Automated Generation of Geometrically-Precise and Semantically-Informed Virtual Geographic Environments Populated with Spatially-Reasoning Agents

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Abstract

Multi-Agent Geo-Simulation (MAGS) is a modelling paradigm which has attracted a growing interest from researchers and practitioners for the study of various phenomena in a variety of domains such as traffic simulation, urban dynamics, environment monitoring, as well as changes of land use and cover, to name a few. These phenomena usually involve a large number of simulated actors (implemented as software agents) evolving in, and interacting with, an explicit spatial environment representation commonly called *Virtual Geographic Environment* (VGE). 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.).

Current MAGS approaches usually consider the environment as a monolithic structure, which considerably reduces the capacity to handle large-scale, real world geographic environments as well as agent's spatial reasoning capabilities. Moreover, the problem of path planning in MAGS involving complex and large-scale VGEs has to be solved in real time, often under constraints of limited memory and CPU resources. Available path planners provide agents with obstacle-free paths between two located positions in the VGE, but take into account neither the environment's characteristics (topologic and semantic) nor the agents' types and capabilities. In addition, agents evolving in a VGE lack for mechanisms and tools that allow them to acquire knowledge about their virtual environment in order to make informed decisions.

In this thesis, we propose a novel approach to automatically generate a semantically-enriched and geometrically-precise representation of the ge-

ographic environment that we call Informed Virtual Geographic Environment (IVGE). Our IVGE model efficiently organizes the geographic features, precisely captures the real world complexity, and reliably represents large-scale geographic environments. We also provide a new hierarchical path planning algorithm which leverages the enriched description of the IVGE in order to support agents' reasoning capabilities while optimising computation costs and taking into account both the virtual environment's characteristics and the agents' types and capabilities. Finally, we propose an environment knowledge management approach to support the agents' spatial decision making process while interacting with the IVGE.

Contents

Chapter 1

General Introduction

Multi-Agent Geo-Simulation (MAGS) is a modelling paradigm [BT04] which attracts a growing interest from researchers and practitioners to simulate various phenomena in a variety of domains such as traffic simulation, crowd simulation, environment monitoring, and changes of land use and cover, to name a few. Such approaches are used to study various phenomena (i.e. car traffic, crowd behaviours, sensor web deployment, etc.) involving a large number of simulated actors (implemented as software agents) evolving in, and interacting with, an explicit spatial environment representation usually called *Virtual Geographic Environment* (VGE).

Creating a VGE populated by autonomous agents is a pretty demanding task which can be broken down into two main blocks: *creating the virtual environment itself*, and *creating the autonomous agents populating it*. On the one hand, so many challenges arise when creating a VGE: what it looks like, how it is represented, what are the objects and agents it contains, etc. Recreating real environments through a computer is a complex task which is still under constant study and development, further reducing the boundaries between virtuality and reality, as they go along.

On the other hand, creating autonomous agents for populating the environment is a task which is just as difficult and complex. The autonomous agents, even though they can be considered as objects within the environment, have a lot of additional properties with their own set of problems to solve: how to represent them, how to make them move, how to make them reason, plan, and act with respect to the VGE's characteristics, etc. What makes the task even more daunting is the fact that the inner workings of real humans and animals are extremely complex and still not fully understood. Approximations and theories are made, implementation solutions are presented and computer programs are created trying to imitate as best as possible the complexity and inner workings of real live creatures, be they instinct driven animals, or conscious and reasoning humans.

Actually, creating realistic environments on one side, and plausible autonomous agents on the other is not enough. Another important problem still needs to be solved: how to make the agents interact with the VGE? How can they evolve within it, perceive it, plan their actions according to the VGE's characteristics? Agents should be able to interact with the VGE and with the objects it contains. Indeed, in order to create reliable MAGS, the agents immersed in the VGE should be able to perform all the tasks their real living counterparts can: perceive their surroundings, gather information and memorize it, detect and avoid obstacles as well as other agents as they move, and plan a path according to what they see and what they know, interact with objects surrounding them, interact with other agents, etc. This is yet another difficult task, with its own set of problems to solve, as complex and essential as the creation of the environment and the agents themselves.

Building precise and enriched VGE and enabling agents to interact with such environments is the problem addressed by this thesis.

1.1. Problems and Research Issues

Building MAGS using agents which can reason about space not only requires appropriate computation algorithms, but also an efficient description of the spatial environment. Such a description must represent the geometrical and topological information which corresponds to geographic features which are provided by *Geographic Information Systems* (GIS). Moreover, this representation should qualify space by associating semantics with geographic features in order to allow spatial 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.). The VGE description should rely on an efficient structure which supports easy and optimized access and query techniques. The complexity of building such a description should only depend on the geometrical complexity of the geographic environment rather than on its scale.

A number of challenges arise when creating such an informed VGE, among which we mention: 1) automatically creating a precise geometric representation of a 3D VGE; 2) automatically integrating several types of semantic information in the geometric representation; and 3) making use of this representation in spatial reasoning algorithms such as navigation and path planning which are required for MAGS.

To enable an autonomous agent to interact with its environment, we might think of storing the entire interaction process within the agent's knowledge model. Thus, the agent would be able to observe the world that surrounds it and to gather raw information from its sensors. After that, it would process this raw data through a complex reasoning module in order to try to derive high-level information and to determine the interaction possibilities offered by the objects it is observing. This approach is extremely complex, very difficult to implement, and is rarely applicable to complex interaction processes. The more complex the object is, the harder it is to derive abstract information and the more complex the reasoning algorithm needs to be. This process can become extremely costly in terms of calculation time and resources when the complexity of the environment and the objects contained in it increases.

Another approach takes advantage of the fact that the agents are evolving in a virtual world which fully stores the entire interaction information. Such a method can ease the load on the agents since it removes the need to determine abstract data by directly providing the agent with the required interaction information. As a consequence, the computation and processing cost of the interaction information is reduced by creating it offline (a sort of an interaction script) and applying it every time agents need it. This method also has its drawbacks: every time an agent interacts with an object the interaction takes place in the exact same way without taking into account its own characteristics, since the interaction process is defined once and for all. Indeed, this technique describes interaction processes for homogeneous agents. An object has to describe the same interaction process in as many ways as the types of agents that can interact with it, taking into account the fact that they are humanoid or animals for example.

1.2. Objectives

The objective of this thesis is sixfold:

1. *to propose a method and a set of tools to automate the generation of virtual geographic environments:* MAGS is basically a modelling and simulation paradigm which frequently involves VGEs of various extents. Time and efforts spent on the generation of these VGEs are considerable and should be reduced through an automated approach.
2. *to propose a method and associated algorithms to precisely describe virtual geographic environments:* most of current VGE approaches lack precision when dealing with complex geographic environments. A precise description of a VGE should take into account both geometric and topologic data characterising the geographic environment.
3. *to propose an approach in order to semantically inform the description of virtual geographic environments:* since spatial reasoning often needs to manipulate qualitative information rather than quantitative data, a conceptualized semantic information should be associated with geographic features. This process of qualification aims at supporting the spatial reasoning capabilities of agents.
4. *to propose an abstraction technique which uses a graph-based structure in order to model large-scale and complex geographic environments:* since geographic environments may be complex, large-scale, and populated with various geographic features, the description of virtual geographic environment should be abstracted, structured in order to support such geographic environments. The abstraction of the virtual geographic environment description should take into account the geometric, topologic, and semantic characteristics of geographic environments.
5. *to propose an approach which allows to represent knowledge about the environment and to provide it to spatial agent:* spatial agents need to access, acquire, and reason about knowledge about the virtual environment in order to make decisions that take into account its characteristics. Knowledge about the environment should be represented using a standard formalism and spatial agents should be provided with a mechanism to acquire and reason about it.
6. *to populate virtual geographic environments with agents endowed*

with spatial reasoning capabilities: MAGS usually involves a large number of agents of different types. Such agents should be able to evolve and interact with the VGE while taking into account both agents' and VGE's characteristics.

1.3. The Proposed Approach

What we propose is a method and associated algorithms to *automatically generate geometrically-precise and semantically-enhanced virtual geographic environments populated with spatially-reasoning agents*. We propose a novel approach to model virtual geographic environments which meets the previously mentioned objectives. First, our approach uses reliable standard spatial data provided by Geographic Information Systems (GIS). In addition, it relies on an exact spatial decomposition technique which fully preserves the geometric and topologic characteristics of geographic features and thus yields a precise description of the virtual geographic environment. Moreover, this description is based on a graph-based structure which allows our approach to handle large-scale geographic environments. This description is enriched with semantic information in order to better qualify the geographic features. Furthermore, since our aim is to support agents' spatial reasoning capabilities, we propose to enhance the virtual environment's description with conceptual semantic information using well-established knowledge representation techniques. Indeed, since the nature of objects is invariant during the MAGS process, and because the interaction process may vary depending on the agent's type, the conceptual semantic information needs to be generic and interpretable by any type of agent. The conceptual semantic information will be separated in two parts: the first part contains the information inherent to the object type (i.e. the car is red), and the second part contains the information inherent to the agent which uses the object's information to reason and act on the environment (i.e. the agent drives the car). Such a conceptual semantic information stored within the environment extends the agents' knowledge about their environment, without being too specific and detailed, and provides agents with useful information in addition to the geometric and topologic data characterizing the VGE. Path planning and navigation are examples of spatial reasoning algorithms that may leverage our geometrically-precise and semantically-enhanced model of large-scale virtual geographic environments.

1.4. Application Domains

In order to illustrate our approach, we propose the following application domains: *urban simulation*, *radio signal propagation in virtual geographic environments*, and *sensor webs deployment in virtual geographic environments*.

1.4.1. Urban Simulation

We propose to use our approach to build a a three-dimensional virtual urban environment populated with agents representing humans, buses, cars, etc. The main novelty of our approach is that we do not rely on representing land-use and other attributes on a regular grid, but instead build a geometrically-precise simulation that uses an exact spatial decomposition technique. Our VGE model also enriches the virtual urban environment's description with semantics in order to qualify the geographic features such as streets of arbitrary orientation, street widths and shapes, and irregular building footprints. The second novelty is the automated and fast generation of such a virtual urban environment. We also provide a set of scenarios involving agents interacting with the informed VGE. These scenarios illustrate the agents' capabilities to detect and avoid collisions with obstacles situated in the VGE as well as path planning, while taking into account the enriched description of the VGE.

1.4.2. Radio Signal Propagation

In the real world, radio transmissions are subject to propagation effects which affect the received signals because of geographic and environmental characteristics (foliage and vegetation, buildings, mountains and hills, etc.). Using our informed VGE, we are able to easily generate a virtual geographic environment which precisely describes the geographic features of the real world. Then, we are able to predict the attenuation effect due to the radio signal's traversal through vegetation area, and buildings using a 3D line-of-sight technique.

1.4.3. Sensor Web

Sensor webs can be thought of as distributed network systems composed of hundreds of resource-constrained nodes. Sensor webs are deployed in large-scale geographic environments for in-situ sensing and data acquisition purposes. The deployment of a large number of sensor nodes in a large-scale geographic environment is a complex task. Moreover, the sensing and communication performance of a sensor web relies on the pattern of its deployment within the specific environment. Using our IVGE model, we are able to simulate a sensor web deployment where sensor nodes are modeled using software agents. These sensor agents leverage our knowledge management approach to acquire knowledge about the environment and adapt their behaviors while taking into account both the IVGE's and sensors' characteristics.

1.5. Contributions

In a departure from the substantial literature on so-called *spatial modelling*, the first contribution of this thesis is a geometrically-precise and semantically-enhanced model of virtual geographic environments based on a graph structure that we call an *Informed Virtual Geographic Environments* (IVGE). The second contribution is a methodology for the automated generation of informed virtual geographic environments based on reliable data provided by *Geographic Information Systems* (GIS) and using the *Constrained Delaunay Triangulation* (CDT) technique as a decomposition paradigm. The third contribution is a geometric, topologic, and semantic abstraction of informed virtual geographic environments in order to build a *Hierarchical Topologic Graph* (HTG) which supports the representation of large-scale geographic environments. The resulting HTG uses a standard formalism (Conceptual Graphs) to express semantic characteristics of the virtual geographic environment. The fourth contribution is a *Hierarchical Path Planning* (HPP) algorithm coupled with a Neighborhood Graph (NG) model to provide agents with for efficient motion planning (navigation and path planning) in informed virtual geographic environments. The fifth contribution is an environment knowledge management approach which allows spatial agents to make decisions that take into account the geographic environment characteristics.

From an application perspective, this thesis illustrates the above mentioned theoretical contributions in domains such as *Urban Mobility*, *Wireless Communications* and *Sensor Webs*. It also provides a set of tools that implement the proposed models and allow users to take advantage of the enriched description of the virtual geographic environment.

1.6. Organisation of the Thesis

The thesis is composed of two parts: 1) *the state of the art* which presents the context of our work and its related research fields and 2) *the contributions* which proceed with a full explanation of the IVGE model that we propose, the means of its enhancement, and the way we leverage it for motion planning purposes (Figure 1.1).

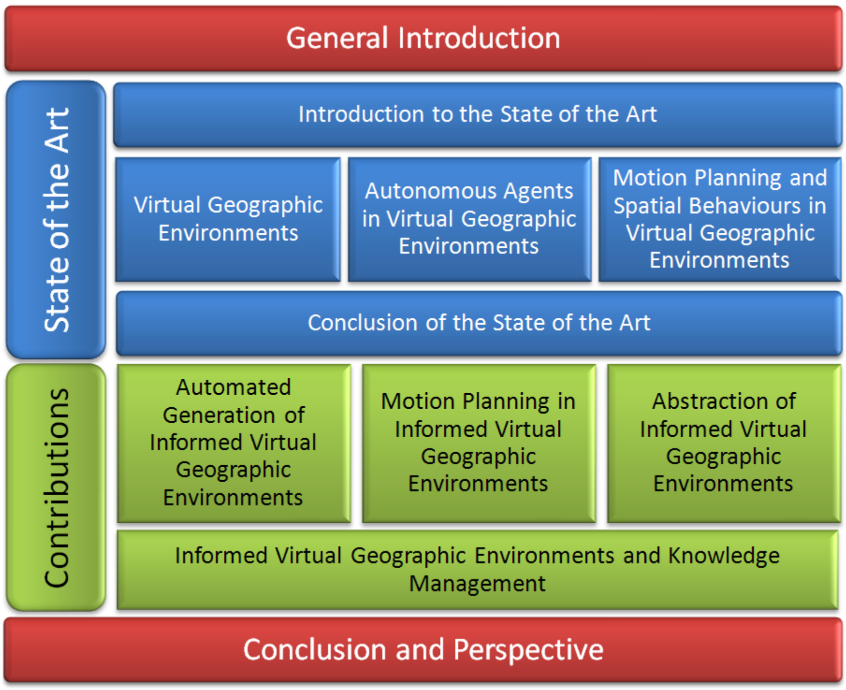


Figure 1.1: Organisation of the Thesis.

The first part is itself composed of three chapters: *Virtual Geographic Environments*, *Autonomous Agents in Virtual Geographic Environments*, and *Motion planning and Spatial Behaviours in Virtual Geographic Environments*.

Chapter 2 provides a survey on the representation of virtual geographic environments. First, it introduces *Geographic Information Systems* and presents the two common spatial decomposition techniques: the *exact* and the *approximate* spatial decompositions. Then, it discusses the use of semantic information in the description of virtual geographic environments. It also outlines the need for a standard formalism to represent such semantic information.

Chapter 3 details the concepts of situated agents and multi-agent systems and focuses on the importance of the environmental characteristics in the agent's decision making process. It also highlights the way agents interact with their environments in terms of perception, reaction, decision, and action.

Chapter 4 is the last chapter of this first part and it introduces the motion planning research field. First, it provides an overview of common path planning algorithms ($Dijkstra$ and $A*$). Then, it introduces the hierarchical path planners that deal with complex large-scale geographic environments. It also presents previous works on spatial behaviours and the way that agents reason about the environment's description and behave accordingly.

Finally, Chapter 5 draws conclusions from this state of the art and outlines the limits of currents approaches.

The contributions part of this thesis is composed of four chapters: *Automated Generation of Informed Virtual Geographic Environments*, *Abstraction of Informed Virtual Geographic Environments*, *Motion planning in Informed Virtual Geographic Environments*, and *Informed Virtual Geographic Environment and Knowledge Management*.

Chapter 6 presents our methodology for the automated generation of informed virtual geographic environments. First, it details the different steps which compose this methodology. Then, it introduces a scenario which illustrates the application of our methodology in order to address the issue of radio signal propagation and attenuation in informed virtual geographic environments.

Chapter 7 presents how to abstract IVGEs in order to support large-scale and complex geographic environments. This chapter details the three processes involved in the abstraction mechanism; (1) the geometric abstraction, (2) the topologic abstraction and, (3) the semantic abstraction.

It also introduces a holonic approach coupled with our abstraction model which are used to build the *Hierarchical Topologic Graph* (HTG).

Chapter 8 presents our optimised *Hierarchical Path Planning* (HPP) algorithm which leverages the hierarchical topologic graph resulting from the abstraction process. In addition, it details how we support spatial agents' navigation and obstacle avoidance in informed virtual geographic environments using a Neighbour Graph (NG) approach.

Chapter 9 presents our approach to manage knowledge about the environment in order to support spatial agents' decision making. This approach uses a standard formalism to express the semantic information that characterises the geographic environment and involves an inference engine in order to allow agents to get knowledge about virtual geographic environments. In order to illustrate our environment knowledge management approach, we present two scenarios in the fields of urban mobility and sensor webs.

Finally, Chapter 10 draws conclusions from our work, outlines its limits, and discusses avenues for future research and applications.

Part I

State of the Art

Introduction to the State of the Art

Multi-Agent Geo-Simulation (MAGS) is a modeling paradigm which is characterized by an explicit spatial environment called Virtual Geographic Environment (VGE) and situated agents which evolve in and interact with this VGE [BT04]. MAGS has a great potential when it comes to explaining the subtle interactions of heterogeneous actors in complex systems, taking into account the geographic aspect of the simulation environment [TB05]. The characteristics of the situated agents (autonomy, proactiveness, perception, navigation, etc.) and the spatial features of the simulation environment make MAGS an attractive approach to develop simulations of complex systems involving agents interacting with each other and with the geographic environment [DHK$^+$07]. In addition, the complexity of the simulation models and their visualization capabilities (cartographic visualization, 2D and 3D displays) make them more realistic and usable for decision-making purposes [AM05]. Thus, MAGS approaches potentially open numerous avenues for exploratory and applied simulations in different fields [BT04].

There are several advantages to use a MAGS approach integrating agent-based models and GIS data in order to simulate various phenomena in a variety of domains such as traffic simulation, crowd simulation, environment monitoring, and changes of land use and cover, to name a few [DHK$^+$07]. Indeed, MAGS facilitates the simulation of complex phenomena using either *micro-simulation* or *macro-simulation* models [TB05]. *Micro-simulation* models operate at the level of the individual behavioural entity, such as a person, a car, or a building. Such models simulate large representative populations of these low-level entities in order to draw conclusions that apply to higher levels of aggregation such as an entire city or an entire country [TB05]. This type of model is distinct from *macro-simulation* models whose explanatory variables already represent collective properties of the complex phenomena. Macro-simulation models evaluate the complex phenomena as a whole without consideration of the characteristics and features of individual entities involved in such phenomena [TB05]. An example of such an aggregate explanatory variable might be the national unemployment rate of a country. Certain types of modeling problems are best dealt with using micro-simulation whereas for others an aggregate approach is more appropriate. However, when it comes time to study and analyze interactions occurring between individual agents or between individual agents and their virtual geographic environment, macro-simulation models are inadequate since they are not able to capture interactions at the individual level [HC07].

For example, MAGS is frequently used to simulate and examine traffic flow and congestion and to understand the interaction of vehicles on the roadway [Wan05]. Macro-simulation models evaluate traffic flow as a whole without consideration of the characteristics and features of individual vehicles in the traffic stream [WCC+07]. In contrast with macro-simulation approaches, micro-simulation models simulate the individual vehicles in the traffic stream and consider the features and characteristics of the individual vehicles and use car-following logic and algorithms to predict and model the movement of each vehicle in the traffic stream [WCC+07].

Several research works applied the MAGS approach to simulate dynamic and complex phenomena in geographic environments [DHK+07]. These research works succeed to measure and model these phenomena and help, for example, to understand how people move in a geographic environment or in an urban setting [TB05]. However, we found few MAGS-based research studies attempting to simulate what we call *Spatial Behaviors*. Spatial behaviors are basically behaviors involving the apprehension of spatial features of the environment in large-scale and complex geographic environments. The nature of the geographic environment, the spatial behaviors to be simulated, and the characteristics of the interactions between the agents and the environment in the simulation (spatial interaction), make this kind of simulation a challenge. Several important features must be considered when building a MAGS model at the micro-level in order to simulate agents' spatial behaviors, among which we mention: (1) *an explicit representation of the virtual geographic environment*; (2) *a situated agent model which is able to evolve within this virtual geographic environment*; and (3) *efficient spatial behaviours algorithms which allow* *agents to interact with the virtual geographic environment.*

In order to enable agents to interact with their virtual environment, it is important to provide an explicit representation of the geographic environment in which agents evolve. In order to capture and analyze such interactions which occur between agents on the one hand and between agents and their geographic environments on the other hand, we use the micro-simulation approach. However, the micro-simulation approach requires a detailed description of the geographic environment as well as of situated agents.

On the one hand, the virtual geographic environment description should provide agents with quantitative and qualitative information in order to extend their knowledge about their environment and to let them reason about it in order to achieve their goals. Indeed, the virtual geographic environment description should be geometrically-accurate in order to capture the complexity of the geographic environment and the geographic features it contains. Moreover, this description should include the topological characteristics of the geographic environment in order to support agents' motion planning algorithms while taking into account dead-end areas, corridors, and crossroads. In addition, this description should also be enriched by semantic information which qualifies the geographic features in order to allow agents' spatial behaviour algorithms to take into account the geometric, topologic, and semantic characteristics of the geographic environment in which they evolve. Chapter 2 presents and discusses different techniques to build an explicit spatial representation of geographic environments. It also outlines the complexity of virtual geographic environments' generation.

On the other hand, situated agents models should take advantage of such an enriched description of the virtual geographic environment in order to reason about it. Chapter 3 and Chapter 4 introduce the notion of situated agents and emphasize the need to take into account the characteristics of the geographic environments in order to support spatial behaviours such as motion planning including path planning and navigation algorithms.

In this state of the art, Chapter 2 provides a short survey of different techniques and models used to build virtual geographic environments. It also discusses the use of semantic information to describe virtual environments and emphasizes the need for using a standard representation.

Next, Chapter 3 introduces the concept of autonomous agents evolving in and interacting with a virtual geographic environment. Finally, Chapter 4 offers an overview of motion planning and spatial behaviours of agents within virtual geographic environments.

Chapter 2

Virtual Geographic Environments

A *virtual environment* is a computer generated scene, composed of objects, in which an autonomous agent operates [Bad06]. This definition is pretty vague and leaves a very broad panel of interpretation of what the *computer generated scene* can be: it can be *realistic*, attempting to faithfully copy the real world in every aspect, or *imaginary* and completely invented. The vagueness of this definition seems to be intentional, and implies a large richness in the nature of the virtual environment. Useful overviews of virtual environments and their many applications are provided in [FMJ06, LB09]. A virtual environment may be thought of as a space subdivision which converts complex geometric data, made up of a great number of polygons, in a more or less informed database. The geometric data may be provided by *Computer Aided Geometric Design* (CAGD) tools in order to design curves and figures in two-dimensional (2*D*) space, or surfaces and solids in three-dimensional (3*D*) space for computer animations purposes [Far01b]. Geometric data may also be provided by *Geographic Information Systems* (GIS), evolving the concept of *Virtual Geographic Environments* (VGE) which is widely used for spatial analysis and decision support purposes [BRR$^+$05].

Building a VGE based on reliable GIS data is a big challenge. Indeed, a geographic environment may be complex and large-scale, and its creation is difficult and needs large quantities of geometrical data originating from the environment characteristics as well as semantic information that qualifies space. To be able to create a VGE, one should have an explicit representation of space using space decomposition techniques.

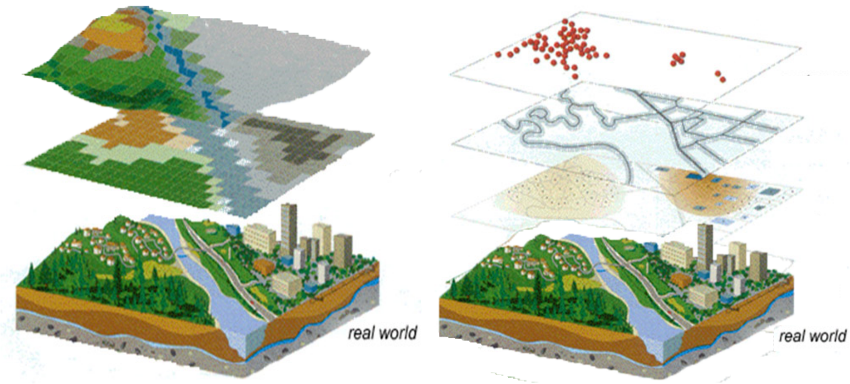
This chapter aims to describe relevant components in the creation of a VGE, as well as some current research issues. First, Section 2.1 introduces the concept of *Geographic Information System* as a fundamental source of georeferenced data. It presents the different models used to describe geographic data and discusses their advantages and disadvantages. Second, Section 2.2 introduces approximate space decomposition approaches. Section 2.3 provides a short survey of exact space decomposition approaches and focuses on Delaunay Triangulation techniques. Section 2.4 introduces and discusses the topologic approach to represent virtual geographic environments. Section 2.5 presents the abstraction of virtual environments and Section 2.6 outlines the integration of semantic information in virtual environments' descriptions. Finally, Section 2.7 concludes this chapter with a synthesis of the proposed models.

2.1. Geographic Information Systems

A *Geographic Information System* (GIS) is a system of hardware, software and procedures to facilitate the management, manipulation, analysis, modelling, representation and display of georeferenced data to solve complex problems regarding planning and management of resources [Goo06]. GISs have grown over the past two decades as an essential tool for urban and resource planning and management [Chr01]. Their capacity to store, retrieve, analyse, model and map large areas with huge volumes of spatial data has led to an extraordinary proliferation of applications [Goo06]. GISs offer two primary data models to describe a geographic environment: *raster* and *vector* data representations [AZ04]. In the following sub-sections, we first present the raster model and then the vector model of GIS data. We then discuss the use of GIS data in agent-based modelling approaches.

2.1.1. Raster Model

The *raster* representation of GIS data is a method for the storage, processing and display of continuous fields of spatial data [LGMR02, AZ04]. Within the raster data model, a region of interest is divided into discrete units, which form a regular grid of cells (Figure 2.1(a)). Each cell is typically rectangular in shape, but not necessarily square [Chr01]. Each cell



(a) (b)

Figure 2.1: Raster model (a) and *Vector* model (b) of GIS data [Chr01].

within this matrix contains a single attribute value and a separate raster is created for each attribute [LGMR02]. The spatial location of each cell is implicitly contained within the ordering of the matrix and a specification of an origin or extent and a cell size (or resolution) [FR02]. A contiguous area containing the same attribute value may be recognised as a polygon, however raster structures cannot identify the precise boundaries of areas such as polygons [Chr01]. With the raster data model, spatial data are not continuous but divided into discrete units [LGMR02].

2.1.2. Vector Model

The vector format is defined by the explicit representation of geographic data [ZLS+08]. Point features are defined by one coordinate pair, a vertex [LGMR02]. Vector features are characterized by the use of sequential points or vertices to define linear segments that approximate a curve (Figure 2.1(b)). Vector lines are often referred to as arcs and consist of a string of vertices terminated by a node [Chr01]. A node is defined as a vertex that starts or ends an arc segment. Polygonal features are defined by a set of arcs that bound the polygon [AZ04]. In vector representation, the storage of the vertices for each feature is important, as well as the connectivity between features, e.g. the sharing of common vertices where features connect [FR02].