Abstraction of Informed Virtual Geographic Environments for the Modeling of Large-Scale and Complex Geographic Environments

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***Abstract*—In this paper, we propose a semantically-informed and geometrically-accurate virtual geographic environment method which allows to use Geographic Information System (GIS) data to automatically built an Informed Virtual Geographic Environment (IVGE). Besides, we propose an abstraction process which uses geometric, toplogic, and semantic characteristics of geographic features in order to build a knowledge-based description of the IVGE relying on a hierarchical graph-based structure. Our IVGE model enables the support of large-scale and complex geographic environments modeling for Situated Multi-Agent Systems (SMAS) in which agents are situated and with which they interact.**

***Keywords*-Informed Virtual Geographic Environments; Environmental Abstraction; Knowledge Representation.**

I. Introduction

During the last decade, the Multi-Agent Geo-Simulation (MAGS) approach has attracted a growing interest from researchers and practitioners to simulate phenomena in a variety of domains including traffic simulation, crowd simulation, urban dynamics, and changes of land use and cover, to name a few [1]. Such approaches are used to study phenomena (i.e., car traffic, mobile robots, sensor deployment, crowd behaviors, etc.) involving a large number of simulated actors (implemented as software agents) of various kinds evolving in, and interacting with, an explicit description of the geographic environment called Virtual Geographic Environment (VGE).

A critical step towards the development of a MAGS is the creation of a VGE, using appropriate representations of the geographic space and of the objects contained in it, in order to efficiently support the agents' situated reasoning. Since a geographic environment may be complex and large scale, the creation of a VGE is difficult and needs large quantities of geometrical data originating from the environment characteristics (terrain elevation, location of objects and agents, etc.) as well as semantic information that qualifies space (building, road, park, etc.).

In order to yield realistic MAGSs, a VGE must precisely represent the geometrical information which corresponds to geographic features. It must also integrate several semantic notions about various geographic features. To this end, we propose to enrich the VGE data structure with semantic information that is associated with the geographic features. Moreover, we propose to abstract this semantically-enriched and geometrically-precise VGE description in order to enable large-scale and complex geographic environments modeling.

In this paper, we present a novel approach that addresses these challenges toward the creation of such a semantically-enriched and geometrically-accurate VGE, which we call an *Informed VGE* (IVGE). We also detail our abstraction technique to support large-scale and complex geographic environments. The rest of the paper is organized as follows: Section II provides an overview of related works. Section III introduces our IVGE computation model. Section IV presents the proposed abstraction approach which is composed of the three processes; (1) geometric abstraction; (2) topologic abstraction; and (3) semantic abstraction. Section V discusses the proposed abstraction approach. Finally, Section VI concludes and presents the future perspectives of this work.

II. Related Works

Virtual environments and spatial representations have been used in several application domains. For example, Thalmann *et al.* proposed a virtual scene for virtual humans representing a part of a city for graphic animation purposes [3]. Donikian *et al.* proposed a modelling system which is able to produce a multi-level data-base of virtual urban environments devoted to driving simulations [15]. More recently, Shao *et al.* proposed a virtual environment representing the New York City's Pennsylvania Train Station populated by autonomous virtual pedestrians in order to simulate the movement of people [13]. Paris *et al.* also proposed a virtual environment representing a train station populated by autonomous virtual passengers, in order to characterize the levels of services inside exchange areas [12]. However, since the focus of these approaches is computer animation

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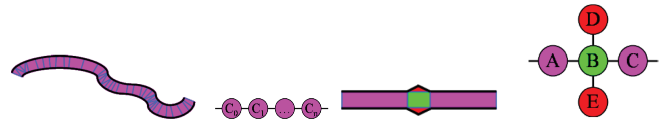
and virtual reality, the virtual environment usually plays the role of a simple background scene in which agents mainly deal with geometric characteristics. Indeed, the description of the virtual environment is often limited to the geometric level, though it should also contain topological and semantic information for other types of applications using advanced agent-based simulations. Current virtual environment models do not support large-scale and complex geographic environments and fail to capture real world physical environments' characteristics. When dealing with large-scale and complex geographic environments, the spatial subdivision which can be either exact or approximate produces a large number of cells [7]. The topologic approach allows representation of such a spatial subdivision using a graph structure and to take advantage of efficient algorithms provided by the graph theory [12]. However, the graph size may still remain large when dealing with geographic environments with dense geographic features [7]. Moreover, geographic features with curved geometries (*Figure 1*) produce a large number of triangles since they are initially represented by a large number of segments.

An *environment abstraction* is a process used to better organize the information obtained at the time of spatial subdivision of the geographic environment. The unification process is addressed principally in two ways: (1) a *pure topological* [8] unification which associates the subdivision cells according to their number of connexions; (2) a more *conceptual* unification which introduces a semantical definition of the environment, like with the *IHT-graph structure* [15]. Lamarche and Donikian proposed a topologic abstraction approach which assigns to each node of the graph resulting from the space decomposition a *topological qualification* according to the number of connected edges given by its arity [8]. The topologic abstraction algorithm aims to generate an abstraction tree by merging interconnected cells while trying to preserve topological properties [8]. When merging several cells into a single one, the composition of cells is stored in a graph structure in order to generate the abstraction tree. The topologic abstraction proposed by Lamarche and Donikian relies on the topological properties of the cells and reduces the size of the graph that represents the space subdivision [8]. However, the topological characteristics are not sufficient to abstract a virtual environment when dealing with a large-scale and complex environment involving areas with various qualifications (buildings, roads, parks, sidewalks, etc.).

Not much research has been done on semantic integration in the description of a virtual environment. The *Computer Animation* and *Behavioral Animation* research fields provide a few attempts to integrate the semantic information in order to assist agents interacting with their environments. Semantic information has been used for different purposes, including the simulation of inhabited cities [3], computer



(a) Curved geometries. (b) Alignment anomalies.

Figure 1: Cells resulting from curved geometries (a) and alignment anomalies (b) [12].

animation [6], and simulation of virtual humans [4]. Farenc has first used the notion of *Informed Environments* [3]. She defined informed environments as a database which represents urban environments with semantic information representing urban knowledge [3]. An informed environment is thus characterized as a place where information (semantic and geometrical) is dense, and can be structured and organized using rules [3]. Building an informed environment as presented by Farenc consists of adding a semantic layer onto a core corresponding to a classical scene (a set of graphical objects) modeled using graphical software for computer animations purposes [3].

Despite the multiple designs and implementations of virtual environments frameworks and systems, the creation of geometrically-accurate and semantically-enriched geographic content is still an open issue. Indeed, research has focused almost exclusively on the geometric and topologic characteristics of the virtual geographic environment. However, the structure of the virtual environment description, the optimization of this description to support large-scale and complex geographic environments, the meaning of the geographic features contained in the environment as well as the ways to interact with them have received less attention.

III. Computation of IVGE

In this section, we briefly present our automated approach to compute the IVGE data using vector GIS data. This approach is based on four stages: *input data selection*, *spatial decomposition*, *maps unification*, and finally the generation of the *informed topologic graph* [10].

GIS Input Data Selection: The first step of our approach consists of selecting the different vector data sets which are used to build the IVGE. The input data can be organized into two categories. First, *elevation layers* contain geographical marks indicating absolute terrain elevations. Second, *semantic layers* are used to qualify various types of data in space. Each layer indicates the physical or virtual limits of a given set of features with identical semantics in the geographic environment, such as roads or buildings.

Spatial Decomposition: The second step consists of obtaining an exact spatial decomposition of the input data into cells. First, an elevation map is computed using the

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Constrained Delaunay Triangulation (CDT) technique. All the elevation points of the layers are injected into a 2D triangulation, the elevation being considered as an attribute of each node. Second, a merged semantics map is computed, corresponding to a constrained triangulation of the semantic layers. Indeed, each segment of a semantic layer is injected as a constraint which keeps track of the original semantic data by using an additional attribute for each semantic layer.

Map Unification: The third step to obtain our IVGE consists of unifying the two maps previously obtained. This phase can be depicted as mapping the 2*D* merged semantic map onto the 2.5*D* elevation map in order to obtain the final 2.5*D* elevated merged semantics map. First, preprocessing is carried out on the merged semantics map in order to preserve the elevation precision inside the unified map. Indeed, all the points of the elevation map are injected into the merged semantics triangulation, creating new triangles. Then, a second process elevates the merged semantics map.

Informed Topologic Graph: The resulting unified map now contains all the semantic information of the input layers, along with the elevation information. This map can be used as an *Informed Topologic Graph* (ITG), where each node corresponds to the map's triangles, and each arc corresponds to the adjacency relations between these triangles. Then, common graph algorithms can be applied to this topological graph, and graph traversal algorithms in particular.

IV. Abstraction of IVGE

In this Section, we describe the abstraction process which optimizes the description of the IVGE. Sub-section IV-A presents the first enhancement which is related to the qualification of terrain. We propose a novel approach of information extrapolation using a one-time spatial reasoning process based on a geometric abstraction. This approach can be used to fix input elevation errors, as well as to create new qualitative data relative to elevation variations. These data are stored as additional semantics bound to the graph nodes, which can subsequently be used for spatial reasoning. Sub-section IV-B introduces the second enhancement which optimizes the size of the informed graph structure using a topological abstraction process. This process aims at building an hierarchical topologic graph structure in order to deal with large-scale virtual geographic environments. Sub-section IV-C details the third enhancement technique which propagates qualitative input information from the arcs of the graph to the nodes, which allows deduction of the internal parts of features such as buildings or roads in addition to their boundaries. Moreover, this technique uses Conceptual Graphs (CG) [14], a standard formalism for the representation of semantic information. Figure 2 illustrates the abstracted IVGE generation model.

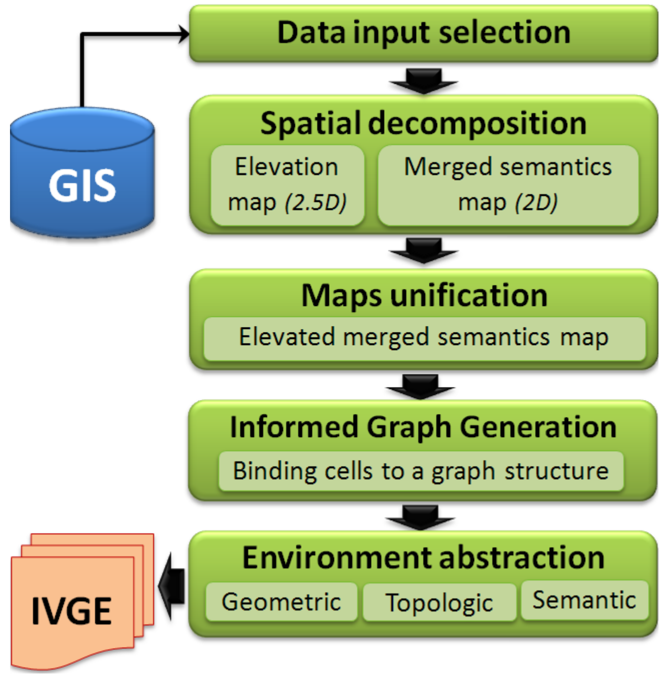

Figure 2: The IVGE global architecture of IVGE generation including the environment abstraction process.

A. Geometric abstraction

Spatial decomposition subdivides the environment into convex cells. Such cells encapsulate various quantitative geometric data which are suitable for precise computations. Since geographic environments are seldom flat, it is important to consider the terrain's elevation and shape. While elevation data are stored in a quantitative way which is suitable for exact calculations, spatial reasoning often needs to manipulate qualitative information. Indeed, when considering a slope, it is obviously simpler and faster to qualify it using an attribute with ordinal values such as *gentle* and *steep* rather than using numerical values. However, when dealing with large scale geographic environments, handling the terrain's elevation, including its light variations, may be a complex task. To this end, we propose an abstraction process that uses geometric data to extract the average terrain's elevation information from spatial areas. The objectives of this *Geometric Abstraction* are threefold. First, it aims to reduce the amount of data used to describe the environment. Second, it helps for the detection of anomalies, deviations, and aberrations in elevation data. Third, the geometric abstraction enhances the environment description by integrating qualitative information characterizing the terrain shape. In this section, we first present the algorithm which computes the geometric abstraction. Then, we describe two processes which use the geometric abstraction, namely *Filtering elevation anomalies* and *Extracting elevation semantics*.

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1) Geometric Abstraction Algorithm: As presented in the previous chapter, the geographic environment is subdivided into cells of different shapes and sizes. The algorithm takes advantage of the graph structure obtained from the IVGE extraction process. A *cell* corresponds to a node in the topological graph. A node represents a triangle generated by the *CDT* spatial decomposition technique. A cell is characterized by its boundaries, its neighboring cells, its surface as well as its normal vector which is a vector perpendicular to its plane.

Now we introduce the notion of a group, which is a collection of adjacent cells. The grouping strategy is based on a coplanarity criterion which is assessed by computing the difference between the *normal vectors* of two neighboring cells or groups of cells. Since a group is basically composed of adjacent cells it is obvious to characterize a group by its boundaries, its neighboring groups, its surface, as well as its normal vector. However, the normal vector of a group must rely on an interpretation of the normal vectors of its composing cells. In order to compute the normal vector of a group, we adopt the *area-weight normal vector* [2], which takes into account the unit normal vectors of its composing cells as well as their respective surfaces. Let S_c denote the surface area of a cell c and $\overrightarrow{N_c}$ be its unit normal vector. The area-weight normal vector $\overrightarrow{N_G}$ of a group G is computed as follows:

$$\overrightarrow{N_G} = \sum_{c \in G} \left(S_c \ . \ \overrightarrow{N_c} \right) / \sum_{c \in G} S_c \qquad (1)$$

The geometric abstraction algorithm uses two input parameters: 1) a set of *starting cells* which act as access points to the graph structure, and 2) a Δ parameter which corresponds to the maximal allowed difference between cells' gradients. Two adjacent cells are considered coplanar, and hence grouped, when the angle between their normal vectors is lesser than Δ. The recursive geometric abstraction algorithm is composed of five steps:

1) For each cell c of the *starting cells*, create a new group G and do step 2.
2) For each neighbouring group or cell n of G, if the neighbour has already been processed, do step 3, else do step 5.
3) If angle $\left(\overrightarrow{N_G}, \overrightarrow{N_n}\right) \leq \Delta$ then do step 4. Otherwise do step 5.
4) Merge n in group G, then evaluate $\overrightarrow{N_G}$ using equation (1). Do step 2 again for G.
5) If n is an unprocessed cell, create a new group G with n and do step 2.

The algorithm starts by visiting all the cells of the virtual environment. For each visited cell *crt_cell*, a new group *crt_grp* is created and the cell is registered as a member (line 2). The area-weighted normal vector of *crt_grp* is computed using equation (1). Besides, the algorithm tests the coplanarity of *crt_cell* with its neighbouring cells (*nxt_cell* belonging to *nxt_grp*) using equation (1) and to decide whether to include these neighbours in the group *crt_grp* to which *crt_cell* belongs. Next, the algorithm explores and processes the neighbouring cells of *crt_cell*. For each neighbour, if it is visited for the first time, a new group is created and the neighbour cell is registered as its first member.

Afterwards, the algorithm computes the angles resulting from the merging of *crt_grp* and *nxt_grp* groups. The area-weighted normal vector resulting from the integration of *crt_grp*'s elements in the *nxt_grp* group is computed. The algorithm goes on by computing the angle between the new (after the merge) and the previous (before the merge) area-weighted normal vectors. The angle is given by the scalar product of the two normalised vectors $\overrightarrow{N}_{crt\_grp}$ and $\overrightarrow{N}_{nxt\_grp}$. If this angle respects the input parameter Δ (line 9), then merging is performed (line 10).

In the proposed algorithm, the geometric abstraction produces coherent groups whose cells are coplanar and with respect to the Δ threshold. The geometric abstraction process abstracts a higher-order topologic graph and produces a new graph with fewer nodes which helps to enhance performance of spatial reasoning mechanisms.

The analysis of the resulting groups helps to identify anomalies in elevation data. Such anomalies need to be fixed in order to build a realistic virtual geographic environment. Furthermore, the average terrain slope which characterizes each group is a quantitative datum described using area-weighted normal vectors. Such quantitative data are too precise to be used by qualitative spatial reasoning. Hence, a qualification process would greatly simplify spatial reasoning mechanisms. Thus the geometric abstraction can improve IVGE by filtering the elevation anomalies, qualifying the terrain slope using semantics and integrating such semantics in the description of the geographic environment.

2) Filtering elevation anomalies: Analysis of the geometric abstraction may reveal an isolated group which is totally surrounded by another single coherent group. These groups are characterised by a large difference between their respective area-weighted normal vectors. Such isolated groups are often characterised by their small surface areas and can usually be considered as anomalies, deviations, or aberrations in the initial elevation data. MAGS users may verify if such groups correspond to real pits or depressions, or substantial mounds or heaps on the landscape. The geometric abstraction process helps to identify them and can help to automatically filter such anomalies using a two phase process. First, isolated groups are identified (*Figure 3(a)*). The identification of isolated groups is based on two key parameters: 1) the ratio between the surface

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areas of the surrounded and surrounding groups, and 2) the difference between the area-weighted normal vectors of the surrounded and surrounding groups. Second, these isolated groups are adjusted to the average level of elevation of the surrounding ones (*Figure 3(b)*). The lowest and the highest elevations (*low_elev*, *high_elev*) of the surrounding group (*surrounding_grp*) are computed. Then, the elevation of all the vertices of the isolated group (*isolated_grp*) are adjusted using the average between *lowest_elevation* and *highest_elevation*. As a consequence, we obtain more coherent groups in which anomalies of elevation data are corrected.

3) Qualification of terrain shape: The geometric abstraction algorithm computes quantitative geometric data which precisely describe the terrain However, handling and exploiting quantitative data is a complex task as the range of values may be too large and calculations or analysis methods may be too costly. Therefore, we propose to interpret the quantitative data representing the terrain shape by qualifying the terrain characteristics. Semantic labels, which are called *the shape semantics*, are associated to quantitative intervals of values that represent the terrain's shape. In order to obtain the shape's semantics we propose a two-step process taking advantage of the geometric abstraction: 1) calculation of the inclination, or the angle α between the weighted normal vector $\vec{N}_g$ of a group *grp* and the horizontal plane; and 2) assigning to each discrete value a semantic category which qualifies it. The discretisation process can be done in two ways: a *customised* and an *automated* approach.

The *customised approach* requires that the user provides a complete specification of the discretisation to qualify the range of slopes. Indeed, the user needs to specify a list of inclination intervals as well as their associated semantic labels. The algorithm iterates over the groups obtained by the geometric abstraction. For each group *grp*, it calculates the inclination value *I*. Then, this process checks the interval bounds and determines in which one the inclination value *I* falls. Finally, the customised discretisation extracts the semantic shape label from the selected slope interval and assigns it to the group *grp*. For example, let us consider the following inclination interval and the associated semantic label : $\{([10,\ 20],\ gentle\ slope),([20,\ 25],\ steep\ slope)\}$. Such a customised specification associates the semantic label "*gentle slope*" to inclination values included in the interval $[10,\ 20]$ and the semantic label "*steep slope*" to inclination values included in the interval $[20,\ 25]$.

The *automated approach* only relies on a list of semantic shape labels representing the slope qualifications. Let N be the number of elements of this list, and T be the total number of groups obtained by the geometric abstraction algorithm. First, the automated discretisation orders groups based on their terrain inclination. Then, it iterates over the ordered groups and associates a uniform number of groups, T/N, to each semantic label from the *semantic set*, each T/N processed groups. For example, let us consider the following semantic slope labels: $\{gentle, medium, steep\}$, and an ordered set S of groups denoted as follows: $S = \{gr_i | i \in \{1,2,..,6\}\}$ with the following respective slope values: $\{5,\ 10,\ 15,\ 20,\ 25,\ 30\}$. For every 2 groups (as $T = 6$ and $N = 3$, $\frac{T}{N} = 2$), the automated discretisation assigns a new semantic slope label: $\{gentle, gentle, medium, medium, steep, steep\}$.

Let us compare these two discretisation approaches. On the one hand, the *custumized discretisation process* allows one to freely specify the qualification of the slopes, choosing ranges that match the problem domain. However, qualifications resulting from such a flexible approach deeply rely on the correctness of the interval bounds' values. Therefore, the customised discretisation method requires to have a good knowledge of the terrain characteristics in order to guarantee a valid specification of inclination intervals. On the other hand, the *automated discretisation process* is also able to qualify slopes without the need to specify interval bounds. This method also guarantees that all the specified semantic attributes will be assigned to the groups without a prior knowledge of the environment characteristics. However, the resulting intervals may have no relation to the problem domain.

4) Improving the geometric abstraction: Thanks to the extraction of slope semantics, terrain shape is qualified using semantic attributes and associated with groups and with their cells. Because of the nature of the classification intervals, adjacent groups with different area-weighted normal vectors may obtain the same semantic slope label. In order to improve the results provided by the geometric abstraction, we propose a process that merges adjacent groups which share the same semantic slope. This process starts by iterating over groups. Every time it finds a set of adjacent groups sharing an identical semantic slope, it creates a new group. Next, cells composing the adjacent groups are registered as members of the new group. Finally, the area-weighted normal vector is computed for the new group. Hence, this process guarantees that every group is only surrounded by groups which have different semantic slopes.

B. Topological abstraction

In Section III, we presented our work on the generation of informed virtual geographic environments using an exact spatial decomposition scheme which subdivides the environment into convex cells organized in a topological graph structure. However, inside large scale and complex geographic environments (such as a city for example), such topological graphs can become very large. The size of such a topological graph has a direct effect on paths'

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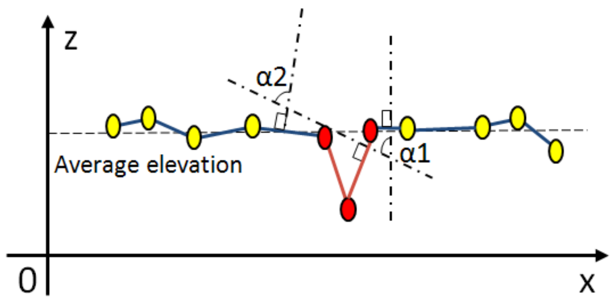
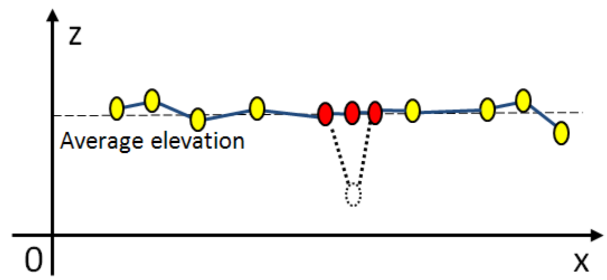


(a) Identifying elevation anomalies. Two isolated groups (in red) and angles (α1 and α2) resulting from the difference between the area-weighted normal vectors



(b) Fixing elevation anomalies. Nodes in isolated groups are adjusted to the average elevation level.

Figure 3: Profile section of anomalous *Isolated Groups* (red colour) adjusted to the average elevation of the surrounding ones (yellow colour).

computation time for path-finding. In order to optimise the performance of path computation, we need to reduce the size of the topological graph representing the IVGE. The aim of the topological abstraction is to provide a compact representation of the topological graph that is suitable for situated reasoning and enables fast path planning. However, in contrast to the geometric abstraction which only enhances the description of the IVGE with terrain semantics, the topological abstraction extends the topological graph with new layers. In each layer (except for the initial layer which is called level 0), a node corresponds to a single or a group of nodes in the immediate lower level (*Figure 4*). The topological abstraction simplifies the IVGE description by combining cells (triangles) in order to obtain convex groups of cells. Such a hierarchical structure evolves the concept of *Hierarchical Topologic Graph* in which cells are fused into groups and edges are abstracted in boundaries. To do so, convex hulls are computed for every node of the topological graph. Then, the coverage ratio of the convex hull is evaluated as the surface of the hull divided by the actual surface of the node. The topological abstraction finally performs groupings of a set of connected nodes if and only if the group ratio is equal or close to one depending on the problem domain. Let C be the convexity rate and $CH(gr)$ be the convex hull of the polygon corresponding to gr. C is computed as follows:

$$C(gr) = \frac{Surface(gr)}{Surface(CH(gr))} \quad and \quad 0 < C(gr) \leq 1 \qquad (2)$$

The convex property of each group's hull needs to be preserved after the topological abstraction. This ensures that an entity can move freely inside a given cell (or group of cells), and that there exists a straight path linking edges belonging to the same cell (or group of cells).

Figure 5 illustrates an example of the topological abstraction process and the way it reduces the number of cells representing the environment. In *Figure 5(a)*, we present the initial vector format GIS data of a complex building.

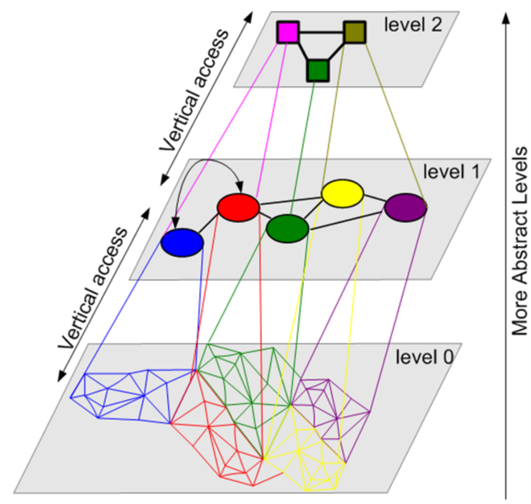


Figure 4: The topological graph extraction from space decomposition and extension into different levels using the topological abstraction.

Figure 5(b) depicts the initial exact spatial decomposition which yields 63 triangular cells. *Figure 5(c)* presents 28 convex polygons generated by the topological abstraction algorithm. The *abstraction rate* of the number of cells representing the environment is around 55%. This rate is computed using the ratio of initial number of cells produced by the space decomposition techniques (63) by the number of convex polygons (28) obtained using the topologic abstraction technique with a convexity rate equal to 1

To conclude, we described in this section a topologic abstraction process in order to enhance the performance of the exploration of the IVGE's description. This process aims to simplify large informed graphs corresponding to large-scale and complex geographic environments. Our topologic abstraction approach reduces the number of convex cells by overlaying the informed graph with a topologically abstracted graph. The resulting IVGE is hence based on

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a hierarchical graph whose lowest level corresponds to the informed graph initially produced by the spatial decomposition. In the following section, we show how we use a well-known knowledge representation formalism to represent the semantic information in order to further enhance the IVGE description with respect to agents' and the environment's characteristics.

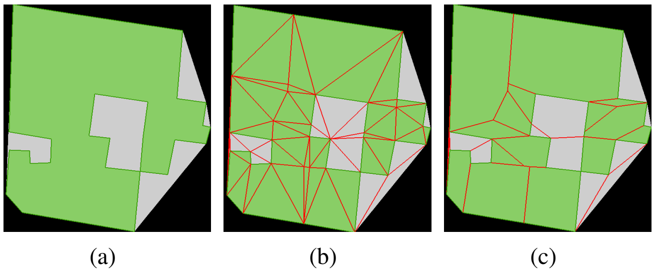

Figure 5: Illustration of the topological abstraction process with a strict convex property (*C(gr)* = 1); (a) the GIS data of a complex building; (b) the exact space decomposition using CDT techniques (63 triangular cells) ; (c) the topological abstraction (28 convex polygons)

C. Semantic Abstraction

Two kinds of information can be stored in the description of an IVGE. Quantitative data are stored as numerical values which are generally used to depict geometric properties (like a path's width of *2* meters) or statistical values (like a density of *2.5* persons per square meter). Qualitative data are introduced as identifiers which can range from a word with a given semantics, called a *label*, to a reference to an external database or to a specific knowledge representation. Such semantic information can be used to qualify an area (like a *road* or a *building*) or to interpret a quantitative value (like a *narrow* passage or a *crowded* place). An advantage of interpreting quantitative data is to reduce a potentially infinite set of inputs to a discrete set of values, which is particularly useful to condense information in successive abstraction levels to be used for reasoning purposes. Furthermore, the semantic information enhances the description of the IVGE, which in turn extends the agents' knowledge about their environment. However, the integration of the semantic information raises the issue of its representation. Therefore, we need a standard formalism that allows for precisely representing the semantic information which qualifies space and which is computationally tractable in order to be used by spatial reasoning algorithms used by agents.

Several knowledge representation techniques can be used to structure semantic information and to represent knowledge in general such as *frames* [11], *rules* [9] (also called *If-Then* rules), *tagging* [16], and *semantic networks* [14], which have originated from theories of human information processing. Since knowledge is used to achieve intelligent behavior, the fundamental goal of knowledge representation is to represent knowledge in a manner that facilitates inferencing (i.e., drawing conclusions) from knowledge. In order to select a knowledge representation (and a knowledge representation system to logically interpret sentences in order to derive inferences from them), we have to consider the expressivity of the knowledge representation. The more expressive a knowledge representation technique is, the easier (and more compact) we can describe and qualify geographic features which characterise IVGE. Various artificial languages and notations have been proposed to represent knowledge. They are typically based on logic and mathematics, and can be easily parsed for machine processing. However, Sowas's *Conceptual Graphs* [14] are widely considered an advanced standard logical notation for logic based on existential graphs proposed by Charles Sanders Peirce and on semantic networks.

Syntactically, a conceptual graph is a network of concept nodes linked by relation nodes. Concept nodes are represented by the notation *[Concept Type: Concept instance]* and relation nodes by *(Relationship-Name)*. A concept instance can be either a value, a set of values or even a CG. The formalism can be represented in either graphical or character-based notations. In the graphical notation, concepts are represented by rectangles, relations by circles and the links between concept nodes and relation nodes by arrows. The most abstract concept type is called the *universal type* (or simply *Universal*) denoted by the symbol ⊥.

A MAGS usually involves a large number of situated agents of different types (human, animal, static, mobile, etc.) performing various actions (moving, perceiving, etc.) in virtual geographic spaces of various extents. Using CGs greatly simplifies the representation of complex situated interactions occurring at different locations and involving various agents of different types. In order to create models for MAGS we consider three fundamental abstract concepts: 1) *agents*; 2) *actions*; and 3) *locations*.

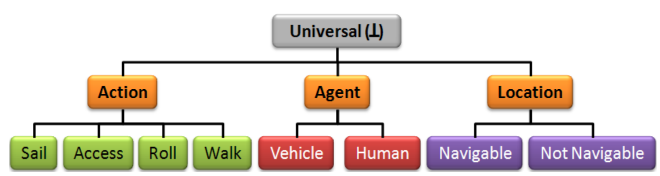

Figure 6: Illustration of the *action*, *agent* and *location* concepts using a concept type lattice.

Taking advantage of the abstraction capabilities of the CGs formalism (through the *Concept Type Lattice* (CTL)) instead of representing different situated interactions of various agents in distinct locations, we are able to represent

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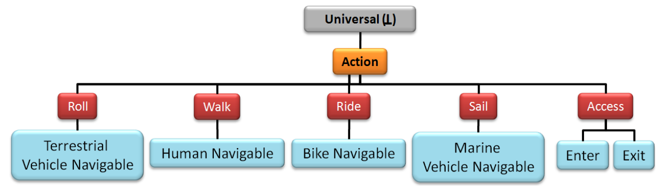
abstract actions performed by *agent archetypes* in *abstract locations*. Moreover, we first need to specify and characterise each of the abstract concepts. The concept type lattice enables us to specialise each abstract concept in order to represent situated behaviours such as path planning of agents in space. Figure 6 presents the first level of the concept type lattice refining the *agent*, *action*, and *location* concepts. Figures 7(a),7(b), and 7(c) present the expansion of the concept type lattice presented in Figure 6. Figure 7(a) illustrates some situated actions that can be performed by agents in the IVGE such as *sailing* for maritime vehicles, *rolling* for terrestrial vehicles, *walking* for humans, and *accessing* for humans to enter or exit buildings (we assume that buildings are not navigable locations from the perspective of outdoor navigation). 7(b) depicts how the *location* concept may be specialized into *Navigable* and *Not Navigable* concepts. The *Navigable* concept may also be specialised into *Terrestrial Vehicle Navigable*, *Pedestrian Navigable*, *Marine Vehicle Navigable*, and *Bike Navigable* which are dedicated navigable areas with respect to agent archetypes and environmental characteristics as specified by the *elementary semantics*. Figure 7(c) illustrates a few agent archetypes that are relevant to our geo-simulation including *pedestrians*, *cars*, *trucks*, and *bikes*.

In order to show how powerful such a representation may be, let us consider the following example. We want to build a MAGS simulating the navigation of three human agents (a man, a woman, and a child), two bike riders (a man and a woman), and three vehicles (a car, a bus, and a boat) in a coastal city. The navigation behaviours of these different agent archetypes must respect the following constraints (or rules): 1) *pedestrian* agents can only move on *sidewalks*, on *pedestrian street*s, and eventually on *crosswalks* if needed; 2) *vehicles* can move on *roads* and *highways*; 3) *boats sail* on the *river* and stop at the *harbour port*; and 4) *bikes* move on *bikeways*, *roads*, and *streets* but not on *pedestrian streets*. Using standard programming languages, it might be difficult to represent or develop the functions related to such simple navigation rules which take into account both the agents' and the locations' characteristics. However, the representation of these navigation rules becomes an easy task when using CGs and our defined concept type lattice. Here are their expressions in CGs:

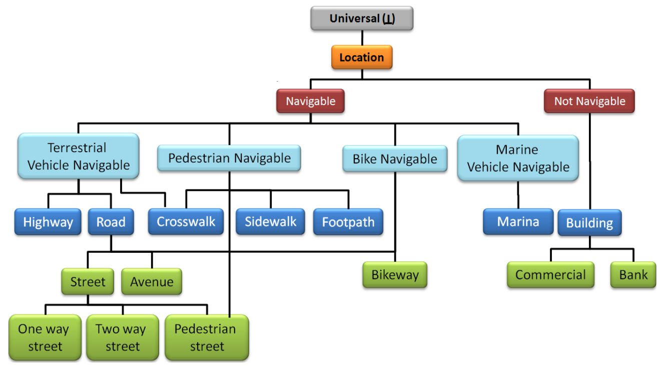
[PEDESTRIAN:*p]<-(agnt)<-[WALK:*w1]->(loc)->[PEDESTRIAN NAVIGABLE:*pn]

[VEHICLE:*v]<-(agnt)<-[ROLL:*r1]->(loc)->[TERRESTRIAL NAVIGABLE:tn]

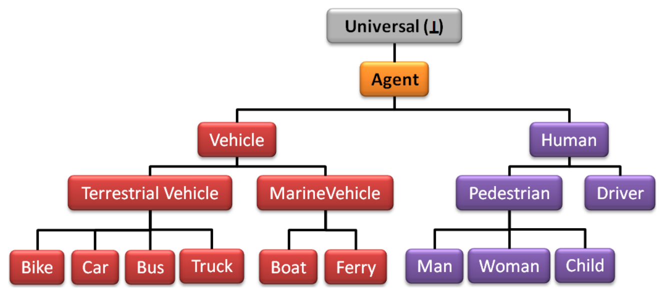
The arrows indicate the expected direction for reading the graph. For instance, the first example may be read: *an agent *p which is a "pedestrian" walks on a location *pn which*



(a)



(b)



(c)

Figure 7: An example of a conceptual description of *agents* archetypes (a), *actions* performed (b), and *locations* situated in a geographic environment (c).

is "pedestrian navigable". Since this expression involves the concepts *Pedestrian*, *Walk* and *Pedestrian Navigable*, this rule remains valid for every sub-type of these concepts. Therefore, thanks to CGs and the concept type lattice, there is no need to specify the navigation rules for men, women, and children if they act as pedestrians in locations such as *pedestrian streets*, *sidewalks*, or *crosswalk*. Indeed, these agent archetypes are subtypes of the *Pedestrian* concept and *pedestrian streets*, *sidewalks*, and *crosswalks* are subtypes of the *Pedestrian Navigable* concept. To conclude, CGs offer a powerful formalism to easily describe different concepts involved in MAGS including agents, actions, and environments.

V. Discussion

Thomas and Donikian proposed an Informed Hierarchical Topologic (IHT) [15] graph representing a part of the city of Renne (France) for human behavior animation purposes.

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This graph is composed of three layers: (1) the *Basic Topological* layer which contains real urban objects modelled as simple spaces such as buildings and road sections; (2) the *Composite Space* layer which is composed of simple spaces or composite spaces of lesser importance; (3) the *Local Area* layer which is the highest level of the IHT-graph and which is composed of composite spaces. This hierarchical urban model allows manual abstraction of buildings into blocks and road-sections and crossings into roads. The abstraction process is done by the user which constrains and considerably limits its application to real world large-scale and complex geographic environments. Thomas's approach relies on a pre-defined decomposition of the virtual environment which is dedicated to urban environments. This decomposition is application-dependent (urban environments) and does not take into account the topologic and the geometric characteristics of the environment.

In contrast with Thomas [15] and Lamarche [8] approaches, our abstraction technique optimizes the representation of the geographic environment while taking into account the geometric, topologic and semantic characteristics of the geographic environment. This abstraction approach relies on an exact space decomposition technique (Constrained Delaunay Triangulation) in order to preserve the geometric and topologic characteristics of the geographic environment rather than on a pre-difined space decomposition. It also integrates semantic information associated with GIS data in order to enrich the description of the IVGE.

Embedding the information directly in the environment allows the support of agents' spatial reasoning capabilities. However, the preparation of the fully augmented geometric model is very time consuming and difficult due to the sheer amount of data. For example, a typical model of a city quarter as used by Farenc can contain several thousands of primitives of many types (such as polygons modeling sidewalk pieces, benches, trees, bus stops, etc.). Moreover, Farenc built the urban environment using data provided by Computer Assisted Graphic Design systems since the purpose of the simulation is computer animation. However, when building virtual geographic environments representing large-scale and complex geographic environments based on reliable GIS data, Farenc's approach can not be used since it is dedicated to exclusively represent urban environments. Indeed, the manual hierarchical space partitioning as proposed by Farenc is not feasible when dealing with geometrically complex environments. Moreover, the data structure of the urban environment's description as proposed by Farenc needs to be enhanced in order to manage a large amount of geometric and topologic data. Finally, the hierarchical structure should be built using the geographic environments's characteristics rather than being defined *a priori* as Farenc proposed.

The work done towards representation of semantic information in virtual environments has been mostly carried out at a geometric level [4]. Gutiuerez proposed a semantic model which aims to represent the meaning, and functionality of objects in a virtual scene [5]. However, since the purpose of Gutiuerez's approach is computer animations, the semantic information integration is located at the object description level rather than enriching the description the geographic environments. Virtual environments are usually created as computer graphics applications, with minimal consideration given to the semantic information [5]. Moreover, semantic information has been used in an *ad hoc* way without any standard formalism. There is a gap between geometry and semantic information in current virtual geographic environment models. Since we believe that semantic information integration into a VGE's description is by nature a knowledge representation problem, a suitable and standard knowledge representation formalism has been proposed to integrate semantic information in the VGE's description.

VI. Conclusion and Future Works

In this paper, we introduced our IVGE model which automatically buids semantically-enriched and geometrically-accurate description of informed virtual geographic environments. We also proposed an abstraction approach of the IVGE's description in order to support large-scale and complex geographic environments. First, we described a ***geometric abstraction*** process which enriches the IVGE description with terrain semantics. Moreover, the geometric abstraction process helps to detect and filter elevation anomalies and qualifies the terrain shape, specifically slope. Second, we detailed a ***topologic abstraction*** which builds an hierarchical topologic graph in order to deal with large-scale virtual geographic environments. This hierarchical structure reduces the size of the topological graph representing the IVGE. Third, we showed how the ***semantic abstraction*** process enhances the hierarchical topological graph using the concept type lattice in order to build different views of the IVGE. We are currently working on the leverage of our enhanced IVGE model to support hierarchical path planning algorithms which take into account both the abstracted description of the IVGE and the agent type's characteristics.

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