Study on a Compatible Model Combining Point Cloud Model and Digital Elevation Model

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Abstract. DEM is an important data source to describe the surface morphology, but it is not a real 3D model, which can not meet the requirements of true 3D description under the ground. LiDAR point cloud data is a new true 3D data with high precision and high density. Based on the analysis of the differences between DEM and point cloud data in acquisition method, data structure and model construction, this paper proposes a 3D point set data model based on regular grid 2D data field, as well as the idea of regional modeling, and tests the feasibility of the data model through the upper and lower boundary modeling method. The experiments show that: (1) the 3D point set data model based on regular grid 2D data field is compatible with complete DEM data and simplified point cloud data, and has good expansibility; (2) the newly-built data model can complete the true 3D modeling of simple underground entity with high efficiency when the amount of data is only doubled; (3) The new data model can be generated by inputting DEM data, point cloud data and simplified algorithm of point cloud data under the same coordinate system. It has the potential of large-scale, multi-scale and automatic output processing, and has a good prospect of popularization.

1. Introduction
As an important digital representation of the earth's surface, digital elevation model (DEM) has a history of half a century [1]. DEM in mathematical sense is to realize the digital simulation of the surface through the continuous function $H = f(x, y)$ in 2D(two-dimensional) space. DEM is not a real 3D(three-dimensional) model, because the geoscience data field in this method is 2D, which only displays the data in the 3D environment, rather than the description of real 3D spatial entities [2]. However, the requirement of true 3D data is high in geoscience research [3-6], 2.5-dimensional DEM data can not fully meet the current application requirements. Under the condition that this mainstream data source cannot be abandoned, scholars have carried out a lot of research on DEM based true 3D geoscience expression [2,7-9]. Simple DEM cannot describe the true 3D description of complex objects such as karst caves, sinkholes, stratum structures, and architectural structures. Only through the method of multi-source data fusion modeling can the true three-dimensional modeling based on DEM be completed. Currently, borehole data is mostly used [10]. LiDAR point cloud data as a new high-precision, high-density true 3D data in recent years, provides a reliable 3D data source for indoor positioning, 3D modeling, high-precision DEM production, etc., and has a good application prospect in the field of assisting DEM to complete true 3D modeling.

This paper attempts to establish a new data model which can be compatible with simplified point cloud data and has the potential of large-scale and multi-scale automatic true 3D processing under the condition of ensuring the integrity and simplicity of DEM data, and studies the 3D description based
on the data model, trying to provide research in complex terrain modeling, Digital Terrain Analysis (DTA), 3D earth, true 3D basic mapping and 3D city In a new direction.

2. Basic Ideas and Key Technologies

2.1. Basic Ideas

We analyzed the current main geoscience modeling models (Table 1). In contrast, DEM model has the best universality, and point cloud model is the most easily obtained true 3D model, but they still have their own limitations.

Data model includes data structure, data operation and data constraint. The difference of data model caused by different data structure is an important source of characteristic difference between DEM data and point cloud data. The commonly used DEM formats include Virtuozo-DEM, CNSDTF-DEM, USGS-DEM, etc. [11]. There are certain differences between various data formats, but the data storage ideas are basically the same. The attributes of regular grid are determined by the starting point, XY spacing and the number of rows and columns in the header file, and then the elevation values are arranged in the file according to certain rules. This idea uses one-dimensional array to realize the storage of 3D point set. The USGS format is slightly different. This format stores row and column elevation data according to the section, and describes the spatial grid with the interval of seconds, but it still uses the combination of grid description and one-dimensional array in essence.

The data files recorded by lidar equipment generally refer to the Las format [12] issued by lidar Committee of the American Society for Photogrammetry and remote sensing (asprs), which contains a large number of parameters such as coordinates, colors, laser return points, scanning angle range, etc. For ease of use, generally the LAS format point cloud data is converted into a variety of other more concise and easy-to-operate formats for processing. At present, the main simplification method for point cloud data is to dilute the point cloud through a certain algorithm.

Ignoring the header file with a very small proportion of data, DEM data can be regarded as a matrix with X rows and Y columns, where X=total points and Y=bytes of a single record. Correspondingly, the point cloud data can be regarded as a matrix with the number of rows X+Δx and the number of columns Y+Δy. Then the difference ΔP between the point cloud data and the DEM data is:

\[
\Delta P = (X + \Delta x) \cdot (Y + \Delta y) - X \cdot Y \\
= \Delta x \cdot \Delta y + \Delta x \cdot Y + \Delta y \cdot X
\]

Currently, the publicly available DEM data have a resolution of 90-meter grids and 30-meter grids, and the resolution of lidar data is up to about millimeters. The length of a single record of point cloud data is at least about 3 to 4 times that of DEM data. Based on the rough estimation of the above data and formula, under the condition of equal area and equal recording accuracy, the data volume of point cloud data is about 9,000 to 360,000 times that of DEM data. There is a huge gap between the amount of DEM data and the amount of point cloud data.

Table 1. Main data format performance comparison.

| Name(format) | geoscience data field | dimension | defect |
|--------------|-----------------------|-----------|--------|
| DEM (*.tif)  | Rule grid/ Triangular irregular network | 2.5D | Unable to describe real 3D entity |
| TIN (No standard format) | | 2.5D | Unable to describe a real 3D entity, with no standard format |
| Contour line (No standard format) | Closed curve | 2.5D | Unable to describe a real 3D entity, with no standard format |
| Entity model (No standard format) | Space field | 3D | The modeling process is complex and |
| Standard Format | Difficult to Generalize in Large-Scale Applications |
|-----------------|---------------------------------------------------|
| Point Cloud (*.OFF, *.PLY, *.PTS, *.PTX, *.XYZ, *.LAS/LAZ) | Large Data Volume, Point Cloud-Based Modeling Processing Process is Complex and Difficult to Generalize in Large-Scale Applications |

Whether the data model can describe the objective object in 3D depends on whether the data model supports the 3D data field. The 2D data field has limitations in the description of complex 3D volume, and there is distortion in the description of true 3D data with the same horizontal coordinate and multi elevation. Therefore, a data model that is compatible with the two needs to focus on data dimensionality reduction, point set thinning, and whether it supports true three-dimensional data.

### 2.2. Data Model and Organization Management

Combined with the data structure of DEM data and the multidimensional characteristics of point cloud data, this paper proposes a regular grid point set data model. The single point form of the model is \((X, Y, Z, O)\), in which the \(XY\) is horizontal coordinate data, the \(Z\) is elevation value, the \(O\) is supplementary dimension, the dimension of supplementary dimension can be expanded according to the purpose, but it should be unified in a single model. The following will discuss the data model in which \(O\) is a one-dimensional identification dimension.

![Figure 1](image)

**Figure 1.** Structure comparison of point cloud data model, DEM data model and compatible data model.

As shown in Figure 1, \(X_0, Y_0\) represents the starting coordinate, \(\Delta X, \Delta Y\) represents the regular grid spacing, and \(I\) is the intensity and RGB color information contained in the point cloud data. The data dimension in \(I\) may be greater than or equal to 1 depending on its purpose and data structure. The compatible data model divides the data into regular grid nodes, and compresses the horizontal coordinate data by starting coordinates and rules description. Points with the same \(XY\) value are called points in the same grid cell. Since in the same grid cell, there will be an odd number of boundary points between the three-dimensional entity and the empty interval from the uppermost non-physical space to the elevation starting surface below the ground surface, so each grid cell will store \(2n+1\) elevations value. Taking Figure 2 as an example, when \(n = 1\), the elevation points to be stored in grid point \(P\) are \(P_1, P_2\) and...
3. Different from DEM and point cloud data model, the number of elevation values corresponding to each 2D grid point \((X_P, Y_P)\) in the compatible model is different, so one-to-many nonlinear structure should be adopted in data management. Although the compatible model is essentially a set of fixed dimension points, each text array needs to correspond to a certain 2D grid dot coordinate when horizontal coordinate compression and decompression is performed, but the same 2D grid dot coordinates may correspond to an indefinite number of body arrays.

3.3D Solid Modeling Based on Compatible Model

The independent point set without topological relation can't describe 3D completely, so establishing topological relation and 3D solid model of points is one of the problems that must be solved to realize true 3D modeling of compatible model. Based on the extensibility of compatible model, the complementary dimension \(O\) of compatible model is simply defined as the upper and lower boundary identifier of 3D entity, \(U\) is used to identify the upper bound of 3D entity, and \(L\) is used to identify the lower bound of 3D entity. The points in the upper and lower bound model are numbered as \(1, 2... 2n + 1\) (\(n \in \mathbb{N}\)), where \(2i + 1\) is point \(U\) and \(2i\) is point \(L\). From top to bottom, the space from point \(U\) to point \(L\) and the space from point \(2n+1\) to the elevation plane is defined as the three-dimensional space where entities exist; the space from point \(L\) to point \(U\) and the space above point \(1\) are defined as a three-dimensional space without entities, and the model is established based on this. It is worth mentioning that this is only one of the possibilities of the compatible model. We only use this model to analyze the feasibility and uncertainty of the compatible model.

The topological relationship of 3D point set does not exist only in the vertical direction. Due to the 2D data field used in DEM data, there is one-to-one correspondence between the two points of the nearest neighbor on the grid. However, in the compatible model, there may be \(2i + 1\) and \(2j + 1\) points in the adjacent 2D grid elements \(A\) and \(B\), and the size relationship of \(i\) and \(j\) is uncertain, which makes it difficult to establish the topology relationship accurately. In this paper, the method of regional modeling is used to solve this problem: firstly, the region with equal points is modeled independently, and the points in the independent modeling area correspond to the serial number from top to bottom. Then, multiple 3D planes or surfaces based on 2D data field can be established by interpolation, and then the 3D solid model can be established according to the identifier of the point layer 3D solid. After the modeling of all independent modeling areas is completed, the 3D solid model in the region can be obtained by merging the models, as shown in figure 3.
The idea of partition modeling can also be applied to restore DEM data from compatible model. The compatible model can completely contain DEM data with the same resolution in the region. DEM data generally describes the surface, so DEM interpolation surface often penetrates buildings and other 3D entities, but based on the extensibility of compatible models, it can contain complete DEM data without affecting the modeling by means of special identifier. In addition, due to the current research results of DEM interpolation algorithm are relatively perfect, the interpolation algorithm with better effect for the area is used to complete the calculation of DEM interpolation surface before the partition modeling, which will provide a very valuable reference in the partition modeling, and even can completely replace part of the interface in the partition modeling, so as to achieve more accurate modeling.

Based on the above ideas, the modeling experiment of the upper and lower bound model is carried out in this paper (figure 4). The real DEM data is selected as the surface layer, which contains 5964 coordinate points. In order to test the modeling effect of the upper and lower boundary model, the underground entity adopts the simulation cave to ensure that the evaluation can be carried out accurately according to the modeling parameters. Using the upper and lower bound model to calculate, the number of total coordinate points increased by 6369, about 106.8%. The amount of text data increased from 214707 bytes to 465307 bytes, an increase of 116.7%. In this experiment, the true 3D modeling was completed without a significant increase in the amount of data, and the feasibility of the upper and lower bound models was preliminarily verified. The uncertainty analysis of the model will be carried out in the third part of this paper.

4. Uncertainty Analysis of Compatible Model
Since the generation method of compatible model is true 3D space analysis, there is no direct function derivation process, and the exact uncertainty propagation formula cannot be derived. Therefore, this paper only focuses on the modeling process and makes some qualitative analysis on the uncertainty reflected by the simulation data in figure 3.

The main data sources of compatible model include DEM data and point cloud data. DEM data is
the data basis of compatible model, and point cloud data is the expansion supplement of DEM data, both of which have a significant impact on the final modeling effect. In theory, all kinds of extension forms of compatible model support the complete and distinguishable record of DEM data, which makes the description of surface by compatible model meet the requirements of application accuracy. The uncertainty of point cloud data mainly comes from its discrete characteristics. The multiple echoes generated in lidar measurement, the mobile units such as vehicles in the survey area, GPS dynamic positioning error and other factors will cause the point cloud distribution discretization. Therefore, it is necessary to filter the point cloud data to eliminate the gross errors. There have been relatively complete researches on point cloud data filtering processing and 3D modeling [13-16], and high-precision DEMs are mostly generated from LiDAR data [17]. The current research results can meet the needs of compatible model applications. The simplified algorithm of the point cloud will also produce a certain degree of uncertainty. At present, there are related researches on gridded point clouds [18-20].

In the process of 3D model construction based on upper and lower bound model, logical uncertainty and model uncertainty may be the biggest test faced by compatible model. In this paper, in order to directly reflect the modeling effect, a simple 3D volume component is used, such as figure 5-(a), adding cone with equal height, diameter of 4 times, 6 times, 8 times resolution and sphere with diameter of 6 times resolution; Figure 5-(b) adopts solid model section diagram array; Figure 5-(c) shows the solid model frame diagram of this part after regional modeling. The upper and lower interfaces are constructed by continuous plane method, and then filled to obtain 3D space entity.

![Figure 5](image)

**Figure 5.** Simulation of underground karst cave and modeling effect of upper and lower boundary model.

The analysis shows that with the increase of the diameter of the cone bottom, the upper and lower bound model for the description of the cone is gradually better, the performance of the four times resolution diameter is slightly fuzzy, and the eight times resolution diameter can reflect the solid features better. However, there is distortion in the description of the sphere. The distortion part is the high slope part of the surface of the sphere. At the same time, this problem also appears in the high slope part of the side of the hole. Simulation experiments show that the compatible model has some problems in describing the high slope surface; with the increase of the object or the decrease of the
grid, the description effect will gradually increase. At the same time, the automatic modeling method of regional cylinder is preliminarily verified, and the smooth 3D solid boundary is achieved without using surface interpolation algorithm. On this basis, the true 3D fitting surface algorithm considering the intersection of upper and lower interfaces is developed, and it is possible to greatly improve the 3D description effect of upper and lower boundary models.

5. Conclusion
This paper proposes a 3D point set data model based on regular grid 2D data field, which can be combined with simplified LIDAR point cloud data to solve the bottleneck of 2.5-dimensional DEM data when facing complex 3D entities. The model uses regular grid description to compress the horizontal coordinates of true 3D data, and supports extended dimension to record attribute information such as identifier, reflection intensity, color, etc. The feasibility of the model is also verified by the simulation modeling experiment of extending the identifier dimension.

Compared with the original DEM data of the experimental area, the volume of the text data of the compatible model data increases about twice after adding the simulation cave. Experiments show that the data model proposed in this paper can realize the true 3D modeling of simple underground entity without greatly increasing the amount of data, and a good balance point is obtained in the trade-off between the amount of data and the modeling effect. At the same time, the generation process of the new data model is relatively simple. At the same time, the generation process of the compatible model is relatively simple. Enter DEM data, point cloud data, and point cloud data simplification algorithm in the same coordinate system, and then generate it after simple calculation and modeling. The complexity of data processing and calculation process is low, and the running speed is fast. It has the potential of large-scale, multi-scale and automatic output processing, which has a good prospect of popularization. However, the practical application effect of this model needs further study.

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