Comparative Analysis of Spatial Interpolation Methods: an Experimental Study

* Qulin Tan, Xiao Xu
Photogrammetric Engineering & Remote Sensing, School of Civil Engineering, Beijing Jiaotong University, Beijing, 100044, China
* Tel.: 086-010-51688207, fax: 086-010-51683764
* E-mail: qltanbjtu@163.com

Received: 16 December 2013   /Accepted: 28 January 2014   /Published: 28 February 2014

Abstract: As being an essential tool for estimating spatial continuous data, interpolation methods have been applied to various disciplines concerned with the Earth’s surface. In the paper, six spatial interpolation algorithms, including an internationally popular ANUDEM method and five other commonly used interpolation methods, were applied in three different landform regions, that is, hills, mountains and alpine area. Quality analysis and accuracy comparison were carried out using random point check, overlay comparison between derived contours with original ones, and 3D visualization analysis etc. Experimental results show that the accuracies of DEMs generated by ANUDEM are the highest. IDW method ranks the second. TIN, Kriging and natural neighbourhood methods have similar accuracy, and the spline-function method is the last. For a specific interpolation method, the greater the terrain undulates, the lower the accuracy of the generated DEM is.

Keywords: Spatial interpolation, Geographic information system, Digital elevation model, Topography, Accuracy.

1. Introduction

Spatial interpolation is the estimation of an unknown attribute values at unmeasured/unsampled points from measurements made at surrounding sites (known values of sampled points) [1-3]. As being an essential tool for estimating spatial continuous data, interpolation methods have been applied to various disciplines concerned with the Earth’s surface. One of the most common applications of interpolation techniques is in the construction of a digital elevation model (DEM), sometimes referred to as a digital terrain model (DTM), which uses range from scientific, commercial, industrial, engineering to military applications [3].

With the increasing applications of spatial interpolation methods, more than ten spatial interpolation models have been developed in different fields. Meanwhile there is a growing concern about their accuracies. And there has been extensive literature published that compared the performance of these interpolators using a given data [1, 2, 4-7]. Some studies indicate that among the many existing interpolation techniques, geostatistical ones perform better than the others [4]. In particular, Zimmerman et al. showed that kriging yielded better altitude estimations than inverse distance weighting (IDW) did, irrespective of the landform type and sampling pattern [8]. However, in other studies neighborhood approaches such as IDW or radial basis functions were as accurate as kriging or even better [7]. Although there have been many studies on the accuracy of interpolation techniques for the generation of digital elevation models (DEMs), there...
are still no consistent findings about the performances of the spatial interpolators. Therefore, it is difficult to select an appropriate interpolation method for a given input dataset.

Among the various studies on the comparison of interpolation techniques for generating digital terrain models, only a few examined the accuracy of interpolation techniques in relation to data sample size, sample spacing and landform types [2, 9].

Especially the effects of terrain morphologies that exist in natural landscapes and over a large range of scales, have seldom been investigated [9]. So there is still a need to evaluate the performance of these techniques in relation to different landform types. The main objective of this study is to evaluate the effects of different interpolation techniques on the accuracy of DEM generation in relation to landform types.

In this paper, hills, mountains and alpine areas are selected as landform adaptability test regions. In addition to the comparison and analysis of five commonly used spatial interpolation methods (e.g. Inverse Distance Weighted (IDW), Kriging, Natural Neighbor (NN), Thiessen polygons (TIN) and Spline), this paper also focuses on the comparative analysis of ANUDEM interpolation application.

The following section summarizes the theoretical rationale behind each of the interpolation methods compared. And the accuracy analysis methods are introduced in section three. Section four is the experimental analysis. Conclusions and discussions are contained in the final section.

2. Spatial Interpolation Methods

Spatial interpolation methods can be classified into global interpolators and local interpolators [3]. Global interpolation method uses all the sampling point data in the study area to make feature fitting for the region; local interpolation method simply uses the neighboring data points to estimate the unknown point value. Global interpolation method is usually not used directly for spatial interpolation, but for detection of the maximum deviation part which is different from the general trend. For the global interpolation method takes short scale and local changes as random and non-structural noise, the information of this local area is lost. In the experiment, the six commonly used spatial interpolation methods belong to local interpolators.

Local interpolation method can just make up for the deficiency of the global interpolation method, which can be used for local abnormal values, and not affected from other points on the interpolation surface. Usually, points that are physically close to each other should be more similar than points that are far away from each other. For example, the elevation of a known point should be rather close to the elevation of another point a few meters away, but could be very different to the elevation of a point many kilometers away. We can therefore say that the degree of change between point values is proportional to the distance between them.

Local interpolation methods use only a limited number of input data points (either within a certain distance from the point being interpolated or a fixed number of points) to apply the interpolation function. The input data used to calculate each function therefore forms a “window”, which moves across the dataset, applying different functions throughout the data. Compared with global methods, local methods usually yield less smooth surfaces. Local methods are not as sensitive to outliers, because their effects will not influence the entire interpolated surface, but only local regions/parts of the interpolated surface. A difficulty using local interpolation methods is to adequately determine the “search window” (number of known data points to be used or search radius).

a) Thiessen polygons (TIN).

The simplest local interpolator is known as Thiessen polygons (TIN) [3]. Unknown points are simply given the value of the closest known points. Thiessen polygons divide a region up in a way that is totally determined by the configuration of the data points, with one observation per cell. Thiessen polygons are divided based on Delaunay triangulation, where the borders of the Thiessen polygons split exactly in half the borders of the Delaunay triangles. The algorithm used to decide which points should form the Delaunay triangle makes a circle with all combinations of known points, and if other known points fall within the circle, then those points are not linked together to form the triangle.

b) Natural Neighbor.

The Natural Neighbor interpolation algorithm finds the closest subset of input samples to a query point and applies weights to them based on proportionate areas to interpolate a value [10]. It is also known as Sibson or “area-stealing” interpolation. Its basic properties are that it’s local, using only a subset of samples that surround a query point, and interpolated heights are guaranteed to be within the range of the samples used. It does not infer trends and will not produce peaks, pits, ridges, or valleys that are not already represented by the input samples. The surface passes through the input samples and is smooth everywhere except at locations of the input samples.

c) Spline method.

Another commonly used local interpolation method is the bi-cubic splines (or often simply known as splines) [3]. The spline interpolation estimates the elevation of a specific point using a mathematical function that minimizes the overall surface curvature, resulting in a smooth surface that passes exactly through the input points. Conceptually, the sample points are extruded to the height of their magnitude; spline bends a sheet of rubber that passes through the input points while minimizing the total curvature of the surface. It fits a mathematical function to a specified number of nearest input points while passing through the sample points.
There are two spline methods: regularized and tension. The regularized method creates a smooth, gradually changing surface with values that may lie outside the sample data range. The tension method controls the stiffness of the surface according to the character of the modeled phenomenon. It creates a less smooth surface with values more closely constrained by the sample data range. The main parameters of the spline interpolation are the number of sampled points used for interpolation, and the weight. For the regularized spline, the higher the weight, the smoother the output surface. For the tension spline, the higher the weight, the coarser the output surface.

d) Inverse Distance Weighted (IDW).

The Inverse Distance Weighted (IDW) interpolation is an exact local deterministic interpolation technique [11]. IDW assumes that the value at an unsampled location is a distance-weighted average of values at sampled points within a defined neighborhood surrounding the unsampled point [3]. In this sense, IDW considers that points closer to the prediction location will have more influence on the predicted value than points located farther away. IDW uses:

\[
Z_0 = \frac{\sum_{i=1}^{N} Z_i \frac{1}{d_i^s}}{\sum_{i=1}^{N} \frac{1}{d_i^s}},
\]

where \(Z_0\) is the predicted value at the unsampled location, \(Z_i\) is the observed value, \(d_i\) is the distance between the prediction location and the measured location, and \(s\) is the number of measured sample points within the neighborhood. \(K\) is the power parameter that defines the rate of reduction of the weights as distance increases.

IDW is forced to be an exact interpolator to avoid the division by zero that occurs when \(d_0 = 0\) at the sampled points. In addition, the maximum and minimum values of the interpolated surface only occur at data points. IDW is an extremely fast interpolation method, though it is very sensitive to the presence of outliers and data clustering. In addition, this method does not provide an implicit evaluation of the quality of the predictions.

e) Kriging.

The Kriging interpolation is similar to IDW in that it weights the surrounding measured values to derive a prediction for an unmeasured location [12]. However, in kriging, the weights are based not only on the distance between the measured points and the prediction location but also on the overall spatial arrangement of the measured points. Kriging assumes that the distance or direction between sample points reflects a spatial correlation that can be used to explain the variation in the surface [3]. To use the spatial arrangement in the weights, the spatial autocorrelation must be quantified through empirical semivariograms.

The semivariogram can have one of the following models: circular, spherical, exponential, Gaussian, and linear. There are two kriging methods: ordinary and universal. The ordinary kriging assumes that the constant mean is unknown, while the universal kriging assumes that there is an overriding trend in the data and this trend is modeled by a polynomial.

Kriging fits a mathematical function to a specified number of points, or all points within a specified radius, to determine the output value for each location. It is a multistep process including: exploratory statistical analysis of the data, variogram modeling, creating the surface, and (optionally) exploring a variance surface. Kriging is most appropriate when there is a spatially correlated distance or directional bias in the data.

Kriging uses

\[
\hat{Z}(s_0) = \sum_{i=1}^{N} \lambda_i Z(s_i),
\]

where \(Z(S_0)\) is the i-th position of the measured value; \(\lambda_i\) is the i-th position measurement values of the unknown weight; \(S_0\) is the predicted position; \(N\) is the number of measurements.

f) ANUDEM.

The ANUDEM algorithm is a locally adaptive interpolation approach proposed by Hutchinson et al. at the Australian National University [13]. The method uses an interpolation technique specifically designed to create a surface that more closely represents a natural drainage surface and preserves both ridgelines as well as stream networks.

The ANUDEM interpolation method is specifically designed for the creation of hydrologically correct terrain surfaces. The procedure couples a drainage enforcement algorithm that removes spurious sinks and pits, with an iterative finite difference interpolation technique based on the minimization of a terrain specific, rotation invariant roughness penalty, defined in terms of the first and second order partial derivatives of the interpolating function. The algorithm acts in an iterative fashion, which calculates grids at increasingly finer resolutions from a coarse initial grid until the user-defined resolution is achieved. The values in the initial coarse grid are the average of all data points, and for subsequent iterations, they are linearly interpolated from the preceding grid. The data points values are assigned to the nearest cell grid, and for those grid without data points inside (i.e. cells between contour lines), the values are calculated by Gauss-Seidel iteration with overrelaxation subject to the roughness penalty mentioned before.

The algorithm is optimized to have the computational efficiency of local interpolation methods, such as inverse distance weighted (IDW) interpolation, without losing the surface continuity of global interpolation methods, such as Kriging and Spline. It is essentially a discredited thin plate spline technique for which the roughness penalty has been
modified to allow the fitted DEM to follow abrupt changes in terrain, such as streams, ridges and cliffs.

3. Accuracy Assessment Method

The evaluation methods of elevation interpolation accuracy in the experiment include arbitrary point method, contour playback method, and terrain attributes visualization analysis [7].

a) Arbitrary point method.

In this study, estimated height (Z) from the selected interpolation technique was compared at each point to the check point using the mean absolute error (MAE), the root mean square error (RMSE) and overall fitness (R²):

\[
MAE = \frac{1}{n} \sum_{k=1}^{n} (Z_k - z_k), \quad (3)
\]

\[
RMSE = \sqrt{\frac{1}{n} \sum_{k=1}^{n} (Z_k - z_k)^2}, \quad (4)
\]

where \(Z_k\) is the DEM interpolated elevation value of check point \(k\), \(z_k\) is the actual elevation value of the check point \(k\), \(n\) is the number of check points. The overall fitness is calculated as:

\[
R^2 = 1 - \frac{\sum_{k=1}^{n} (Z_k - z_k)^2}{\sum_{k=1}^{n} (Z_k - \bar{z})^2}, \quad (5)
\]

where \(\bar{z}\) is the average of the actual elevation values.

b) Contour playback method.

In practice application, in order to evaluate the overall accuracy and the similarity between DEM and the actual terrain, we generally use contour playback method to check the contour error. Contour playback method includes the original contour playback (if take the contour elevation point as a reference point) and playback intermediate contour lines. This article selects original contour playback, and then compares it with the original contours.

c) 3D Visual Analysis.

With the development of computer vision technology, especially 3D graphics visualization and virtual reality technology development, people are eager to transfer the traditional 2D to 3D display and analysis. 3D terrain visualization has become one of the hot directions in the field of information technology in recent years. Three-dimensional visualization helps users get an intuitive understanding of the relationship among spatial data. 3D visualization of DEM is able to help us with analysis of the data. 3D stacking method of DEM can easily identify the anomalies in the DEM elevation data generated by different interpolation methods.

4. Experimental Analysis

The Longjing county, Yanbian Korean Autonomous region in northern China has complex and varied terrains. Three kinds of landforms of the region, including hills, mountains and alpine areas, were selected for the evaluation of the interpolation techniques under different topography conditions. The existing 1:50000 topographic maps were scanned and digitized to get contour line data spacing of 10 m [5]. The grid size of the DEM generated by interpolation is set to 25 m. The six most commonly used interpolation methods, i.e. Thiessen polygons (TIN algorithm), Inverse Distance Weighted (IDW) interpolation, Spline, Kriging, ANUDEM, and Natural Neighbor, are all available in ArcGIS software developed by ESRI [14].

4.1. Hilly Area

Hills are low, top round, gentle slopes, which mostly are the transition zones from mountains to plains. Generally, height difference is less than 300 m. The lowest elevation of the selected hilly area is 450 m and the highest elevation is 681 m, and the height difference is 231 m. Because the interpolated DEMs are created from topographic maps, the accuracy of the DEMs will not be higher than the original topographic maps. We randomly choose 32 elevation checkpoints in the topographic map as a reference dataset, uniformly distributed throughout the study area, shown in Fig. 1.

Fig. 1. Vectorized contour map and elevation check points of the hilly area.

The errors calculated by arbitrary point method are presented in Table 1. As can be seen from Table 1, RMSE values of various methods are less than 7 m. On the whole, ANUDEM interpolation algorithm is adaptable to hilly topography with the highest accuracy, and IDW method ranks the second. TIN, Kriging and Natural Neighbor have little difference in the indicators, and their precisions are similar. Spline method ranks the last to use in hilly topography.
Table 1. Errors of six different interpolation methods in hilly area.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>MAE(m)</th>
<th>RMSE(m)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANUDEM</td>
<td>2.704</td>
<td>5.864</td>
<td>0.98781</td>
</tr>
<tr>
<td>TIN</td>
<td>5.512</td>
<td>6.438</td>
<td>0.98333</td>
</tr>
<tr>
<td>IDW</td>
<td>4.894</td>
<td>6.153</td>
<td>0.98499</td>
</tr>
<tr>
<td>Kriging</td>
<td>5.517</td>
<td>6.436</td>
<td>0.98340</td>
</tr>
<tr>
<td>Natural Neighbor</td>
<td>5.495</td>
<td>6.435</td>
<td>0.98336</td>
</tr>
<tr>
<td>Spline method</td>
<td>5.857</td>
<td>6.939</td>
<td>0.98053</td>
</tr>
</tbody>
</table>

Fig. 2. Error curves of six different interpolation algorithms in hilly area.

The ME curves of various interpolation DEMs are shown in Fig. 2. It can be seen that the error value of ANUDEM algorithm is smallest than the other interpolation methods, spline function method fluctuate widely in the error value, and TIN, Kriging and Natural Neighbor methods produce similar error variation.

Fig. 3 shows a comparison of the extracted contours from DEMs generated by the six kinds of interpolation algorithms and the original contours.

Fig. 3. Contour playback comparison in hilly area (original contours: red, extracted contours: blue).

4.2. Mountain Area

The surface of mountain topography is complex and diverse. The surface undulation of the selected mountain landscape is 390 m. 26 elevation checkpoints were randomly chosen in the topographic map, uniformly distributed throughout the study area (Fig. 5). They act as elevation...
reference data to verify the accuracy of the generated DEMs.

Fig. 5. Vectorized contour map and elevation check points in mountain area.

The errors calculated by arbitrary point method are shown in Table 2. As can be seen from Table 2, RMSE values of various methods are less than 10m. Similar with the hilly topography, ANUDEM interpolation algorithm is adaptable to mountain topography with the highest accuracy. IDW method ranks the second, and TIN, Kriging and Natural Neighbor methods have little difference in the indicators and their accuracies are similar. Spline method ranks the last for interpolation in mountain topography.

Table 2. Errors of six different interpolation methods in mountain area.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>MAE(m)</th>
<th>RMSE(m)</th>
<th>$R^2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANUDEM</td>
<td>5.918</td>
<td>7.083</td>
<td>0.99977</td>
</tr>
<tr>
<td>TIN</td>
<td>7.733</td>
<td>9.250</td>
<td>0.99962</td>
</tr>
<tr>
<td>IDW</td>
<td>7.231</td>
<td>8.862</td>
<td>0.99965</td>
</tr>
<tr>
<td>Kriging</td>
<td>7.479</td>
<td>9.111</td>
<td>0.99963</td>
</tr>
<tr>
<td>Natural Neighbor</td>
<td>7.643</td>
<td>9.150</td>
<td>0.99963</td>
</tr>
<tr>
<td>Spline method</td>
<td>8.118</td>
<td>9.985</td>
<td>0.99956</td>
</tr>
</tbody>
</table>

The ME curves of various interpolation DEMs are shown in Fig. 6. It can be seen that the error value of ANUDEM algorithm is the smallest than the other interpolation methods, and the errors of other five algorithms are similar.

Fig. 6. Error curves of six different interpolation algorithms in mountain area.

Fig. 7 shows a comparison of the extracted contours from DEMs generated by the six kinds of interpolation algorithms and the original contours. Overall, the goodness of DEMs fit in mountain area is lower than in hilly area. Relatively, the extracted contours from TIN, Kriging and Natural Neighbor are better to fit with the original contours, but jaggies phenomenon is serious. The extracted contours from ANUDEM are smooth but poor fit in the valley. The extracted contours from IDW and Spline are poor to fit with the original contours, with quite serious serration phenomenon.

Fig. 7. Contour playback comparison in mountain area (original contours: red, extracted contours: blue).

Fig. 8 shows the comparison of three-dimensional visualization of the generated DEMs of different interpolation algorithms with reference DEM. In the figure, reference DEM is gray and interpolation DEMs are red and blue. As can be seen by the stacking, the DEM generated by ANUDEM is the best to fit the reference DEM, followed by the IDW, Kriging and spline algorithms. TIN and Natural Neighbor methods rank the last.

4.3. High Mountain Landscape

The height difference undulation is more than 600 m in high mountain region. This paper selects a typical high mountain area with 758 m altitude difference undulation. 26 elevation checkpoints were randomly chosen in the topographic map (Fig. 9), which were uniformly distributed throughout the study area as a reference data to verify the accuracy of the DEMs.
The errors calculated by arbitrary point method are shown in Table 3. As can be seen from Table 3, RMSE values of various methods are less than 13m. Similar with the hilly topography, ANUDEM interpolation algorithm is adaptable to high mountain topography with the highest accuracy. DEMs generated by TIN, IDW, Kriging and Natural Neighbor methods have little difference in the indicators and the precision of IDW is slightly better than the other three algorithms. Spline method ranks the last for interpolation in high mountain topography.

Fig. 8. The DEM stack analysis in mountain area.

Fig. 9. Vectorized contour map and elevation check points in high mountain area.

The ME curves of various interpolation DEMs are shown in Fig. 10. It can be seen that the error value of ANUDEM algorithm is the smallest than the other interpolation methods, and the errors of TIN, IDW, Kriging and Natural Neighbor methods are similar. Spline function method fluctuates widely in the error value.

Fig. 11 shows a comparison of the extracted contours from DEMs generated by the six kinds of interpolation algorithms and the original contours. The result shows that the extracted contours from AUNDEM is the best to fit with the original contours.

Table 3. Errors of six different interpolation methods in high alpine area.

<table>
<thead>
<tr>
<th>Algorithms</th>
<th>MAE (m)</th>
<th>RMSE</th>
<th>R²</th>
</tr>
</thead>
<tbody>
<tr>
<td>ANUDEM</td>
<td>6.661</td>
<td>8.799</td>
<td>0.99983</td>
</tr>
<tr>
<td>TIN</td>
<td>9.021</td>
<td>10.732</td>
<td>0.99969</td>
</tr>
<tr>
<td>IDW</td>
<td>8.612</td>
<td>10.571</td>
<td>0.99970</td>
</tr>
<tr>
<td>Kriging</td>
<td>8.997</td>
<td>10.764</td>
<td>0.99969</td>
</tr>
<tr>
<td>Natural Neighbor</td>
<td>8.999</td>
<td>10.700</td>
<td>0.99970</td>
</tr>
<tr>
<td>Spline method</td>
<td>9.158</td>
<td>12.315</td>
<td>0.99959</td>
</tr>
</tbody>
</table>

Fig. 10. Error curves of six different interpolation algorithms in high mountain area.

Fig. 11. Contour playback comparison in alpine area (original contours: red, extracted contours: blue).

Fig. 12 shows the comparison of three-dimensional visualization of the generated DEMs of different interpolation algorithms with reference DEM. In the figure, reference DEM is gray and
interpolation DEMs are red and blue. As can be seen by the stacking, the DEMs generated by ANUDEM and IDW are better to fit the reference DEM for high mountain landscape. TIN, Kriging, Natural Neighbor and Spline methods have similar fitting degree with the reference DEM.

Fig. 12. The DEM stack analysis in high mountain area.

5. Conclusions and Discussions

Interpolation technique plays an important role in achieving a high accuracy of DEM. The influence of interpolation technique on the DEM accuracy depends on landform types in addition to the distribution of sample points and other factors. This research has examined six interpolation techniques (ANUDEM, TIN, NN, IDW, spline, and kriging) in three different landform regions. Adaptability of the six commonly used spatial interpolation algorithms to terrain variation are examined and discussed in three different landform types. The qualitative and quantitative analysis comparisons based on arbitrary point method, contour playback method and visual analysis, show that the ANUDEM algorithm is superior to the other techniques with the smallest RMSE error and least interpolation artifacts. IDW is the second superior method. Spline method has the lowest accuracy. Other interpolation methods have similar moderate accuracy. For a specific interpolation method, the greater the terrain undulates, the lower the accuracy of the generated DEM is.

In recent years, with the rapid development of geographic information system, DEM has played a huge role in surveying, geology, resource and environment management, hydrologic analysis, civil engineering and other relating fields. This study may provide a valuable reference for spatial-interpolated DEM generation in different geomorphic regions.

Acknowledgements

The work was supported by the National Natural Science Foundation of China (Grant No. 40801121, 51078020) and the Fundamental Research Funds for the Central Universities (2012JBM078).

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