Model-Based Control of Three Degrees of Freedom Robotic Bulldozing

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This brief paper investigates the control of a robotic bulldozing operation. Optimal blade position control laws were designed based on a hybrid dynamic model to maximize the predicted material removal rate of the bulldozing process. Experiments were conducted with a scaled-down robotic bulldozing system. The control laws were implemented with various tuning values. As a comparison, a rule-based blade control algorithm was also designed and implemented. The experimental results with the best optimal controller demonstrated a 33% increase in the average material removal rate compared to the rule-based controller.
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1 Introduction

1.1 Motivation. There is an increasing interest in automated mobile equipment in the construction, agriculture and mining industries to improve productivity, efficiency, and operator safety. These machines belong to a class of mobile vehicles with a tool for manipulating its environment to accomplish a repetitive task. A particularly challenging problem is the automation of a bulldozer for the removal of excavated material, such as the underground mining operation illustrated in Fig. 1. The resistance faced by the blade from the environment and the traction properties of the tracks may vary significantly depending on the physical properties of the media (e.g., density and hardness) and the distribution of particle sizes and shapes. Furthermore, the process is inherently influenced by the coupled dynamics between the blade and tracks. This brief paper proposes novel optimal model-based blade control laws for a robotic bulldozing operation.

1.2 Related Work on Bulldozer Control. Investigations on bulldozer control have primarily focused on blade position control for grading soil, e.g., Refs. [1] and [2]. These control system schemes are typically designed for operator assist applications and tend to be ad hoc approaches that lack optimality and robustness in task execution. Typical assumptions include uniform soil conditions and constant vehicle speed. Artificial intelligence methods have been employed for higher-level coordination of multiple robotic excavation machines, including bulldozers, for remote site preparation tasks, e.g., Refs. [3] and [4].

Other related work includes the control of excavation machines used for digging tasks. Unlike bulldozing, which involves pushing material forwards, digging involves scooping, lifting, and carrying material. The machine is typically modeled as a multiple-link robotic manipulator mounted on a static base with control design involving position and/or force feedback, e.g., Refs. [5–8]. Systematic model-based low-level control of the bulldozing process has not been addressed in the existing literature.

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Fig. 1 Teleoperated bulldozer used for underground mining

1.3 Scope. The robotic bulldozing operation considered in this brief paper is characterized by the primary low-level dynamic behavior of a typical bulldozing process, specifically the X, Z, and pitch DOF, where X is the direction of forward motion and Z is the elevation. Similarly, the variation in the environment is reduced to mainly the X and Z dimensions. We assume the material to be pushed consists of fragmented rock or stones. Regarding the control of the process, our focus is on enhancing productivity. Specifically, the control objective is to maximize the material removal rate. The process model is summarized in Sec. 2. The design of the model-based controller is presented in Sec. 3. The experimental procedure is described next, along with a discussion of experimental results. Conclusions are drawn in Sec. 5.

2 Hybrid Dynamic Model of Robotic Bulldozing

A hybrid dynamic model of a 3-DOF robotic bulldozing process has been presented in Ref. [9]. The model is summarized here since it forms the basis for the control laws presented in Sec. 3. It incorporates a set of ten discrete operation modes defined by continuous dynamics and a set of discrete event mode transitions. A set of hybrid nonlinear dynamic system equations model the continuous dynamics. The model structure is the same for all modes, only the parameters change. Figure 2 illustrates the state variables and some of the auxiliary variables. In this figure, δ_a is the maximum effective length of material accumulated in front of the blade. The system equations employed in the design of the model-based controller are as follows:

$$\dot{d}_a = v_b \cdot \left(C_{da1,\Gamma} \cdot d_a + C_{da2,\Gamma} \cdot h_a + C_{da3,\Gamma} \cdot h_b + C_{da4,\Gamma} \cdot h_{\delta r} + C_{da5,\Gamma} \cdot \zeta\right) \tag{1}$$

$$\dot{x}_b = v_b \tag{2}$$

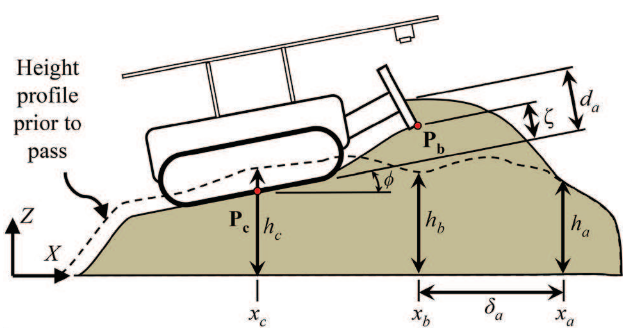

Fig. 2 Illustration of the state variables d_a, x_b, z_b, z_c, φ, and ζ; and auxiliary variables h_a, h_b, and h_c (note that $P_b = [x_b\ z_b]^T$ and $P_c = [x_c\ z_c]^T$)