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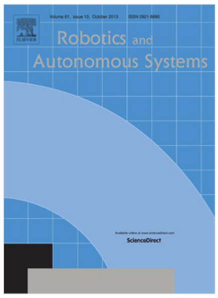

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Daniel M. Lindmark, Martin Servin

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Computational exploration of robotic rock loading

Daniel M. Lindmark[a], Martin Servin[a]

[a]Umeå University, Umeå, Sweden

Abstract

A method for simulation-based development of robotic rock loading systems is described and tested. The idea is to first formulate a generic loading strategy as a function of the shape of the rock pile, the kinematics of the machine and a set of motion design variables that will be used by the autonomous control system. The relation between the loading strategy and resulting performance is then explored systematically using contacting multibody dynamics simulation, multiobjective optimisation and surrogate modelling. With the surrogate model it is possible to find Pareto optimal loading strategies for dig plans that are adapted to the current shape of the pile. The method is tested on a load-haul-dump machine loading from a large muck pile in an underground mine, with the loading performance measured by productivity, machine wear and rock debris spill that cause interruptions.

Keywords: robotic excavation, autonomous loading, rock pile, multibody dynamics, discrete element, surrogate modelling
2010 MSC: 00-01, 99-00

1. Introduction

Loading piles of fragmented rock is a challenging task, for a machine operator and even more for an autonomous system. For this reason mining vehicles for loading, hauling and dumping (LHD) are still not fully automated but rely on a human operator controlling the loading task, by remote or from within the machine. With fully autonomous control, productivity is lower and maintenance needs are higher than with operators [1]. The difficulty lies in perceiving the state of the pile, planning and controlling a movement that quickly fills the bucket, avoiding excessive wear on the machine, and leaving the pile in a state well-suited for continued loading. Interruptions in the loading occur when rock debris are left in front of the pile or if an overhang is created. Improper handling, like ramming into a large boulder or filling the bucket unevenly, causes damage to the machine.

This paper describes and tests a method for simulation-based development of systems for robotic loading of fragmented rock piles. The idea is to formulate a generic loading strategy as a function of the observed shape of the pile and the kinematics of the machine, and to use multi-objective optimisation and contacting multibody dynamics to determine the strategy that maximises performance from a large set of realistic simulation experiments. Surrogate modelling is used to explore the loading strategy design space and to identify the Pareto optimal strategies. The aim is to show that this is a feasible and useful approach for developing and testing automation strategies for robotic rock loading. The method is tested on a specific LHD system for underground mining. Statistically significant relations between the loading strategy and performance are found, and the computational complexity of the method is analysed.

Robotic loading can be divided into pile analysis, high-level dig planning and low-level loading control. In this paper, we apply the method to the dig planning task only. The bucket motion is given a generic representation depending on some design variables that parametrise the entry point in the pile, the dig depth, bucket curl and target fill ratio. The dig motion planner takes the vehicle kinematics, observed pile geometry and the design variables as input and outputs a specific bucket trajectory and corresponding motion plan for the machine. Objective functions are introduced for the productivity, joint damage and amount of rock debris in front of the pile causing interruptions. Together, the objective functions determine the loading performance. The simulations are based on a detailed 3D multibody dynamics model of the vehicle and the rock pile. The machine model includes actuator models and a control algorithm to execute the motion plan. The actuators have limited force, and the machine may lose ground traction if the pile resistance is large enough to cause frictional slippage. Consequently, the simulated bucket trajectory may deviate from the plan. This provides realism that is not available when using a kinematic model of the vehicle or bucket. For each simulation, the forces and moments in the joints of the machine are measured, as well as the loading cycle time, final bucket fill ratio as well as the resulting state of the pile. Both the actuating forces and the constraint forces keeping the joints

Email addresses: daniel.lindmark01@umu.se (Daniel M. Lindmark), martin.servin@umu.se (Martin Servin)

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