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Gain scheduled state feedback velocity control of hydrostatic drive transmissions

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ABSTRACT

In this paper, a velocity tracking controller for hydrostatic drive transmissions is developed. The solution is based on a state-dependent model that incorporates nonlinear characteristics of the system. A full state feedback controller is devised and the gains are scheduled on measured speed and pressures, together with approximated volumetric flow. The effects of uncertainties, especially those related to equilibrium values of pressures, are eliminated by utilizing so-called D-implementation. This technique eliminates the need for equilibrium values, which are model based and thus uncertain.

To demonstrate the efficacy of the controller, the solution is implemented on a 4.5-ton wheel loader. For comparison purposes, a constant gain state feedback controller with integral action is devised, and also a linear PID controller is tuned. The results show that the benefits of the devised controller are significant when it is compared to these two controllers. Moreover, the controllability of the machine is maintained in every situation.

1. Introduction

Non-road mobile machines are a fundamental part of several fields of industry. They are a requisite for modern agriculture, the construction and mining industries, increasing productivity of numerous essential and hazardous tasks. Even though some autonomous systems are in operation even today, e.g. in mining (Bills & Cherrington, 2013) and ports (Freundlich, 2013), the majority of these machines are operated by humans. Moreover, skilled operators are a scarce resource. Thus, operator assistance functions have emerged as key factors in the competition between manufacturers. Closed loop velocity control, also known as cruise control in the automobile industry, is one example of such systems.

One can argue that cruise control is not a required functionality for manually operated work machines. However, it improves the quality of work with inexperienced drivers and also enables experts to concentrate better on their work. Nevertheless, autonomous and cooperative machines are the main motivation for this research work. Agricultural tasks that need regular speeds such as combine-tractor synchronization and also convoying in mining machinery are just a few examples of where accurate speed tracking is essential for safety and performance.

Several sources of nonlinearities exist in hydrostatic drive transmissions (HSD) (Merritt, 1967). Gain scheduling is a widely used control scheme for nonlinear systems, possibly due to its relative simplicity. It has been shown in several different applications, e.g. vapor compression (Yang, Pollock & Wen, 2015), wind turbine control (Jafarnejadsani and Pieper, 2015), air-fuel ratio of engines (Postma and Nagamune, 2012) and autonomous underwater vehicles (Silvestre and Pascoal, 2007) that this method works well in practice. In addition to gain scheduling, state-dependent (SD) system models are a common practice in the modeling of hydraulic systems in this community. For example, Strano and Terzo based their feedback controller on the state-dependent Riccati equation, which they utilized for the pole placement of a hydraulic actuation system (symmetric cylinder) (Strano and Terzo, 2015). Also Taylor and Robertson assigned poles for a hydraulic manipulator control with SD model (Taylor and Robertson, 2013). Nevertheless, research on the control of hydraulic rotary actuators is limited as the majority of investigated hydraulic systems include only hydraulic cylinders. The number of moving parts and gaps is multiple in hydraulic piston motors or pumps used in the HSD of this study. This makes, e.g. the efficiency models of cylinders substantially simpler. In fact, it is common to consider cylinders leakless, or model their volumetric efficiency with a constant value.

Knowledge about the operation point of the system is essential for successful state feedback, i.e. in hydraulic systems pressure information is required. Balkan, Caliskan, Dolen, Kilic and Koku (2014) stated that it is difficult to estimate the pressure dynamics of hydraulic systems if flow rate measurement is not available (Kilic et al., 2014). Moreover, they investigated the chamber pressures of a hydraulic cylinder. A standard practice is to utilize a system model for pressure

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calculations, but this leads to inaccurate estimates due to, e.g. the uncertainties of friction modeling. To tackle this challenge, the so-called D-implementation developed by Coleman, Kaminer, Kahrgonekar and Pascoal (1995) is used in this paper. D-implementation replaces the calculation of some of the operation points with the derivatives of the states. This is realized by placing a derivative and integral at a certain points in the control loop. It is shown that this operation does not change the closed loop properties of the design, yet constant operation points vanish by derivation.

Several research teams have developed cruise control systems and some of these are intended for HSDs, such as the MPC solution for combine harvesters by Baerdemaeker, Coen, Missotten and Saeys, (2008), who controlled both engine speed and pump displacement, but they presented results only for one step response with 6-km/h velocity reference. Guo and Hu utilized an adaptive fuzzy-PD method for the velocity control of a tractor (Guo and Hu, 2014). Their approach requires defining many rules and membership functions for the controller, which is quite common for fuzzy systems. The demonstrated operating speed in this research was 0.8–1.4 m/s. In both of these studies, control design was validated with field tests in which the HSD was composed of variable pump, hydraulic motor and mechanical transmission.

However, most cruise control solutions are developed for on-road vehicles with no hydraulic components. For example, Askari, Ordys and Shakouri (2012) used an approach similar to SD in their nonlinear model predictive control (Shakouri et al., 2012) and detailed their design to switch between velocity and distance tracking modes in (Shakouri & Ordys, 2014). Yadav and Gaur combined internal model control and fuzzy logic for speed control of heavy duty vehicles (Yadav & Gaur, 2015).

In this paper, a gain scheduled velocity controller (GSVC) for hydrostatic drive transmissions is designed. The solution is based on full state feedback and D-implementation. Utilization of D-implementation ensures that the uncertain friction model of the system does not impair the response, and steady-state accuracy together with disturbance rejection are preserved. In addition, the presented control concept does not include an excessive amount of tunable parameters as the only required information is the dynamic equations of the system and parameter values as functions of the states. Therefore, the GSVC is easy to design and tune for machines of different sizes and HSD layouts. It can also be extended for throttling control of hydraulic cylinders: see Jelali and Kroll (2003) for dynamics models of such systems.

The SD parameters of the utilized system model are the volumetric and hydro-mechanical efficiencies of the motors and pump of HSD. Although the efficiencies are functions of the states, the variation is not great and allows for the employment of gain scheduled pole placement using full state feedback. Overall, ignoring time variations in the system during the design is justified for slowly varying system parameters and scheduling (Shamma and Athans, 1992). In general, the accuracies of SD parameters impact the performance of state feedback controllers and some retuning might be required due to changing conditions. For example, if the effects of temperature are not considered, some adjustments might be necessary, e.g. according to seasonal weather. The devised GSVC is not that sensitive to inaccuracies of the model because D-implementation lifts the requirement of constant operating points as measured states are replaced by their derivatives.

Next, we summarize the contributions of this paper. The presented research addresses the control problem of velocity tracking of hydraulic rotary actuators. The initial simulation results and proof of concept were presented in a conference paper (Backas, Ghabcheloo & Huhtala, 2015). Here, the design is extended and the controller is implemented to a real research platform, a 4.5-ton wheel loader. The efficacy of the controller is demonstrated under disturbance and with multiple velocity reference values up to 5 m/s. To the best of our knowledge, this is the first time these control techniques have been experimented in HSD systems, although many of these aspects have been covered separately in different studies: mostly on throttling control, less on rotary actuators. Hydraulic pumps and motors are significantly more complex (i.e. more difficult to model) than hydraulic cylinders utilized in the majority of studies related to hydraulic systems. Nonlinearities of HSDs make their control much more demanding than mechanical power trains of on-road vehicles, for which most cruise control systems have been devised. Moreover, testing the control system in field experiments in several different operating points, and under positive and negative disturbances, means that the utilized models will not match the plant exactly and guarantees a certain level of robustness.

The rest of the paper is organized as follows. Section 2 presents the hydraulic system and dynamic equations of the research platform machine. A detailed presentation of the GSVC is provided in Section 3. Section 4 describes different implementation aspects related to the controller. In Section 5, the experimental field test results are presented, in which the functionality of the GSVC is compared with the ones obtained with a linear proportional-integral-derivative (PID) controller and a constant gain full state feedback controller with integral term.

2. System description and modeling

In this section, the research platform machine - namely its HSD and control systems - is introduced. For more detailed description of the systems of the machine, an interested reader is referred to Backas et al. (2011). Moreover, the dynamic equations of translational motion of the machine to be used by the GSVC are presented.

2.1. Research platform machine

The utilized research platform was engineered at the Department of Intelligent Hydraulics and Automation (IHA) in Tampere University of Technology (TUT). The machine is presented in Fig. 1.

The HSD of the machine is a closed hydraulic circuit. This means that the fluid utilized in the transfer of power is fed back to the pump from the motors instead of being circulated through a tank. A hydraulic diagram of HSD, including control commands, is presented in Fig. 2.

The prime mover (denoted M in Fig. 2), a 100-kW diesel engine, provides power to a hydraulic pump connected directly to the engine. The pump is a variable displacement type, i.e. its output flow (see Q_p of Fig. 2) can be controlled both by its swash plate angle (displacement ratio ε_p) and by the speed of the engine shaft n_e. Subscript *com* indicates command variables in Fig. 2. Moreover, the pump can provide flow in both directions, allowing forward and reverse motion. The produced volumetric flow is directed to 4 hydraulic motors connected to each wheel of the machine. The displacement ratios of these hub motors (ε_m) can be changed between two discrete settings, full and 50% of the maximum. The maximum displacements of the HSD pump (V_p) and motors (V_m) are 110 and 470 cm^3, respectively. Variables p_A and p_B are the pressures of volumes A and B, respectively.

In this HSD system, the flow through the flush valve (in the middle of Fig. 2) always comes from the volume that has the lower pressure and the flow of the boost pump (see Q_b of Fig. 2) is also directed to this

Fig. 1. Research platform.