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Predictive operator modeling for virtual prototyping of hydraulic excavators

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ABSTRACT

Stricter laws with regard to emission regulation and rising fuel costs have led to an increasing demand for highly efficient mobile machinery. Electronic components and hybrid propulsion systems can help to achieve these goals, but they also make the development of typical construction machinery such as hydraulic excavators a complex, expensive and time-consuming task. An improvement in the development process can be achieved through the usage of virtual prototypes. In this work, a physical simulation model of a 40-ton excavator is presented as an example for the virtual machine. However, virtual prototyping requires not only a detailed machine model, but also a driver model that computes realistic actuation signals during simulation. Therefore, a predictive driver model based on a state machine and decentralized model predictive controllers has been developed. The accelerated proximal gradient method is applied in the dual domain in order to solve the underlying constrained optimization problem. Results for the combined simulation of the virtual driver and the virtual excavator are presented. Particularly, the influence of different driver parameters is analyzed with regard to the resulting cycle time and fuel consumption.

1. Introduction

An increasing awareness for the environmental effects of pollutants from vehicles has led to a stricter regulation of emissions. This holds true not only for road vehicles, but also for construction machinery such as excavators or wheel loaders. The STAGE and TIER norms in Europe and the US have led to new technological challenges for the equipment manufacturers and their suppliers [1,2]. At the same time, the cost for diesel fuel is on the rise in the long term, and as a consequence, customers demand more efficient machinery. Therefore, a significant improvement of the currently used systems and components becomes necessary with regard to efficiency. In addition, alternative solutions such as hybrid propulsion systems need to be further investigated and broadly introduced into the markets as soon as possible.

However, the development of highly efficient machinery and research on hybridization approaches are both time-consuming and costly, and require engineering knowledge in various fields. Today's construction machinery represent complex mechatronic systems, including mechanical, hydraulic, electrical and electronic components. In particular, the development of prototypes and experiments with such machines requires a high effort with unsure outcome. To overcome these issues, virtual prototyping has become a promising approach as part of the development and engineering process. Essentially, a virtual prototype is a simulation model of the considered machine with a specified level of detail, allowing for machine analysis even at an early development stage. Without the need for an actual prototype, different hydraulic architectures and hybridization approaches can be assessed and compared with regard to functionality, performance and efficiency. Various publications show the benefit of this strategy, including work on electric or hydraulic hybridization of excavators and commercial vehicles [3–7] and approaches towards more efficient hydraulics in mobile machinery [8–10]. Further applications include the model-based development of driver assistance systems [11,12] or autonomous vehicles [13–16].

Previous work mostly concentrated on modeling the machine and analyzing its performance during simulation studies [3,17]. However, in order to obtain realistic simulation results, physical simulation approaches require the generation of realistic machine inputs, i.e., actuation signals for the steering wheel or the joysticks, as the real human driver would generate them for the real prototype. Only the combination of a validated machine model or at least validated component models, realistic driving cycles based on actual earth moving tasks and an appropriate operator model guarantees the significance and resilience of simulation results obtained during virtual prototyping. In consequence, considerable attention should be paid to the applied operator model.

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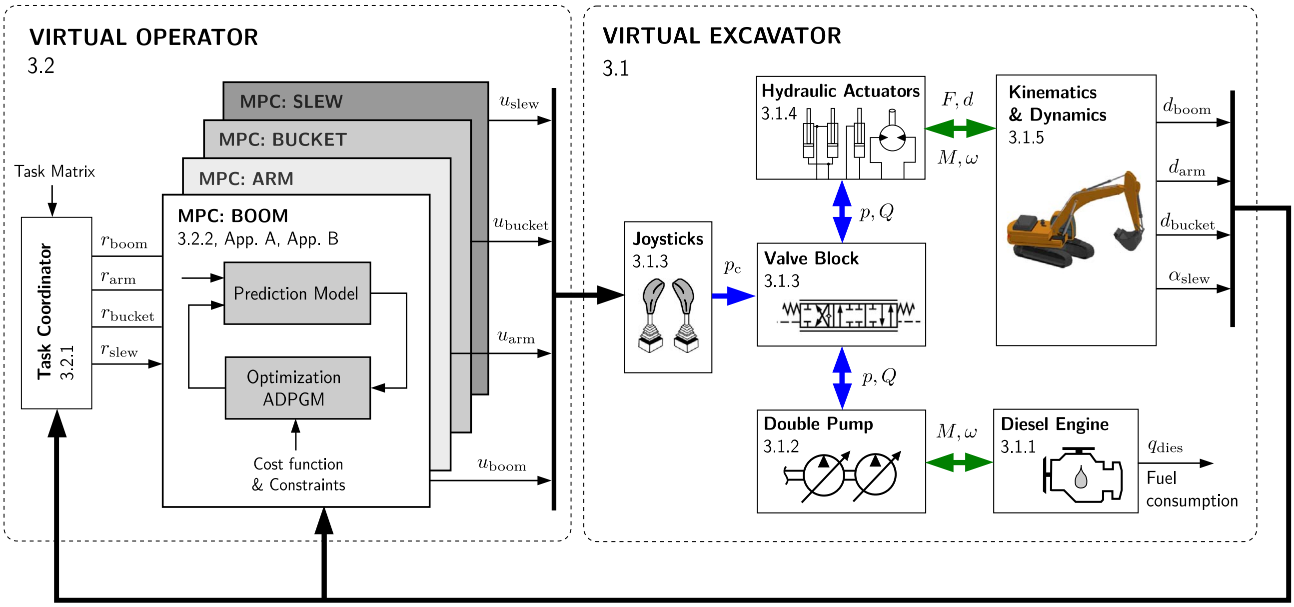

Fig. 1. Structure of the presented simulation model. The virtual operator is implemented by means of the task coordination module and four model predictive controllers determining the appropriate joystick actuation signals in order to perform a given task. Also notice the various physical domains within the virtual excavator and their interaction paths.

2. Operator models for construction machinery

2.1. Previous work

Research on driver behavior in automotive environments has led to a large number of applicable models and publications [18–20]. This includes control oriented [20] and even predictive driver models [21,22], mostly used for analyzing driver behavior, its influence on traffic, and vehicle performance. In contrast, the modeling of construction machinery operators has received little attention. Filla et al. have presented an event-driven operator model for a wheel loader [8,23], mainly based on a state machine that assigns the appropriate actuation signals for both longitudinal and lateral dynamics and the working hydraulics as a function of the current machine state. Oh et al. also considered a wheel loader operator, combining a state machine, a linear quadratic regulator for controlling the longitudinal dynamics and a linear model predictive controller for influencing the lateral dynamics [10]. At least partially, their approach includes predictive elements. Bender et al. firstly presented a decentralized model predictive control approach with a linear, time varying prediction model in combination with a state machine used for task coordination for modeling the operator of an excavator [24]. Later, they showed an extension of this model including a nonlinear prediction model in Hammerstein structure [25]. The resulting nonlinear optimization problem was solved using a sequential quadratic programming algorithm. This leads to more realistic simulation results, but also to an increase in complexity, identification efforts and computation time. The work presented here builds upon this previous work, but considers a more detailed model of the excavator and a new formulation of the predictive virtual driver based on linear model predictive control and the accelerated dual proximal gradient method for solving the underlying optimization problem. Additionally, the possibility to implement different operator types will be utilized and their variations with regard to performance will be analyzed.

2.2. Human pperator characteristics

Taking a closer look at the human operator and incorporating earlier research on driver modeling, some typical characteristics of the human driver can be found. In particular, human operators show predictive behavior, i.e., they know the behavior of their machine from experience and take this into account when performing any given task. Therefore, they can operate the machine at its performance limits, leading to minimum cycle time, and they consider constraints such as maximum cylinder strokes or steering angles at the same time [20]. For the purpose of virtual prototyping, we will restrict our operator model to a control theoretic interpretation without any consideration of driver motivation.

2.3. Operator model requirements

From the above observation, important requirements for a realistic operator model can be derived, namely,

- Model based and predictive decision making,
- The consideration of machine constraints,
- (Time-)optimality with regard to task execution.

Since the driver model will be used within a virtual prototyping framework, additional requirements with regard to its practical implementation and usage exist, namely,

- A modular structure,
- The ability to simulate different operator types.

Only with an extendable modular structure, the driver model will be applicable to various types of mobile machinery with different degrees of freedom. Since different human operators can lead to a large variation in machine performance and fuel consumption, it is also desirable to simulate different operator types with the virtual driver. An intuitive approach for tuning the parameters of the driver model is necessary for the driver model being of practical value.

Considering these requirements in summary, modeling the operator in a control oriented framework seems both feasible and promising. In particular, an interpretation of the driver as model predictive controller (MPC) is intuitive, as MPC uses a simplified model for the prediction of