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A dynamic evacuation simulation framework based on geometric algebra

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A B S T R A C T

Integrating dynamic analysis models into geographic information system (GIS)-based evacuation simulations is important yet complex. Different models must be smoothly assembled according to the data processing flow to obtain a dynamic, data-forced evacuation simulation. However, because of the diversity of data types and dynamic data updating among different models, closely integrated evacuation simulations are complex and inefficient. In this study, geometric algebra (GA) is introduced to develop a dynamic evacuation simulation framework for a hazardous gas diffusion scheme. In the framework, geospatial data are first integrated into a unified virtual scene with different forms of multivector representation. The major simulation models of gas diffusion, risk assessment, and dynamic evacuation routing compose the major steps of the evacuation simulation. On the basis of the generalized multivector structure, dynamic exchange and updating geospatial data at different evacuation steps can be performed seamlessly with the multivector structure and GA operators. The framework is tested with a case study of a three-dimensional residential area, which shows that our framework can support the integration of dynamic evacuation processes and the model integration is direct and smooth. This framework may also provide a new solution for the integration and dynamic data updating in spatiotemporal GIS.

1. Introduction

Evacuation simulation under hazardous gas diffusion (ESHGD) is a typical and complex urban evacuation scenario (Jianwen, Da, & Wenxing, 2014). The evacuees, who should move from affected areas to safe zones, need to select the optimal evacuation route that meets various constraints (e.g., the maximum accumulated toxic load and the cost or distance of evacuation) according to updated risks. However, even using simple ESHGD to solve the potential optimal evacuation route in the warning phase remains complex and cumbersome.

In ESHGD, the evacuation simulation is performed in the spatiotemporal domain (Peeta, Sharma, & Hsu, 2011; Pultar, Raubal, Cova, & Goodchild, 2009; Zhang & Chang, 2014). Once the hazardous gas leaks, it will diffuse dynamically based on the climate and terrain conditions, which will result in dynamic changes in the affected area and risk levels. Taking this problem into account, the complex computing-by-updating operation is needed to support the dynamic data exchange and updating. Therefore, different geospatial data (e.g., census data, weather conditions, and road networks) and analysis models (e.g., gas diffusion and risk assessment models) involved in ESHGD should be closely assembled with dynamic data exchange to force the overall operation (Brachman & Dragicevic, 2014; Bretschneider & Kimms, 2012; Chen, Kwan, Li, & Chen, 2012; Yuan, Fang, Wang, Lo, & Wang, 2009).

Geographic information system (GIS) is the major platform supporting ESHGD (Liu, Chi, Li, Rui, & Lin, 2015). In most existing GIS, integration of the various data and the dynamic updating of information among different models are inefficient (Jianwen et al., 2014; Liu et al., 2015; Mao, Lu, Du, & Chen, 2011). For data integration in current GIS, different types of geospatial data are represented using different data structures (e.g., vector data, spatiotemporal field data, and network data). There is no rigid mathematical background to combine and integrate the above data types (Yuan et al., 2009). These issues also lead to model integration being usually loosely coupled based on external file exchange in existing GIS-based ESHGD, which significantly reduces the efficiency, increases the complexity of system architecture, and provides limited support for model integration (Shekhar et al., 2012). For dynamic updating model data, current GIS separates the temporal and spatial dimensions (Yuan et al., 2010), which complicates the dynamic data updating (e.g., of weights, constraints, topology, and network routes) (Alçada-Almeida, Tralhão, Santos, & Coutinho-Rodrigues, 2009; Onorati, Malizia, Diaz, & Aedo, 2014). From the analysis perspective, ESHGD requires dynamically geospatial computation power (e.g., dynamic computation of geometric and topological relationships). However, because of the lack of a formalized, unified operator, the adaptive ability of traditional Euclidean geometry toward dynamic environments is poor (Yuan, Yu, Luo, Yi, & Lü, 2013; Yuan et al., 2010). All of the

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above problems limit the extent to which GIS can support complex ESHGD.

Data integration and dynamic updating between different analysis models can be realized by integrating the geospatial representation and computation under a unified mathematical framework. Geometric algebra (GA), a unified engineering language, has the potential to unify the representation and computation in the spatiotemporal domain (Dorst, Fontijne, & Mann, 2008; Hildenbrand, 2013; Hitzer, Nitta, & Kuroe, 2013). In GA, different geospatial data can be represented as certain forms of multivectors. Multidimensional vector data, spatiotemporal field data, and network data can be represented as a hierarchical Grassmann structure (Yuan et al., 2013), a multivector function (Dorst et al., 2008), and a GA adjacency matrix (Schott & Staples, 2010; Yuan, Yu, Luo, Zhang, & Hu, 2014), respectively. Geometric computing in GA is mostly multidimensionally unified and coordinate–free. Therefore, it can support dynamic adaptive computing, which makes the spatiotemporal computing simple and direct (Yuan et al., 2012). The proposed multivector-based data structures (Yuan, Yu, Luo, Zhou, & Lü, 2011) and geospatial analysis models (Yuan, Yu, Luo, Yi, & Lü, 2014; Yuan et al., 2012, 2013) for the complex geospatial analysis are also required by ESHGD. Furthermore, unified data representations and adaptive operator-based calculation will simplify the integration and updating of different geospatial data in ESHGD.

In this paper, we introduce GA to construct a dynamic simulation framework for ESHGD. On the basis of mathematical expressions for different types of geospatial data, a framework that integrates different forms of geospatial data is constructed to connect gas diffusion simulation, risk region determination, risk assessment, and dynamic optimal evacuation path extraction models. Dynamic data updating and computing are developed with the help of a generalized multivector structure and GA operators. A case study of a three-dimensional residential area is also developed to evaluate the framework. The article is organized as follows: The overall framework of GA-based ESHGD is introduced in Section 2. Methods, including the representation of integrated data, operator-based computation, and optimal route finding, are provided in Section 3. A case study is presented in Section 4. Discussion and conclusions are provided in Section 5.

2. Overall framework of GA-based ESHGD

Faced with the development of GA-based ESHGD in GIS, the geospatial data-integrated representation and dynamic computation raise three challenges. First, although the representation of different types of geospatial data can be seen as a special form of a multivector, there seems no good solution for integration and dynamic data updating between different multivectors. Therefore, projection and transformation of data between different multivector-based representations are required. Because the different geospatial data (e.g., field, vector, and network data) represented in GA are all algebraic structures (Yuan et al., 2013), multivectors integration can be achieved by developing a generalized data model and general data structures. With the integrated data structures, operations on geospatial data can be flexible and direct, thus providing an efficient way to update and exchange data between different geospatial data.

The second challenge is how to estimate and update the risk regions of gas diffusion. Using mathematical models to simulate the dynamic gas diffusion, the risk regions should be dynamically generated and updated. The risk regions can be represented by the outer product-based GA expression (Yuan et al., 2011). At the same time, the *meet* operator can be used to express the intersecting points of risk polygons and the road network (Yu, Luo, Hu, Yuan, Zhu, & Lü, 2015). The intersecting points denote the coordinates of the evacuation destinations that can be dynamically updated during the simulation, thus simplifying the dynamic construction and adaptive updating of risk polygons. Third, the evacuation routes should be dynamically updated along with the risk regions. Fortunately, network elements (e.g., nodes and paths) as basic elements (e.g., blades) of GA have advantages in weight updating and dynamic path searching (Yuan, Yu, Luo, Zhang, & Hu, 2014). As dimensional calculations are used for the formalized expression of network topology and weight, the dynamic creation of network paths and the integration of constraints become more flexible. Network topology and weight can be easily updated by adjusting the coefficients of the multivector structures (Schott & Staples, 2010; Yuan, Yu, Luo, Zhang, & Hu, 2014).

On the basis of the unified multivector representation and computation, we develop a GA-based ESHGD framework (Fig. 1). The progress of the framework is as follows. (1) Constructing the data model that can integrate the geospatial data in the multivector structure to form a unified scene. (2) Developing dynamic data exchange and updating mechanisms between models (hazardous gas spatiotemporal diffusion model, risk assessment model, and evacuation route-planning model) by using the GA operator-based computation. (3) Assembling the data and models with dynamic data exchange and an updating mechanism into a unified scene. Finally, the GA-based ESHGD can be achieved.

3. Development and implementation of the GA-based ESHGD

3.1. Construction of an integrated scene based on multivectors

Three major types of data, including multidimensional vector data (e.g., three-dimensional buildings, two-dimensional land parcels, and regions), spatiotemporal field data (e.g., meteorology, atmospheric motion, and hazardous gas diffusion), and network data involving elements (e.g., nodes, edges, and routes), are expressed and integrated into the ESHGD scene representation.

The vector data are represented as the basic geometric elements. Complex geometries can be uniformly represented according to a Grassmann structure. The GA-based 3D data model supports the algebraic and adaptive representation of complex geometric objects in a hierarchical and coordinate-free way. A typical GA representation is

$$\begin{aligned} GeoObjMv = {} & Obj.Points + Obj.Lines<Obj.PointsIndex> \\ & + Obj.Planes<Obj.PointsIndex> + \cdots \\ & + Obj.Spheres<Obj.PointsIndex> + \cdots + Topo.MV \\ & + Relation.MV \end{aligned} \tag{1}$$

With the *outer* product represented in the form of Eq. (1), the geometric structure and shape can be adapted according to changes in point coordinates, and simple topological and geometric relationships can be adapted according to the algebraic relationships using the powerful GA operators (Yu, Luo, Yuan, Hu, Zhu, & Lü, 2015).

Given a GA space $Cl(p,q)$, a scalar/vector $\boldsymbol{a}$ in the spatiotemporal field F can be defined as $\boldsymbol{a} = x_a e_1 + y_a e_2 + \cdots + w_a e_n$, where $e_1, e_2, \cdots, e_n$ $(n = p + q)$ is the basis vector of the GA space $Cl(p,q)$ and $x_a, y_a, \cdots, w_a$ are the coefficients (the amplitude of the projection) of each basis vector (Dorst et al., 2008). Then, any spatiotemporal field can be represented as a multivector field:

$$M = \sum_A M_A e_A = <M>_n + <M>_s + \cdots + <M>_t \tag{2}$$

where $A = \{n, s, \cdots, t\}$ is the incident of the vector basis of the GA space. According to Eq. (2), an arbitrary multivector field can be represented as a multivector function:

$$f(M) = \sum_A f_A(M) e_A. \tag{3}$$

For network data, nodes are represented using the vector basis, and routes are represented as high-order blades. The topology and interconnection between nodes and routes can be represented by the oriented join product (Yuan, Yu, Luo, Zhang, & Hu, 2014). Given an n-node undirected graph $G(V,E)$ and node set $V = \{N_1, N_2 \cdots, N_n\}$, we can code the