Development of a Hybrid Dynamic Model and Experimental Identification of Robotic Bulldozing

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The low-level modeling and control of mobile robots that interact forcibly with their environment, such as robotic excavation machinery, is a challenging problem that has not been adequately addressed in prior research. This paper investigates the low-level modeling of robotic bulldozing. The proposed model characterizes the three primary degrees-of-freedom (DOF) of the bulldozer, the blade position, the material accumulation on the blade, and the material distribution in the environment. It includes discrete operation modes contained within a hybrid dynamic model framework. The dynamics of the individual modes are represented by a set of linear and nonlinear differential equations. An instrumented scaled-down bulldozer and environment are developed to emulate the full scale operation. Model parameter estimation and validation are completed using experimental data from this system. The model is refined based on a global sensitivity analysis. The refined model is suitable for simulation and design of robotic bulldozing control strategies. [DOI: 10.1115/1.4023061]

1 Introduction

1.1 Motivation. A major unaddressed challenge with mobile robots is the control of vehicles interacting forcibly with their environment, such as robotic tractors, bulldozers, loaders, and snow plows. Forces and motions are inherently coupled between the tool (e.g., bucket or blade) and the means of vehicle propulsion (e.g., wheels or tracks). Furthermore, they are often operated within uncertain and unstructured environments, such as the underground mining operation shown in Fig. 1. There is a growing industrial interest in the development of robotic mobile machinery to improve productivity, efficiency, and safety.

Modeling of the interaction dynamics between this type of vehicle and its environment is imperative for the development of advanced control strategies. In particular, this includes the design of model-based controllers and process simulation. This paper focuses on the modeling of robotic bulldozing.

1.2 Related Work on Bulldozer Automation. The literature on bulldozer automation is very sparse. The main area of focus has been on blade position control for grading soil, e.g., Refs. [1] and [2]. Typical assumptions include uniform soil conditions and constant vehicle speed. These control system implementations tend to be ad hoc schemes for operator assist applications that lack a systematic approach with respect to optimality and robustness in task execution. A few papers have presented high-level artificial intelligence approaches for coordinating multiple autonomous robots for complex excavation operations, e.g., Refs. [3] and [4]. The low-level modeling and control of the bulldozing process, i.e., the interaction between the bulldozer and its environment, has not been addressed in the existing literature.

1.3 Related Work on Scaled-Down Excavation Tasks. Other related work includes modeling and control of excavation tasks using a small tool carried by a robotic manipulator and a scaled-down experimental environment. In Ref. [5] the bucket motion of a front loading excavator machine was simulated using a PUMA 560 robot arm. A fuzzy-logic based control strategy was developed by emulating the actions of skilled human operators. Experiments were performed within a simulated rock excavation environment. A theoretical model was developed in Ref. [6] to predict the resistive forces on the bucket of an excavator known as a load-haul-dump machine during the scooping phase of operation. The predicted forces agreed well with those obtained using a scaled rock pile environment. A method is presented in Ref. [7] for identifying the unknown parameters required for real-time prediction of interaction forces between an excavator tool and the soil using a hybrid dynamic soil model. A Mitsubishi RV-M1 robotic manipulator was used to push a flat metal tool through the soil. Force measurements were obtained using a six-axis ATI Mini40 force/torque sensor. Their experimental results demonstrated good correlation between the estimated and measured forces. It must be noted that the interaction dynamics with soil are significantly different than with fragmented rock or stones. Furthermore, all of these investigations neglected the coupled dynamics between the implement and the mode of propulsion that are present in bulldozing.

1.4 Related Work on Full Scale Farm Machinery. An analytical model was developed in Ref. [8] for the yaw dynamics of a farm tractor for the purposes of improved automatic steering

Fig. 1 Teleoperated bulldozer used in underground mining

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