumented computer-controlled mini excavator to estimate the gravitational parameters. Load pins are used for indirect measurement of the joint torques from cylinder reaction forces. It is investigated via experiments that bucket payload can be estimated with a 5% accuracy. Furthermore, direct measurement of the actuators' friction shows that considerable amount of static friction exists inside the cylinders that cannot be neglected.

1. INTRODUCTION

The mini excavator is a heavy-duty human-operated hydraulic machine. This machine has a manipulator-like structure as shown in Figure 1. Typically, a human operator controls the main four links of the manipulator in joint-space coordinates through movements of two 2–DOF mechanical hand levers. Considerable improvements in the performance of these types of machines can be achieved by computer-assisted control [1]. Indeed, human factor experiments have shown that resolved-mode endpoint velocity control leads to faster task completion time [2]. In such an approach, the two hand levers are replaced by a 4–DOF joystick (three translational and one rotational degree of freedom). The operator is able to directly control the motion of the implement in Cartesian-space rather than coordinating the movements of all links to provide desired endpoint (bucket) motion.

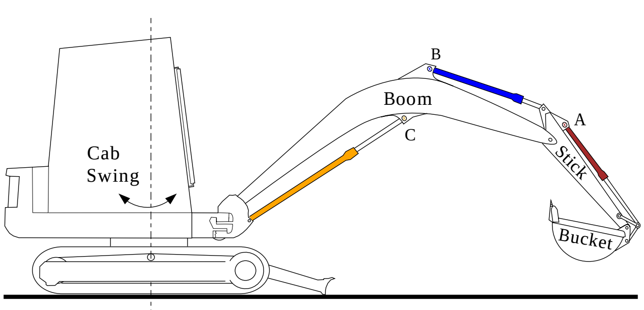

Figure 1. Schematics of the mini excavator

To perform closed loop computer control, several displacement, fluid pressure and force sensors are required and the pilot stage of the main valves has to be modified. Identification of the gravitational parameters and actuator friction analysis can be performed using these sensors.

Joint torque sensors for electric motor robots such as PUMA have been designed and reported in the literature [3,4]. This is useful for implementation of the joint torque control, reduction of the effective friction and measurement of the external forces [3,4]. A new approach is proposed here for sensing the joint torques of a hydraulic machine, which is based on load pin force sensors installed on hydraulic cylinder hinges.

Application of force feedback to heavy-duty hydraulic manipulators has been addressed in [2,5,6]. Indirect measurement of the endpoint forces is required in order to implement master-slave force-reflecting resolved motion control. In [5,6], the endpoint forces were measured from cylinder pressures. Because of the actuator friction (or sealing friction), force measured from cylinder pressures is not a suitable representation of the external force. An alternative method is proposed here to estimate the gravitational parameters and to measure the endpoint forces.

This paper is organized as follows: Machine instrumentation is briefly explained in Section 2. The new approach for decoupled estimation of the gravitational parameters is introduced in Section 3. Joint torque measurement using the installed sensors is explained in Section 4. Experimental results for estimation of the gravitational parameters are reported in Section 5. Bucket load estimation using the identified parameters is presented in Section

6. Section 7 is devoted to the analysis of the static friction inside the actuators. Conclusions and future work are outlined in Section 8.

2. MACHINE INSTRUMENTATION

The following sensors have been installed on each of the backhoe[1]actuators :

- ☐ A linear position sensor to measure the piston displacement.
- ☐ A load pin to measure the reaction force of the cylinder to its hinge. This reaction force sensor is sensitive to both tension and compression. In Figure 1, the load pins for the bucket, stick and boom are designated as A, B, C. Note that these load pins are fixed to the body of the machine. Reaction force and torque sensors have been explained in [7].
- ☐ Two hydraulic pressure sensors to measure the line pressures.

The pilot stage of the main valves has also been modified to be able to control the machine by computer [8]. This issue is not studied here, because the experiments are done with the manipulator in the idle condition. The sensors and the modified pilot valve have been connected to a VME-bus based computer system. The resolver outputs are connected to an R/D board in the VME cage. All other sensor outputs are directed to the A/D board in the VME cage.

3. ESTIMATION OF THE GRAVITATIONAL PARAMETERS

Assuming that there is no load in the bucket and the manipulator is not actuated, the torque measured at each joint is produced by the gravitational forces on the bucket, stick and boom links. Figure 2 shows a schematic representation of the manipulator links. The assigned joint angles are $(\theta_2, \theta_3, \theta_4)$. The cab swing angle is not shown in Figure 2, as it is not considered in this study. In Figure 2, cg_i is the center of gravity for link i with the polar coordinates (r_i, α_i) in the corresponding link.

The Link angles with respect to the horizontal plane are

$$\theta_2, \quad \theta_{23} \triangleq \theta_2 + \theta_3, \quad \theta_{234} \triangleq \theta_{23} + \theta_4 \qquad (1)$$

The joint torque equations are as below:

$$\begin{aligned}
\tau_4 &= M_{bu} g r_4 cos(\theta_{234} + \alpha_4) \\
\tau_3 &= \tau_4 + M_{bu} g a_3 cos\theta_{23} + M_{st} g r_3 cos(\theta_{23} + \alpha_3) \\
\tau_2 &= \tau_3 + (M_{bu} + M_{st}) g a_2 cos\theta_2 + M_{bo} g r_2 cos(\theta_2 + \alpha_2)
\end{aligned} \qquad (2)$$

[1] The term “backhoe” denotes to the bucket, stick and boom links.

Now, define the static parameter vector $\underline{\Phi}_s$ as follows:

$$\underline{\Phi}_s = \begin{bmatrix} \varphi_1 \\ \varphi_2 \\ \varphi_3 \\ \varphi_4 \\ \varphi_5 \\ \varphi_6 \end{bmatrix} = \begin{bmatrix} M_{bu} r_4 cos\alpha_4 \\ M_{bu} r_4 sin\alpha_4 \\ M_{bu} a_3 + M_{st} r_3 cos\alpha_3 \\ M_{st} r_3 sin\alpha_3 \\ (M_{bu} + M_{st}) a_2 + M_{bo} r_2 cos\alpha_2 \\ M_{bo} r_2 sin\alpha_2 \end{bmatrix} \qquad (3)$$

Intuitively, we expect all these parameters to be positive. Using the definition (3), equations (2) can be expressed in the following decoupled vector forms:

$$\begin{aligned}
\tau_4 &= [gc_{234} \quad -gs_{234}] \begin{bmatrix} \varphi_1 \\ \varphi_2 \end{bmatrix}, \\
\tau_3 - \tau_4 &= [gc_{23} \quad -gs_{23}] \begin{bmatrix} \varphi_3 \\ \varphi_4 \end{bmatrix}, \\
\tau_2 - \tau_3 &= [gc_2 \quad -gs_2] \begin{bmatrix} \varphi_5 \\ \varphi_6 \end{bmatrix},
\end{aligned} \qquad (4)$$

where $c_{234} = cos\theta_{234}$, $s_{23} = sin\theta_{23}$ and so on. Thus, the gravitational parameters can be determined from the three decoupled equations of the form $\Delta\tau = \underline{W}^T \underline{\varphi}$, where the regressor vectors W are functions of the link angles with horizontal plane.

If the static experiment is repeated *n* times for different configurations of the manipulator, three composite coefficient matrices with *n* rows and *2* linearly independent columns are obtained. Thus the parameter vector $\underline{\Phi}_s$ can be estimated using the linear least squares algorithm.

Note that according to definition (3), the parameters are constant if the centers of gravity are fixed within their

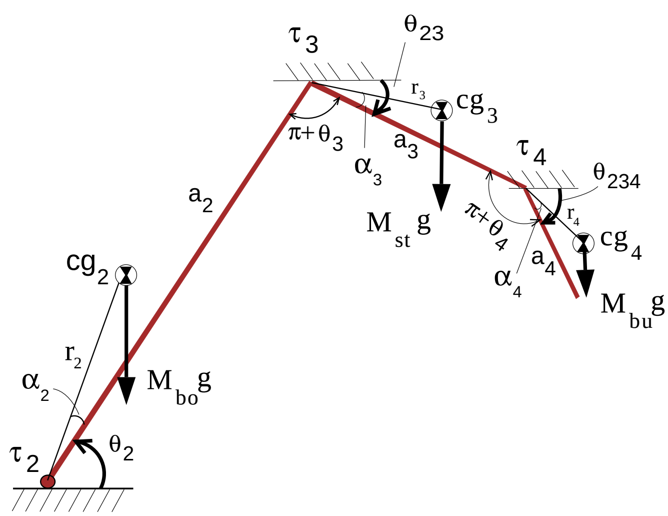

Figure 2. Gravitational forces on the links. Note that for this configuration, $\theta_2 > 0, \theta_{23} < 0, \theta_{234} < 0$.

links. Because of the cylinders and their minor linkages, this assumption is not correct. In other words, $cg_i's$ depend on the manipulator configuration. In spite of this fact, for simplicity, we assume that $cg_i's$ are fixed. The variation of the $cg_i's$ would affect standard deviation of the estimated parameters. The parameters which are more dependent on the location of $cg_i's$ will be estimated with higher standard deviations.

In the next section, we explain how this experiment can be carried out using the outputs of the installed sensors.

4. JOINT TORQUE MEASUREMENT

The only position sensors are the linear sensors installed on each actuator. Using the geometry of the machine, the trigonometric mapping between linear displacement of each piston and corresponding joint angle can be found. This mapping $(\theta(x))$ is essential to find the joint angles given the piston displacements. In addition, as will be explained, its derivative $J \triangleq d\theta/dx$ can be used to derive the joint torques from load pin readings, and also to convert linear velocity of the piston to angular velocity of the joint. Instead of using the trigonometric mapping to calculate $\theta(x_0)$ and its derivative $J(x_0)$ for a given x_0, it is beneficial to use polynomial approximation for $\theta(x)$. Horner's algorithm [9] can be used for recursive calculation of the polynomial and its derivative for a given piston displacement. For an n-th order polynomial, 2n-1 multiplications and 2n-1 additions are needed to calculate the polynomial and its derivative [9]. Therefore, for our 5th order polynomial 9 multiplications and 9 additions are required for simultaneous calculation of $\theta(x_0)$ and $J(x_0)$ for a given x_0. This is particularly important for real time calculations.

Let's discuss the bucket actuator in detail. The stick and boom actuators can be dealt with similarly. Figure 3 shows the bucket actuation system.

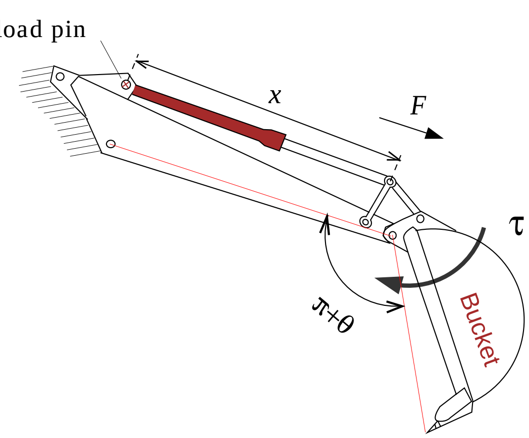

Figure 3. The bucket degree of freedom

Using the trigonometric relations for the four-bar linkage, the mapping $\theta(x)$ was obtained. It was verified that $\theta(x)$ can be approximated with the following polynomial:

$$\begin{aligned}\theta = &-417.6293x^5 + 2049.1x^4 - 4019.9x^3 \\ &+3939.4x^2 - 1932.1x + 380.5009\end{aligned} \tag{5}$$

With this approximation, the maximum angular error was 0.3 degree, which corresponds to a negligible position error of $3.7mm$ at the bucket tip. Piecewise polynomial approximation can be used to achieve higher accuracy, if necessary. Figure 4 shows the polynomial $\theta(x)$ and its derivative $J(x)$ for the full range of bucket motion.

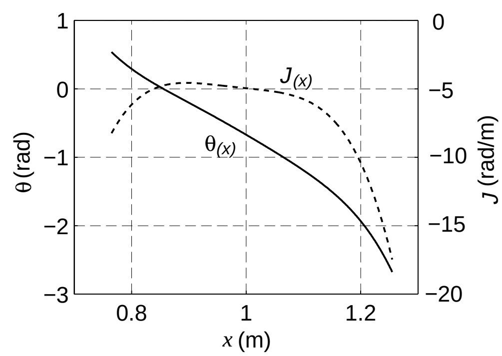

Figure 4. Polynomial approximation for the bucket actuator.

In Figure 3, the joint torque τ is due to the weight of the bucket. Neglecting the joint friction, the virtual work principle [10] implies that

$$\tau d\theta = F dx, \tag{6}$$

where F is the gravity force on the bucket piston. In a static condition, where the main valves are all closed, Newton's third law gives

$$\begin{aligned}F_r &= F \\ F_p &= F - F_f\end{aligned} \tag{7}$$

where,

F_r = reaction force sensed by the load pin,
$F_p = P_1A_1 - P_2A_2$ = the force measured from pressure readings,
F_f = static friction between the piston and cylinder.

According to (7),

1. Due to the static friction inside the actuator, load pin reading is a more accurate representation of the external force than the force measured from pressure sensors.
2. Actuator friction can be directly measured from load pin output and cylinder pressures, i.e., $F_f = F_r - F_p$.

Equations (6) and (7) can be combined to obtain the following expression for the bucket joint torque,

$$\tau(x_0) = F_r / J(x_0). \quad (8)$$

Finally, using the chain rule, the following equation for conversion of piston linear velocity to the joint angular velocity is obtained.

$$\dot{\theta}(t) = \dot{x}(t) J(x) \quad (9)$$

5. EXPERIMENTAL RESULTS

The static experiment described in Section 3 was repeated $n = 110$ times for different configurations of the manipulator. The sensor outputs were recorded for off-line analysis. Using the polynomial approach explained in Section 4, the joint angles and joint torques were calculated for each configuration. The linear least squares algorithm was used to identify the gravitational parameters. Standard deviation of the estimated parameters were calculated using the method explained in [11]. The estimated parameters and their standard deviations are listed in Table 1.

parameter	estimated value $(Kg.m)$	standard deviation $(Kg.m)$
φ_1	26.75	1.09
φ_2	12.80	1.20
φ_3	113.66	1.52
φ_4	7.44	1.35
φ_5	645.31	3.41
φ_6	17.62	4.58

Table 1. Estimated parameters and their standard deviations.

According to Table 1, the parameters $(\varphi_2, \varphi_4, \varphi_6)$ are estimated less accurately compared to the other parameters. Therefore, these parameters must be more sensitive to the variation of the links centers of gravities (see definition (3)).

Figure 5 shows the measured joint torques and their estimated values using the parameters of Table 1. According to Figure 5, the torque estimation of the bucket link has higher relative errors than the stick and boom. Bucket joint friction is the main reason. Note that the bucket is less heavy than the stick and boom, and therefore its gravitational torque is comparable to its joint friction. Standard deviations of the torque estimation errors are listed in Table 2.

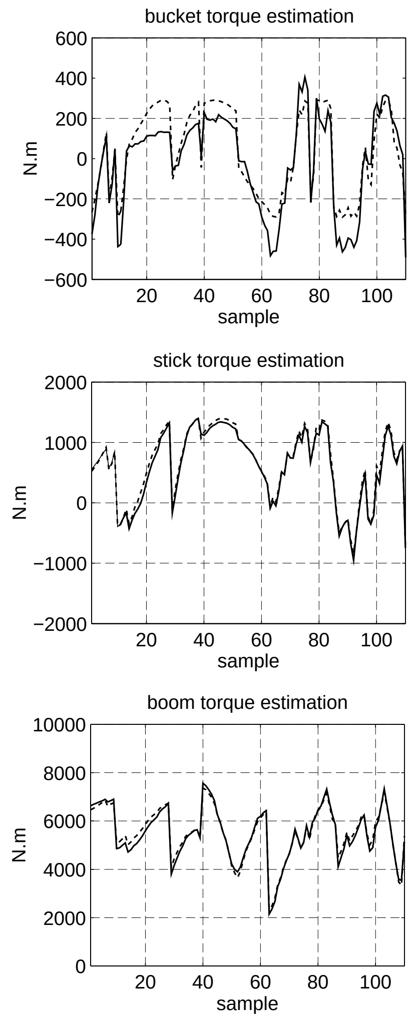

Figure 5. Measured (solid line) and estimated (dotted line) no-load joint torques.

joint torque	standard deviation of estimation error $(N.m)$
bucket, τ_4	82.86
stick, τ_3	49.56
boom, τ_2	158.28

Table 2. No-load torque estimation errors.

Using the identified parameters in Table 1, the no-load static joint torques can be estimated from joint angles. This can be employed to;

1. Improve the trajectory tracking performance by gravity compensation.
2. Measure the external forces applied to the manipulator. In particular, bucket load estimation is studied in the next section.

6. BUCKET LOAD ESTIMATION

Define $\tau_{34} \triangleq \tau_3 - \tau_4$, $\tau_{23} \triangleq \tau_2 - \tau_3$ and $\tau_{24} \triangleq \tau_2 - \tau_4$. Equations (2) can be reformulated as:

$$\begin{aligned}(\tau_{34})_{NL} &= M_{bu} g a_3 cos\theta_{23} + M_{st} g r_3 cos(\theta_{23} + \alpha_3),\\ (\tau_{23})_{NL} &= (M_{bu} + M_{st}) g a_2 cos\theta_2 + M_{bo} g r_2 cos(\theta_2 + \alpha_2).\end{aligned} \quad (10)$$

Here NL corresponds to the no-load condition. Now, with a mass M inside the bucket, the torques change to

$$\begin{aligned}\tau_{34} &= (\tau_{34})_{NL} + M g a_3 c_{23},\\ \tau_{23} &= (\tau_{23})_{NL} + M g a_2 c_2.\end{aligned} \quad (11)$$

Three methods to measure the load, based on equations (11) are:

$$\begin{aligned}M &= \frac{1}{g a_3 c_{23}}(\tau_{34} - (\tau_{34})_{NL}),\\ M &= \frac{1}{g a_2 c_2}(\tau_{23} - (\tau_{23})_{NL}),\\ M &= \frac{1}{g a_2 c_2 + g a_3 c_{23}}(\tau_{24} - (\tau_{24})_{NL}).\end{aligned} \quad (12)$$

The denominator of the first two expressions may approach zero for some specific configurations of the manipulator. Since the denominator of the last expression is always positive (due to the joint angle limitations), it will be used for bucket load estimation. Using equation (4) for no-load joint torques, we obtain

$$\widehat{M} = \frac{\tau_2 - \tau_4 - g c_{23}\varphi_3 + g s_{23}\varphi_4 - g c_2 \varphi_5 + g s_2 \varphi_6}{g a_2 c_2 + g a_3 c_{23}}. \quad (13)$$

With a known load of $M = 100Kg$ inside the bucket, the manipulator was put into ten different configurations. Figure 6 shows the measured joint torques and the estimated no-load torques. The following estimated values were obtained using equation (13):

$$\begin{aligned}\widehat{M} = &100.88,\ 103.63,\ 98.07,\ 98.47,\ 102.74\\ &102.02, 103.37,\ 95.76,\ 98.18,\ 99.07\end{aligned} \quad (14)$$

which has a mean of $100.22Kg$ and standard deviation of $\sigma = 2.68Kg$.

The main sources of error are:

1. The load pins are connected to the body of the manipulator instead of the cylinder, therefore, due to the small rotation of the cylinders, they are not measuring the whole reaction force. In the future, we will calculate the cylinder angle w.r.t. the corresponding load pin axis to eliminate this measurement error.
2. As discussed earlier, because of the cylinders and their minor linkages, the assumption that the gravitational parameters are fixed is not correct.
3. The geometry of the machine was not available and tape measuring was used to find the lengths.

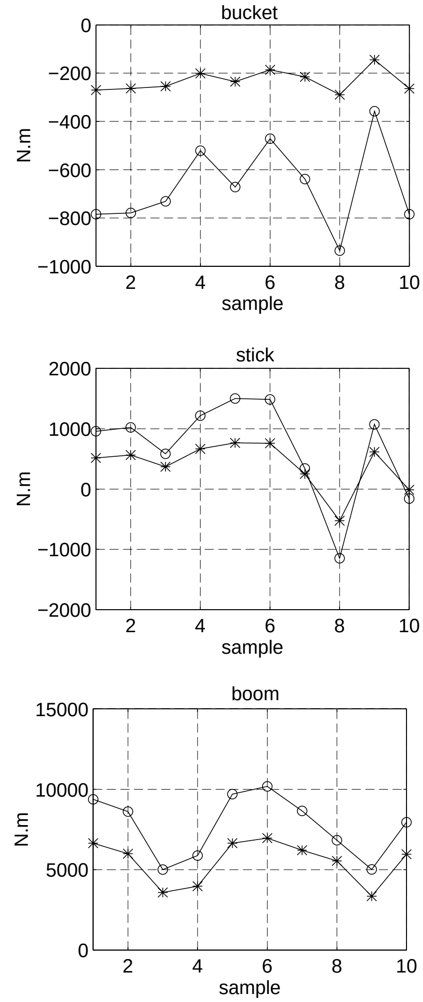

Figure 6. Measured joint torques with load (o) and estimated no-load torques (*) of the backhoe links.

7. ACTUATORS STATIC FRICTION

As explained in Section 4, it is better to use load pin outputs to calculate the joint torques. Experiments with the mini excavator and other experiments reported in [5] show that if pressure readings are used for torque measurements, the results would be erroneous. This is mainly due to the significant static friction that exists inside the actuators, as was pointed out by the authors of [5].

Figure 7 shows the measured force of the bucket actuator (F_r and F_p) and calculated static friction ($F_f = F_r - F_p$) using the n=110 trials of the static experiment. According to Figure 7, considerable static friction exists inside the bucket actuator.

The mean and standard deviation of the static friction inside the backhoe actuators are listed in Table 3.

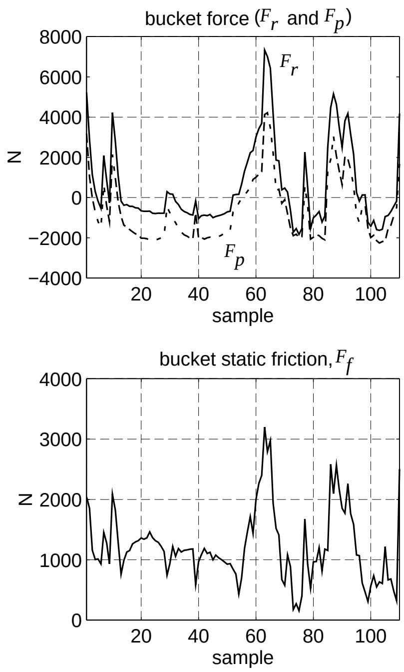

Figure 7. Bucket forces and static friction.

Actuator	mean of static friction (N)	standard deviation of static friction (N)
bucket	1221.74	601.55
stick	1226.21	880.97
boom	-2915.59	716.16

Table 3. Actuators static friction

8. CONCLUSION

Estimation of the mass related (gravitational) parameters of a mini excavator system was considered in this paper. Load pin readings were used to calculate the joint torques. Decoupled static equations of the joint torques were obtained and the least squares estimation were applied to these equations. The identified parameters were used to estimate the bucket load. According to the experimental results, payload estimation using load pins can be performed within 5% accuracy. Since it was found that considerable static friction exists inside the actuators, therefore pressure readings were not used to measure the joint torques.

The estimated gravitational parameters will be used in the future to compensate for gravity in the control of the implement and to measure the external forces applied to the manipulator (for force feedback experiments). This will significantly improve the performance of the teleoperated hydraulic machines.

An important property of a general rigid-body manipulator dynamics is its linearity in a set of well-defined parameters $\underline{\Phi}$ [10]. In this paper, the static parameter vector $\underline{\Phi}_s$ was estimated, which is in fact a subset of the complete parameter vector $\underline{\Phi} = [\underline{\Phi}_d^T \quad \underline{\Phi}_s^T]^T$. Our future research will focus on estimation of $\underline{\Phi}$, employing dynamic experiments.

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