# MODELLING OF ROBOTIC BULLDOZING OPERATIONS FOR AUTONOMOUS CONTROL


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## ABSTRACT

The low-level modeling and control of mobile robots that interact forcibly with their environment, such as excavation machinery, is a challenging problem in robotics research. This paper investigates the modeling of a robotic bulldozing operation for the purpose of autonomous control. The distinct operating modes are contained within a hybrid system modeling framework. The dynamics of the individual modes are represented by a set of five nonlinear differential equations. Model parameter estimation and validation were completed using experimental data from a scale model bulldozer. The average normalized root-mean-square prediction errors for the five states were 0.9%, 3.1% and 4.4% for one-step, five-step and ten-step ahead prediction horizons, respectively. The model will be used for the future development of model-based optimal bulldozing control.



***Index Terms***— autonomous robots, bulldozing, hybrid dynamic systems, system identification.


## 1. INTRODUCTION

A major challenge with mobile robots is the control of vehicles interacting forcibly with their environment, such as 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.

The literature on bulldozer automation is very sparse. The main area of focus has been on blade position control for grading soil, *e.g*.[1][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*.[3][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.


**Figure 1:** Teleoperated bulldozer used in underground mining.

The complete bulldozing process involves the position and orientation of the machine (*i.e.* 6 degrees-of-freedom), the 3-dimensional environment (*i.e.* a volume of material distributed on a hard floor), and their interaction dynamics. In this paper we kinematically constrain the process such that the machine is reduced to three degrees-of-freedom (X, Z and pitch) and the variation in the environment is reduced to mainly the X and Z dimensions. The dynamics of the bulldozing process are described in section 2, followed by a description of the experimental system. The structure of the dynamic model is presented in section 4. The experimental procedure is presented next, followed by the model fitting and validation. Conclusions are drawn in section 7.

## 2. DESCRIPTION OF THE BULLDOZING PROCESS

A bulldozer consists of a main body driven by two motorized tracks. A blade for pushing material is joined to the machine by two arms. The blade is raised/lowered by a position controlled actuator. During the bulldozing process, the torque generated by each track drive motor is translated into a shear force between the track and the surface it is in contact with. A complex combination of the geometry and physical properties of the material below the tracks, and of the tracks themselves, determines the maximum torque that can be transferred before traction loss, or track slip, occurs. The amount of slip depends on the profile and area of the tracks; bulldozer weight and its distribution; static and dynamic friction functions; and the strength of the underlying material. The effective environment force on the blade is a combination of friction forces on the blade and the resistance of the material being pushed. The force is transmitted from the blade, through the blade arms and the main body, into the tracks. Lowering the blade tends to increase the environment force and vice-versa. For constant track motor hydraulic pressure (or voltage if the motor is electric) the forward speed of the blade will decrease when the blade is lowered due to the increased force and resulting increased traction loss. The decrease is nonlinear since the rate of material accumulation is proportional to the speed, and the friction functions are nonlinear. Our nonlinear model of this process is presented in section 4.