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Optimal control of wheel loader actuators in gravel applications

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ABSTRACT

The paper is about finding the global optimum for a wheel loader work cycle in a gravel application. This includes simulating the gravel and extracting the trajectories for the main actuators; propulsion, lift and tilt, during the work cycle. The optimal control method is dynamic programming and the optimum is calculated with regard to fuel efficiency [ton/l] but can be weighted towards productivity [ton/h].

The analytical optimal control results are compared to an extensive empirical measurement done on a wheel loader and shows around 15% higher fuel efficiency compared to the highest fuel efficiency measured among real operators.

1. Introduction

The wheel loader is considered as one of the most versatile construction equipment machines that perform multiple tasks on work sites. However, in this paper the focus is on a wheel loader working in a bucket application as part of a production chain performing a "*short loading cycle*". This use case has been chosen for demonstration of the method, due to the fact that this is one of the most common applications for larger wheel loaders. The versatile usage and large variations in operator behavior, due to multiple actuators, make optimizing fuel efficiency [ton/l] and productivity [ton/h] a challenge when designing a wheel loader. The variation due to operator behavior, among experienced operators can be as much as 150% in fuel efficiency and 300% in productivity [1]. Customers who buy construction machines use them as tools to make money as a business; consequently the running costs, such as fuel, maintenance and operator wage, are essential to minimize. Taking economics and environmental care into consideration, it is important to optimize the fuel efficiency [ton/l] and productivity [ton/h] of each construction machine.

The literature contains several studies related to optimization of construction machines and wheel loaders in particular. However these papers have only considered machine speed and lifting during the transport phase [2,3] or only minimized consumed fuel per travelled distance when considering the drive line [4], both of which are great simplifications of the problem. In this paper a method for optimizing the complete work cycle, including the loading phase, is presented. The loading phase is important because about one third of the energy is spent in the gravel pile. This is visible in literature such as [5] where simple performance indicators are used to study fuel efficiency improvement of a complete wheel loader work cycle by optimizing bucket design and bucket filling. The bucket filling phase is also the most difficult part of the cycle for the operator. Optimal driving, for on-road applications, is covered in literature such as [6–11] while similar problems are solved for off-road in [2,3,12] and an optimization of a full work cycle in a grapple application of a wheel loader is solved in [13]. In the literature, there is a tendency to simplify the models of the major components to suit the optimization tool chosen. If the problem is non-convex, dynamic programming is the only reasonable method that guarantees global optimum. In this paper, a method is developed based on dynamic programming to ensure that the global optimum is found, with regard to fuel efficiency and productivity. In [14–17] a global optima has been found, using dynamic programming, to evaluate control strategies, in off-road machines, that need less computational power but do not ensure a global optimum solution for the complete machine as a system. However these papers only consider the primary energy converter side, for example: the internal combustion engine and/or the hydraulic pumps. The method presented in this paper also takes into consideration the actuators and does not rely on a recorded work cycle.

The main research contribution in this paper is to formulate a dynamic programming problem that is able to be able to optimize the actuator movements in a complete work cycle with regard to fuel efficiency at a given productivity, including the three main actuators; propulsion, lift and tilt. This is done with a proven environmental model, to guarantee correct interaction between the gravel pile and bucket, and with models of the wheel loader based on maps of real

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measurement data of all major components in the wheel loader. The result of the optimization, calculated in Section 5, is then compared to the empirically best work cycle found in an operator deviation measurement study, presented in Section 2.

The optimization in this paper excludes the route optimization, handled in literature such as [2,18–20]. In [2] the transport part of the work cycle is optimized, including path planning, with steering, machine velocity and load receiver angle, with more simplified equation based models of the internal components.

Secondary research contributions are that this method is shown to be able to be used in the early phases of research and development when performing concept evaluations between different machine concepts and system optimization of the main components in each concept [21] Using the proposed method overcomes the traditional difficulties in simulating wheel loader efficiency and productivity with ad-hoc rule based algorithms. In [22,23] dynamic programming is used to determine the size of the electrical energy storage in a diesel-electric hybrid machine, while [21] demonstrates how the method presented in this paper applied to all major subsystems in the complete machine. It was also shown in [24] to be possible to extract from the results of this method, the input required for operator assist systems, automatic functions, and autonomous construction machine control development.

For a complex system such as a wheel loader, solving an optimal control problem, and ensuring the solution is a global optimum, requires thorough knowledge about the system. Without this knowledge it is difficult to choose the most suitable optimal control method. In addition, when modeling the wheel loader, it is difficult to make the correct decision regarding reasonable simplifications and system boundaries. These decisions are often necessary to solve the problem within a reasonable computation time. For this reason an introduction to the wheel loader is given below and some of the largest challenges when simulating and controlling a wheel loader are discussed. The method presented in this paper can be applied in other industries that are facing similar challenges when performing a new machine concept evaluation or developing operator assist functions. Applicable industries are where the machine topology with parallel power flow, material interaction, and machine performance limitations are set by the operator, see Fig. 2 and Section 2.1. Industries can be, but are not limited to, i.e. agriculture and forestry. An example is found in [25,26], where dynamic programming is used in the energy optimization of the hydraulic system of forestry equipment. In contrast to the examples in [14–17,22,23,25,26], in this paper the complete machine is considered.

1.1. Paper outline

In the remaining parts of Section 1 a short background description of the wheel loader and the definition of the wheel loader operation optimization are presented. In Section 2 an empirical study is presented where an empirical best case in regards to fuel efficiency, with an acceptable productivity, is found. In Section 3 the wheel loader configuration, with limitations and boundaries, is presented. The problem formulation is set up in Section 4. In Section 5 the numerical theoretical optimum is calculated. The optimization method, wheel loader and environment simulation models and implementation of the optimization algorithms, with limitations, are presented as well. In Section 6 a comparison analysis is done, investigating the differences between the numerical theoretical optimal solution and the empirical best case found in Section 2. The results are presented in Section 7, followed by a discussion in Section 8 and the conclusions are presented in Section 9.

1.2. Wheel loader background

As described in [1,27,28], the wheel loader is a versatile working machine used in a vast variety of applications with different attachments such as bucket, grapple [13], material handling arm, etc. In this paper, the focus is on wheel loaders that are part of a production chain, in particular, bucket applications. The tasks are most often either loading material from the face of a material pile or a virgin bank, loading materials ranging from blasted rock to clay and natural sand, or re-handling, meaning handling material after the crusher, either to feed the next part in the production chain, to stockpile or to load onto trucks out from site. With each application, the wheel loader's work cycle looks different. The most common work cycles for production chain wheel loaders in bucket applications are the "*short loading cycle*", also called "V-cycle" or "Y-cycle" in literature such as [29,30], and the "load and carry cycle". The major differences between the two cycles are the transport distance, the initial velocity into the gravel pile and that the need for using all actuators at the same time is more critical in the "*short loading cycle*". A visualization of a "*short loading cycle*", loading blasted rock onto an articulated hauler from face as a part of a production chain, is shown in Fig. 1.

Fig. 1. A wheel loader performs a "*short loading cycle*" in blasted rock from face, as a part of a production chain [31].

There are two major differences between the more commonly known and studied optimization of an on-road vehicle and of a wheel loader, that increase the complexity of the system, and hence also the optimization. Firstly, the wheel loader has more actuators, propulsion, lift and tilt, comparing to a single propulsion actuator in the car, hence the operator is central in the control loop, see Fig. 2, meaning that different operator behaviors have a higher impact than in a normal on-road application. This results in more degrees of freedom to optimize in the wheel loader case. Secondly, the interaction with the environment in a car is only the interaction with the ground and air and can be simulated using the vehicle motion equation [32] while in the wheel loader the interaction is more complicated. When filling the bucket all three actuators are working against a gravel pile in a complex power balance, see Fig. 2.

The schematic picture of the power flow in a wheel loader in Fig. 2 reveals the complexity of the system. There is not only a coupling in the power flow at the combustion engine, which is coupled to the torque converter and the hydraulic pumps, but also at the bucket, where the wheels and cylinders are coupled via the gravel pile in the bucket filling phase. This means that the operator needs to balance the power available from the combustion engine between the two main power consumers, driveline and working hydraulics, at all times. Furthermore, the working hydraulics consists of two main functions, lift and tilt, and a number of support functions, such as steering and auxiliaries.

A gravel pile model is necessary to get the correct coupling on the bucket-side of the schematic picture in Fig. 2. This can be compared to the rolling resistance in an on-road application but it is responsible for almost all of the fuel consumed in the bucket fill phase, and around one third of the total amount of fuel consumed in a "*short loading cycle*" [33]. The importance of including the gravel pile cannot be emphasized enough.