An algorithm for rapid ground surface mesh generation used in complex terrain wind field simulation

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Abstract. In the study of wind engineering problems, it is of considerable importance to obtain accurate surface wind field characteristics. Surface features have significant impacts on the characteristics of small- and micro-scale wind field, so the fine reconstruction of terrain features is the basis of small- and micro-scale wind field simulations. However, since the GIS data obtained by satellite scanning cannot be directly used for CFD numerical simulation, the geographic information data is usually of considerable amount and contains a large number of waste points, thus difficult to be completed by manual modeling. To solve this problem, an automatic waste point repair algorithm and a grid aggregation method based on greedy algorithm are proposed, which can quickly and efficiently reconstruct the surface and generate the grid. Relying on the national numerical wind tunnel project and integrating the above core algorithms with the pre-processing and post-processing modules, a general and efficient surface mesh generation software ESM (Earth Surface Mesh) has been developed. Compared with the surface modeling and grid generation modules provided by other software, ESM has more comprehensive functions, and surface grid rapid generation technologies such as waste point data processing, grid adaptive refinement based on elevation change, high fidelity interpolation technology and partition splicing generation. It supports more interfaces and can generate structured and unstructured grids. The preliminary example shows that the surface grid generated by ESM meets the needs of wind engineering simulation.

1. Introduction

In recent years, with the increasing demand for micro site selection of wind farms, evaluation of urban regional wind environment and pollutant diffusion simulation, there are more and more studies on the characteristics of small- and micro-scale wind farms and atmospheric dispersion [1-3]. While small- and micro-scale wind field usually involves distances ranging from several kilometers to tens or hundreds of kilometers, the fluctuation of terrain would have a great impact on the characteristics of surface wind field [4]. Thus, fine reconstruction of terrain characteristics is the key to small- and micro-scale wind field simulations [5]. However, the Digital Elevation Model (DEM) data obtained by satellite scanning is not consistent with the current mainstream Computational Fluid Dynamics (CFD) software format [6], and in itself has some waste points, which cannot be directly applied in CFD...
simulation. Elevation data from different sources have significant influence on the accuracy of building reconstruction. Previous studies show that the building height data retrieved from the WorldView-2 optical (stereo) images are of poor quality [7]. Besides, the DEM data is usually of considerable amount, thus difficult to be processed via manual modeling. Some existing wind engineering software provides surface modeling and grid generation modules, and some literatures have studied how to convert GIS data into meshes [8-10]. Zheng et al. [11] proposed an algorithm for coordinate transformation and another algorithm that generates a complex real terrain grid model, which could import converted terrain data into a gridding platform for constructing the CFD terrain grid model. Shimbo et al. use a modified Heaviside B-Spline interpolation method to interpolate the DEM data with elevation discontinuity [12].

But these functions are relatively simple, usually does not support the output of general CFD grid data format, and does not have adaptive refinement and other functions [13, 14]. To solve this problem, the present study proposes automatic algorithms for rapid surface reconstruction and grid generation, waste point data processing, adaptive grid refinement based on elevation change, high fidelity interpolation and zonal grid generation techniques. Relying on the national numerical wind tunnel project, a general and efficient surface mesh generation software ESM (Earth Surface Mesh) has been developed. ESM has comprehensive functions, including DEM data and contour data processing, structured or unstructured surface grids generation, and supporting grid output with general CGNS and STL formats. ESM can also realize the functions of domain decomposition and mesh splicing, and operate the mesh generation of large-scale terrain.

Small- and micro-scale wind field simulation requires refined surface model and grid formulated by DEM data. The mainstream global DEM data includes Shuttle Radar Topography Mission (SRTM) and ASTER GDEM, which are mainly divided into 30m precision and 90m precision products. ESM software supports rapid generation of surface grid through SRTM GL1 and ASTER GDEM V2/V3 data.

However, due to the inconsistency with the current mainstream CFD software format, and the existence of waste points, DEM data cannot be directly used in CFD simulation. If the simulation area is large, the required amount of DEM data is correspondingly large. To solve this problem, this paper proposes automatic algorithms for rapid surface reconstruction and grid generation, waste point data processing, adaptive grid refinement based on elevation change, high fidelity interpolation and partition splicing techniques. The main processing flow of ESM software includes data preprocessing, DEM splicing, discrete point structuring, structured data triangulation and other steps to obtain the structured grid in CGNS format and the triangulated grid in STL format.

2. Waste point processing algorithm
Waste point treatment mainly includes two parts: filling value removal and abnormal value repair. The filling value and abnormal value are not normal elevation values, so they need to be repaired before generating surface grid.

2.1. Invalid filling value
In the process of generating DEM data from satellite radar images, some pixels cannot calculate effective data for various reasons, and a fixed invalid value is filled in uniformly. For invalid filling values, since each geographic information packet usually gives a large negative value by default, these invalid filling values can be found by traversing the whole region. Taking SRTM as an example, its invalid padding value is -32768. After finding these invalid filling points, the repaired elevation values are given by bilinear interpolation method using the surrounding adjacent point data. The left panel of Figure 1 shows the process of waste point processing, including reading DEM data, traversing pixels, updating waste points by bilinear interpolation algorithm, etc. The right panel of Figure 1 shows a DEM image with waste points.
Figure 1. SRTM filling value removes algorithmic processes and interface operations.

![Diagram of algorithmic processes](image)

Figure 2. A diagram of the dual linear interpolation algorithm.

\[
\begin{align*}
  f(x, y_1) &\approx \frac{x_2-x}{x_2-x_1} f(Q_{11}) + \frac{x-x_1}{x_2-x_1} f(Q_{21}) \\
  f(x, y_2) &\approx \frac{x_2-x}{x_2-x_1} f(Q_{12}) + \frac{x-x_1}{x_2-x_1} f(Q_{22})
\end{align*}
\]

Figure 2 shows the schematic diagram of bilinear interpolation algorithm, which performs the first linear interpolation along the x direction, get the R2, R1 pixel, and the second linear interpolation in the y direction with R2, R1 to get the value of P.

2.2. Elevation outliers

Elevation outlier means that the elevation value of a pixel is obviously abnormal from that of surrounding pixels. These values are usually not true values and need to be processed. The process of detecting outliers first and then repairing them through bilinear interpolation is adopted. The specific process is shown in Figure 3.

![Diagram of outlier repair process](image)
The key of the elevation outlier repair module is the outlier detection algorithm. In this paper, the background elevation image is calculated through the morphologically closed operation (Equation (3)) in the new top-hat algorithm. The difference image can be obtained by subtracting the background image from the original image, and the abnormal value can be determined according to the given threshold parameters, which can be processed quickly and automatically with the help of interpolation algorithm.

By designing a reasonable operator structure, the new top-hat algorithm takes into account the characteristics of outliers themselves and the shape characteristics of outliers, and better conforms to the characteristics of outlier aggregation in DEM images. In Figure 4, Bi and Bo are two flat structural elements, and the diameter of Bo structural element is larger than that of Bi structural element. \( \Delta B = Bo - Bi \) is the annular edge area between Bo and Bi, and its diameter is the same as that of Bo. Bb is a flat structural element with a diameter between Bi and Bo and the same shape as Bi and Bo.

\[
(f \cdot B_{oi})(x) = [(f \oplus \Delta B) \ominus B_b](x)
\]

\[
NWTH(x, y) = \max(f(x, y) - (f \cdot B_{oi})(x, y), 0)
\]

where Equation (3) means that the DEM image \( f \) is first processed via \( \Delta B \) operator to carry out morphological expansion operation, and then via \( B_b \) operator to obtain the closed operation result (background image) of the new top-hat transform. Equation (4) indicates that the abnormal value image is obtained by subtracting the background image from the original image, and the result is non-negative.

The non-zero pixels of the abnormal value image are not all abnormal values. It is determined pixel by pixel through the global threshold and the locally calculated concave convex coefficient. In case of abnormal deviation of elevation values of multiple adjacent pixels at local positions in the modeling area, the elevation difference between these abnormal values may not be large, but they are generally deviated from the surrounding area, forming a similar bulge terrain. In order to solve this problem, after calculating the concave convex coefficient, the given concave convex coefficient threshold and global threshold are used to comprehensively determine whether these points are abnormal points.

![Figure 4. Top-hat algorithm diagram.](image)

![Figure 5. Calculation of concave convex coefficient.](image)
The calculation formula of concave convex coefficient is:

\[ C_D = \frac{(h_{\text{max}} + h_{\text{max}}')/2}{\bar{h}} \]  

(5)

where, \( h_{\text{max}} \), \( h_{\text{max}}' \) and \( \bar{h} \) represent the maximum, minimum and average elevation of adjacent points respectively, which are shown in Figure 5 with different values of concave convex coefficient.

For the outlier data points found in the detection, the same bilinear interpolation method as the filling value repair can be used to repair them.

3. Grid generation algorithm and test cases

In wind engineering simulation, finite volume based CFD method is widely used. The solver of finite volume method needs to read structured or unstructured meshes. ESM software uses an efficient algorithm to generate quadrilateral structured mesh and triangular unstructured mesh. The algorithm can adjust the density of the generated mesh.

3.1. Discrete point structuration

Structured grid has the advantages of simple data structure, rapid generation and small storage capacity. At present, DEM data measured by satellite are usually structurally arranged, which can be easily converted into surface grid format readable for CFD software. ESM software first preprocesses DEM data, and then generates surface grid model in CGNS format according to the spatial relationship between discrete points. Because the scale of CFD simulation is often on the order of tens of kilometers, it does not need too fine grids, the software also provides an algorithm for grid coarsening.

3.2. Discrete point triangulation--fast generation of Delaunay triangular meshes by divide and conquer method

When displaying complex terrain, the triangulated grid can better deal with sharp elevation changes, such as mountain peaks, ridges, depressions and so on. When generating Delaunay triangulation, the commonly used algorithms are point by point method, divide and conquer method and so on. Although the patching algorithm between each region of divide and conquer method is relatively complex, due to the fact that the scale of grid points is on the order of hundreds of thousands in this paper, the selection of divide and conquer method will greatly shorten the grid generation time, since its parallel idea has obvious advantages in large-scale grid generation. The main steps of divide and conquer method are:

- Sort the point set V in ascending order with abscissa as the main coordinate and ordinate as the auxiliary coordinate, then recursively perform the following steps;
- The point set V is divided into two approximately equal subsets VL and VR;
- Generate triangulation in VL and VR;
- The generated triangulation is optimized by the Local Optimization Procedure proposed by Lawson to make it a D-triangulation;
- Find the bottom line and top line connecting the two convex shells in VL and VR;
- Merge the two triangulations in VL and VR from the bottom line to the top line.

3.3. Grid aggregation algorithm based on greedy strategy

The discrete points are needed when generating surface meshes, but the original DEM data is usually too much. ESM designs a multi-level aggregation framework based on the characteristics of DEM data, the main idea of which are described as follows:

- First, the DEM image is logically divided into multiple layers and encoded, as shown in Figure 6. The encoding is continuous and unique, and at the finest level one pixel has one code;
Figure 6. DEM image logical segmentation framework.

- Taking the coding (cCode) of the first pixel as the starting point, calculate whether the maximum elevation difference between the pixels (four adjacent pixels) contained in its upper level is greater than the aggregation threshold. If it is less than the aggregation threshold, calculate whether the maximum height difference between the pixels (adjacent 16 pixels) included in the higher level is greater than the aggregation threshold; If it is greater than the aggregation threshold, the pixels contained in the upper layer complete aggregation (it is considered that the internal elevation is uniform), and the starting pixel grid code (bCode) and ending pixel grid code (eCode) of the upper layer are calculated;

- Starting from the pixel represented by the encoded eCode + 1, repeat the previous step until the encoding of the last pixel is covered, and the aggregation is completed.

The aggregation effect is shown in Figure 7. In this figure, the red grids are aggregated by elevation difference aggregation threshold 50 m, and the green grids are aggregated by elevation difference aggregation threshold 200 m. The aggregation algorithm is only suitable for unstructured grid generation, and the aggregated discrete points are used as the basis for triangular grid generation.

Figure 7. Aggregation effect of the grid.
4. Test cases

The test cases for structural and unstructured grid generation are shown in this section, and the efficiency of the ESM software and a commercial software is compared.

4.1. Structural grid generation case

The structural grid generation capability is tested with an island terrain. Figure 8 shows the DEM data of the island terrain, which is about 42 km long and 31 km wide, and the DEM data accuracy is 30 m. As can be seen from Figure 8, the island has an obvious ridge, and there are considerable fluctuations and folds on the slopes of both sides. In order to ensure the accuracy of surface reconstruction, the ESM software uses the discrete point data with original DEM resolution, and takes into account the actual needs of CFD simulation to properly smooth some too sharp mountains. The structured grid of surface generated by ESM is demonstrated in Figure 9, which shows that the grid is of good quality and clearly reflects the fluctuation of terrain.

![Figure 8. DEM data of an island.](image)

![Figure 9. A structured grid generated by the ESM.](image)

4.2. Unstructured grid generation case

A terrain with small hills and plains in Weifang City is tested to verify unstructured grid generation function in ESM. The left panel of Figure 10 shows the triangulated grid of the terrain generated by ESM software, and the local magnification map of the grid is on the right. The grid recovers the detailed characteristics of hills and plains well. Due to the aggregation algorithm, the grid is fine in places with drastic elevation changes such as hills, and coarse in plain areas.

![Figure 10. Terrain triangulation mesh and local magnification.](image)
4.3. Efficiency test
Compared with the existing mainstream commercial software, the efficiency of ESM surface grid has obvious advantages. Commercial software usually first obtains contours based on DEM data, then generates triangulated meshes based on these contours. Taking SRTM GL1 single image as an example (50 m resolution covers 1°×1° geospatial space), Table 1 shows that ESM uses only 50s to generate a triangular mesh, while the commercial software uses over 5 minutes.

|                | ESM   | Commercial software |
|----------------|-------|---------------------|
| Running time   | 50 s  | 305 s               |

5. Conclusions
In order to facilitate the evaluation and simulation of wind field on complex terrain, a set of fast and general surface modeling method is proposed, and the corresponding mesh generation software ESM (Earth Surface Mesh) is developed. The main research results can be summarized as follows: First, a fast method for detecting abnormal points is proposed. In this method, the elevation peak is detected by the new top hat algorithm, and the abnormal point data is detected by the two parameter judgment criteria of elevation difference and concave convex coefficient. Second, a grid aggregation algorithm based on greedy strategy is proposed. The algorithm aggregates adjacent grids based on the variation range of elevation difference, which can greatly reduce the number of unstructured grids meanwhile maintain the original appearance of the terrain. Third, the divide and conquer method is used to quickly generate Delaunay triangular mesh, which has good grid generation speed and scale, and can generate high-quality surface grid to meet the needs of wind engineering simulation.

In the future research, we will carry out the following work: 1) the quality of surface grid generated by the software will be further improved to be directly used for wind field simulation; 2) realize large-scale parallel grid generation; 3) support the automatic generation of surface grid of contour data.

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