Construction and Application of 3D Geological Models for Attribute-oriented Information Expression

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Abstract

To address the problem of geological structure modeling combined with property modeling during the geological three-dimensional (3D) modeling researches, a method for attribute-oriented information expression was proposed, and its applications to 3D geological modeling was also demonstrated. Smoothing methods for the stratum 3D model which was based on the modified butterfly subdivision surface modeling technique was established, thereby expressing the stratified information and lithological information for geological bodies. Based on the tetrahedron mesh discretization technique in the extended advancing-front method, a method for obtaining a 3D voxel model of geological bodies was proposed, as well as a method for generating an irregular data field to describe orebody components and grade information. Combined with the direct volume rendering technique, this method allows the visualization and analysis of orebody components and grade information. Using a salt mine as an example, the effectiveness of the proposed methods by performing salt rock 3D geological modeling and attribute information expression based on its geological exploration data was verified.

Key Words: 3D Geological Model, 3D GIS, Attribute Information Expression, Direct Volume Rendering, Irregular Data Field

1. Introduction

In three-dimensional (3D) space, complex geological bodies exhibit many characteristics, such as composite structures. Multi-dimensional visualizations of this information can be obtained by establishing accurate 3D geological models via knowledge discovery and by mining geological exploration data [1,2]. The realistic depiction of geological structures using 3D models provides a new research method for geological engineers, which may facilitate the analysis of geological phenomena, internal structures, and attribute information related to geological bodies [3,4].

3D geological models which can be established using geological exploration data are mainly to express the geometric shapes and topological relationships among geological objects [5–8]. In theoretical and practical applications of 3D geological modeling, previous studies have demonstrated the benefits of 3D spatial data organization and management, 3D spatial data modeling, the expression and visual analysis of 3D spatial relationships, and other features [9–11]. These methods have been applied in many fields such as engineering geology, hydrogeology, environmental geology, prospecting and explora-
tion for mineral resources, geotechnical engineering, and numerical simulations of rock mechanics [12, 13]. In a previous study [14] indicated that both 3D GIS and 3D GMS obtain similar results when establishing realistic 3D geoscientific information systems that include many factors. The 3D geological modeling is difficult to meet the needs of geo-science analyses, so many researchers are now considering methods for describing information related to the internal attributes of geological bodies [15–19]. However, there are many constraints when establishing and visualizing models of the properties of geological bodies using geophysical and geochemical attribute data, and thus further research is needed in this area [20].

Geological objects and other phenomena generally comprise geometry, topology, and attribute information. At present, methods consider geometrical representations and topological descriptions during 3D modeling and simulations of geological objects and phenomena, whereas attributes and semantic information are often treated as supplementary information. Therefore, the effectiveness of 3D geological models cannot be assured and the models may have low practical utility. In this study, the expression of attribute-oriented information in 3D geological modeling as well as the descriptions of the stratum lithology, components, and grade information of geological bodies during 3D geological structure modeling were considered. A unified modeling method for basic geometric objects, topological relationships, and attribute information for geological bodies was proposed, thereby establishing a link between 3D GIS and geo-science analysis. Therefore, 3D geological models can be used in practice to provide a scientific basis and technical support for engineering decisions.

2. Implementation of a 3D Geological Modeling Algorithm for Expressing Attribute-oriented Information

Multi-source geological databases are established based on GIS technology to allow the effective organization and management of related data, which is used in 3D geological modeling and to express attribute information. Thus, a method for 3D stratum modeling using stratified stratum information and lithologic information where smoothing methods were employed in the 3D stratum models was proposed, which are based on the modified butterfly subdivision surface modeling technique. In addition, topology checking for 3D stratum models was performed to express the stratified information and lithologic information of geological bodies. And 3D voxel models for geological bodies were established based on the tetrahedral mesh discretization technique in the extended advancing-front method. Thus, an irregular data field is generated for describing orebody components and grade information. When combined with the direct volume rendering techniques, the proposed method allows the visualization and analysis of components and grade information.

2.1 Construction of the 3D Stratum Model and the Expression of Lithologic Information

2.1.1 Construction of the 3D Stratum Model

According to the 3D modeling method for geological bodies that uses geological drilling data as the main data source, tri-prism (TP) models were proposed by Houlding [21], which are suitable for modeling stratified geological bodies. Based on TP models, generalized tri-prism (GTP) models were proposed by Lixin [22]. Given the efficiency of 3D stratum modeling and the convenience of describing and analyzing geological attribute information based on 3D stratum models, GTP models were employed as an intermediate modeling unit. First, GTP models of 3D geological bodies are established using drilling data, and boundary representation (B-Rep) models of 3D geological bodies are then extracted from the GTP models. The specific implementation steps are described as follows.

(1) The outer boundary conditions and the coordinates of drill sites are taken as reference points. Using the standard Delaunay triangulation construction algorithm, surface triangulation models are generated to
express the topological associations among different strata in the area modeled.

(2) Using the GTP model construction method based on drilling data, all of the triangles in the surface triangulation models generated in the previous step are traversed to obtain the drilling objects on triangle vertices. According to the standard sequence of strata, three drills on the vertices of each triangle are traversed in all strata. During this process, the top elevation of each stratum is regarded as the vertex coordinate of the upper triangles in the GTP, the floor elevation of each stratum is regarded as the vertex coordinate of the lower triangles, and the lithologic numbers of strata are regarded as the attribute information for GTPs. After all of the triangles have been treated in this manner, the GTP models are obtained for the 3D geological bodies in the research area.

(3) When the GTP models are complete, the GTP units with adjacent sides and the same attributes in the GTP models are merged by a generalized search method. The repeated lateral quadrangles are also deleted and the lateral quadrangles of GTP units on the boundaries of the models need to be triangulated.

(4) Next, all of the GTP units are merged and the B-Rep models of 3D geological bodies in the research area are obtained. Finally, the stratum information in the modeled area is determined.

Due to the sparseness of engineering geological drilling data and the complexity of geological morphology, the 3D geological models established using these discrete and sparse exploration data often contain numerous defects. In particular, they are rough and they do not coincide with the actual situation, thereby contradicting the descriptions and expressions of geological attribute information. According to a previous study [23], the established 3D stratum models can be refined and smoothed by the subdivision surface modeling technique, as shown in Figure 1(a) and (b).

Figure 1 shows that after processing twice with the modified butterfly subdivision technique, the 3D stratum model can express the geological environment more clearly than that established directly based on drilling data. The homogeneous 3D stratum models can then be subjected to a smoothing treatment using the existing surface subdivision strategy. For 3D stratum models with different types of lithology, the geometric consistency and topological effectiveness of the two contact surfaces between the 3D models in each stratum will be degraded when the existing surface subdivision strategy is used. Therefore, based on the established smoothing methods for 3D stratum models, the concept of subdividing virtual drilling data was proposed in a previous study [24]. The stratum model of drilling data based on semantic descriptions was designed according to the stratigraphic sequence. Using the adaptive modified butterfly subdivision algorithm, a method for generating subdivided virtual drilling data which was introduced into the modeling process was proposed. Smoothed 3D stratum models are established based on the geological structure rule. Compared with the traditional smoothing methods for 3D geological models, our proposed smoothing treatment for models can facilitate the improved description and expression of lithological attribute information for geological bodies.

2.1.2 Topology Checking for 3D Stratum Models

The geometrical morphology of geological bodies tends to be complex and uncertain, so topological errors will be generated after the treatment of 3D stratum models. And these topological errors may make the 3D stratum models invalid. Therefore, topology checking and repair of 3D stratum models are necessary.

Based on the Half-Edge data structure, an effective
topology checking and repair method for 3D stratum models was proposed, where the steps are summarized as follows, and the flowchart is shown in Figure 2.

TopCheckStep1. The first step is to assess whether multilateral collinear errors exist by traversing triangle lists in the generated 3D stratum models. If a multilateral collinear error is present, the area of the triangle patches is zero, and thus a “zero area” exists. If multilateral collinear errors are not present, the program jumps to TopCheckStep3.

TopCheckStep2. Repairs are performed for different types of multilateral collinear errors, such as deleting useless triangle patches, adding new divided triangle patches, or supplementing the topological relationships of triangle patches, half sides, and vertices. The program then returns to TopCheckStep1.

TopCheckStep3. This step assesses whether normal vector errors are present. First, the normal vectors are calculated from three vertices of each triangle. Next, the calculated results are compared with the normal vectors, which are obtained from the topological reconfiguration. Normal vector errors must be present if the angle between two vectors exceeds 90 degrees; otherwise, there may be no errors of this type, and the program jumps to TopCheckStep5.

TopCheckStep4. The normal vector errors are repaired by adjusting the order of the vertices in triangle patches. The program then returns to TopCheckStep1.

TopCheckStep5. This step assesses whether there are crack or cover errors. First, if all of the triangles in the 3D models have been traversed, the program jumps to TopCheckStep7; otherwise, the length of each edge in the triangle patches is calculated to assess whether the length of one or more edges is less than a minimal threshold $\epsilon$. Crack or cover errors are present if the length of one or more edges is less than $\epsilon$. In general, $\epsilon$ is set $\leq 10^{-6}$, or it can be set based on external conditions. If there are no errors, the program jumps to TopCheckStep7.

TopCheckStep6. The same method is used to repair crack and cover errors. This method merges edges to delete the error-related edges and it resets the topological relationships among adjacent triangle patches, edges, and vertices. The program then returns to TopCheckStep1.

TopCheckStep7. The program for effectiveness checking and repair of the entire 3D stratum models is then complete.

After completing topology checking and correction for the initial 3D stratum models, the effective 3D stratum models are obtained, as well as the descriptions and expressions of lithological information for the geological bodies.

2.2 Construction of 3D Voxel Models of Geological Bodies and the Expression of Grade Information

Geo-science analysis and calculation models should be loaded into 3D stratum models to allow the expression and analysis of orebody grade and component information. In addition, the 3D spatial surface models must
be subdivided to obtain discrete elements that support geo-science analysis and calculation. Due to their many excellent characteristics, tetrahedral elements are used widely in geo-computation, such as the finite elements method and finite volume method. In order to address the needs for expressing and analyzing geological attribute information by considering the complexity of objects in geoscience, the mesh advancing-front method is employed, as described previously [25]. A tetrahedral mesh discretization method that considers the external boundary and interior feature constraints in entities is employed to obtain high quality meshes for expressing and analyzing geological attribute information.

As mentioned earlier, 3D voxel models can be obtained from 3D spatial surface models based on the mesh discretization technique. By embedding geo-science analysis and calculation models in 3D voxel models, the corresponding geo-science characteristics known as the attributes of mesh nodes can then be calculated. Finally, a regular or irregular data field is structured. To display the interior geo-science characteristics of 3D spatial objects, a technique is needed for visualizing the characteristics. Therefore, based on the Marching Cube, which is a visualization method for irregular data fields used in computer graphics, a direct volume rendering method for irregular data field that can exclude occluded units is proposed, which is calculated based on geo-science models.

3. Analysis of the Example of an Salt Mine Application

Using the proposed 3D geological modeling methods for attribute-oriented information expression, a salt mine was selected as the research subject and the effectiveness of the proposed methods by analyzing example expressions in the attribute information for salty strata based on geological exploration data for the mine was verified.

3.1 Lithology Description of Salty Strata Based on 3D Stratum Models

We established a 3D stratum model of the research subject using the proposed 3D stratum modeling method, as shown in Figure 3(a). Cross-profiles of strata were obtained by analyzing a fence diagram of the established 3D stratum model and the expression of stratified information and lithologic information for geological bodies was achieved effectively, as shown in Figure 3(b). Figure 3 shows clearly that the spatial distributions of different lithological strata were represented intuitively and effectively by the 3D salt mine stratum models and their cross-profiles, while retaining good geometric continuity and topological consistency between the adjacent strata.

3.2 Visualization of Components and Grade Information for the Strata of the Salt Mine Based on Volume Rendering

Based on the 3D stratum model, a 3D voxel model of geological bodies in the salt mine was established using the tetrahedron mesh discretization technique in the extended advancing-front method. The geostatistical interpolation method was applied to the 3D voxel model to obtain grade information for the mesh nodes and an irregular data field was then established for the grade content of the rock orebody in the salt mine. After combining with the direct volume rendering method, the strata components and grade information for the salt mine were visualized, as shown in Figure 4. And compared with the survey data, the simulation analysis result is in line with the actual situation.

Using the direct volume rendering technique, the components and grade information for the rock geological bodies in the salt mine were expressed intuitively with different color values and the overall spatial distribution

\[\text{Figure 3. Lithology and attribute information expression for salty strata. (a) 3D stratum model and its lithologic information. (b) Cross-profiles of strata and their stratified information.}\]
of the geological bodies was determined. The rich features contained in the irregular data field may help to provide insights for scientific researchers, thereby improving the efficiency of research.

4. Conclusions

At present, the attribute characteristics of geological bodies are not considered sufficiently during the 3D modeling and simulation of geological objects and related phenomena. To address this problem, a method for 3D geological modeling that expresses attribute information was proposed, and a method for 3D stratum modeling and topology checking were also developed. Finally, a method for expressing stratified information and lithologic information related to geological bodies was obtained. 3D voxel modeling methods for geological bodies were established based on the mesh discretization technique and a method for representing grade information related to geological bodies based on direct volume rendering. These methods facilitate the unified expression and description of basic geometric objects, topological relationships, and attributes information for geological bodies.

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References


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