Virtual Environments for Planning Underground Mining Operations

Frédéric Labrosse Philippe Debanné Jean-Yves Hervé Paul Cohen
NSERC-Noranda Chair in Mining Automation
École Polytechnique, Montréal, Québec, Canada
[labrosse,debanne]@ai.polymtl.ca

Abstract

This paper describes current work aimed at developing a multi-attribute modeling system for underground mines. We present a model framework that allows the integration of various types of data pertaining to a mine's structure and operations. We then introduce 3D graphical mine representations, instantiated from the mine model, whose purpose is two-fold: first, they provide a means to visualize a mine's operational attributes in their current states as described by sensed data; secondly, they serve as the basis for simulations to plan and analyze various mining activities. We briefly describe several applications under development using this type of virtual mine testbed.

Résumé

Le présent article décrit des travaux portant sur le développement d'un système de modélisation multi-attributs de mines souterraines. Nous présentons une structure de modèle permettant d'intégrer divers types de données ayant trait à la structure et aux opérations d'une mine. Nous présentons ensuite des représentations graphiques 3D de mines, générées à partir du modèle, qui ont deux fonctions. D'une part, elles permettent de visualiser simultanément plusieurs attributs de la mine, dans leurs états immédiats tels que fournis par les données sensorielles acquises. D'autre part, elles servent d'environnement de simulation afin de planifier et d'analiser diverses activités minières. Nous décrivons brièvement plusieurs applications utilisant ce type de banc d'essai virtuel.

1 INTRODUCTION

The operation of an underground mine encompasses a wide spectrum of activities, such as surveying and mapping, blasting, ore extraction and hauling, ventilation, *etc.* Monitoring these activities and planning changes in their operating modes relies heavily upon the availability of appropriate information and upon its representation, management, and exchange. This paper describes current work at the NSERC-Noranda chair aimed at developing a multi-attribute modeling system for underground mines. This system will integrate key aspects of a modern mining operation and will, from the initial planning stages onward, provide an efficient means of processing and representing up-to-the-minute information gathered from the mine's ongoing activities.

Traditionally, each mining activity used its own database, leading to considerable duplication of information. Currently, the mining industry is looking at how to integrate all these databases into a more global one that is shared between the various activities (Devine & Brogden 1994, Sas 1994). Recently, Mottola, Scoble, Peck & Baiden (1995) proposed a representation in which information is decomposed according to activity types. Because their decomposition is not based upon information types, it inevitably leads to a certain amount of information duplication. Huang, Hassani & Daneshmend (1995), on the other hand, propose a model whose hierarchy is based upon information types. However, relations between the various parts of their model are not clear.

In this article, we describe an underground mine model which integrates various types of information relevant to a mine's activities (Section 2). Section 3 presents a graphical software package that uses instances of the model to generate virtual underground mines. These virtual mines are useful for visualizing various aspects of a mine's current activities through the modeling of instantaneous data. The virtual representations are also used to analyze mining activities based on up-to-the-minute information and plan changes through realistic predictive scenarios. Section 4 provides several illustrations concerning the design and control of autonomous hauling and surveying systems for underground mining vehicles.

2 THE UNDERGROUND MINE MODEL

2.1 The General Model

The mine model presented here is based upon a generic objet model described in (Labrosse, Hervé & Cohen 1996*a*). The purpose of this mine model is to integrate *classes of information* (or *attributes*) produced, utilized and exchanged by various mining activities such as surveying, mapping, mine planning, ventilation, *etc*, for the purpose of operation management and control.

The first of the mine model's attributes is the geometry of excavations. While processes such as hauling require geometric descriptions of navigable openings, traffic management only needs a topological description of these same openings in terms of drift lengths. Likewise, ventilation needs a topological description of excavations, augmented by parameters describing the airways' resistance. Mine planning requires representations of the ore body to be excavated and of the current accessibility to its different regions. Most activities require a decomposition into four major types of excavations: drifts, intersections, stopes, and shafts. A more precise description of this attribute is given in Section 2.2.

The hierarchy of activities which take place in each excavation, *i.e.* blasting, extraction, loading, hauling, dumping, ventilation, *etc.*, constitutes another attribute of the mine model.

A third attribute, mainly used in mine planning, is the representation of ore bodies. It includes geometrical information as well as ore grade and rock competence. The geometry of the ore body can use an octree representation (Kavouras, Masry, Smart & Reeler 1988); ore grade, rock competence, reflectivity and other relevant information may be associated to each leaf of the octree.

Mining operations need information about the status of installation infrastructure and equipment, from a global description down to individual devices, and may be represented by a specialization tree, *i.e.* an inheritance hierarchy (Huang, Hassani & Daneshmend 1995).

To integrate the various types of information just described, the interdependencies between the model's attributes must be represented. For instance, excavations must be spatially positioned with respect to the ore body. Likewise, pieces of equipment must be positioned within excavations, using (possibly time-varying) geometrical relations between reference points belonging to equipment pieces and to associated excavations. The functions of each excavation within mining operations may also be specified by means of an association between possible usages and excavation types (see Section 2.2).

2.2 Geometry of the Excavations

We briefly describe here the geometry of the four main types of excavations: drifts, intersections, stopes, and shafts. A more detailed description can be found in (Labrosse, Hervé & Cohen 1996*b*). In order to provide a hierarchical description, drifts are segmented into drift sections. Since the main purpose of the detailed geometric description is vehicle navigation, drift sections are represented as clothoidal ribbons of constant width and height. A clothoid is a curve whose curvature varies linearly with arc length. It's parametric equation is $\kappa(s) = \kappa_0 + ks$, where $\kappa(s)$ is the curvature, s is the arc length, κ_0 is the initial curvature, and k is the rate of change of curvature. Clothoids are useful to represent drifts as they can be followed by vehicles (Fleury, Souères, Laumond & Chatila 1995) and are widely used in autonomous navigation (Dickmanns, Mysliwetz & Christians 1990, Juneau, Hurteau, Freedman & Chevrette 1993). Moreover, the curves formed by the axes of successive sections are continuous in position, orientation, and curvature in order to ensure drift navigability. Each drift section is, therefore, described by its width, height, length and by the curvature's initial value and rate of change.

The 2D space composing an intersection is, first, represented by its boundaries and by the relations between the positions and orientations of adjacent drifts. At a second level, each wall joining adjacent drifts is split into wall sections of low curvature, represented as 3D cubic curves.

The mine's decomposition introduces other geometrical parts such as floors and roofs. The complete generic decomposition is shown in Figure 1.

Two relations exist between the geometrical parts: the *connection* and the *attachment*. The former specifies the identity of mutually connected drifts, intersections, and stopes. The latter specifies the geometrical parameters of each connection.

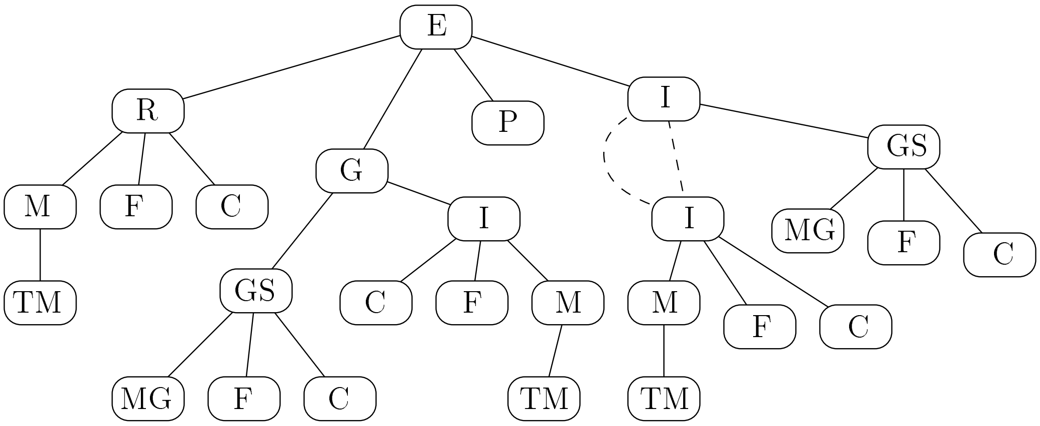


Figure 1: Generic decomposition tree for geometry (dashed lines indicate possible recursion). D: drift, DS: drift section, DW: drift wall, E: excavations, F: floor, I: intersection, R: roof, S: stope, Sh: shaft, W: wall, WS: wall section.

3 VIRTUAL MINES

We now introduce *virtual mines*, which are 3D graphical representations based upon the mine model described in Sections 2 and using sensory data gathered from the real mine. The main attribute consists of the geometry of excavations. According to the decomposition tree in Figure 1, the objects at the lowest level of the hierarchy are drift sections, wall sections, and floors and roofs of intersections and stopes. The following paragraphs describe how these objects' geometric parameters are combined with their related surface roughness values in order to completely describe them in 3D space.

3.1 Graphical Construction of Excavations

The model of the mine associates to each surface a value of surface roughness, whose actual value is computed on the basis of gathered survey data as explained in Section 4. Three parameters, *i.e.* fractal dimension, bump density and average bump deviation, are applied to an initial surface to obtain its final shape. The fractal algorithm used is found in (Peitgen & Saupe 1988).

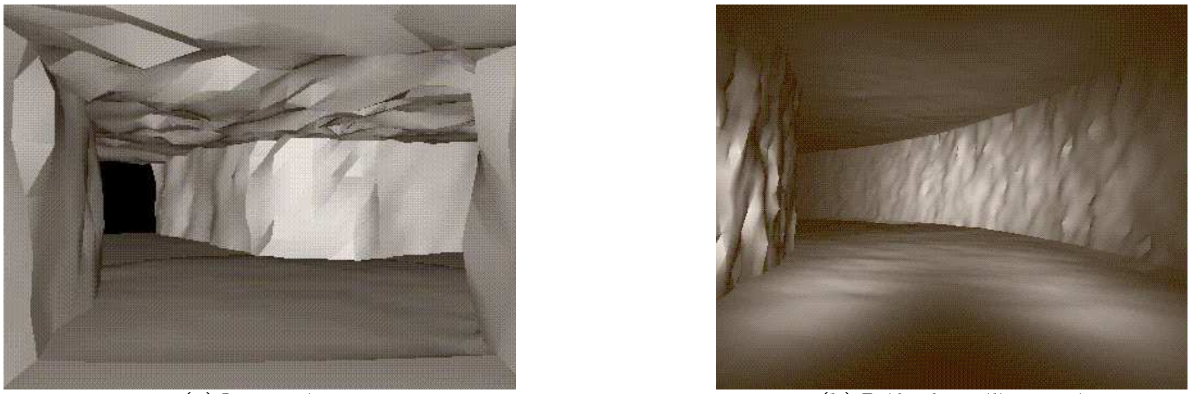
A drift section starts off as a straight cylindrical shape of rectangular section. The shape is *oriented*, with coordinate frames linked to the start and finish of the drift. Each of the four sides has its own fractal dimension, and the fractal algorithm is applied to each side separately. Different drift types result from bending the straight shape along its length to follow the parametric equation of the desired drift's axis. Clothoidal parameters extracted from survey data modify the transversal and curvilinear coordinates, while slope data will affect the elevation coordinate.

A wall section is created using the geometric transformation between the two adjacent drifts. A planar or cubic spline surface is, first, generated in the direction of the vector joining the two drifts. Fractal deformations are then applied in accordance with survey data. Floors and roofs are generated in a similar manner.

3.2 Visualizing Virtual Mines

An instance of the model specifies the mine's excavations as a network of drifts, intersections and stopes, and the relations between these elements. The various graphical components of the corresponding virtual mine are created as described in Section 3.1 and are placed in a scene database. Transformations between components are inserted at the appropriate locations in the scene database. Figure 2 shows two rendered images taken inside instances of virtual mines. The first image corresponds to an intersection of several drifts, while the second shows a curved drift.

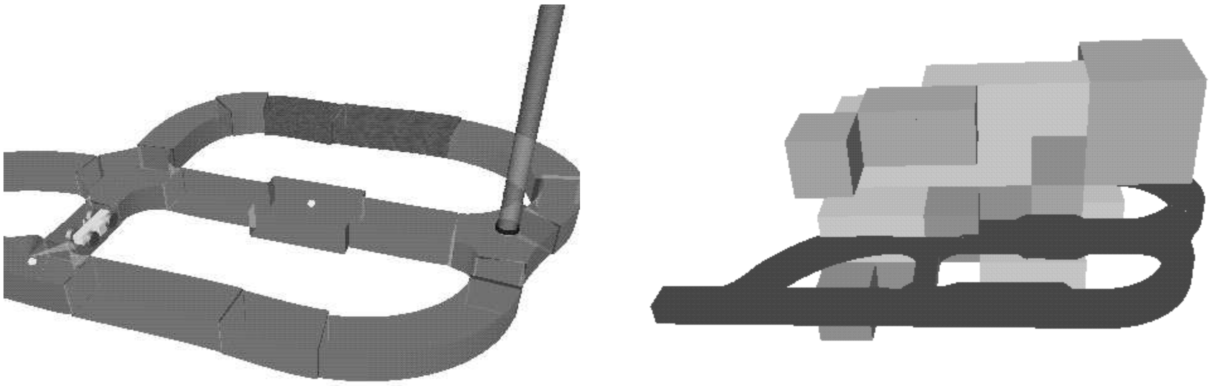
Other attributes from the model may also be visualized as part of the rendered 3D scene. In Figure 3(a), the excavation geometry is enhanced with additional components representing infrastructure and equipment.



(a) Intersection **(b)** Drift of curvilinear axis

Figure 2: Rendered images inside virtual mines.

Different rock types are displayed using textures applied to one region of the mine. The equipment shown includes a vehicle, light sources and a door and duct for ventilation. Likewise, Figure 3(b) illustrates the excavation geometry in relation to the ore body geometry, the latter being represented by an octree.



(a) Excavations, equipment and other information **(b)** Excavations and ore body

Figure 3: Visualizing several mine attributes.

4 APPLICATIONS OF THE MINE MODEL

Virtual mines may serve as an efficient means to plan, monitor and analyze a large range of mining activities. This function is all the more important considering the fact that operation management and control require reliable and up-to-the-minute information about the mine and its equipment. The virtual models proposed here, once built, can be continually updated on the basis of sensory information acquired by and transmitted from the various components and equipment within the mine. We briefly describe here three applications currently developed in our laboratory, based upon our mine model.

4.1 Surveying and Mapping

Traditionally, an underground mine must be surveyed periodically by hand, but this procedure is lengthy, costly and often dangerous for the surveyors. A first application of the virtual models previously described concerns the development of a automated mine surveying system (Debanné, Hervé & Cohen 1997). It is assumed that the surveying vehicle possesses initial knowledge of the mine's topology in the form of a graph identifying the drifts and their intersections. The vehicle follows, in the real environment, a global path described in the topological graph. This involves displacing itself within drifts and intersections (*i.e.*

local navigation) and establishing the correspondence between these structures and the graph (*i.e.* global navigation). Concurrently with these two forms of navigation, the robot must collect survey data about the shape of the mine sections it encounters.

The surveying unit consists of a vehicle equipped with structured light range sensors which take lateral and frontal range profiles of the drift walls. The frontal range profiles, through segmentation and analysis, are used both in local navigation and landmark-based positioning (*i.e.* detecting transitions between mine sections). Densely-spaced lateral range profiles along the robot's path provide the rough information for mine mapping and survey database updating.

The vehicle identifies local reference points for each topological element by using geometric properties of the shape of walls at the transitions. The final result of the robot's exploration is a set of local metrical maps describing each topological element. Design and testing of the sensory-information processing techniques use a virtual mine of the type previously described and a model of the surveying vehicle. The robot's trajectory through the mine and the acquired range profiles are visualized through a graphical computer interface (Figure 4).

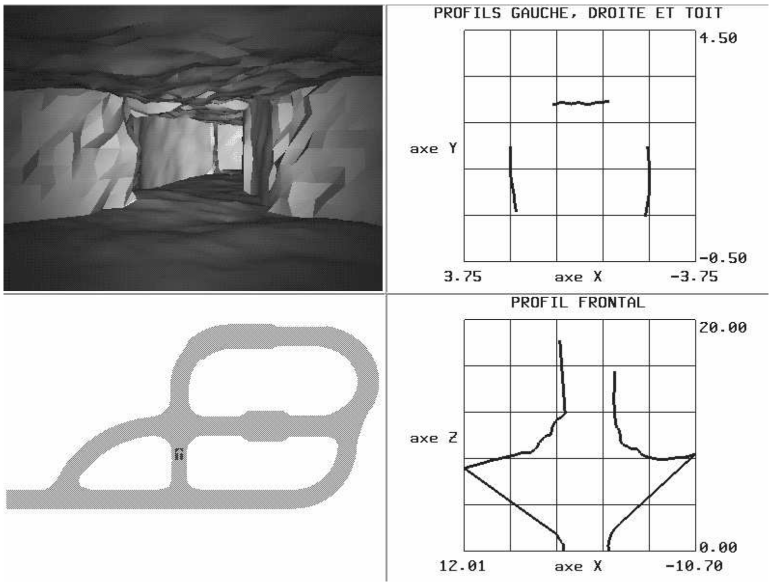


Figure 4: Graphical exploration interface

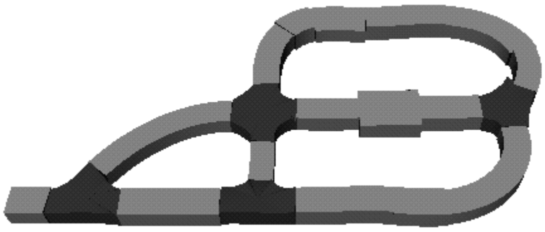


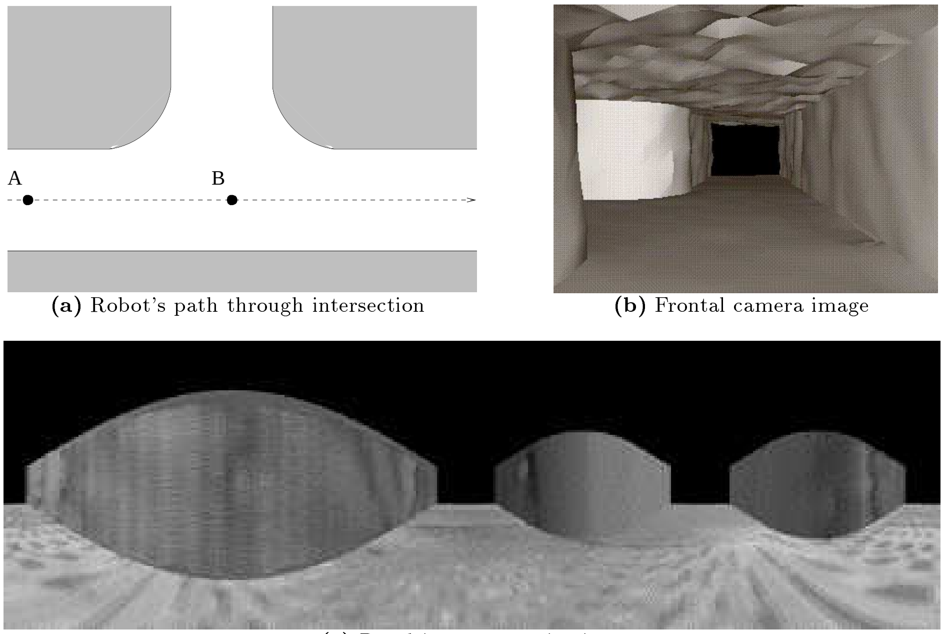
Figure 5: Reconstructed excavation geometry

Figure 6: Virtual mine drift with obstacle

The local maps of the topological elements are subsequently used as input to a program that constructs a geometric representation of the mine's excavations for the model (Labrosse, Hervé & Cohen 1997). Figure 5 shows the reconstructed excavation geometry for the mine surveyed in Figure 4.

4.2 Natural Landmark Recognition

Another application concern the development of a natural landmark recognition technique as a means for an autonomous unit to relocate itself while navigating in a drift environment (Béranger 1996). Specifically, the unit must recognize and position itself with respect to drift intersections. The technique uses sequences of images taken by a frontal camera as the robot approaches intersections. By extracting the floor boundaries in the images, the robot builds an internal representation of each intersection encountered, according to a geometrical model. Next, image textures are extracted and mapped on the reconstructed intersections to generate panoramic views; these are used in the landmark recognition process. To test this approach, image sequences were created by moving a CCD camera and spotlight through several virtual mine intersections. Figure 4.2 illustrates the process of panoramic view construction for the case of a T-shaped intersection.



(a) Robot's path through intersection

(b) Frontal camera image

(c) Resulting panoramic view

Figure 7: Construction the panoramic view of a T-shaped intersection.

4.3 Obstacle Detection and Avoidance

Autonomous navigation within mine drifts requires a reliable device for avoiding collisions with obstacles along the vehicle's path in order to ensure the safety of the vehicle, the environment and nearby human workers. An obstacle detection system has been developed which is adapted to the difficult environmental conditions in underground mines (*i.e.* sparse lighting, uneven surfaces) and with a short enough decision cycle to allow the vehicle to come to a complete stop before colliding with a detected obstacle (Melamed, Polotski, Piotte & Cohen 1998).

The system uses a set of forward-aimed structured light projectors coupled with CCD cameras. Camera images are processes to extract and track over time discontinuities in the light planes' intersections with the drift floor and walls. Several spatio-temporal criteria determine whether or not such discontinuities indicate the presence of obstacles. Extensive computer simulations were carried out which used models of the vehicle motion and sensors. The geometry of the environment was provided by virtual mines drifts of different shapes, to which obstacles were added. An example of virtual mine drift containing an obstacle is seen in Figure 6. The simulation results show that the proposed design and image processing algorithm meet the requirements imposed by the particular operation conditions.

5 CONCLUSION

We have presented an underground mine model which integrates various types of data needed to manage a mine's operations. A mine is represented by several attributes, each taking the form of a hierarchical database. Relations between attributes allow the management of a particular mining activity to access and combine the different sources of information required. This idea of database sharing reduces data duplication and enables us to create a complete, dynamic picture of the mine.

We have also shown how our mine model leads naturally to virtual mines, which are 3D graphical mine representations. We described the virtual mines' dual purposes of graphical model visualization and providing a simulation environment for the planning and testing of different mining operations. In particular, we discussed the application of our mine model to the design and control of autonomous navigation and data collection by vehicles in underground mines.

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