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Robust position control design for a cylinder in mobile hydraulics applications[☆]

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ABSTRACT

Automation of various agricultural tasks, which are nowadays routinely executed by operators of hydraulically actuated tractors equipped with front-end loaders, is an important open problem. The so-called self-leveling task is considered here, where the lifting and lowering motions of the loader are performed manually while the orientation of the tool must be adjusted automatically. The proposed controller is constituted by a proportional feedback, a disturbance compensator based on an observer and a relay controller. A model-based tuning procedure for the controller parameters is discussed and an implementation is validated experimentally on an industry-standard commercial set-up.

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1. Introduction

In heavy duty mobile applications, hydraulics is preferred because it is cost-effective, compact, and able to handle force impact (Eriksson, 2010). However, hydraulic systems are rather challenging to control as they are highly nonlinear and highly uncertain. The nonlinearity, present in the flow expression, makes it hard to define a resistance of a hydraulic conduit. In addition to nonlinearity, several parameters depend on temperature and operating pressure (e.g. bulk modulus). Thus, it is important to consider the working region of hydraulics applications. This distinguishes industrial applications from the mobile ones, which affects the choice of controllers.

Within industrial hydraulics applications, it is common to set a tight tracking performance for a specific task in a conditioned environment with the availability of precise sensors, e.g. position to acceleration sensors. Feedback linearization (Sohl & Bobrow, 1999) and its variant to cope with variation in supply pressure (Mintsa et al., 2012) have been reported and performed better than PID. Sliding mode control is reported to help an aluminum pressing machine in Komsta et al. (2013). PID with friction compensation has performed better in an industrial hydraulics application (Tafazoli et al., 1998). However, identifying friction models from experiments is time-consuming (Bonchis et al., 1999). Besides, friction models are dependent on several other parameters than velocity (Bittencourt et al., 2010), including temperature, which is greatly spanned in the mobile hydraulics systems.

In mobile hydraulics applications, robustness is preferred since they are characterized by a wide range of operating region (e.g. varying payloads, flow inputs, velocities, and temperatures). Besides, aiming at an economically efficient product that is working in a rough environment makes it not feasible to involve precise sensors and a high-end electrical control unit in the control design. The comparison of controllers for a mobile hydraulics application is reported for position control on a laboratory version of a mining manipulator in Bonchis et al. (2002). The quantitative comparison showed that Variable Structure Systems (VSS) (Utkin, 1977) is one of the controllers that performs the best. In addition to its robust characteristic, VSS is found to be an easy-to-use and precise algorithm to meet industrial demand (Komsta et al., 2013).

In theory, this approach will maintain the desired trajectory regardless the presence of bounded disturbances provided there is an implementation with an infinite switching frequency of the actuator. The effect of discontinuous control within VSS is similar to the ability of discontinuous dry friction to stop a motion under uncertain but sufficiently small forces. However, this approach suffers from chattering as the actuator's switching frequency is commonly limited in practice (Shtessel et al., 2014a). Researchers are proposing methods to reduce chattering, such as substituting the sign function with its continuous approximation or designing the discontinuous term as the control function derivative (Shtessel et al., 2014a).

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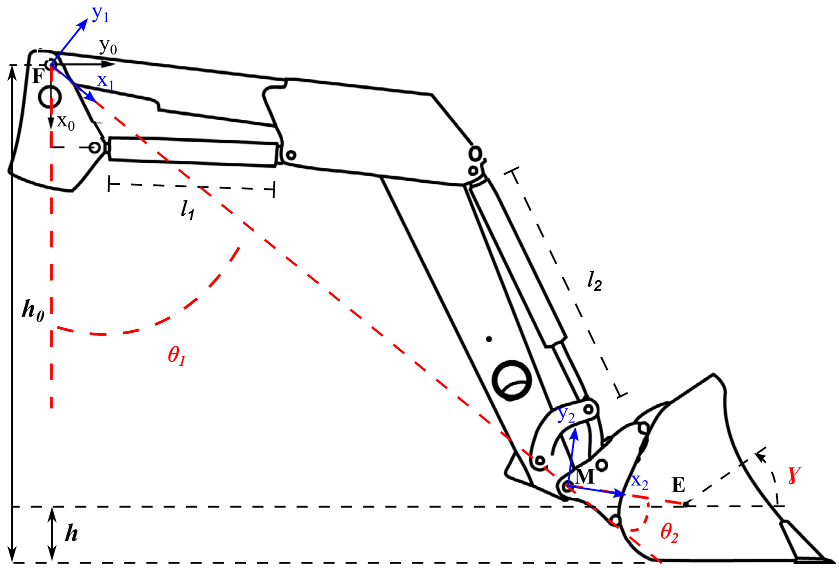

Fig. 1. A front end loader under consideration. l_1, l_2 show the extension of the lift and tilt cylinders respectively.

Besides VSS, robustness with respect to external disturbances and dynamic uncertainties is also a property of Active Disturbance Rejection Control (ADRC) (Han, 2009). In addition, several successful industrial implementations have also been reported (Herbst, 2013). Though a little work is found on mobile hydraulics systems, its idea of counteracting the disturbances based on its estimation inherits the ability to cope with uncertainties and perturbation in these applications. Similar to the spirit of ADRC, a disturbance estimation approach based on an observer is employed here as well.

Having presented the idea of VSS and disturbance estimation, a combination of these disturbance compensation approaches is proposed to realize the self-leveling task in our mobile hydraulic system, a Front End Loader (FEL). While both techniques are developed to compensate matched disturbances, merging them allows to achieve superior performance. The previous work shows that the proposed controller fulfills the performance in terms of sufficiently small errors and oscillations in lowering motion, where parameters are tuned via a time-consuming trials-and-errors in experiments (Yung et al., 2015). However, the study of error dynamics and a formal tuning procedure were not developed. In contrast, the present work introduces a methodology for the tuning of the controller parameters in order to achieve a desired performance under the presence of external perturbations and noise in measurements, and includes a stability analysis of error dynamics of a self-leveling task for an uncertain and disturbed Front End Loader dynamical model.

In control systems perspective, self-leveling is a control problem of a hydraulic cylinder in the presence of certain disturbances, mainly from the driver. The driver manually operates the other cylinder that introduces a disturbance to the controlled cylinder due to the mechanical coupling. Besides, this operation also introduces a disturbance due to hydraulic coupling, i.e. a reduced hydraulic supply to the controlled cylinder as the supply provides the source for both cylinders. This work is focus on tuning parameters of the proposed controller to realize Electronic Self Leveling (ESL) under mechanical coupling disturbances when the flow supply is sufficient.

To come to this focus, the paper is organized as follows: the description of self-leveling task is presented in Section 2, followed by a description of the mobile hydraulic circuit and system dynamics in Section 3. Based on this system representation, the proposed controller and zero dynamics analysis are presented in Section 4. The tuning procedure is described in Section 5. The validation in experiment, in terms of robustness to lowering velocities, is reported in Section 6.

2. Self leveling task and problem formulation

Our mobile hydraulic system, a Front End Loader (FEL), is shown in Fig. 1. It is a 2-degrees-of-freedom (2-DOF) robot that is hydraulically actuated. Based on the assigned frames ($x_0 - y_0, x_1 - y_1, x_2 - y_2$), the lift and tilt angular positions are denoted as θ_1 and θ_2, respectively. The bucket's generalized coordinates are chosen as the height, h, and the orientation angle, γ, which can be computed from the specified angular positions using forward kinematics:

$$h = h_0 - (\overline{FM} c_1 + \overline{ME} c_{12}) \tag{1}$$

$$\gamma = \theta_1 + \theta_2 - \pi/2 \tag{2}$$

where $\overline{FM}$ is the distance between pivot points, $\overline{ME}$ is the distance between second pivot point and bucket's Center of Gravity (COG), c_1 denotes $\cos(\theta_1)$ and c_{12} denotes $\cos(\theta_1 + \theta_2)$.

As for now, most of the commercially available products have these coordinates indirectly controlled by the operator via a joystick, which directly commands extension of the hydraulic cylinders. Extending or retracting the first/lift cylinder, changing l_1 and hence θ_1, causes lifting or lowering motion (modifying h), respectively, as well as changing the bucket orientation (modifying γ). Besides, extending and retracting the second/tilt cylinder, changing l_2 and hence θ_2, will tilt-out and tilt-in the bucket (modifying γ), respectively.

The fact that extending the first cylinder will result in simultaneous change of both coordinates is inconvenient for some tasks, especially with a loaded bucket. Thus, the so-called self-leveling problem is introduced. Within the self-leveling scheme, the extension of the second cylinder, l_2, is manipulated automatically such that γ is constant as the first cylinder is extended/retracted by the driver. With the manual operation, the driver should control both axes of the joystick to realize the self leveling (Fig. 2). With self leveling task, the driver will only control one axis, which might reduce mental strain in the long run.

Expressing the self leveling task as a control problem, it is the control of a hydraulic cylinder in the presence of disturbances, mainly from the lift cylinder motion. Particularly, we want to control the tilt cylinder extension, l_2, in order to maintain a constant bucket angle, γ, with at most 2 degrees tracking error despite the variation of the lift cylinder extension.

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