FORCE SENSOR FOR CONSTRUCTION MACHINES BY THEY DRIVING HYDRAULIC CYLINDERS

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Abstract: The paper considers force sensor based on the hydraulic cylinders used to powered the arms of construction machines from dynamics point of view, to the aim to sense interaction between the tool of machine and operating environment, in particular between soil and excavator robot. The regression matrix method is used to identify static dynamic and frictional parameters of machine, which will be used to estimate the force necessary to move machine, while the difference between measured and estimated forces will be the expected result or interaction force. Moreover, the method shows as to consider machine dynamics using position an tilt sensors only. The force sensor can be used also as on-board weighting system.

Keywords: interaction force sensor, hydraulic cylinders, weighting system, machine dynamics

1. INTRODUCTION

In a previous paper [1] was investigated the possibility to use an improved on-board weighting system as force sensor, to sense the soil-bucket interaction force of robotics or automated excavator. In particular the paper [1] considered the static analysis of the sensor, made by the hydraulic cylinders driving the bucket and stick with respective mechanisms or links.

Continuing the previous one, the present work is focused about the dynamic analysis of the sensor, to allow it to sense the interaction force or weight of moved material during the working cycle without to stop the machine.

The problem isn't simple, because the measured forces are the sum of many terms, the gravitational term due to the of weight of bucket, stick and other links, the dynamics terms due to move them, the frictional term due to the friction of cylinders and pins and load term obviously.

The force sensor or system is based on the measures of the pressures on two cylinder only, so to allow the use of this principle with a wide range of construction machines, as loaders and forklifts. At the same time to make system simple, the system doesn't use velocity or acceleration sensors, but angular or linear position and tilt sensors only.

To compute the dynamic term one needs to know the inertia moments of concerned parts of machine, which are not easy to compute, not even using CAD software. So one thinks to identify these parameters by an approach used to built robot adaptive control, based on regression matrix.

This approach, torque filtering and system identification method, like Least Square Estimator, allow to carry out the unknown inertial, static (gravitational) and frictional parameters without use of acceleration sensors. The filtered regression matrix and estimated parameters allow to compute the estimated forces, which by difference with measured forces provide value and direction of interaction force.

For simplicity, the influence of excavator boom and/or machine movements are not considered.

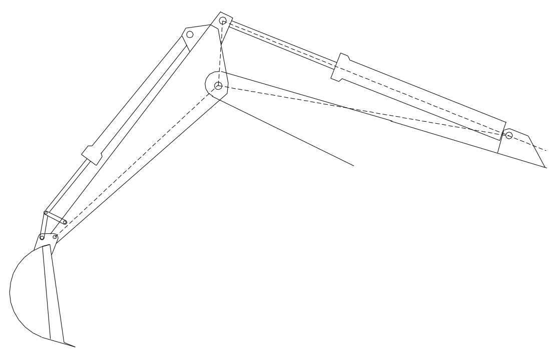

Figura 1

2. FROM STATIC ANALYSIS

The previous work has focused the static analysis of force sensor suitable to sense the soil bucket interaction force, so as the weight of object or moved material.

In practice the static analysis is represented by a system of two static equation with two unknowns, where w is the force or weight to compute and F_1 and F_2 are the forces measured by the differential pressures of the two hydraulic cylinders. For example the following system is related to an excavator stylised in the fig. 1, where W is the force or weight to compute, the unknown is α_x, while h_1 and h_2 are the forces due to the weights of bucket and stick of machine or tares.

$$W l_x \sin\alpha_x = F_1 l_x \sin\left[\Phi_1(\pi - \theta_1)\right] - h_1(\theta_1,\theta)$$

$$W\left[l_x \cos(\pi - \theta_1) + l_B\right]\cos\left[\alpha_x - \left(\frac{\pi}{2} - \theta_1\right)\right] = \quad (1)$$

$$= F_2 l_A \sin\Phi(\theta) - h_2(\theta_1,\theta)$$

Two variables could seem few, but they are a sufficient number to obtain the weight of moved material or the contact force on the fixes contact line of bucket, which are the main requests for many automated tasks and processes of agricultural, earth-moving and handling machine.

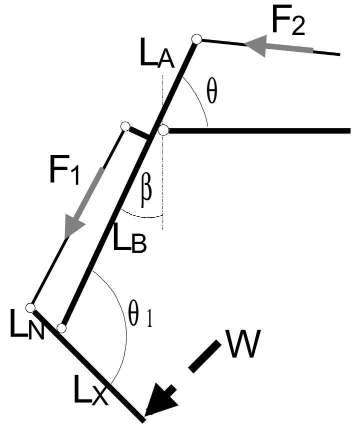

Figura 2

The system required two angular or linear sensors to measure bucket and stick or arm positions, a tilt sensor to have a vertical reference, a CPU and pressure sensor obviously.

3. DYNAMIC ANALYSIS

To compute the interaction force or weight acting on tool during machine movement, one needs to consider the dynamics of parts or all machine, because parts of forces F_1 and F_2 are due to accelerate these parts of machine.

Now to simplify, one avoid to consider the complex dynamics of main frame of many types of machines, here one is considered the dynamics of bucket and stick only, while one is possible to consider the contribution to their dynamics of boom excavator movement.

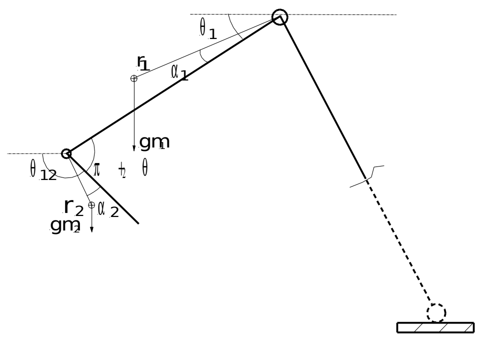

Figura 3

Considering as example the bucket and stick of excavator only, they Newton-Euler dynamics can be to show by the following equations [2],

$$\begin{bmatrix}\tau_1\\ \tau_2\end{bmatrix} = \begin{bmatrix}I_{11} & I_{12}\\ I_{21} & I_{22}\end{bmatrix}\begin{bmatrix}\ddot\theta_1\\ \ddot\theta_1 + \ddot\theta_2\end{bmatrix} + \begin{bmatrix}C_{11} & C_{12}\\ C_{21} & C_{22}\end{bmatrix}\begin{bmatrix}\dot\theta_1^2\\ \dot\theta_1^2 + \dot\theta_2^2\end{bmatrix}$$
$$- \begin{bmatrix}h_{11} & h_{12}\\ h_{21} & h_{22}\end{bmatrix}\begin{bmatrix}m_1 g\\ m_2 g\end{bmatrix} + \begin{bmatrix}l_{11} & l_{12}\\ l_{21} & l_{22}\end{bmatrix}\begin{bmatrix}F_x\cos\alpha_x\\ F_x\sin\alpha\end{bmatrix} \quad (2)$$

where the torques τ_1 e τ_2 are due to F_1 e F_2 forces, I is the inertia matrix, in particular h is the gravity matrix, F_x is the interaction force to compute.

Again

$$I_{11} = I_1 + m_2 r_2 l_1 \cos(\theta_2 + \alpha_2) + m_2 l_1^2 + m_1 r_1^2$$
$$I_{12} = I_2 + m_2 r_2^2 + m_2 r_2 l_1 \cos(\theta_2 + \alpha_2)$$
$$I_{21} = m_2 r_2 l_1 \cos(\theta_2 + \alpha_2)$$
$$I_{22} = I_2 + m_2 r_2^2$$
$$C_{11} = m_2 r_2 l_1 \sin(\theta_2 + \alpha_2)$$
$$C_{12} = m_2 r_2 l_1 \sin(\theta_2 + \alpha_2)$$
$$C_{21} = m_2 r_2 l_1 \sin(\theta_2 + \alpha_2)$$
$$C_{22} = 0$$
$$h_{11} = r_1 \cos(\theta_1 + \alpha_1)$$
$$h_{12} = r_2 \cos(\theta_1 + \theta_2 + \alpha_2) + l_1 \cos\theta_1$$
$$h_{21} = 0 \qquad h_{22} = r_2 \cos(\theta_1 + \theta_2 + \alpha_2)$$
$$l_{11} = l_1 \sin\theta_x \qquad l_{12} = l_1 \cos\theta_x + l_x$$
$$l_{21} = 0 \qquad l_{22} = l_x$$

The positive direction of angles and torque is respect to figure 3 clockwise.

As one cam see, the dynamic equations (2) differ from static ones (1) by the terms depending on angular acceleration and velocity. Theoretically, knowing masses, inertia moments, positions of gravity centers and all angular accelerations and velocities, one could solve the system and carry out the values of forces supply by hydraulic cylinders.

Unfortunately many times one isn't possible to know or disassemble the machine to measure these parameters with sufficient accuracy, so these parameters must be carried out or better identified during the running of machine.

4. REGRESION MATRIX

To compute masses, inertia moments, positions of gravity centers, useful values of distances and angles of bucket, stick, arm and other links of an excavator isn't a simple task. Moreover, to measure angular accelerations could be expensive, while to carry out them from angular positions by double derivative could introduce many errors and noise.

The well note theory of regression matrix [3] allows to identify the model of system and at same time to avoid the use of angular accelerations, in fact it is used for the adaptive control of robot

The previous dynamic equations can be represented by the following relationship

$$\tau = W\left(\ddot{\theta},\dot{\theta},\theta\right)\Phi \qquad (3)$$

where W, the regression matrix, is a matrix of non linear functions, while is linear respect to Φ link parameters, in particular masses and inertia moments.

$$\Phi = \begin{pmatrix} \phi_d \\ \phi_s \end{pmatrix}$$

Knowing the static parameters ϕ_s , the dynamic parameters can be computed solving the linear system.

Now putting $\Delta\tau = \left[\tau_2 \quad \tau_1 - \tau_2\right]^T$ and the previous equations in other form, the unknown parameters become

$$\Phi = \begin{bmatrix} I_2 + m_2 r_2^2 \\ I_1 + m_2 l_1^2 + m_1 r_1^2 \\ m_2 r_2 \cos\alpha_2 \\ m_2 r_2 \sin\alpha_2 \\ m_2 l_1 \cos\theta_1 + m_1 r_1 \cos\left(\theta_1 + \alpha_1\right) \end{bmatrix}$$

where the first two terms are the dynamics parameters, the other three terms are the static parameters.

To solve the system without to measure the angular accelerations the measured torques are filtered by linear filter. Supposing the previous equations of torque putted in the form

$$\tau = \dot{h} + g \qquad (4)$$

where

$$\dot{h} = \frac{d}{dt}\left(I(\theta)\dot{\theta}\right) \quad g = -\dot{I}(\theta)\dot{\theta} + C\left(\theta,\dot{\theta}\right)\dot{\theta} + G(\theta)$$

and filtering this one (4) by a linear stable filter, one obtain the following form,

$$\tau_f = f*\tau = f*\dot{h} + f*g$$

where $*$ is the sign of convolution, in this way the filtered torque doesn't depend on the angular accelerations.

$$\tau_f = \dot{f}*h - f(0)h - fh(0) + f*g \qquad (5)$$

Now, the equation $\tau = W\Phi$ is linear respect to Φ parameters, so filtering the torque by a linear filter the Φ parameters don't change, while the new regression matrix W_f doesn't depend on the velocities.

The estimated parameters $\hat{\Phi}$ by the filtered regression matrix could give so the estimated filtered torques.

$$\hat{\tau}_f = W_f(\cdot)\hat{\Phi} \qquad (6)$$

The difference between measured and estimated filtered torques

$$\tilde{\tau} = \tau_f - \hat{\tau}_f \qquad (7)$$

is the base for the recursive identification of the unknown parameters Φ for the adaptive control of robot [3], but in this case it is used to compute the environment interaction force.

In practice the filtered torque allows to identify the static and dynamic parameters to use to compute the contribution of dynamics to measured torques and/or forces, in other words it allows to compute the "dynamic tares" of bucket and stick.

Moreover one suppose the filtered torque has an other interesting aspect, in fact it allows to consider the filtering the contributions or noise due to the movements of other parts of machine and the oscillations of cylinder pressures due to oil elasticity on the carried out forces.

5. Force measurement

Until now one has been considered the torques τ_1 and τ_2, which are produced by hydraulic cylinders and the relative mechanisms. The relationships between force and torque, so as linear displacement of rod of hydraulic cylinder and angular displacement of link depend on trigonometric functions.

The typical mechanism is shown in figure 4, the relationship between angular position θ' of arm and cylinder length r is

$$\theta' = \arccos\left(\frac{L_2^2 + f^2 - r^2}{2L_2 f}\right)$$

while the relationship torque-force is given by the next one

$$\tau = FL_2\sin\left(\theta' + \phi\right)$$

where

$$\theta' + \phi = arc\tan\frac{f\sin\theta'}{L_2 - f\cos\theta'}$$

and θ' differs to θ of a constant angle α_f.

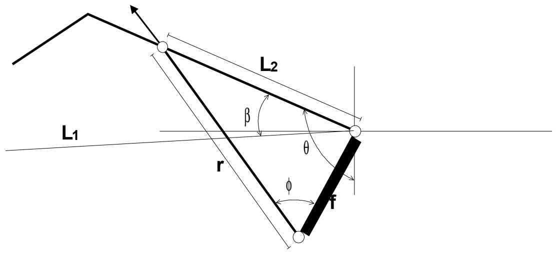

Figura 4

The forces worked by cylinders (single rod type) are due to differential pressures and the different areas of rod, moreover, the cylinders themselves introduce yet errors in the measure of force by friction forces and the elastic component of fluid.

The friction of cylinder depends on the pressures so on force F_i worked by cylinder itself, the material and number of seals, the velocity of rod, the diameters of cylinder and rod, moreover the friction of first detachment depends on the time too.

In many cases one is impossible to compute reliable friction coefficients by construction data, so friction forces must be identified.

To describe friction is used the famous equation

$$F_f = f_c \operatorname{sgn}(v) + f_v v \qquad v \neq 0 \qquad (8)$$

where the static friction coefficient f_c depends on contact area, working pressure, type of seal, while one has knowledge about viscous friction coefficient f_v , but from [4] it's possible to carry out an approximated evaluation, increasing the diameter of cylinders, f_v increases less respect to f_c, almost to depend on cylinder diameter linearly.

From the previous relationship one can put in evidence the contributions of friction to the torques

$$\tau_{f2} = \operatorname{sgn}(\dot{\theta}_2)\varphi_{f1} + \dot{\theta}_2\varphi_{f2}$$

$$\tau_{f1} = \operatorname{sgn}(\dot{\theta}_1)\varphi_{f3} + \dot{\theta}_1\varphi_{f4}$$

where $\Phi_f = \begin{bmatrix}\varphi_{f1} & \varphi_{f2} & \varphi_{f3} & \varphi_{f4}\end{bmatrix}^T$ are the new four parameters to add the previous vector Φ.

Identified the Φ_f parameters and supposing the dependence of friction force on cylinder force to be linear, the real friction coefficients of cylinder could be carried out doing the ratios

$$a_{s2} = \frac{\varphi_{f1}}{\tau_2} \quad a_{d2} = \frac{\varphi_{f2}}{\tau_2} \quad a_{s1} = \frac{\varphi_{f3}}{\tau_1} \quad a_{d1} = \frac{\varphi_{f4}}{\tau_1}$$

for every sampling and computing the respective mean values.

6. Identification

In this way the vector Φ is now of nine unknown parameters, while in practice one has a system of two equations, so one proceed to identify first the static parameters and second the dynamic one.

The static parameter are five, three gravitational one and the static friction parameters, if

$$\Phi_s = \begin{bmatrix} f_{c2} \\ f_{c2} \\ m_2 r_2 \cos(\theta_2 + \alpha_2) \\ m_2 r_2 \sin(\theta_2 + \alpha_2) \\ m_2 l_1 \cos\theta_1 + m_1 r_1 \cos(\theta_1 + \alpha_1) \end{bmatrix}$$

so from $\begin{bmatrix}\tau_2 & \tau_1 - \tau_2\end{bmatrix}^T = \mathbf{W}\Phi_s$ the regression matrix becoms

$$W = \begin{bmatrix} \operatorname{sgn}(\dot{\theta}_2) & 0 & g\cos\theta_1 & -g\sin\theta_1 & 0 \\ 0 & \operatorname{sgn}(\dot{\theta}_1) & 0 & 0 & g \end{bmatrix}$$

To identify static parameters LS methods has been used.

To identify dynamic parameters the angular velocities have been derived by difference of angular displacements, while the torques are filtered by a simple low pass first order filter with cutting frequency of 10 Hz.

The identification process, used to identify static and dynamic parameters, isn't recursive obviously, it has been tested by simulation using approximated models of bucket, stick, hydraulic cylinders and relative mechanisms.

In practice this frequency will be choice optimising two opposite requirements, to filter the dynamics or noise due to fast movements of machine and to have a large bandwidth to sense the fast variations of soil stiffness, to detect buried object, variation of soil slope, soil-air transition.

The simulation doesn't include an evaluation of interaction force, because isn't simple to simulate bucket soil interaction, so to have an reliable evaluation of the proposed system, one needs to wait tests on real machine.

REFERENCES

[1] F. Malaguti. "Development of On-Board Weighting and Force Sensor system for Construction Machines: Static Analysis". Proceedings of 14th ISARC, June 8-11 1997, Pittsburgh, USA.

[2] A.J. Koivo. "Fundamentals for Control of Robotic Manipulators", J.Wiley & Sons, 1989.

[3] F.L Lewis, C.T. Abdallah, D.M. Dawson. "Control of robot Manipulators", Macmillan Publ. Company, 1993.

[4] S. Tafazoli, P.D. Lawrence, S.E. Salcudean. "Identification of Inertial and Friction Parameters for Excavator Arm", IEEE Trans. on Robotics and Automation, vol. 15, no. 5, October 1999.

[5] F. Malaguti. "Variable Structure Control in Excavator Robot", Proceedings of 11th ISARC, Brighton, U.K.. 24-26 May, 1994