A NEW DATA STRUCTURE FOR REFINED DIGITAL ELEVATION MODELS

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ABSTRACT:

A new DEM called Hybrid Mesh DEM (HM-DEM) with a hybrid mesh is put forth to improve the DEM's capacity of representation of different kinds of micro-terrains and complex landscapes. The conceptual model of HM-DEM and its data structure, namely Hybrid Mesh Data Structures (HMDS) are also put forth and discussed in details. The HMDS is encapsulated into an object called HmDem which is comprised of a GridHeader structure, a SubGrid sub-object, many SubTin sub-objects, a PeaPnts and a FeaLines structure arrays by use of vc++ language. The HMDS is used to represent many micro-terrains like steep cave, eroded loess tableland with terraces and different kinds of channels and large landscapes with complicated terrains, such as river with steep banks, and so on, in our case study. The results show that HBDS can be used to depict different kinds of complex micro-terrains and landscapes mentioned above with high resolution and efficiency except for reverse terrains which slope angle is more than 90 degrees. What we have done about HBDS and HM-DEM becomes very important complementarities of the basic theory study and constructing technology of traditional DEMs.

1. INTRODUCTION

Grid-based Digital Elevation Model (G-DEM) has become a dominant DEM data structure and got wide application in many fields. In China, the G-DEM is regarded as a standard DEM data format in national terrain database. The DEM datasets at 4 different scale levels was constructed and are playing significant roles in the economical and social development of China. However, more and more evidences show that it is the grid data structure that causes a series of errors, uncertainty or even mistakes in representation of terrains and some specific applications. For example, in order to represent micro-terrains with high resolution, the size of grid cell should be decreased, but which will cause rapid increase of data and decrease of terrain analytical efficiency, and losing of the mountain peaks while constructing G-DEM, etc. On the other hand, Triangulated Irregular Networks (TINs), especially Constrained Delaunay Triangulated Irregular Networks (CD-TINs) can represent local complex terrains very well, but they need complex data structures and a lot of data storage, which restricts their application in large study areas. Therefore, a new type of DEM, namely HM-DEM, and its data structures called HMDS, are put forth in order to solve the problems. Our case study shows that both different kinds of micro-terrains, such as steep cave, "V" and "U" Channels and complex landscapes can be represented very well with high resolution by HMDS, and the HMDS can meet the needs of HM-DEMs well.

2. CONCEPTUAL MODEL OF THE NEW REFINED HM-DEM

2.1 Relationship between HM-DEM and traditional DEM*s*

G-DEM and TIN-based DEM (T-DEM) are two main DEMs that are used widely in different kinds of applications at present. The HM-DEM is a new type of DEM with both global grids and local embedded TINs. The idea of integrating regular Grid with TINs is accepted by many scholars and many studies about it have also proceeded in the fields of 3D geovisualization of large scale terrains in recent year (Eck, 1995; Gerstner, 2003; Li, 2006; Mahdi, 1998). High resolution and geometric detail of different kinds of terrains commonly requires high storage costs and computation time (Lindstrom, 2001 and 2002). Therefore, the main aims of these studies are to maintain a good trade-off between resolution and storage requirements of the hybrid models while realizing the visualization of large scale landscapes (Amor,2004; Baumann, 2000; Bóo, 2005; Yang, 2005). Their studies mainly focus on the simplifying technology of complex terrains and optimizing technology of different kinds of visual algorithms.

The aim of HM-DEM is to improve the capacity of representation of different kinds of complex micro-terrains with high efficiency and make it to be an important complementarity of traditional DEMs. The HM-DEM includes a lot of contents, such as efficient elevation points' sampling strategy, suitable data structures, index technology with high efficiency and many terrain analytical methods and so on. Many previous studies have been done by the authors and obtained a series of important results. A new classification about feature points and lines, namely DEM Feature Points and Lines Classification (DEPLC)，and a new elevation points sampling method for constructing HM-DEM, namely TIN-based Sampling Method

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(TSM) have been put forth (Zhao, 2007 and 2008). Our previous study shows that the DEPLC and TSM can be used to represent many many kinds of micro-terrains, such as isolated hill and terraces, with high resolution. All we have done will be of great benefit to the establishment of conceptual model of HM-DEM.

2.2 Conceptual Model of HM-DEM

The G-DEM has a lot of advantages, such as simple data structure, easiness of terrains analysis and integrating itself with Remote Sensing data, which makes it the main type of DEM. At the same time, it also owns many disadvantages, such as high redundancy of elevation points, losing of many important micro-terrains like mountain peaks, etc. On the other hand, though the T-DEM can represent different kinds of micro-terrains with high resolution, it also has many shortages, such as complex data structure and great storage of data, which makes it cannot be used to represent large scale terrains. In order to solve these problems, the new DEM, namely HM-DEM, is put forth by the authors.

The HM-DEM is a hybrid mesh that is comprised of local CD-TINs and global square grids. The local CD-TINs, which are constructed by use of feature points and constrained feature lines, are embedded seamlessly into main grid-based DEM. Many important feature points, feature lines and feature polygons are used to construct CD-TINs where the important micro-terrains or complex landscapes need to be represented with high resolution in a HM-DEM. For example, a Peak Elevation Point (PEP) can be used to represent the highest mountain point while two breaklines can be used to depict nearly vertical cliffs and a region to depict a pond or a deep and cliffy vertical cave. Therefore, it is necessary to classify all the elevation points and their corresponding feature lines. The classification, namely DEPLC, of all elevation points and feature lines is shown in figure 1.

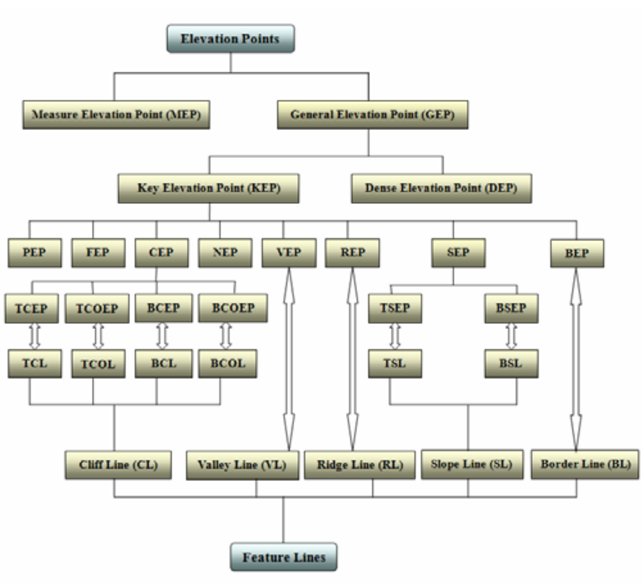

Figure 1. The class architecture of elevation sampling points and their corresponding feature lines

The DEPLC is a classification scheme about key feature points and feature lines for constructing HM-DEM. In order to represent complex micro-terrains with high resolution and high efficiency, all key feature points and feature lines used to construct HM-DEM are abstracted into as few classes as possible, which can be used to depict the complex micro-terrains effectively. According to the DEPLC, all feature points are divided into two main classes, namely Measure Elevation Point (MEP) and General Elevation Point (GEP) respectively and correspondingly all feature lines into five main classes, namely Cliff Line (CL), Valley Line (VL), Ridge Line (RL), Slope Line (SL) and Border Line (BL) respectively (See Figure. 1).

MEP is the survey control point in the study area and has a higher accuracy in elevation survey. All MEPs are used to represent the skeleton relief; hence, they are all involved in the construction of CD-TINs.

GEP is the other elevation points except for MEP in the study area, and their elevation can be obtained by field survey or from digital stereo photographic images. According to the importance, GEP is subdivided into two kinds of subclasses, namely Key Elevation Point (KEP) and Dense Elevation Point (DEP) respectively.

KEPs are the necessary elevation sampling points with comparatively high elevation accuracy for representing the sketch of the complex micro-terrains while DEPs are required only when very high quality visualization is the main goal of users. Otherwise, it is not necessary that all the DEPs are used to construct CD-TINs. KEP is divided into eight subclasses according to their distributing type, namely Peak Elevation Point (PEP), Foot Elevation Point (FEP), Cliff Elevation Point(CEP), Nek Elevation Point(NEP), Valley Elevation Point(VEP), Ridge Elevation Point(REP), Slope Elevation Point(SEP), Border Elevation Point(BEP) respectively. CEP is subdivided into four subclasses, namely Top Cliff Elevation Point (TCEP), Top Cliff Offset Elevation Point (TCOEP), Bottom Cliff Elevation Point (BCEP) and Bottom Cliff Offset Elevation Point (BCOEP) while SEP is subdivided into other two subclasses, namely Top Slope Elevation Point (TSEP) and Bottom Slope Elevation Point (BSEP) respectively.

All the feature lines are also divided into corresponding classes and subclasses. In order to depict the break lines and slope lines with finer resolution and higher efficiency, they are subdivided into four and two subclasses respectively. Cliff line is subdivided into four subclasses, namely Top Cliff Line (TCL), Bottom Cliff Line (BCL), Top Cliff Offset Line (TCOL) and Bottom Cliff Offset Line (BCOL). Slope line is subdivided into two subclasses, namely Top Slope Line (TSL) and Bottom Slope Line (BSL).

PEPs do not only mean the mountain peak points, they also includes any other elevation points which have the local highest elevation, such as the highest points of a small round hillock and any other local highest points of raised terrain and so on. Therefore, PEPs are very important when any raised relief is represented with fine resolution and there should be one PEP at least. Otherwise, false mesa will be created by present ways of constructing CD-TINs. Some DEPs can also be used to depict the refined surface shape around the PEPs. With these DEPs, the complex micro-terrain can also be represented with finer resolution and the visualization of the mountain peak will has higher fidelity.

FEPs also do not only refer to the lowest points in valley, they includes any other elevation points which has the local lowest elevation, such as the lowest points on the bottom of ponds or reservoirs, any other local lowest points of sunk terrains, etc. These kinds of terrains cannot be depicted with fine resolution if there was not a FEP used during construction of CD-TINs and they always will be filled up mistakenly. Some DEPs can also be used to represent any other higher elevation points around FEPs, which can help to depict the complex micro-terrain in the valley with fine resolution.

NEPs are some special elevation points used to represent the surface shape between two continuous maintains, which have the lowest elevation along the direction of the mountains' extension and have highest elevation along the direction which is perpendicular to the mountains' extension at the same time. Any other elevation points situated at the similar terrains should also be considered as NEPs. In order to represent the nek with finer resolution, some DEPs can also be included while constructing of CD-TINs.

REPs refer to any elevation sampling points which form any ridge lines. REPs have local highest elevation along the direction which is perpendicular to the ridge lines. Therefore, all the ridge lines should be taken as barrier lines which cannot be spanned by any Delaunay triangles while constructing CD-TINs. Otherwise, the mountain ridges may be cut off by some flat triangles falsely. Any other elevation points situated at the similar feature lines can also be considered as REPs, such as cuspidal ridge of pile dams and any other similar feature lines.

VEPs refer to any elevation sampling points which form any valley lines. VEPs have local lowest elevation along the direction which is perpendicular to the valley lines. Thus, all the valley lines should also be considered as barrier lines which cannot be spanned by any Delaunay triangles during the construction of CD-TINs. Otherwise, the valley may be filled up by some flat triangles mistakenly. Any other similar feature lines like riverbed lines and any other sunken feature lines can also be taken as valley lines.

CEPs are defined as the elevation sampling points which form any break lines, which mainly refer to the cliff lines. Because that the elevation of CEPs changes sharply from BCEPs to TCEPs, all the break lines should be taken as barrier lines which cannot be spanned by any Delaunay triangles. Because the continuity of terrain surface are the precondition of present tessellated surface model, it is impossible to represent these kinds of terrain like any cliffs and steep slopes with almost 90 degree gradient directly by present tessellated model. In order to depict break lines by use of the present tessellated surface model, TCOLs or BCOLs must be used. The rupture of terrain surface can be changed into continuous surface by use of TCOLs or BCOLs.

SEPs refer to the elevation sampling points which form slope lines. Different from cliff lines, slope lines refer to the top and bottom edge lines of any slope with less than 90 degree gradient. Slope lines are mainly used to depict the smooth slopes. Not all smooth slopes has both top slope line and bottom slope line, some spired slope only have bottom slope line while some other slopes only have top slope line.

The BL consists of the Border Elevation Points (BEP). It refers to the lines that form the border of certain specific features, which cannot be considered as any kind of the lines among TCL (or TCOL), BCL (or BCOL), TSL and BSL. It means that if a line can be considered as both TCL and BL, it should be regarded as TCL. The borders of flat path should be considered as a typical BLs when the two border lines cannot be regarded as any kind of the lines among TCL (or TCOL), BCL (or BCOL), TSL and BSL. Another possible typical BL is the internal or external border lines of the study area.

In order to represent complex micro-terrains with high resolution and efficiency, a new elevation sampling method, namely TSM, is put forth by the authors. This sampling method chooses elevation sampling points according to the need of constructing CD-TINs. Any important elevation points, such as PEPs, TCEPs and BCEPs should be chose to construct CD-TINs. Some other important information is also needed to construct the correct CD-TINs besides the elevations points. For example, the important feature lines like BLs, which are made up of a series of ordered elevation sampling points, also should be included as necessary constrained feature lines while constructing CD-TINs. All the feature points and feature lines should be sampled according to the following basic principle of TSM.

First of all, all the MEPs in the study area should be sampled according to correlative field survey criterions, and all the MEPs are included while constructing CD-TINs.

Secondly, all the discrete KEPs including PEPs, FEPs and NEPs in the study area should be sampled, and all the MEPs are included while constructing CD-TINs. ALL other KEPs including BEPs, CEPs, REPs, SEPs and VEPs in the study area should also be sampled and included while constructing CD-TINs. These KEPs should be sampled along their corresponding feature lines. For example, the VEPs should be sampled along their corresponding valley lines. The sampling density of all the KEPs sample points should be determined by the map scale and the need of users.

Thirdly, DEPs can also be sampled in some areas with very complicated micro-terrains, and not all the DEPs should be included while constructing CD-TINs. KEPs are the necessary elevation sampling points with comparatively high elevation accuracy for representing sketch of the complex micro-terrain while DEPs are required only when very high quality visualization is the main goal of users. Otherwise, it is not necessary that all the DEPs are used to construct CD-TINs.

3. A NEW DATA STRUCTURE CALLED HMDS FOR THE HM-DEM

3.1 Introduction of HMDS

The traditional data structure of G-DEM is very simple, only the elevation value and the positions of grid points are recorded. All the elevation points have no attribute information, and which causes the losing of many important elevation points like peak points. These problems can be partly solved by use of the CD-TINs, which can record the attribute information by making the peak points as vertices of the triangles and using constrained feature lines. Because of the complexity of the micro-terrains and the need of representation of refined terrains, it is necessary to put forth a new data structure to meet the need of DEOLC and HM-DEM. The new data structure includes more attribute information, which is very useful while constructing HM-DEM and making terrain analysis by use of HM-DEM.

3.2 Representation of HMDS

It is necessary that a new data structure should be put forth to represent the HM-DEM because it cannot be represented by any traditional DEM data structures. On the basis of the data structures of current G-DEMs and CD-TINs, a new object-oriented data structure for this new DEM is put forth. A hybrid mesh is encapsulated into a large object called HmDem that is comprised of two sub-objects, namely SubTin and SubGrid, a structure and two structure arrays by use of visual c++ language, namely GridHeader, FeaPnts and FeaLines respectively. The SubTin objects are used to store the local CD-TINs, and the SubGrid is used to store the information of global square grid. Some important information is stored by the GridHeader structure, such as the number of feature points and feature lines, etc.

A HM-DEM is represented by a HmDem object which includes a GridHeader, a SubGrid sub-object, many SubTin sub-objects, a FeaPnts and a FeaLines structure array (See Figure 2).

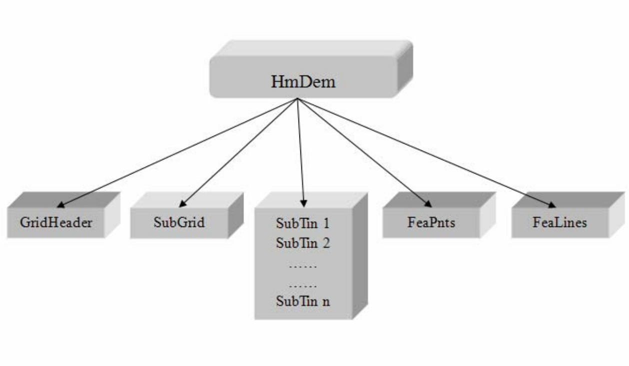

Figure 2. The representation of HMDS for HM-DEM

The version and projection information of the HmDem and minimum of x, y coordinates, cell size and numbers of columns and rows of the SubGrid, etc, are stored in GridHeader structure. The information of local TINs, such as the number of triangles, topological relationship, and so on, is stored in each SubTin object. The SubGrid is the residual part when the whole hybrid mesh subtracts all of the SubTins, and some important information, such as the number and index data of SubTins, are stored in it. The information of all feature points in the HM-DEM like the type and attribute of the feature points is stored in FeaPnts structure array while the information of all feature lines in FeaLines structure array. In a word, all kinds of the elevation points, including feature points and feature lines can be stored by the HMDS.

4. CASE STUDY

4.1 Background of Case Study

In order to find out whether the HMDS can represent different kinds of complex micro-terrains and landscapes with high resolution and high efficiency or not, many virtual micro-terrains and complex landscapes have been built according to actual terrains located at loess tableland in Shanxi Province and the hybrid mesh sampling strategy, namely TSM. The main micro-terrains include steep cave, eroded loess tableland with different kinds of channels eroded by water and different kinds of cliffs and slopes. The complex landscapes include many kinds of complex terrains, such as river and its steep banks, terraces, steep caves and so on.

4.2 Representation of Complex Micro-terrains and Landscapes with High Resolution

Many virtual terrains, including micro-terrains such as steep vertical cave, eroded loess tableland with 6 terraces and different channels including typical “V” and “U” channels are represented very well by use of local CD-TINs and SubTin objects. The visual results are show in Figure 3 and Figure 4.

First of all, a steep vertical cave which bottom is not flat is depicted perfectly by use of CD-TINs. The CD-TIN includes 53 elevation sampling points which form 92 Delaunay triangles. A TCL and a BCOL feature lines and a FEP feature points also take part in the construction of the CD-TINs. It is the BCOL and TCL that make it possible to represent the steep cave well. And it is the FEP and other 7 DEPs in the bottom of the cave make it possible that the uneven bottom can be depicted with high resolution. The TCL is made up of 14 TCEPs while the BCOL 14 BCOEPs. The CD-TINs also include 4 MEPs and other 13 DEPs.

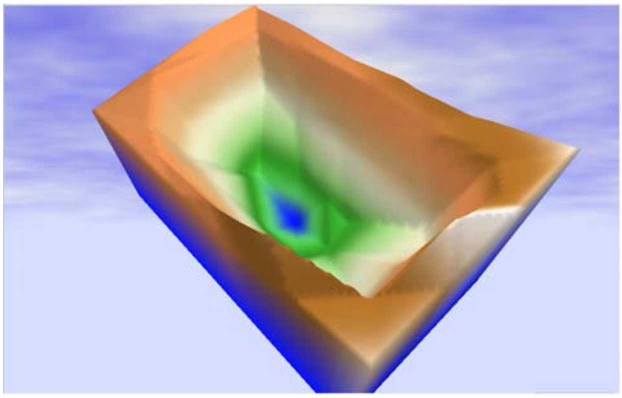

Figure 3. High resolution representation of the steep vertical cave with complex micro-terrains

Secondly, two typical channels with “V” and “U” sections on loess tableland with terraces are also depicted very well with high resolution by use the same way with the above. Both channels incise the third and fourth terrace of the loess tableland. They are shaped into “V” and “U” sections by different kinds of geological eroding functions. Six terraces with different height from 1.5m to 89.5m are also represented well (See Figure. 4). Therefore, the HM-DEM is very useful for the study of eroded loess tableland.

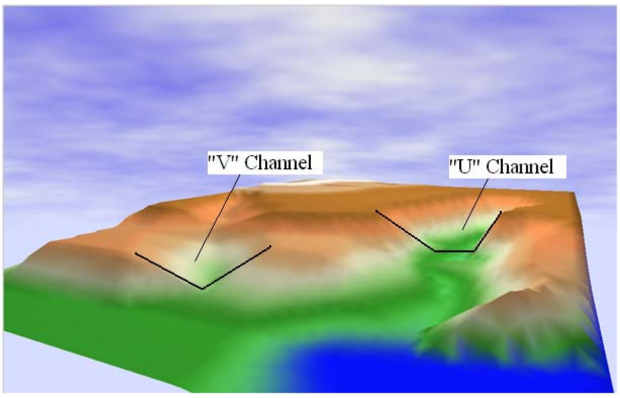

Figure 4. High resolution representation of the eroded loess tableland with complex landscapes

Though all the important micro-terrains mentioned above are represented well by local CD-TINs, there are many shortages for CD-TINs, such as the complexity of data structure, large data storage, etc. It is not suitable that CD-TINs are used to represent large scale study area. Therefore, the HMDS is used to represent more complicated and larger scale landscapes.

Finally, the landscapes include a river with steep banks, a long slope and many other micro-terrains, such as peak points, steep caves, complex terraces with different kinds of channels like "V" and "U" channels, and so on. All the complicated terrains mentioned above are also represented by a HMDS, and the effect of visualization is quiet well (See Figure. 5). The flat riverbed and slope are represented by grid while the other complicated micro-terrains by local CD-TINs that are embedded into global grid seamlessly. The HMDS includes a GridHeader structure, a SubGrid object and 6 SubTin objects. And the SubTins include many feature points and feature lines.

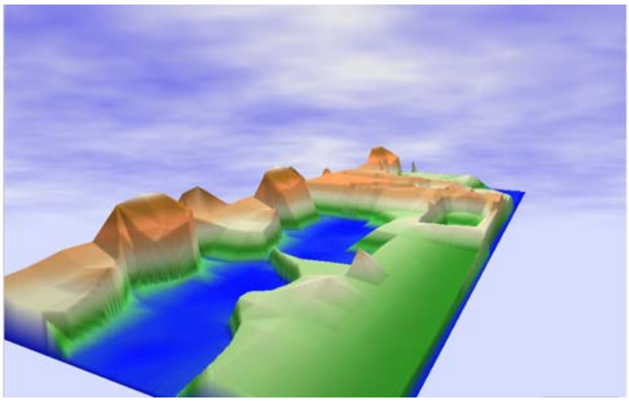

Figure 5. High resolution representation of the eroded loess tableland with complex landscapes

4.3 Results and Discussion

The case study shows that both single micro-terrain like a steep cave and complex landscapes can be represented well by the HMDS. And the HMDS is used to construct a HM-DEM and realize the visualization of the HM-DEM successfully. It indicates that the HMDS is reasonable and the way of constructing HM-DEM by use of HMDS, DEPLC and TSM is feasible. Nevertheless, there are a lot of problems, such as the efficiency while the HMDS is used to represent larger actual landscapes, need further study.

5. CONCLUSIONS

A new type of DEM called HM-DEM and its data structures, namely HMDS, have been put forth to meet the needs of high resolution representation of different kinds of complex micro-terrains and landscapes. Our case study shows that HBDS can be used to depict different kinds of complex micro-terrains and landscapes with high resolution and efficiency except for reverse terrains which slope is more than 90 degrees. What we have done about HBDS and HM-DEM is very important complementarities of the basic theory study and constructing technology of traditional DEMs, and it is necessary to perfect the data structures, constructing technology of HBDS and HM-DEM in the future.

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