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Section-constrained local geological interface dynamic updating method based on the HRBF surface

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ABSTRACT

Boundaries, attitudes and sections are the most common data acquired from regional field geological surveys, and they are used for three-dimensional (3D) geological modelling. However, constructing topologically consistent 3D geological models from rapid and automatic regional modelling with convenient local modifications remains unresolved. In previous works, the Hermite radial basis function (HRBF) surface was introduced for the simulation of geological interfaces from geological boundaries and attitudes, which allows 3D geological models to be automatically extracted from the modelling area by the interfaces. However, the reasonability and accuracy of non-supervised subsurface modelling is limited without further modifications generated through explanations and analyses performed by geology experts. In this paper, we provide flexible and convenient manual interactive manipulation tools for geologists to sketch constraint lines, and these tools may help geologists transform and apply their expert knowledge to the models. In the modified modelling workflow, the geological sections were treated as auxiliary constraints to construct more reasonable 3D geological models. The geometric characteristics of section lines were abstracted to coordinates and normal vectors, and along with the transformed coordinates and vectors from boundaries and attitudes, these characteristics were adopted to co-calculate the implicit geological surface function parameters of the HRBF equations and form constrained geological interfaces from topographic (boundaries and attitudes) and subsurface data (sketched sections). Based on this new modelling method, a prototype system was developed, in which the section lines could be imported from databases or interactively sketched, and the models could be immediately updated after the new constraints were added. Experimental comparisons showed that all boundary, attitude and section data are well represented in the constrained models, which are consistent with expert explanations and help improve the quality of the models.

1. Introduction

1.1. 3D regional geological modelling

Regional geological surveys represent the integrated investigation of the geological and mine conditions of a target area (PAN et al., 2004). Geological maps, section maps, etc., are the primary expressions of geological survey results and important reference materials for infrastructure construction. These two-dimensional (2D) expressions have been studied and used for many years; however, they were not sufficiently intuitive. With the development of computer graphics, three-dimensional (3D) reconstructions, such as stereo and vivid 3D geological models (Roche et al., 2012), replaced the traditional 2D maps. Moreover, these 3D models exhibit powerful analysis abilities, such as finite element analyses and kinetic analyses (Yin and Groshong, 2006; Taromi et al., 2015; Uzkeda et al., 2016), thereby providing designers and constructors with intuitive references for project location selection and disaster predictions. Therefore, 3D geological models were gradually recognised and adopted in geological and engineering designs and construction.

Although regional 3D geological models exhibit higher performance than 2D geological maps, the modelling process for constructing

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regional 3D models using geological survey elements still remains difficult and is not always robust. Moreover, regional geological features cannot be modelled using a single model but require an integrated modelling approach; therefore, complex geometric properties as well as topological and hierarchical relationships should be considered (Turner, 2006).

Because of the considerable number of requirements in regional geological modelling, powerful interpolation surfaces that have been widely used in computer-aided design (CAD), including Non-Uniform Rational B-Splines (NURBS) (Zhong et al., 2008; Piegl and Tiller, 2012), Coons surfaces (Zhou et al., 2016), etc., may not be suitable for regional geological modelling. Although a number of these surfaces have also been used in complex geological interface construction, they are primarily used in single model modelling and not integrated model modelling. When applying these surfaces, a considerable number of data pre-treatments, manual interactions and model corrections are usually required to satisfy different geological constraints, and special operations may be needed to maintain the complex relationships between different models.

Instead of introducing surface models from the CAD domain into the geological modelling field, a number of modelling methods have been created and widely used in geological modelling. The traditional connection method (Ming et al., 2010), which has been widely used in mine modelling, was integrated by various modelling software programs, including Micromine (Micromin, 2016) and Vulcan (Vulcan, 2014). The voxel modelling methods (e.g., general tri-prism [GTP]) (Wu, 2004) are useful for stratum and coal seam modelling and can interpolate drill hole data to construct stratum models. The discrete smooth interpolation (DSI) method (Lévy and Mallet, 1999), which is similar to the finite element difference method, has been integrated into GOCAD software (Wex et al., 2014; Philippon et al., 2015) and widely used in geological modelling. The uncertain modelling method, which is usually based on geostatistics (Chaplot et al., 2006; Li and Heap, 2008; Liu et al., 2014), has also been popular in the modelling domain, and GeoModeller software was developed based on the co-kriging interpolation (Lajaunie et al., 1997; Calcagno et al., 2008; Perrouty et al., 2014; Hassen et al., 2016).

A variety of geological models have been constructed based on these modelling methods; however, a number of unavoidable limitations occur in realistic regional modelling. Because of a lack of drill hole data, connection modelling and GTP modelling methods are not useful. The DSI method is suitable for regional modelling, although too many modelling steps are required, and the modelling efficiency is not satisfactory (Smirnoff et al., 2008). For uncertain modelling, too many pre-treatments are required before the workflow could be modelled, leading to tedious modelling processes. Moreover, the consistency between the models and the origin elements was also unsatisfactory.

1.2. Extraction modelling based on the HRBF-based surface

Considerable number of interpolation surfaces lack the ability to reasonably simulate geological conditions because of the sparse distribution of the modelling elements. The surface used in geological modelling should have better interpolation capacity, in terms of CAD. Therefore, the geological data properties should be used in the modelling workflow, and spatial connection is the most important property, as revealed by the first law of geography (Miller, 2004). This important property explains why current methods, including kriging interpolation and the inverse distance weight (IDW) method, are capable of simulating geological conditions (Zimmerman et al., 1999).

In recent years, an interpolation method that treats the spatial distance as a basis function, which is referred to as the radial basis function (RBF) (Zongmin, 1992), has been used in the point cloud domain, and different types of RBFs have been proposed to adapt different types of point clouds, including the normal RBF (Carr et al., 2001) and HRBF (Macedo et al., 2011), among others. Additional surface models have also been introduced into the geological modelling domain and have been found to be suitable for mine modelling (Cowan et al., 2002; Knight et al., 2007; Basson et al., 2016; Guo et al., 2016b) and interface modelling (Amorim et al., 2014).

1) Extraction modelling workflow

In a previous work (Guo et al., 2016a), we used the interface outcrop lines extracted from the geological boundaries to construct the geological interfaces using HRBF interpolation methods. During this simulation, the coordinate data as well as the vector data were integrated, thus, the attitudes were also satisfied. On this basis, a fundamental body was constructed, which contained all target models, and we extracted all geological models from this fundamental model through the geological interfaces. The powerful spatial division capacity made the spatial Boolean operation easy. Note that the implicit expression of the surfaces could not be displayed in the computer, and we used a series of vertical scanning lines to realize the polygonization of the implicit surfaces. The modelling method was suitable for simulating basic geological structures, including folds, faults, and strata, and it was used in realistic modelling experiments.

2) Limitation of previous method

However, only the attitudes and boundaries were used in this method to simulate the geological interface based on the HRBF surface. In the shallow area, the interface was primarily based on the boundaries and attitudes, whereas in the deep area, the interface models were determined by the properties of the interpolation surface. Therefore, the geological interface models in the deep area were sometimes out of control. To explain the limits of this method, a boundary bending to the left and the corresponding attitude pointing to the right, as shown in Fig. 1(a), were chosen to construct the geological interface. The target interface model is the surface shown in Fig. 1(b), and model simulated by the HRBF surface is shown in Fig. 1(c). The experiment is diagrammed in Fig. 1(c), which shows that in the shallow area, the geological interface would extend to the right, whereas in the deep area, it would extend to the left. Some constraint conditions were needed to

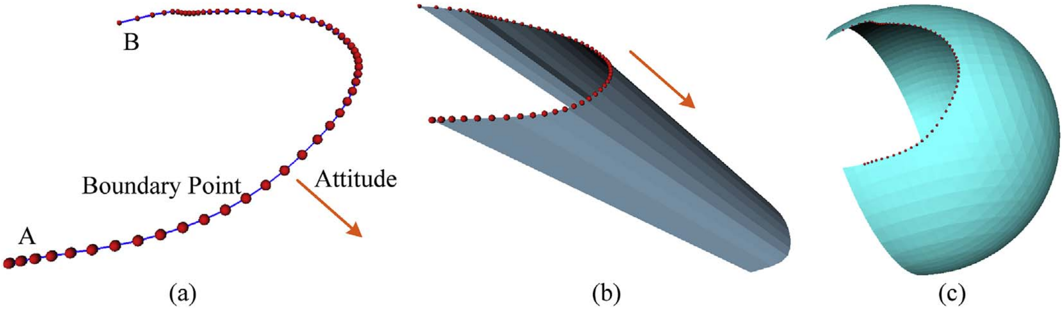

Fig. 1. Unsatisfactory extension of the surface. (a) The boundary and attitude data, (b) an ideal interface model, and (c) a model constructed by the HRBF surface.