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A grid-based spatial data model for the simulation and analysis of individual behaviours in micro-spatial environments

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ABSTRACT

As crowd simulation in micro-spatial environment is more widely applied in urban planning and management, the construction of an appropriate spatial data model that supports such applications becomes essential. To address the requirements necessary to building a model of crowd simulation and people–place relationship analysis in micro-spatial environments, the concept of the grid as a basic unit of people–place data association is presented in this article. Subsequently, a grid-based spatial data model is developed for modelling spatial data using Geographic Information System (GIS). The application of the model for crowd simulations in indoor and outdoor spatial environments is described. There are four advantages of this model: first, both the geometrical characteristics of geographic entities and behaviour characteristics of individuals within micro-spatial environments are involved; second, the object-oriented model and spatial topological relationships are fused; third, the integrated expression of indoor and outdoor environments can be realised; and fourth, crowd simulation models, such as Multi-agent System (MAS) and Cellular Automata (CA), can be further fused for intelligent simulation and the analysis of individual behaviours. Lastly, this article presents an experimental implementation of the data model, individual behaviours are simulated and analysed to illustrate the potential of the proposed model.

1. Introduction

Individual spatiotemporal activity in micro-spatial environments is closely related to the management of unconventional emergencies, traffic control and dispersion, urban planning and other applications [1–7]. By constructing a real or virtual geographical environment, crowd simulation can dynamically simulate individual spatiotemporal activities and predict the evolution of crowd behaviour, which has scientific and practical value for efficient, scientific and well-organised decisions in people–place relationships and in improving urban and emergency management. Despite the wide-spread use of crowd simulations, an appropriate spatial data model that supports such applications is currently not available.

Geographic Information System (GIS) is an important tool for studying people–place relationships and can be used to in support of geographical process modelling, expression and analysis. The advantages of combining geographic environment expression and analysis using GIS and with crowd simulations include the realisation of an integrated analysis of the

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geographic environment and individual behaviours and an improvement in the fidelity and efficiency of individual behaviour modelling. However, GIS is mainly focused on geographic entities, phenomena, procession and spatial environments at the macro-scale and lacks the ability to model the behaviours and related incidents of individuals and groups in society and economic activities. GIS is primarily used for place-based information regarding people–place relationships in earth's systems and cannot sufficiently address people-based geo-processes [8–11]. A closer integration of GIS and the personal behaviours has been proposed recently. Miller [8] holds that traditional GIS, which is a place-based system, cannot completely describe people–place relationships, and people-based GIScience (Geographic Information Science) must be evaluated in greater detail. The use of Virtual Geographic Environments (VGE), which originated from the integration of VR and geography, is an important research field in GIScience. From the perspective of VGE, Gong and Lin also proposed the concept of human-oriented GIS [10,11]. However, research methods and spatial data models for people-based GIScience or human-oriented GIS have received little attention.

Spatial data models form the theoretical basis of GIS spatiotemporal expression and the simulation, prediction and analysis of geo-processes. Multiple spatial data models for modelling individual behaviours have recently been proposed. For example, activity is a common method used to model individual spatiotemporal behaviour [12–14]. According to Axhausen [15], an activity is defined as the main activity carried out at a location, including the waiting time before or after the activity. Activity-based spatial data model focuses on modelling individual travel behaviours, and tracking analysis is a key application, the method of modelling spatial environment is not the key in the model. Crowd simulation is the focus in computer science [2,16]. Cell-based model is the common way of modelling the spatial environment. The cell used for crowd simulation is most commonly expressed as a two-dimensional (2D) square grid similar to the GIS raster cell but smaller. For example, the cell size in EXODUS (a crowd simulation software package) is 0.5 m $\times$ 0.5 m [17]. In most cases, a person will occupy one cell at any given time. The spatial data model used for crowd simulation lacks the complexity required to describe the multiple types of semantic information associated with geographic entities. When the model applied is to large-scale geographic environments, the attribute storage space is consistently too large, and it is time-consuming to search for the individual by location. In addition, the spatial relationships among geographic entities are not expressed, which complicates the spatial analysis of individual behaviours. Many researchers have realised the advantages of GIS spatial data models and have started to apply GIS in crowd simulation. For example, Liu and Chen [18], and Lee and Kwan [19] modelled the spatial environment of a crowd simulation based on the ArcGIS Geodatabase vector data model and arc-node model respectively. However, both methods are ineffective when describing the geometric characteristics of micro-spatial environments (e.g., the irregular shapes of indoor rooms or outdoor squares cannot be given a fine level of definition) [20]. Based on an GIS arc-node model, Tang and Ren [21] constructed a network using cells and then applied the network to the simulation and analysis of individual behaviours. However, the basic unit of the spatial data model remains the cell. As the number of cells increases, the required computational cost also increases. Therefore, with this method, it is difficult to rapidly calculate individual behaviours, which does not meet the demands of crowd simulation in a complex or large-scale spatial environment.

The objective of this article is to develop a new spatial data model for crowd simulation in micro-spatial environment to remedy the defects of the existing data model. The specific objectives are as follows: (1) analyse the requirements of modelling people and place in micro-spatial environments, then defining the basic unit of the people–place spatial data connection and building a spatial data model for individual behaviour simulation and analysis; (2) study the methods of modelling spatial environments and simulating individual behaviours with the data model we advanced; and (3) implement a crowd simulation for a specific study area using the data model and analyse the usability of the model.

2. Modelling people and place in micro-spatial environments

Although people and place can be modelling from various perspectives in macro-spatial environments, there are still many differences and some special requirements of modelling them in micro-spatial environments.

2.1. Modelling people in micro-spatial environments

People can be described according to different levels with different contents. Individual, groups and organisations can be regarded as three levels of people in geography. An individual is a person with independent behaviours. The individual is the smallest and undividable unit in the people–place relationship. A group refers to a number of objective-driven people. The organisation level is superior to the group level. In sociology, an organisation, including a country, enterprise, government, or association, is established according to specific tenets and systems. Modelling people as individuals, the individual unique behaviour in the crowd can be described, and the behaviour of the group and organisation can be expressed as an assembly of individuals. Following this, individual-based models can be seen as the best way of modelling people in micro-spatial environments.

In a four-dimensional (4D) coordinate system comprising the time dimension and a three-dimensional (3D) space, an individual can be expressed as an object that can move freely, occupy a specific space, and have particular attributes. From a mathematical perspective, an individual I can be expressed as a multi-dimensional function of spatiotemporal positions and attributes:

$$I = f(S, A) \tag{1}$$