Extended Abstract

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Estimation of digging forces in hydraulic excavators by means of a two-stage observer

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Excavators are engineering vehicles widely employed in earthworks, like digging of holes, foundations, material handling, demolitions, mining, and so on. An excavator consists of a cabin for the operator on a rotating platform sat atop a wheeled or tracked system for movement, and of a robotic arm, which in turn comprises a boom, a stick, and a bucket, moved by means of hydraulic actuators. In order to perform the required working tasks, the excavation forces (or digging forces) developed by the excavator actuators must be greater than the resistive ones offered by the soil to be excavated. This means that very high forces, able to tip over the excavator, can be involved during working tasks. One way to forecast the excavator tipping over, and hence to improve human operator's safety, is to know the amount of digging forces. Unfortunately, such forces are very difficult, if not impossible to measure, therefore models and strategies to estimate the digging forces become necessary. Additionally, the knowledge of digging forces is fundamental in the development of unmanned excavators too, for which there is a growing interest for the sake of work efficiency and safety of operators. Up to now, to the best of authors' knowledge, digging forces are determined by means of some interaction models between the bucket and the soil, (see for example [1]). Such models are typically difficult to determine and change for each type of soil.

This paper shows that state observers can be usefully employed to estimate digging forces, and that accurate estimates can be achieved regardless of the knowledge of interaction models or soil models. In this work the estimation process is carried out using the two-stage approach presented in [2] and the extended Kalman filter. Following such an approach two partially coupled observers are implemented. The first one, named kinematic observer, reconstructs the kinematic state of the excavator (i.e. the angular position, velocity and acceleration of each link) exploiting the excavator kinematic constraint equations, and measured kinematic quantities, i.e. both the angular displacements θ_b, θ_s, and θ_{bc} of the boom, stick and bucket, and the accelerations denoted by symbols $\mathbf{a}_1$, $\mathbf{a}_2$, $\mathbf{a}_3$ in Fig 1. Figure 1 shows the planar model with three degrees of freedom employed, which neglects the swing displacement of the excavator (i.e. the rotation about the vertical axis). Such an hypothesis is not restrictive for our aim, since during digging tasks no swing motion is usually imposed by an operator. The second observer, named force observer, estimates the digging forces and the payload mass by employing an augmented excavator dynamic model, the estimated kinematic state, and the measured actuation forces ($\mathbf{F}_1$, $\mathbf{F}_2$, and $\mathbf{F}_3$), a schematic representation of the force observer is provided in Fig 2.

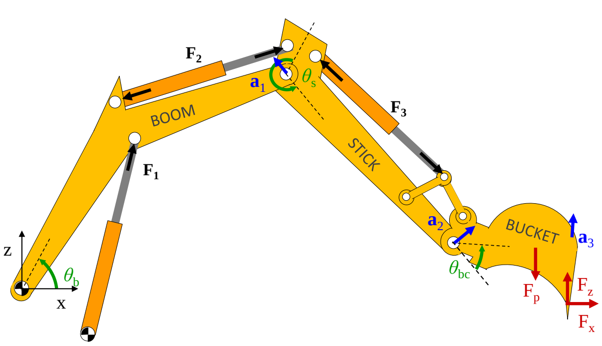

Fig. 1: Excavator scheme

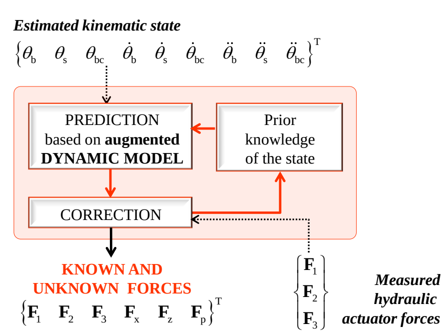

Fig. 2: Force observer

The approach in [2] requires to augment the dynamic model with random walk models, in order to have a well-defined system of equations. In this paper, differently from [2], the dynamic model is augmented with first order lowpass filter models, which are more adequate to represent the excavator low dynamics, due to the low bandwidth actuators. In contrast, random walk models assume infinite-bandwidth so they are not suitable to represent the dynamics of excavators.

A numerical validation of the estimation strategy is provided. All the signals used in the estimation process have been exported from the excavator simulator developed at the Mechanical Engineering Laboratory (LIM) of the University of La Coruña [3]. In the simulator, the excavator has been modeled using natural coordinates. Noise has been added to all the simulator signals supposed to be measured in order to simulate the use of transducers. All the variables estimated through the proposed approach are plotted in Fig. 3, in which just a sample portion of each signal is shown in order to represent more clearly what happens in the interaction phase between the bucket and the ground. Similar results are obtained for the whole simulated test. The same figure also shows the actual values of the variables to be estimated (i.e. the one delivered by the simulator, without noise), which are often almost overlapped to the estimated ones. Figure 3 clearly shows that good estimates of both the kinematic variables and digging forces can be obtained with the proposed approach. As for payload estimation the results achieved are less accurate, but still useful to evaluate the amount of material in the bucket and the overall material handled. Such a less accurate estimate is a consequence of the rather low payload force, which in practice is comparable to measurement errors on hydraulic actuator forces.

Overall the results obtained are very satisfactory: on the one hand they prove that digging forces can be estimated effectively and efficiently (real time estimation can easily be achieved), on the other, they confirm the effectiveness of the two-stage observer adopted.

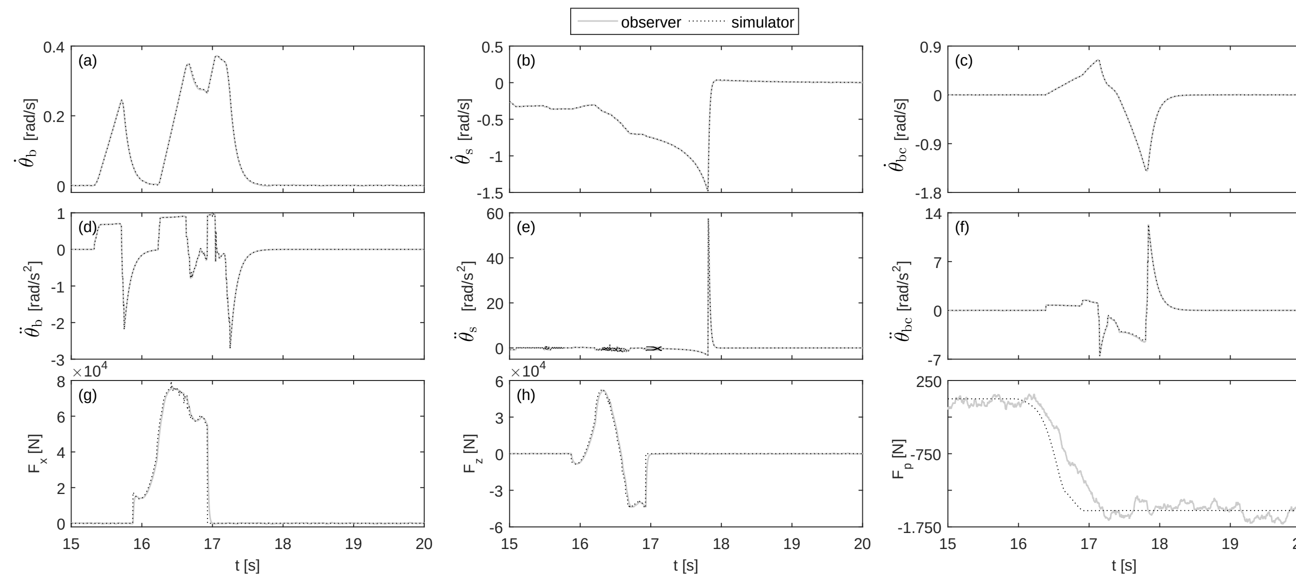

Fig. 3: Estimated angular velocities (a, b, c) and angular accelerations (d, e, f) of the boom (a, d), stick (b, e), and bucket (c, f). Estimated digging forces in x-direction (g) and z-direction (h), payload force (i)

References

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