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Predictive control of a diesel electric wheel loader powertrain

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ABSTRACT

Wheel loaders often have a highly repetitive pattern of operation, which can be used for creating a rough prediction of future operation. As the present torque converter based transmission is replaced with an infinitely variable device, such as an electric or hydraulic transmission, a freedom in the choice of engine speed is introduced. This choice is far from trivial in the extremely transient operation of these machines, but the availability of a load prediction should be utilized.

In this paper, a predictive engine and generator controller, based on stochastic dynamic programming, is described, implemented and evaluated. The evaluation is performed against non-predictive controllers in the same system, to lift out any possible benefits of utilizing the repetition based prediction. Simulations and field tests show that the controllers are able to handle disturbances introduced from model errors, the machine environment and the human operator, and that the predictive controller gives around 5% lower fuel consumption than the non-predictive reference controllers.

1. Introduction

1.1. Background

Wheel loader operation is highly transient and repetitive, and contains periods of high tractive force at low speeds, while the engine delivers power to both the transmission and the hydraulics. The most common layout of heavy wheel loader powertrains is presented in Fig. 1. The engine is connected to a hydraulic pump and a torque converter. The torque converter is connected to an automatic gearbox, which connects to the drive shaft.

In this setup the torque converter is a crucial component since it provides some disconnection between the engine and vehicle speeds. This disconnection makes the system mechanically robust but it also causes high losses. Just as for most other vehicles, substantial work is ongoing for reducing emissions and increasing fuel efficiency. One approach for reducing fuel consumption is to replace the torque converter based transmission with another solution. The combination of low speeds, high forces and transient operation motivates the use of some type of continuously variable transmission (CVT).

The repetitiveness of the operation may form the basis of a prediction of future operation, which can be used in a predictive controller. This paper studies such repetition based predictive control of the engine and generator in a diesel electric wheel loader.

1.2. Problem formulation

The problem studied in this paper is the minimization of the expected amount of fuel needed for completing a series of loading cycles, using a CVT wheel loader, by utilizing the cycle bound operation as a basis for prediction. The problem has been studied and some control strategies have been presented in the paper (Nilsson, Fröberg, & Åslund, 2014), though the evaluation was only made through simulations.

The machine is operated by a human driver, which introduces major uncertainties in the power trajectories. The machine is also operated in an environment which is difficult to model. This is particularly evident in the pile of material from which the machine fills its bucket. The tests are designed to investigate the performance of the controller under such severe prediction uncertainties.

In this paper the control strategy previously presented in the paper (Nilsson et al., 2014) is implemented and field tested, using the series hybrid electric vehicle described in Stein et al. (2013). The novelty of the paper lies in: (i) a verification, including all relevant disturbances, of the results presented in the paper (Nilsson et al., 2014); (ii) a thorough investigation, including field tests, of the benefit of the combination of using a CVT and cycle based optimal predictive control, in a wheel loader powertrain; (iii) an evaluation of using stochastic dynamic programming when there are severe disturbances and uncertainties; (iv) an implementation of stochastic dynamic programming with a distance dependent load probability.

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1.3. Previous work

There is a substantial amount of work done on different types of advanced drivetrains for construction equipment. An evaluation of the minimum fuel consumptions of the standard and a CVT vehicle is made in Nilsson and Åslund (2012b). Several other papers, such as Lennevi (1995), Rydberg (1998), Zhang, Alleyne, and Prasetiawan (2002) and Kumar, Ivantysynova, and Williams (2007), study the use of hydrostatic CVTs in wheel loaders, though the focus is on component control. In Filla (2008) and Lin, Wang, Hu, and Gong (2010) several advanced drivetrains are presented. In Stein et al. (2013) a series electric hybrid and the hydrostatic device studied in Nilsson et al. (2012b) are presented. Neither Filla (2008) and Lin et al. (2010) nor Stein et al. (2013) describe any controllers though. An electric transmission is used in this paper since hydrostatic transmissions have much slower component dynamics, which cannot be neglected. The series hybrid described in Stein et al. (2013) is used for the online tests described in this paper.

An investigation into differences in driver performance and style in traditional machines can be found in Frank, Skogh, and Alaküla (2012).

A few heuristic CVT control strategies can be found in Liu and Paden (1997). These control concepts however do not fully utilize the potential of the transmissions. Conversely, there are some papers, such as Pfiffner (2001), Nilsson, Fröberg, and Åslund (2012a), and Sivertsson and Eriksson (2012), treating optimal transient engine operation. These, on the other hand, are based on perfect predictions and do not present solutions for handling disturbances. There are other areas in which optimal control without perfect prediction has been implemented. For on-road vehicles, and apart from ECMS, as described in Sciarretta and Guzzella (2007), there have been several proposals, e.g. Hellström (2010) and Khayyam, Nahavandi, and Davis (2012), for utilizing increased availability of information, such as road maps and GPS data, for predictive control. This type of information is in general not available for off-road applications. Wheel loader operation is often highly repetitive and often follows one of a few common patterns, which might enable a prediction based on pattern recognition, such as that presented in Lin, Jeon, Peng, and Moo (2004) or in Nilsson, Sundström, Nyberg, Frisk, and Krysander (2014). In Johannesson, Åsbogård, and Egardt (2007), Kolmanovsky and Filev (2010), Leroy, Malaize, and Corde (2012) and McDonough et al. (2012) stochastic dynamic programming (SDP) is used for optimal control based on an uncertain prediction, though these all treat on-road vehicles. The paper Nilsson et al. (2014) analyses three different SDP implementations for use in a CVT wheel loader. This last paper forms the basis for the controllers implemented and tested in the work presented here.

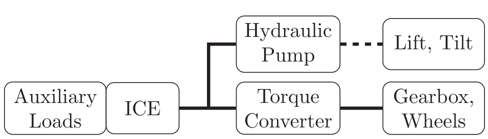

Fig. 1. The reference vehicle powertrain setup. Solid lines are mechanical connections and dashed lines are hydraulic connections.

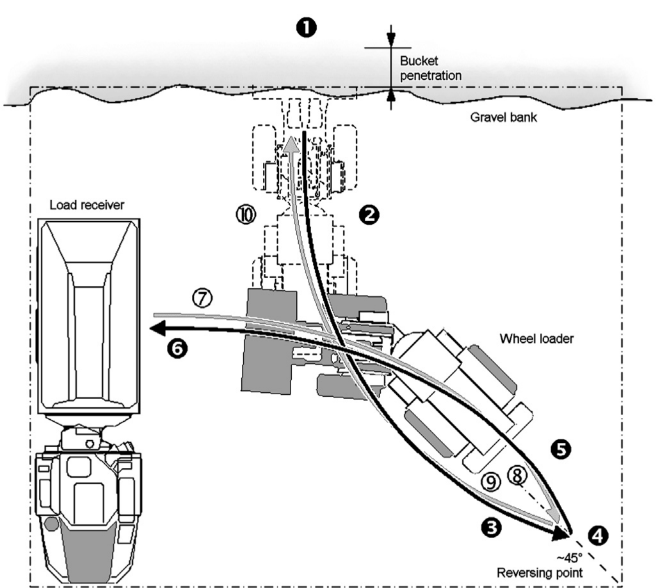

Fig. 2. Overview of the short loading cycle, from Filla (2008).

2. System and concept overview

This paper investigates the benefit of utilizing the repetitiveness of wheel loader operation for making a load prediction, and controlling the engine speed in a diesel electric transmission based on this prediction. This section describes the operation, the vehicle and the transmission, and the optimization involved in building the controller. The main controller, the two reference controllers and some auxiliary controllers are described in Section 3.

2.1. The short loading cycle

One of the most common operational patterns for wheel loaders is the short loading cycle (SLC). In this cycle, the machine loads material from a source, a pile, to a receiver, often a dump truck. Fig. 2 gives an overview of a short loading cycle. In the definition of the SLC used here the cycle consists of four legs which are defined by the driving direction changes. Referring to the notations in Fig. 2, the first leg starts when the vehicle leaves point 4 and ends when the vehicle has filled the bucket at point 1. The second leg is the movement from point 1 to point 4, the third is the movement from point 4 to point 6 and the fourth is the movement from point 6 to point 4. The bucket is raised during leg two and three and emptied at point 6. Each leg commonly has a duration of 5–10 s, with another 5–10 s for filling the bucket. After some cycles, usually around four, the receiver is full and has to be replaced. During this the machine is usually resting in a dormant state. The dormant state is not included in this paper since it is easily detected and handled. Details about this operation can be found e.g. in Filla (2011), Wang, Zhang, Sun, and Yu (2012) and Nezhadali and Eriksson (2013).

2.2. Test vehicle description

The control strategies of this paper are designed for an arbitrary infinitely variable transmission (IVT), such as a diesel electric or hydrostatic system. Field tests were performed using the supercapacitor series hybrid vehicle presented in Stein et al. (2013), which is based on a production Volvo wheel loader (Volvo Construction Equipment, 2006). The vehicle was controlled so to avoid using the supercapacitor, making a diesel electric powertrain.

The layout of the test vehicle powertrain is presented in Fig. 3. To the left is the engine-generator set, and to the right are the electrically powered hydraulic pumps for the bucket and arm and the electric propulsion. The auxiliary loads consist mainly of the fan and hydraulic steering. The auxiliary loads, engine and generator are together denoted the ‘genset’. The driver has superior control of the propulsion and the bucket lift and tilt, along with some of the auxiliary loads, especially the steering. In this project the right-hand side of the system is seen as a set of power