Methodology for Automatic Generation of Distributed Urban Spatial Models from GIS Data

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ABSTRACT

Urban spatial models are important to many professions, and they can be used in a wide range of urban decision-making applications. This paper describes a methodology for automatic generation of an urban spatial model from a GIS source. The methodology uses a Voronoi polygon-based method in order to split the urban space. After partitioning the GIS, functional characteristics are used to generate zones of interest at each Voronoi polygon. The paper also presents examples of applications of the model: a two dimensional model used for micro-simulation of traffic, and a three-dimensional model used for simulation of air pollution.

KEYWORDS: mobility, urban model, Voronoi diagram, GIS, distributed system

The spatial data representation of urban systems presents several challenges. Data may be heterogeneous, unordered, or they may come from multiple sources. The classical geographical information systems (GIS) approach use layers as data representation units; each layer is related to a subject, and many layers can be overlapped to show a variety of subjects. The classical approach offers overlapping layers for the same space, though when a specific spatial partition is required the data integration may not be that efficient if there are many layers. We propose a data representation model based on spatial partitions, which saves several complex features from a specific urban space. Also the proposed data model offers a hierarchical structure that may be easier to understand than a classic approach.

This paper presents a methodology for generation of a spatial data model, and two implementations illustrating the proposed model's functionality. This paper is organized in the following way: the second section reviews some previous work in urban representation schemes. The third section lays out the methodology for the construction of the model. The fourth section shows an example of its implementation on an urban landscape and showcases two different modeling applications using our methodology as a basis: an urban traffic simulator and an urban air quality simulation. Finally, the fifth section presents conclusions.

Related Work

Geographic information systems (GIS) have two types of generalizations: cartographical and model-based generalizations (Muller, 1995). The former is a constraint-based process used by cartographers to reduce the complexity of maps in scale reduction processes, the latter is used in many application areas for structuring elements for many other cartographic objects (Jiang, 2004). Cartographical and model-based generalizations may be combined in order to help cartographers and urban planners, some examples of this are shown in this section.

Jiang (Jiang, 2004) presents a model generalization approach based on a computational application of graph modeling principles. It is a functional representation of a city based on a street network. Its main objective is retaining the main characteristic elements of a given street network. Streets are represented by vertices and intersections are represented by edges. The proposal is validated using a middle-sized Swedish city, Sätra.

Urban Space Methodology: Definitions

Partition of Urban Space for Scalability and Distribution

The following model proposal is made to create a design of an urban space, and supports distribution and scalability, and allows the development of a micro-simulation capable of handling entire cities or large portions of them depending on the processing capacity available. Hence, the overall time for the simulation depends on the most complex, and therefore more computationally expensive partition of the region of interest.

Definition and Generation

We chose road intersections as the computational units of the model, because these are the points where the most complex mobility phenomena occur. For this reason the partition of the urban space is based on two-dimensional points which represent each intersection in the road network. A Voronoi diagram (De Berg, 2000, 147) is constructed based on these points, generating a convex polygon around each intersection. Before building the polygon, clustering algorithms based on Euclidian distance may be applied to the intersection points, avoiding an excessive division of the urban space (for example, a cloverleaf interchange). The area enclosed by each polygon may be simulated in separate processors. Figure 1 shows the Voronoi polygons drawn over the GIS data (Fig. 1).

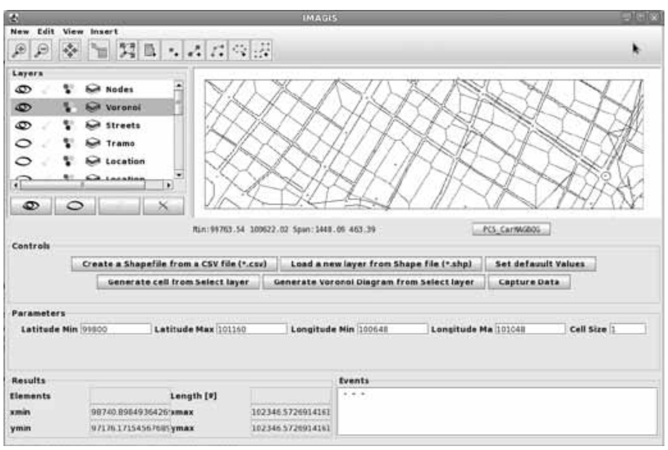

Figure 1. Data Processing application screenshot

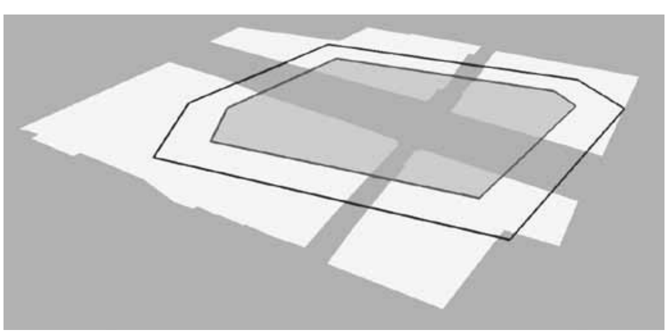

Figure 2. Urban mobility simulator, Voronoi Polygon and shared regions

Handling the Distribution Issues: Shared Regions

In order to synchronize the results between distributed simulations, a method of sharing information between neighbor intersections is needed. Therefore, shared regions have been defined between every pair of adjacent polygons, and they are calculated automatically in the data entry step.

There are two types of shared regions associated to a Voronoi polygon. The first one is a subset of the polygon located near its boundaries. Changes in the variables inside this subset must be replicated to the corresponding neighboring intersection. The second type is a region outside the polygon near its boundaries. This space is controlled by the neighboring polygons and it must replicate the information of the neighboring polygons. Figure 2 illustrates the region encased in the Voronoi polygon (green) and the shared regions with neighbor polygons (yellow) (Fig. 2).

The automatic generation of the shared regions is controlled by a reference distance, which determines the shared regions size. A group of parallel lines to the Voronoi polygon at reference distance to each side of it define a corresponding enlarged, shared polygon. The intersections between each neighbor enlarged polygon and the current polygon define the first type shared regions. The intersections between the current enlarged polygon and each neighbor polygon define the second type ones.

Urban Model: Structuring the Voronoi Polygon

We propose three categories of elements for describing the content of a polygon: zones, stretches networks and point objects.

Zones

A zone is a two-dimensional connected division of the Voronoi polygon, so it is not necessarily a convex polygon. Zones represent abstractions of the urban space; they have special characteristics that make them important to urban modelers. Zones do not define partitions over the Voronoi polygon; there are points in the polygon which do not belong to any zone, likewise there are points which belong to multiple zones. The sources for these zones are specific layers from GIS files that contain polygons or multi-polygon, and sometimes lines or polylines; the sources also hold important features like cadastral registers.

Principal zone types:

- Block: blocks are the smallest area surrounded by streets.
- Property (land lot): properties are divisions of a block. There may be buildings on them; GIS data contains the height of buildings on each property, if there are any.
- Street: streets are areas where vehicles may move. Streets do not always belong to the road network.
- Sidewalk: sidewalks are pedestrian pathways located along a street.

- Plaza (Town Square): plazas are public open spaces, where people may gather and interact.
- Horizontal signs: horizontal signs are two-dimensional regions that affect the mobility of mobile actors from one or more types. Generally they are marked on the pavement.
- Anomaly: Anomalies represent urban areas where order has been broken. There may be street's structural damage.

Stretches and Stretch Networks

A stretch (also called a segment) is a zone where mobile actors may move. A stretch has a direction of movement, which indicates the course of movement of mobile actors using the stretch. A stretch may even have two directions of movement, like a highway with more than two lanes.

A stretch network is a composition of stretches. Stretch networks determine the movement space for mobile actors (for example, automobile networks, pedestrian networks, subway networks, etc.) Hence, a stretch network is also associated with a mobile actor type. The stretches data sources are lines and polylines with direction of movement, common nomenclature, number of lanes, etc.

Point Urban Objects

A point urban object represents the space positioning of an urban object of interest. Examples of objects of interest which may be represented in this way are trees, street lamps, utility poles or sculptures. However, we identified vertical traffic signs as the most relevant point objects, because of their influence on urban mobility. We identified two types of such signs: passive vertical signs and active vertical signs. Passive vertical signs do not change over time; examples of this kind of signal are warning signs and restrictive signs. Active vertical signs present a programmed behavior. Examples of this kind of signal are traffic lights and railroad signs.

Urban Space Methodology: Implementation and Usage

Implementing the Model

A sample application extracting the data needed for our model was made using GIS data from the Colombian city Bogotá. The implementation was divided into three steps: data entry, data processing and data persistence. The application was developed using Java for the data entry and data processing steps and MySQL for the persistence step. A preliminary step is required to guarantee the data quality and the non-coherent data points from heterogeneous data sources. To accomplish this interactive software tools were developed to manually alter the GIS data.

The data entry step reads the GIS data containing the required information, using an open source GIS processing API, GEOTOOLS (GEO, 2010). GEOTOOLS opens GIS files and manipulates their data as a Java collection. After loading the required files, the data processing step transforms the original GIS data to generate the nodes for creating the Voronoi diagram and the zones are structured into Voronoi polygons; lastly, specialized objects are created to contain the processed data. Some basic operations like data format conversions, concatenation, grouping or relating are necessary for data processing. Figure 1 shows the data processing application in action, after dividing the urban space in Voronoi polygons (Fig. 1). Finally, in the data persistence step, the generated objects are persisted using the DBMS MySQL.

Using the Model: Urban Mobility Micro-simulation

We are developing an urban traffic micro-simulator in order to introduce psychological traits and other behavior patterns in mobile agents, for example, motor vehicles and pedestrians. Micro-simulations are computationally expensive because they simulate a great quantity of agents, so an adequate space partitioning method is required for distribution of each space partition to available processors. Therefore, our urban model is useful for this kind of simulation. Each Voronoi polygon and related agents may be processed by a different CPU. Micro-simulations need each dynamic element or agent to know a local portion of the whole space, to ensure this it is suitable to generate another partition over the Voronoi polygon with smaller, square regions (called cells). The simulation consistency depends on the cell area size, so a 0.5-meter resolution has been chosen. Each cell has information about overlapping zones, signs and mobile actors. Figure 3 shows a Voronoi Polygon with blocks and streets information. It also shows the discrete partitioning in cells 0.5 meters wide (Fig. 3).

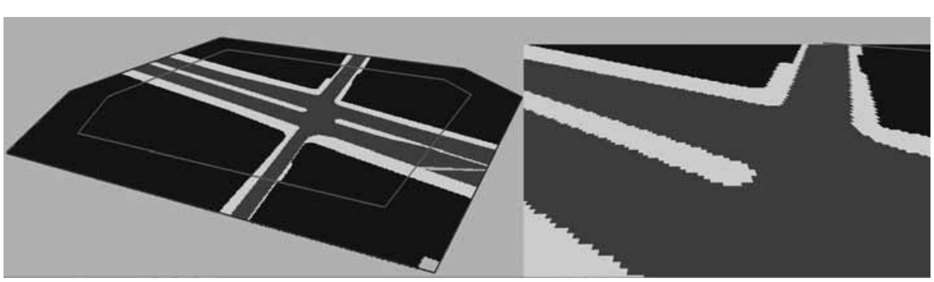

Figure 3. Right side, urban mobility simulator. Left side, cell partitioning

Using the Model: Urban Air Quality Modeling

We are also developing an air quality model (AQM). The AQM is being developed to provide a computer fluid dynamics infrastructure based on the Lattice Boltzmann method (LBM) for an air quality simulator. The AQM needs information about the land lots and the buildings on them, and the streets on each Voronoi polygon, in order to feed the LBM with a group of solid obstacles to oppose the air flow. The AQM is to receive sources of pollutants from the urban mobility simulator, using the automobile vehicle actors. Figure 4 illustrates a Voronoi Polygon with rendered buildings from the land lots data and air parcels over the street space (Fig. 4).

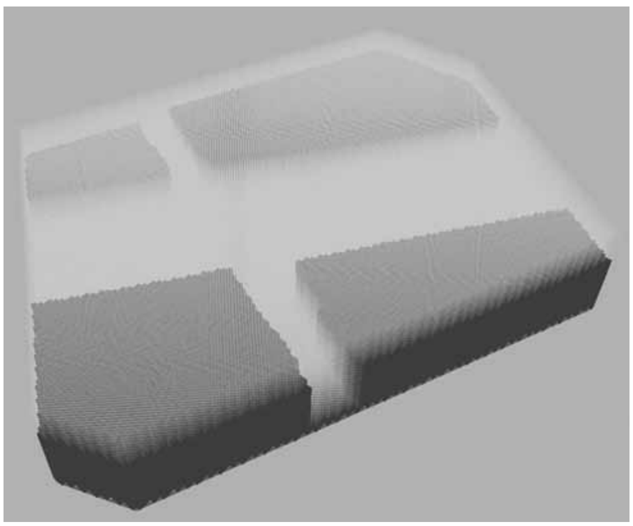

Figure 4.Urban air quality model, Voronoi polygon rendered buildings

Conclusions

This paper proposes a methodology for generating an urban model based on spatial partitions of existing GIS data with the objective of helping distributed applications such as micro simulation-based models for urban phenomena.

The strategy of using intersections to systematically divide the city GIS representation, as well as the use of Voronoi diagrams, has provided good results. The geometric features of Voronoi diagrams allow extending the model naturally in order to add concepts like neighboring intersections and shared zones.

The presented implementation supports the construction of models for distributed simulations. Two examples of such simulations were presented, a micro-simulation of urban mobility phenomena and an air quality simulation. However, whatever potential this automatic approach has, it also exposes the need for interactive software tools to administer missing data that is not present in the GIS data frequently available in developing countries.

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