Title:
Research on Terrain Physical Modelling Directly from Digital Elevation Model Data

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Introduction:
Terrain physical models are needed in many application domains of GIS, such as town planning, landscape architecting, land-use planning, transportation planning, military strategy planning, watershed and geological education, etc. Rapid Prototyping (RP) is a kind of advanced manufacturing technology which builds physical models layer by layer in accordance with the Computer Aided Design (CAD) models. RP system use Stereo Lithography (STL) file format to fabricate physical models, which express the geometric surface information through a set of connected triangle facets. Whereas the GIS data is mostly stored as Digital Elevation Model (DEM) file format, which use elevation data to describe the terrain surface information through a set of regular grids or irregular triangles. Therefore, when using the RP system to fabricate a terrain physical model, the GIS data should be converted to the STL file firstly.

   Many researchers have tried to use RP techniques to make terrain physical models from the GIS data. Most of them converted the GIS data to the STL file through several intermediate stages by using commercial software or developed program. However, these methods did not simplify and optimize the terrain data, which makes the STL file enormous and faulty. The manufacturing efficiency and quality of terrain physical models is lower. This paper presents a methodology to convert the DEM file of a terrain model directly to the STL file, which can be processed and fabricated by RP system, various formats of the DEM file can be converted into the STL file using the presented methodology directly. The model data was simplified and optimized according to the scale and the preset threshold. As a result, the processes of data conversion are eliminated and the volume of model data is reduced effectively. Furthermore, terrain physical models can be fabricated by RP system in less time and less cost.

Main Idea:
At present, RP software generally uses a standard STL file format to describe 3D models. This kind of STL file uses a set of triangle facets to approximate the surface of 3D model, which has various advantages, for instance, simple repetitions and expedient treatment method. The disadvantage is that there are copious redundant data to ensure the machining precision of large-sized models. The number of triangle facets must be quite big. Take a model with 1201×1201 elevation points for example, the number of triangle facets is about 2.88 million after transformation, and the STL file converted from this DEM file can be up to 800MB. For avoiding the ambiguity caused by data redundancy and shortening the time of RP manufacturing, the DEM data must be simplified in advance according to the scale given by users, and create a new STL file with less facets. The proposed method can read various DEM file formats and create 3D STL files by adding base and walls around DEM data. Furthermore, the simplifying algorithm can reduce the number of triangle faces on the basis of model quality assurance. The specific conversion process is shown in the figure 1.
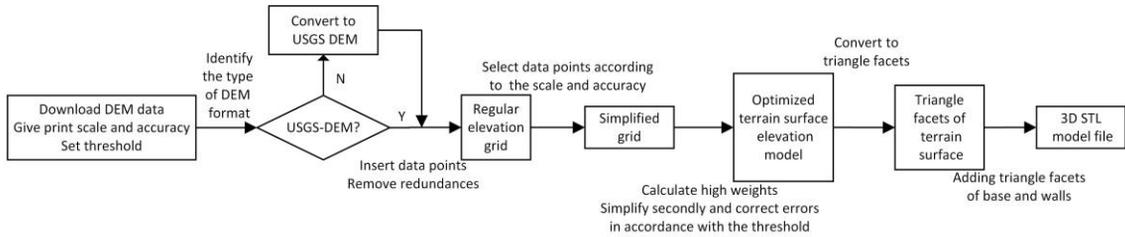
Fig. 1: Conversion process from DEM data to 3D STL model.

Creation and Correction of Elevation Grid

Before direct transformation of STL file, those three typical DEM formats should be identified and processed standardly, since they have the basic same key description of the net structure, this paper converts CNSDTF DEM and Virtuozo DEM to USGS DEM before further handling. Firstly, extract threshold information of the three DEM file formats according to their threshold rules, the common part of their threshold information include plane coordinates, plane resolution and the number of rows and columns, which is key information of triangle DEM storage structure. Secondly, screen threshold information and extract the common part of DEM formats, namely consensus information. Finally, in accordance with storage rules, rewrite the corresponding data to obtain USGS DEM.

As is shown in the figure 2, 7.5-minute USGS DEM is a quadrilateral elevation grid, but not a quadrate or rectangle geographical area. DEM file is formed by a set of profiles, the first y-coordinate of each profile is different. In order to facilitate the conversion of triangle elements, the quadrilateral elevation must be converted to rectangle grid firstly. The elevation data can be transformed to rectangle elevation grid as figure 3 by inserting *null_data* to those new grid points without elevation data. The parameter *null_data* is given a false negative data -32767, indicating those grid points without elevation data are not physical points. Internal vacant points and external redundant points need to be examined after the creation of rectangle elevation grid.
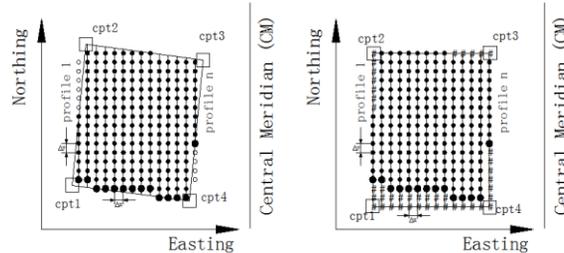

Fig. 2: Final elevation grid.

Optimization of Terrain Surface Model

The revised elevation grid data should be simplified according to print scale γ and accuracy μ given by users to reduce the number of elevation points. Elevation points of 7.5-minute USGS DEM are ordered by 30-meter intervals, assume the print scale is 1:60000 (1 millimeter represent 600 meters), the print accuracy of x-direction and y-direction is 0.1 millimeter, the real resolution is only 60 meters. Therefore, elevation points of grid can be simplified directly to remove indistinguishable data points (As shown in figure 3).
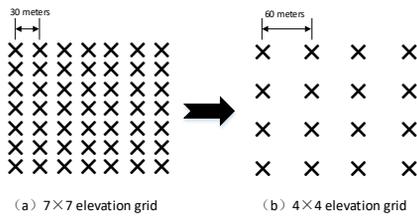
（a）7×7 elevation grid   （b）4×4 elevation grid

Fig. 3: Elevation grids after the first simplification.

（a）elevation grid after the first simplification   （b）elevation grid after two simplifications   （c）triangle elevation grid （Z - axis mirroring）
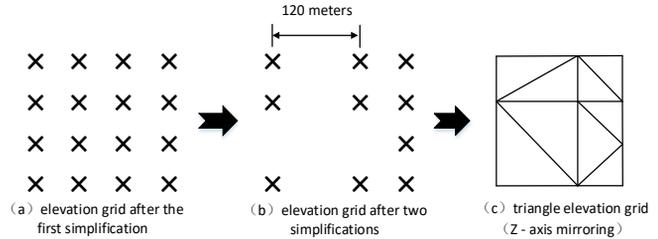
Fig. 4: Elevation grids after the second simplification.

Since the interval between every two elevation points through x-direction or y-direction is fixed, this paper introduced a new high weight K to measure height difference between neighboring elevation points, and use the given threshold to simplify the elevation grid secondly and correct errors. For instance, the number of triangle facets converted from the elevation grid in the figure 4(a), equals to 72, after second time simplifications, the number of triangle facets will be reduced dramatically,　equals to 9 as is shown in the figure 4(c).

In order to ensure that created triangle facets corresponding to the real terrain surface, it is necessary to identify the concave-convex characteristic of elevation grids while converting two time elevation grid to triangle facets. As for no planar elevation grid, link different diagonals will obtain antipodal terrain structures. This paper calculates dihedral angles of polygonal grid through curvature analysis (Hao J *et al.*, 2011), and regard them as the parameter of concave-convex characteristic to divide elevation grid element. As is shown in the figure 5, the data volume of elevation data is reduced effectively after two time simplifications, and the accuracy of model remain fits production requirement.
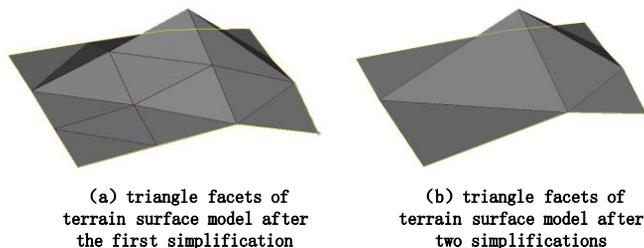
(a) triangle facets of terrain surface model after the first simplification

(b) triangle facets of terrain surface model after two simplifications

Fig. 5: the terrain surface model after the first simplification and the model after the second simplification.

Creation of 3D terrain models
STL file of terrain surface model can be obtained by storing these triangle facets according to the file format, the STL file of 3D terrain model cannot be completed until adding the base and walls. The altitude of base should be less than the minimum elevation value, which can be directly funded from record A of DEM file. The altitude of base of STL model equals to the minimum elevation value minus the height of walls h given by users, elevation points of base are correspond to points of terrain surface, that is to say, they have the same x and y value, different z value.

Using the minimum perimeter method to build triangle facets of base, the specific process is as follows: regard the corner point with the minimum x and y values as the starting point, select its neighboring points of x/y-direction to form the first triangle facet; then create a set of new triangle facets based on the two points and contrast their perimeters, choose the facet with the minimum perimeter to store; by that analogy until triangle facets cover the entire base as is shown in the figure 6(b). Since border points of base are correspond to border points of terrain surface, the triangle facets of walls can be created speedily through linking diagonals directly (as is shown in the figure 6(c)). What must be noticed is that the direction of all normal vectors of triangle facets of base and walls point to

the bottom of model, the red surface of triangle facets represents inner model, the grey surface of triangle facets represents exterior model. The final STL model is shown in the figure 6(d).
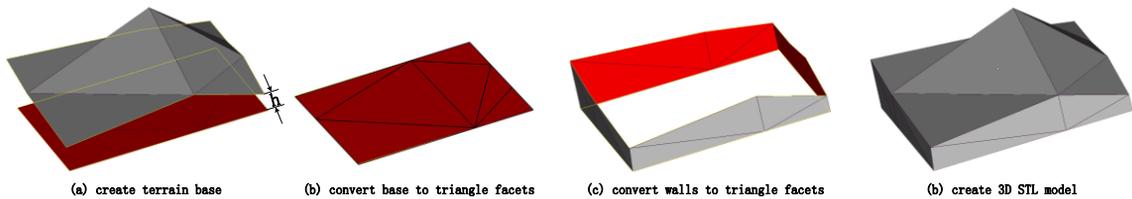

(a) create terrain base   (b) convert base to triangle facets   (c) convert walls to triangle facets   (b) create 3D STL model

Fig. 6: 3D terrain STL model.

Experimentation and Discussion

The experiment took samples of a coastal region of China, which covers an area of 47 square kilometers and contains a chain of mountains, a mountain brook, flattened seashores and widespread ocean (as is shown in the figure 7). Corresponding file was downloaded from the official website of USGS (http:/www.usgs.gov), chose 7.5-minute USGS DEM file format with 30-meter intervals and the number of elevation points is 51967.

Fig. 7: 3D terrain map of sample area (from Google Earth).

According to the optimization algorithm given by this paper, the real resolution is simply 60 meters, thus the number of elevation points will be reduced to 12991. What should be done next is building optimized STL surface model and adding triangle facets of base and walls. Since the accuracy of RP system in z-direction is high (resolution is 0.03mm, threshold θ equals to 3), the threshold value of elevation was assigned as 54 meters, those elevation points whose high weights are less than 54 meters were simplified. The 3D terrain STL model displayed in Magics RP is shown in the figure 8, three localized regions were selected to zoom into view. The region A represents a mountain peak with regular height changes, the density and size of its triangle facets are relatively steady; the region B represents a junction of flat ground and mountain valley, distributions of triangle facets have obvious differences; the region C represents ocean with relatively small height changes, triangle facets are big in size and little in number.
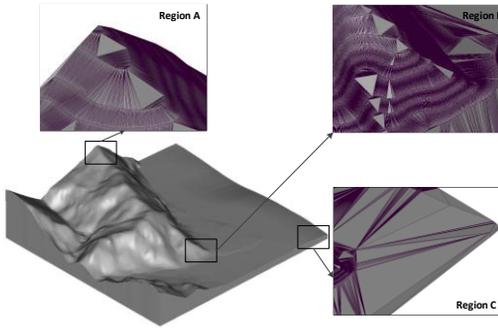
Fig. 8: STL model of sample area.

Fig. 9: Physical model of sample area.

The number of triangle facets converted directly from DEM file without any simplification is 675,142,272; after the first simplification, the number was reduced to 42,191,520; after the second simplification and adding base and walls, the final number became 964,372, which is just 1.4‰ of the origin number. STL file was stored in ASCII format, and the size is 189MB. The 3D STL file was downloaded into HRPS-IIA system to fabricate terrain physical model, which is shown in the figure 9.

Conclusions:
This paper proposed a method and a terrain data simplify algorithm that can convert USGS DEM data that expressing 3D terrain surface to 3D STL file, and developed corresponding program by VC++ software. Which can be used to transform five types of USGS DEM formats and create 3D models directly, omitting intermediate processes and saving corresponding data loss. A coastal region of China was chosen for verification, USGS DEM data of this region was transformed successfully to 3D STL model, proving the effectiveness of this convert program. The STL file was downloaded into Magics RP for visual displaying and repairing, the final STL file was downloaded into HRPS-IIA system to fabricate a terrain physical model. Virtual 3D terrain was built quickly and accurately, which can be used in the field of designing, planning and education.

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