PIECEWISE SPATIAL CONFLATION AND MERGING OF DTMs: CONTINUOUS TRANSITION OF OVERLAPPING ZONES

Yaron Katzil
Yerach Doytsher
Department of Transportation and Geo-Information Engineering
Faculty of Civil and Environmental Engineering
Technion - Israel Institute of Technology
Haifa, Israel, 32000
katzil@tx.technion.ac.il
doytsher@technion.ac.il

ABSTRACT

DTMs describing the terrain relief constitute a central component of mapping and GIS in general and photogrammetric mapping in particular. DTMs are used in various applications - all requiring the DTM to be free of gaps and discontinuities. In practice however, the same area may be covered by several overlapping terrain databases collected from diverse sources, differing in their densities or accuracy. The goal in these cases is to merge all databases in order to achieve a complete and continuous representation of the terrain, with the continuity expressed both in terms of continuous height representation and continuous topological representation (morphological structures). Algorithms currently used to merge overlapping terrain databases offer a partial solution only regarding the completeness and continuity requirements, as they address only the issue of height representation of the terrain, but not its characteristics. A new spatial conflation algorithm is proposed for merging two adjacent DTMs. While merging the two separate overlapping terrain datasets (DTMs), the algorithm is aimed at achieving a continuous topological representation and "correct" morphological structures of the terrain. Based on terrain’s characteristic analysis and homologous 3D point pairs within the two adjacent DTMs, a piece-wise spatial 3D transformation for merging the overlapping region of the adjacent DTMs is defined and applied. In contrast with the current relatively inaccurate methods, the proposed algorithm facilitates an accurate 3D conflation and merging process of different DTMs into a unified DTM, taking into account both the completeness and the continuity requirements.

INTRODUCTION

GIS and computerized mapping systems developed in recent decades led to the establishment of geo-spatial databases of the terrain – altimetry and planimetry – for various mapping and planning purposes. Although most planimetric data are discrete in nature, terrain relief is a three-dimensional continuous entity describing the terrain. Since terrain reality is continuous, the digital description of the relief is expressed by discrete data (discrete points and/or typical break-lines) known as DTM (digital terrain model) or DEM (digital elevation model).

DTMs describing the terrain relief constitute a central component of mapping and GIS in general and photogrammetric mapping in particular. DTMs are used in various applications, all requiring that no gaps or discontinuities are included in the DTM. In practice, however, the limitations of photogrammetric and other measurement methods for collecting the relief information may cause discontinuities and gaps in the database.

A related problem is the data fusion or conflation of multiple layers of terrain data. The same area may be covered by several adjacent partially overlapping terrain databases collected from different sources, differing in their densities or accuracy. The goal in these cases is to merge all databases in order to achieve a complete, contiguous and continuous representation of the terrain, with the continuity expressed both in terms of continuous height representation and continuous topological representation (morphological structures). Conflation in general and map conflation in particular is discussed by Gillman (1985), Lupien and Moreland (1987), Saalfeld and Fritsch (1988), and in White and Griffin (1985). The problem of conflating DTM datasets however, is rarely addressed.

Algorithms currently used to merge overlapping terrain databases allow a partial solution only to the completeness
and continuity requirements, as they address only the issue of height representation of the terrain, and not its characteristics – Laurini (1998). In practice, two types of algorithms are used, one being an expansion of the other:

- **“Cut and paste”**
  The less accurate (usually lower density) database is replaced with the more accurate (usually higher density) database in the overlapping zones.

- **“Height smoothing”**
  Heights of the merged database in the edge zones between the two databases are calculated using a weighted average of heights from both databases, with weighting defined as a function of the different database accuracy levels.

These two methods are usually used to merge fully overlapping DTM databases. The “cut and paste” method defines a process that preserves the height differences (or elevation and planimetric datum differences) between the databases. Thus, the result is a merged database of the area covered by the two databases that is usually neither continuous nor complete. While the “height smoothing” method is an improved method from the height continuity standpoint, it still suffers from topological discontinuities. Datum differences in both planimetry and altimetry are also a cause of topological discontinuities that produce height differences. In the “height smoothing” case, a point in the merged database can, for example, be a mathematical average of a point along a ridge in the first database and a point along a valley in the second database. Thus, the nature of the terrain is not preserved. From the topological standpoint, applications using the merged database may even create a product of lower accuracy than when using one of the original databases.

In order to avoid these complications when merging terrain databases, an alternative approach and a new algorithm is proposed. This algorithm deals with the overlapping region of the two databases assuming the existence of a set of homologous point pairs between the two DTMs. The set of homologous point pairs may be extracted by one of the methods used to register two DTMs, which are not part of the current research. Methods registering two adjacent DTM datasets and extracting the set of homologous point pairs are described in Afek and Brand (1998), Besl and McKay (1992), Brookshire et al. (1990), Feldmar and Ayache (1994), Walter and Fritsch (1999), Zhang (1994) and Lowe (2004). In this work, the set of homologous point pairs is automatically extracted using the Scale Invariant Feature Transform (SIFT) algorithm described in Lowe (2004), which is applied to the set of shaded relief images of the source adjacent DTMs. The shaded relief images calculated using the algorithm described in Katzil and Doytsher (2003). SIFT (Lowe, 2004) is a methodology for finding corresponding points in a set of images. The method designed to be invariant to scale, rotation, and illumination.

**PROPOSED PIECEWISE FUSION ALGORITHM**

**General Description**

In order to merge the overlapping region of adjacent DTM databases in such a manner that preserves height continuity and the nature of terrain, there is a need to handle both the heights of the gridded DTM as well as the morphological structures of the terrain. The proposed fusion algorithm consists of the following steps:

- Global geometric transformation of one of the adjacent DTMs (the one which is less accurate) by a three-dimensional affine transformation calculated using a given set of homologous point pairs.
- Triangulation of the overlapping region based on the given set of homologous point pairs.
- Local geometric correction by morphing each of the adjacent DTMs to the merged DTM coordinate system.

**Global Geometric Transformation**

Using a given set of pairs of homologous points \( \{L_i, R_j\} \), a three-dimensional affine transformation, described in Equation (1), is calculated and applied to the less accurate of the two adjacent DTMs, as well as to its corresponding points in the set of homologous point pairs. The source grid coordinate system of transformation is the less accurate DTM and its target grid is the more accurate DTM.
\[ X' = R^T mM(X - C) + C \]  

(1)

Where:
- \( X^T = (x \ y \ z) \) - A point in the source grid coordinate system.
- \( (X')^T = (x' \ y' \ z') \) - A point in the target grid coordinate system.
- \( R^T = (x_0 \ y_0 \ z_0) \) - Coordinate system shift.
- \( C^T = (x_c \ y_c \ z_c) \) - Center of rotation.
- \[
    m = \begin{pmatrix}
        m_x & 0 & 0 \\
        0 & m_y & 0 \\
        0 & 0 & m_z 
    \end{pmatrix}
\] - Scale matrix.
- \[
    M = \begin{pmatrix}
        m_{11} & m_{12} & m_{13} \\
        m_{21} & m_{22} & m_{23} \\
        m_{31} & m_{32} & m_{33} 
    \end{pmatrix}
\] - Rotation matrix.

**Homologous Point Pairs Triangulation**

A triangulation (triangular network) is constructed in the overlap region of both DTMs based on the given set of homologous point pairs. The triangulation is built by applying Constrained-Delaunay-Triangulation (CDT) on one part of the set of the homologous point pairs. An example of the triangulation is presented in Figure 1 applied to the test data used in the current work.

![Figure 1: Homologous point pairs triangulation.](image)

**Target Triangulation Construction Of The Overlapping Region**

Based on the homologous point-pairs triangulation in the source DTMs, a triangulation is constructed in the overlap region to be used as the target coordinate system. Each target triangle is a linear combination of a homologous triangles pair. The linear combination takes into account both the accuracy of each source DTM and the distance from each sides of the overlap region.

**Linear Combination Of Homologous Triangulations**

Using both the accuracy of each source DTM and the distances from each sides of the overlap region, a target
triangulation is constructed by applying a linear combination schema mechanism to each of the homologous triangles (each triangle corner node is a point pair).

\begin{align*}
x &= \frac{x_L \cdot \overrightarrow{P_L} + x_R \cdot \overrightarrow{P_R}}{\overrightarrow{P_L} + \overrightarrow{P_R}} \\
y &= \frac{y_L \cdot \overrightarrow{P_L} + y_R \cdot \overrightarrow{P_R}}{\overrightarrow{P_L} + \overrightarrow{P_R}}
\end{align*}

(2) \quad (3)

Where:
- \( \{ \overrightarrow{P_L}, \overrightarrow{P_R} \} \) - Normalized weights to be used in the linear combination.

**Fusion Of The Overlap Region**

The fusion algorithm is using all three triangulations in order to create the target merged DTM. The source location of each of the DTM grid points within each of the triangles of the target coordinate system is calculated for both source homologous triangles using isoparametric triangle coordinate system. Then, the height of these source points is being measured from the source DTMs and the target height is calculated using the linear combination with weights calculated for the source points.

**Triangular Coordinates.** The geometry of a triangle is specified by the location of its three corner nodes on the \( \{x, y\} \) plane. The nodes are labeled 1, 2, 3 while traversing the sides in counterclockwise fashion. Location of triangle corner nodes are defined by their Cartesian coordinates: \( \{x_i, y_i\} \) for \( i = 1, 2, 3 \). The area \( A \) of the triangle, given by equation (4), is a signed quantity; positive if the corners are numbered in cyclic counterclockwise order.

\[
2A = \begin{vmatrix}
x_1 & x_2 & x_3 \\
y_1 & y_2 & y_3 \\
1 & 1 & 1
\end{vmatrix} = (x_2y_3 - x_3y_2) + (x_3y_1 - x_1y_3) + (x_1y_2 - x_2y_1)
\]

(4)

Points of the triangle may also be located in terms of a parametric coordinate system - triangular coordinates: \( \{t_1, t_2, t_3\} \). The line \( t_i = \text{const} \) represents a set of straight lines parallel to the side opposite to the \( i^{th} \) corner, as presented in Figure 2. The equations of sides 2–3, 3–1 and 1–2 are \( t_1 = 0 \), \( t_2 = 0 \) and \( t_3 = 0 \), respectively. The three corners have coordinates \( (1, 0, 0) \), \( (0, 1, 0) \) and \( (0, 0, 1) \). The three midpoints of the sides have coordinates \( (1/2, 1/2, 0) \), \( (0, 1/2, 1/2) \) and \( (1/2, 0, 1/2) \), the centroid has coordinates \( (1/3, 1/3, 1/3) \). The coordinates are not independent because their sum is 1: \( t_1 + t_2 + t_3 = 1 \). The conversion from \( \{x, y\} \) to \( \{t_1, t_2, t_3\} \) and vise versa is shown in equations (5) and (6).

\[
\begin{align*}
\begin{bmatrix}
t_1 \\
t_2 \\
t_3
\end{bmatrix} &= \frac{1}{2A}
\begin{bmatrix}
(x_2y_3 - x_3y_2) & (y_2 - y_3) & (x_3 - x_2) \\
(x_3y_1 - x_1y_3) & (y_3 - y_1) & (x_1 - x_3) \\
(x_1y_2 - x_2y_1) & (y_1 - y_2) & (x_2 - x_1)
\end{bmatrix}
\begin{bmatrix}
x \\
y
\end{bmatrix}
\end{align*}
\]

(5) \quad (6)

**Linear Interpolation using Triangular Coordinates.** Consider a function \( f(x, y) \) that varies linearly over the triangle domain. In terms of Cartesian coordinates it may be expressed as \( f(x, y) = a_0 + a_1x + a_2y \), where \( a_0, a_1 \)
\[ f(t_1, t_2, t_3) = f_1 t_1 + f_2 t_2 + f_3 t_3 = \begin{bmatrix} f_1 \\ f_2 \\ f_3 \end{bmatrix} \cdot \begin{bmatrix} t_1 \\ t_2 \\ t_3 \end{bmatrix} \]

(7)

**Calculating target height.** Target height is calculated for each of the target grid points using the homologous triangles containing that grid point. Using the plane coordinates \{x, y\} of each grid point, the triangular coordinates \{t_1, t_2, t_3\} are calculated for that point from the destination triangle. Then, these triangular coordinates \{t_1, t_2, t_3\} - are used to calculate the height of the source points in each of the source triangles - \(h_L(x_L, y_L)\) and \(h_R(x_R, y_R)\) applying the triangular interpolant of each of the source triangles. Given these source heights \(h_L(x_L, y_L)\) and \(h_R(x_R, y_R)\), the target height is calculated using a weighted average with weights calculated as described in equations (2)-(3). Following is the chain of calculations needed in order to provide the target height:

\[
\begin{align*}
\{x, y\} &= \{t_1, t_2, t_3\} \text{ using equation (7)} \\
h_L &= h_L(x_L, y_L) = f_L(t_1, t_2, t_3) \\
h_R &= h_R(x_R, y_R) = f_R(t_1, t_2, t_3) \\
h &= \frac{h_L \cdot P_L + h_R \cdot P_R}{P_L + P_R}
\end{align*}
\]

(8)-(11)

**TESTS AND RESULTS**

Two DTM datasets of mountainous terrain with 10 and 25 meters density were selected for the test area. The two adjacent DTMs derived using different type of sources – one by automatic extraction of DTM from stereoscopic images using photogrammetric methods and the other by digitizing of topographic maps. In addition, homologous point pairs were extracted in the overlapping region of these adjacent DTMs. The SIFT algorithm of matching two images was applied to the set of shaded relief images of the source adjacent DTMs.

The adjacent DTMs were merged into one seamless DTM by using the proposed fusion algorithm. In Figure 4 the overlapping region is presented - the two source DTMs and two versions of the merged DTM, one by applying the proposed algorithm and the second by applying the “cut and paste” method. In Figure 4c the result of the “cut and paste” method is presented. This method requires defining a “cutting line” to be the transition line between the two DTMs; in our case the “cutting line” is defined to pass in the middle of the overlapping region. In Figure 4c a line of discontinuity is easily observed, more over structures of the terrain appears more than once in the merged DTM around
both sides of the discontinuity line. In Figure 4d the result of the proposed fusion algorithm is presented showing full continuity of the merged DTM. In order to differentiate between the two methods, the same area in both figures (4c and 4d) was marked with an ellipse and it is very easy to observe the continuity versus discontinuity of the terrain by applying the two methods. In fact, it can be seen that the proposed fusion approach preserves a continuous topological representation and "correct" morphological structures of the terrain. In Figure 5b the complete merge of the adjacent DTMs using the proposed fusion algorithm is presented. In this figure on the left side is the original left DTM, on the right side is the original right DTM and in the middle is the merged overlapping zone. For comparison purposes, in Figure 5a the merged DTM using “cut and paste” method is presented.

Table 1 presents a comparison between the two merged DTMs in the overlapping region. It particularly shows that even though the selected area is characterized by a mountainous terrain, the maximal residual and the standard deviation of the proposed algorithm are significantly improved compared with the “cut-and-paste” method. Table 2 presents the change of height differences in the overlapping zone. The height differences are measured towards the more accurate source DTM. The change of height difference distribution is shown in Figure 3.

Table 1. Comparison results of merging two adjacent DTMs using different approaches.

| Proposed fusion algorithm versus “Cut and Paste” |
|---------------------|---------------------|
| Number of Points    | 1449621             |
| Standard Deviation improvement | 31%               |
| Maximal Difference improvement | 51%               |

Table 2. Results of merging the overlapping zone with the proposed algorithm.

| Comparing the merged overlapping zone to the more accurate source DTM [meters] |
|---------------------|---------------------|---------------------|---------------------|
|                      | Average of absolute differences | Standard deviation | Minimum difference | Maximum difference |
| Original differences | 53.22 | 67.26 | -329.84 | 221.87 |
| “Cut and Paste” method | 24.75 | 44.53 | -319.46 | 192.66 |

**SUMMARY**

This paper suggests a new approach and an algorithm for fusing the overlapping region of two adjacent DTMs. This algorithm is aimed at achieving a continuous topological representation and correct structures of the terrain as described by the merged DTM. The suggested approach and algorithm were tested and compared to currently used DTM merging methods. The new approach, which proved to be efficient in achieving a continuous topological representation of the terrain, preserves the morphological structures and a continuous height description of the terrain, is a step toward merging terrain data from diverse sources into a single, coherent DTM, creating a seamless DTM database.
Figure 3. Height difference distribution of overlapping zone.
(a) Original differences (top).
(b) Merged DTM compared to the more accurate source DTM (bottom).

REFERENCES


Figure 4. Merged DTM of the overlapping region.
(a) Source DTM (left).
(b) Source DTM (right).
(c) “cut and paste” results.
(d) Proposed fusion algorithm results.
Figure 5. Complete merge of the two DTMs - "Cut and Paste" versus the proposed fusion algorithm.
(a) "Cut and Paste" method (top).
(b) Proposed fusion algorithm (bottom).