Object modeling and application to the case of underground mines

Frédéric Labrosse

This document presents the research that I have done for my Ph.D. in the *Groupe de Recherche en Perception et Robotique* of École Polytechnique of Montréal (Canada) and within the NSERC-Noranda Industrial Chair in Mining Automation. My thesis is entitled "Modélisation de l'Objet et application à ses représentations" (Object Modeling and Application to its Representations). The term *Object* refers here to complex systems composed of several elements whose types could be very different. Our model constitutes a framework to integrate these elements while preserving their distinction to allow ease of manipulation.

First, we describe the object model (Section 1) and, then, a particular application of the model done within the Chair: the modeling of underground mines to provide information usable by vehicles that navigate in an autonomous fashion (Section 2).

1 GNOME : A GeNeric Object ModEl

Whether our objective is object recognition, object reconstruction from measurements, creation of virtual environments, manipulation of objects by a robotic arm, or path planning for a mobile robot, a model of the objects involved is necessary. Having said this, there are different ways in which to represent a given object, depending on the task to perform with it or the agent performing the task. From this point of view, most existing models are myopic in the sense that they are dedicated to a particular task and, often implicitly, a particular agent. Therefore, we have developed a GeNeric Object ModEl (GNOME), which is independent of the task and the agent.

GNOME is a multiple-level model to represent objects through their various attributes (geometry, color, texture, density, *etc.*). Each attribute is represented independently of the others by a tree of hierarchical decomposition of attribute-objects (objects defined in the attribute's representation space), and by a graph representing relations between these attribute-objects, *e.g.* connections, relative pose, ordering *etc.* The set of all trees and graphs for all attributes constitutes the object's *structure*.

Each attribute-object and relation can be quantified by an application. The application's equation of an attribute-object's quantification specifies the shape (*e.g.* a cube or a sphere), while values of the equation's parameters specify the dimensions (*e.g.* the side or the radius). Quantifying the relations consist in linking a function to the relations' graph that indicates the relations and their quantification for each arc in the graph: this gives a labeled graph.

The set of all quantifications (of the attribute-objects and relations) constitutes the object's *quantification*.

Up to now, the attributes have been represented independently, but they are in fact not independent, and inter-attribute relations must be introduced. Since these relations can be quantified, they are represented by a labeled graph. One example of such a relation is correspondence. This relation gives, for example, the color (through color attribute-objects) of the different geometrical parts of the object (through geometry attribute-objects).

Due to the model's modularity and the data structures (graphs and trees) chosen, a representation can easily be modified when it is no longer appropriate (*e.g.* because of a change of task or agent). For example, attributes can be added or removed or the decomposition hierarchy of an attribute can be reorganized.

We have developed a formalism based on set theory. [LHC96c] gives this formalism as well as a more detailed description of the model and a simple example. I have presented the model in the *64^e congrès de l'Association Canadienne Française pour l'Avancement des Sciences* ([Lab96]).

2 An Application of the Model

In the framework of the NSERC-Noranda Industrial Chair in Mining Automation (held by my advisor), we have applied GNOME to the modeling of underground mines, in order to provide useful information for the navigation of autonomous mining vehicles, which is an important part of mining automation. Several mine models have been reported that represent various attributes (topography, geology, hydrography, ore grade, *etc.*), but these attributes are either not useful for navigation or they are under an inappropriate form for our task (block or CAD models[1]).

We have thus developed an underground mine model to study navigation problems such as autonomous navigation or path planning and learning. Moreover, mine representations following our model are being used to build virtual mines, within which a vehicle can navigate and take measurements of its environment.

The next section will describe the mine model, while Section 2.2 briefly describes virtual mines as well as examples of their utilization. Finally, Section 2.3 shows how we use surveying data to build mine representations.

2.1 The Mine Model

The attributes actually represented in the model are the mine's geometry, the roughness of walls, rock types, lighting, and obstacles. The purpose of geometry and obstacles is clear.

[1]Block models decompose the space in cells each indicating the presence or absence in the corresponding volume of what is represented while CAD models represent volumes by their boundaries.

Roughness of walls and rock types can be used to predict noise levels of sensors measuring the environment. Lighting can be used to, *e.g.*, plan paths everywhere lighted. Other attributes such as vehicle traffic could be added if the application of interest was, for example, traffic management.

At the first level of the geometric decomposition tree, there is an attribute object called "mine," which is decomposed into galleries, intersections, and rooms. The fact that navigation in galleries is different than navigation through intersections (or in rooms) justifies this decomposition. A gallery is decomposed into a sequence of gallery sections represented as clothoidal ribbons (which most accurately represent curved paths followed by a vehicle) which preserve continuity of orientation and curvature at their meeting points. Intersections and rooms are decomposed into walls, a ground and a ceiling. A complex intersection is first decomposed into more basic ones. A wall (of an intersection or of a room) is decomposed into a sequence of wall sections represented as cubic polynomial surfaces, with discontinuities at corners. Qualitative and quantitative connection relations between these various attribute-objects are represented.

Roughness is represented as a fractal dimension and a density of bumps. Rock is represented based on a classical geological taxonomy. Several types of light sources are included in the model: punctual, directional, and spotlights.

Some inter-attribute relations are represented, such as the association of roughness and rock type to gallery and wall sections, ceilings, and grounds, or the positioning of light sources and obstacles within the mine.

[LHC96b] gives the formalism associated to the mine model. [LHC96a] describes a preliminary version of the mine model as well as the virtual mines (Section 2.2).

2.2 The Virtual Mine Environment

Based on the mine model, we have developed a program generating virtual environments from mine representations (using the *Open Inventor* library on a *Silicon Graphics* workstation)[2]. One utilization of virtual mines is to simulate a vehicle navigating in the mine and acquiring for the moment two types of data: photometric CCD camera images and profiles given by laser range-finders. For the latter, an important part of 3D modeling work was required: creating surfaces that represent roughness as spatial deviations (rather than just texture mapping), and ensuring that the connections between these rough surfaces are "clean", *i.e.* continuous.

The sensory data extracted from virtual mines is used for different research projects (obstacle detection and intersection recognition). Also, the virtual mines are used as environments for robotic exploration and surveying, or to learn trajectories based on sensory responses. Figure 1 shows two views of such a virtual mine. An article describing the gen-

[2]This work was started by an undergraduate trainee who I supervised and continued by a graduate student who I am supervising.

Figure 1: Two views of a virtual mine

eration of these virtual mines have been submitted to *Centennial Meeting of the Canadian Institute of Mining, Metallurgy and Petroleum/XVIth Congress of the Council of Mining and Metallurgical Institutions* ([LDHC98]).

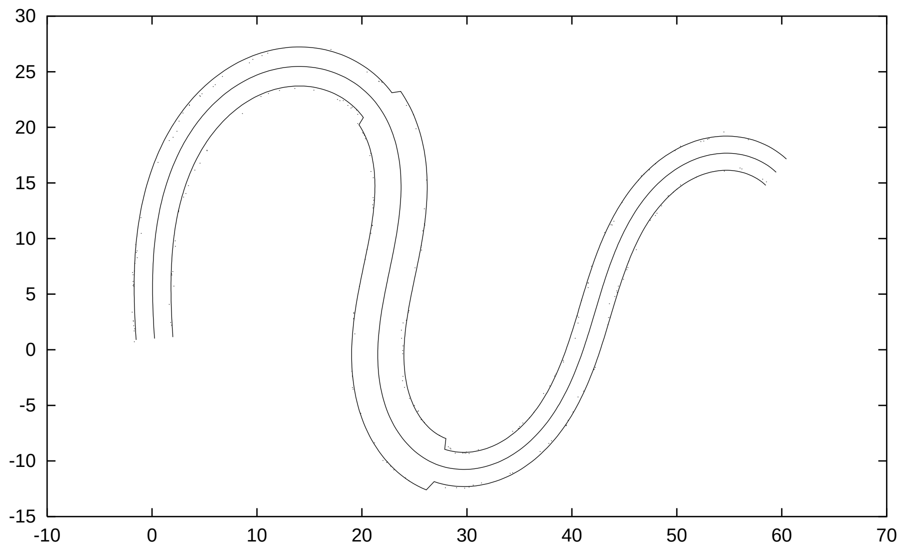
2.3 Reconstruction of Mine Representations

In order to use the mine model developed, we want to build mine representations based on this model. To build such a representation, we use surveying data, which can be provided by two types of surveying procedure. One is traditional surveying, in which a crew walks through the mine, makes measurements, and reports these measurements in field notes. The surveyors base themselves on practical knowledge to identify salient features of the mine where measurements are necessary. Measurements thus provided are generally sparse. The second procedure is automated surveying by an autonomous vehicle that explores the mine and acquires dense lateral and vertical range measurements along its path[3].

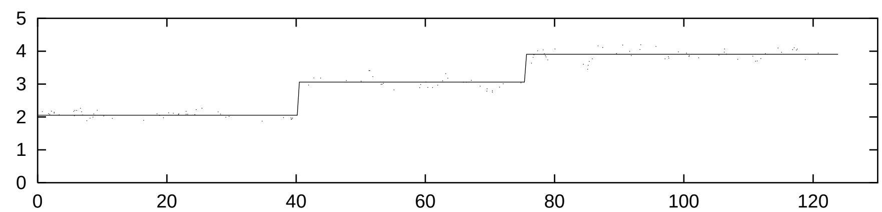
Regardless of the surveying procedure used, our reconstruction method fits gallery, intersection, or room models to the surveying data, minimizing a distance between models and data. Since the distance function can have numerous local minima (due to the continuity we impose between clothoidal ribbons, in the case of galleries), we use a simulated annealing procedure. Figure 2 shows an example of reconstructed gallery.

An article on this model-based reconstruction will be presented in *SMC'97* ([LHC97]).

[3]The automated exploration and surveying of mines constitutes the subject of the Master thesis of a student who I am supervising.



(a) The walls



(b) The ceiling

Figure 2: An example of gallery reconstruction from dense data

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