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Adaptive sampling applied to blast-hole drilling in surface mining

Nasir Ahsan *,[1], Steven Scheding *,[2], Sildomar T. Monteiro *,[3], Raymond Leung *,[2], Charles McHugh *,[4], Danielle Robinson *,[4]

Australian Centre for Field Robotics, Engineering Link Building, The University of Sydney, NSW 2006, Australia

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ABSTRACT

This paper describes an application of adaptive sampling to geology modeling with a view of improving the operational cost and efficiency in certain surface mining applications. The objectives are to minimize the number of blast holes drilled into, and the accidental penetrations of, the geological boundary of interest. These objectives are driven by economic considerations as the cost is, firstly, directly proportional to the number of holes drilled and secondly, related to the efficiency of target material recovery associated with excavation and blast damage. The problem formulation is therefore motivated by the incentive to learn more about the lithology and drill less. The principal challenge with building an accurate surface model is that the sedimentary rock mass is coarsely sampled by drilling exploration holes which are typically a long distance apart. Thus, interpolation does not capture adequately local changes in the underlying geology. With the recent advent of consistent and reliable *real-time* identification of geological boundaries under field conditions using measure-while-drilling data, we pose the local model estimation problem in an adaptive sampling framework. The proposed sampling strategy consists of two phases. First, blast-holes are drilled to the geological boundary of interest, and their locations are adaptively selected to maximize utility in terms of the incremental improvement that can be made to the evolving spatial model. The second phase relies on the predicted geology and drills to an expert based pre-specified *standoff* distance from the geological boundary of interest, to optimize blasting and minimize its damage. Using data acquired from a coal mine survey bench in Australia, we demonstrate that adaptively choosing blast-holes in Phase 1 can minimize the total number of holes drilled to the top of the coal seam, as opposed to random hole selection, whilst optimizing blasting by maintaining a reasonable compromise in the error in the stopping distances from the seam. We also show that adaptive sampling requires, for accurate estimation, only a fraction of the holes that were initially drilled for this particular dataset.

1. Introduction

Certain surface mining procedures require modeling the underlying geology to optimize blasting. An incorrect notion of the underlying geology can increase the damage caused by fragmentation due to subsequent blasting particularly when dealing with relatively horizontal geological boundaries.

A geology model can be acquired from past exploration data which has been interpreted by geologists and geophysicists. However, such information only provides a rudimentary estimate of the underlying geology because the exploration holes can be spaced hundreds of meters apart. Therefore, it is imperative to have some *local* spatial model of the underlying geology. This necessitates drilling some blast holes through the target geological boundary (the boundary of the target material that is being mined). Since drilling through the target boundary is costly, it is desirable to minimize the number of times we must do so. Thus, the problem can be stated as acquiring an accurate local model of the underlying geology to improve blast-hole design whilst minimizing the number of holes drilled through the target boundary. Furthermore, an accurate local model also reduces the need to resort to extraneous processes or using geophysical data to increase confidence in the model's prediction. This is advantageous since these processes

* Corresponding authors.
E-mail addresses: a.nasir@acfr.usyd.edu.au (N. Ahsan), s.scheding@acfr.usyd.edu.au (S. Scheding), sildomar@mail.rit.edu (S.T. Monteiro), r.leung@acfr.usyd.edu.au (R. Leung), charles.mchugh@riotinto.com (C. McHugh), danielle.robinson@riotinto.com (D. Robinson).

[1] Author works at the Australian Centre for Field Robotics (ACFR), School of Aerospace, Mechanical and Mechatronics Engineering, University of Sydney, and the Department of Robotics and Intelligent Machine Engineering, National University of Sciences and Technology Pakistan. The work described in this paper was undertaken while this author was at the ACFR.

[2] Authors work at the Australian Centre for Field Robotics (ACFR), School of Aerospace, Mechanical and Mechatronics Engineering, University of Sydney.

[3] Author works at the Kate Gleason College of Engineering, Rochester Institute of Technology, USA.

[4] Authors work at Rio Tinto, Australia.

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ordinarily lie outside the drill-blast loop and are not related to core production.

With the advent of measure while drilling (MWD) data it has become possible to build local geology models. MWD data includes drill performance parameters such as rotary speed, penetration rate, weight on bit, and torque which can be monitored in real-time, and can be used to optimize the drilling process [1]. A significant correlation between these parameters and the ground-truthing strategy of geophysical logging, typically used for lithology characterization, was demonstrated in [2]. Much work has also shown the potential of these parameters in directly characterizing the lithology [3–5]. Thus, using MWD data it is possible to detect geological boundaries in real-time (in a consistent manner), and therefore, learning of *local* geology models. This process is illustrated in Fig. 1. Constructing local geology models using MWD also relieves the operators from resorting to geophysical logs for ground-truthing, varying interpretations of drillers, or relying entirely on sparsely distributed a priori exploration data. The measurements are collected by sensors mounted on large drill rigs for blast hole drilling. An example of an autonomous blast hole drill rig is illustrated in Fig. 2.

The *choice* of holes drilled through the target boundary is essential for building an accurate local model. For instance, it is entirely likely that drilling five holes and having them spread over the entire bench may actually yield a more accurate model than 10 holes in close proximity to each other. This, in fact, is a *sampling* problem. Incorporating model feedback for iterative data selection has been shown to result in accurate models with minimal effort, which in the drilling context would translate to minimizing the number of holes drilled through the target boundary. For instance, after drilling the first hole through the target boundary, one can use the model (locations of the boundary) to identify the next best drilling location based on model feedback. This new location can possibly be the farthest position from the current drilled blast hole, because the model cannot confidently extrapolate its current measurements to that location. This new blast hole is then drilled through the target boundary, then the MWD data is appended to the current training set, and the model is re-learned to suggest another drilling location. This process can be repeated until the model believes it can confidently extrapolate its predictions over the entire survey bench. Such methods have been applied in practice and are known to produce accurate models with very little training data [6–9]. These techniques are known as *adaptive sampling*.

The objective of this paper is to investigate whether adaptive sampling can produce accurate local geological models to optimize blast-hole design with minimal drilling through the target boundary. To this effect, we propose a 2-phase adaptive drilling strategy which first iteratively identifies which holes to drill through the target boundary to build some notion of the underlying geology, after which it sweeps through the entire survey bench drilling each hole to a pre-specified *standoff* distance from the target boundary to minimize damage due to blasting. The standoff distance is an expert based pre-specified parameter that if applied to a *perfect* model of the underlying geology will result in optimal blasting with minimal damage due to fragmentation. We show that our 2-phase sampling strategy minimizes the number of holes drilled through the target boundary whilst maintaining a reasonable compromise in the stopping distances (deviation from ideal standoff distance).

The rest of this paper is structured as follows: in Section 2 we present some necessary background and terminology. In Section 3 we present the proposed adaptive sampling algorithm along with a baseline counterpart. The data, demonstration of adaptive sampling, experimental setup and results are presented in Section 4. A discussion of the results and the approach is then presented in Section 5. We conclude the paper in Section 6 with a discussion on directions for future research.

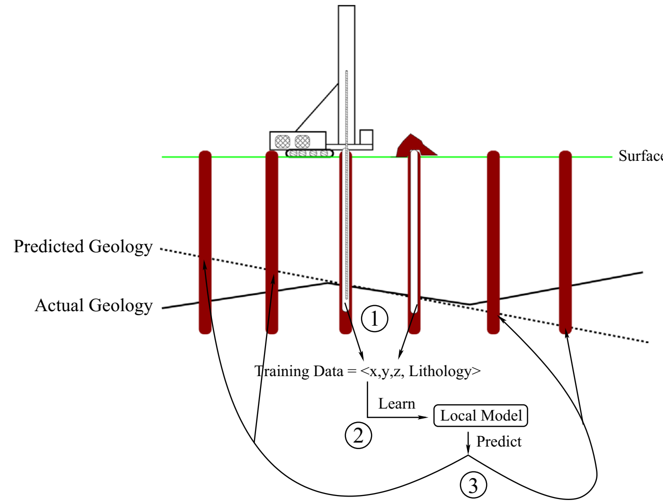

Fig. 1. Building a local spatial model of the underlying two class geological boundary using MWD data. Note the Lithology at each point $\langle x, y, z \rangle$ is characterized by MWD data collected at that point.

Fig. 2. An autonomous blast hole drill rig used for collecting MWD data.

2. Preliminaries and background

In this section we present the terminology used in the paper followed by a background on adaptive sampling and the spatial modeling approach.

2.1. Terminology

We now present some basic terminology used throughout the paper. It suffices to classify a blast hole into the following categories: discovery holes (DH), exploitation holes (EH), mistaken holes (MH), and total drilled holes (TDH). These are defined as follows. DH are holes intentionally drilled through the target