AN APPROACH FOR THE SEMANTICALLY CORRECT
INTEGRATION OF A DTM AND 2D GIS VECTOR DATA

A. Koch

Institute of Photogrammetry and GeoInformation (IPI), University of Hannover, Germany
Nienburger Straße 1, 30167 Hannover
koch@ipi.uni-hannover.de

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ABSTRACT:

The most commonly used topographic vector data, the core data of a geographic information system (GIS) are currently two-dimensional. The topography is modelled by different objects which are represented by single points, lines and areas with additional attributes containing information, for example on function and size of the object. In contrast, a digital terrain model (DTM) in most cases is a 2.5D representation of the earth's surface. The integration of the two data sets leads to an augmentation of the dimension of the topographic objects. However, inconsistencies between the data may cause a semantically incorrect result of the integration process.

This paper presents an approach for a semantically correct integration of a DTM and 2D GIS vector data. The algorithm is based on a constrained Delaunay triangulation. The DTM and the bounding polygons of the topographic objects are first integrated without considering the semantics of the objects. Then, those objects which contain implicit height information are further utilized: object representations are formulated and the semantics of the objects is considered within an optimization process using equality and inequality constraints. The algorithm is based on an inequality constrained least squares adjustment formulated as the linear complementary problem (LCP). The algorithm results in a semantically correct integrated 2.5D GIS data set.

First results are presented using simulated and real data. Lakes represented by horizontal planes with increasing terrain outside the lake and roads which are composed of several tilted planes were investigated. The algorithm shows first satisfying results: the constraints are fulfilled and the visualization of the integrated data set corresponds to the human view of the topography.

1. INTRODUCTION

1.1 Motivation

The most commonly used topographic vector data, the core data of a geographic information system (GIS) are currently two-dimensional. The topography is modelled by different objects which are represented by single points, lines and areas with additional attributes containing information, for example on function and size of the object. In contrast, a digital terrain model (DTM) in most cases is a 2.5D representation of the earth's surface. The integration of the two data sets leads to an augmentation of the dimension of the topographic objects. However, inconsistencies between the data may cause a semantically incorrect result of the integration process.

Inconsistencies may be caused by different object modelling and different surveying and production methods. For instance, vector data sets often contain roads modelled as lines or polylines. The attributes contain information on road width, road type etc. If the road is located on a slope, the corresponding part of the DTM often is not modelled correctly. When integrating these data sets, the slope perpendicular to the driving direction is identical to the slope of the DTM which does not correspond to the real slope of the road. Another reason for inconsistencies is the fact, that data are often produced independently. The DTM may be generated by using lidar or aerial photogrammetry. Topographic vector data may be based on digitized topographic maps or orthophotos. These different methods may cause inconsistencies, too.

Many applications benefit from semantically correct integrated data sets. For instance, good visualizations of 3D models of the topography need correct data and are important for flood simulations and risk management. A semantically correct integrated data set can also be used to produce correct orthophotos in areas with non-modelled bridges within the DTM. Furthermore, the semantically correct integration may show discrepancies between the data and thus allow to draw conclusions on the quality of the DTM.

1.2 Related work

The integration of a DTM and 2D GIS data is an issue that has been tackled for more than ten years. Weibel (1993), Fritsch & Pfannenstein (1992) and Fritsch (1991) establish different forms of DTM integration: In case of *height attributing* each point of the 2D GIS data set contains an attribute "point height". By using *interfaces* it is possible to interact between the DTM program and the GIS system. Either the two systems are independent or DTM methods are introduced into the user interface of the GIS. The *total integration* or *full database integration* comprises a common data management within a data base. The terrain data often is stored in the data base in form of a triangular irregular network (TIN) whose vertices contain X,Y and Z coordinates. The DTM is not merged with the data of the GIS. The merging process, i.e. the introduction of the 2D geometry into the TIN, has been investigated later by several authors (Lenk 2001; Klötzer 1997; Pilouk 1996). The approaches differ in the sequence of introducing the 2D geometry, the amount of change of the terrain morphology and the number of vertices after the integration process. Among others, Lenk and Klötzer argue that the shape of the integrated TIN should be identical to the shape of the initial DTM TIN. Lenk developed an approach for the incremental insertion of object points and their connections into the initial DTM TIN. The sequence of insertion is object point, object line, object point etc. The intersection points between the object line and the TIN edges (Steiner points) are considered as new points of the integrated data set. Klötzer, on the other hand, first introduces all object points, then carries out a new preliminary triangulation. Subsequently, he introduces the object lines,

determines the Steiner points, adds both to the data set. Since the Delaunay criterion is re-established in the preliminary triangulation, the shape of the integrated TIN may deviate somewhat from the one of the initial DTM. The methods have in common, that inconsistencies between the data are neglected and thus may lead to semantically incorrect results. Rousseaux & Bonin (2003) focus on the integration of 2D linear data such as roads, dikes and embankments. The linear objects are transformed into 2.5D surfaces by using attributes of the GIS data base and the height information of the DTM. Slopes and regularization constraints are used to check semantic correctness of the objects. However, in case of incorrect results the correctness is not established. A new DTM is computed using the original DTM heights and the 2.5D objects of the GIS data.

2. SEMANTIC CORRECTNESS

2.1 Consequences of non-semantic integration

In our investigations a digital terrain model (DTM) is represented by a triangular irregular network (TIN). Bridges, vertical walls and hang overs are not modelled correctly because it is a 2.5D representation. The topographic vector data we consider are two-dimensional. The topography is modelled by different objects which are represented by single points, lines and areas. The integration of the data sets leads to an augmentation of the dimension of the topographic objects.

Figure 1 shows two examples of the non-semantic integration of a DTM and 2D topographic vector data. The height values of the lakes do not show a constant height level (left side of Figure 1). Several heights of the lakes near the bank are higher than the mean lake heights.

At the right side of Figure 1 the roads are not modelled correctly in the corresponding part of the DTM. The slopes perpendicular to the driving direction are identical to the mean slope of the corresponding part of the DTM. There are no breaklines on the left and right borders of the roads. Also, some neighbouring triangles of the DTM TIN show rather different orientations.

2.2 Correct integration

If we divide the topography into different topographic objects (road, river, lake, building, etc.), like the data of a GIS, there are several objects which have a direct relation to the third dimension. These objects contain implicit height information: For example, a lake can be described as a horizontal plane with increasing terrain at the bank outside the lake. To give another example, roads are usually non-horizontal objects. We certainly do not know the mathematical function representing the road surface, but we know from experience and from road construction manuals that roads do not exceed maximum slope

and curvature values in road direction. Also, the slope perpendicular to the driving direction is limited.

Of course, all other objects are related to the third dimension, too. But it is difficult and often impossible to define general characteristics of their three-dimensional shape. For example, an agricultural field can be very hilly. But it is not possible in general to define maximum slope and curvature values because these values vary from area to area.

The objects containing implicit height information which need to be considered for the semantically correct integration can be divided into three different classes (see Table 1). The first class contains objects which can be represented by a horizontal plane. The second class describes objects which are composed of several tilted planes. The extent of the planes depends on the curvature of the terrain; the planes should be able to adequately approximate the corresponding part of the original DTM. The last class shown in Table 1 describes objects which have a certain relation to other objects. Bridges, undercrossings and crossovers contain a certain height relation to the terrain or water above or beneath.

Object	Representation
Sports field, race track, runway, dock, canal, lake, pool	Horizontal plane
Road, path, railway, tramway, river	Tilted planes
Bridge, undercrossing, crossover	Height relation

Table 1: Some topographic objects and their representation in the corresponding part of the terrain

To integrate a DTM and a 2D topographic GIS data set in a semantically correct sense, the implicit height information of the mentioned topographic objects has to be considered. That means, after the integration process the integrated data set must be consistent with the human view of the topography and the height representations as shown in Table 1 have to be represented correctly.

3. AN ALGORITHM FOR THE SEMANTICALLY CORRECT INTEGRATION

The aim of the integration is a consistent data set with respect to the underlying data model taking care of the semantics of the topographic objects.

Topographic objects which are modelled by lines but which have a certain width, are first buffered. The buffer width is taken from the attribute "width" if available, otherwise a default value is used. Thus, the lines are transformed into elongated areas, the borders of which are further considered. The next step of the algorithm is a non-semantic integration of the data sets.
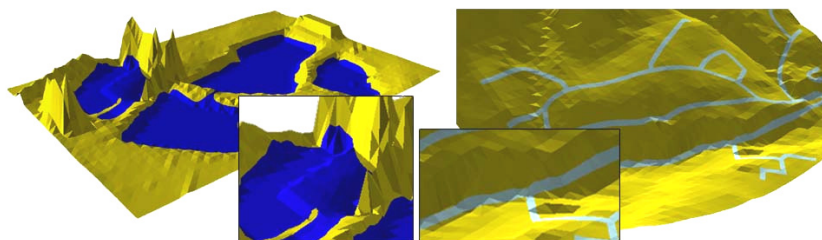

Figure 1: Results of the integration of a DTM and a 2D vector data set without considering the semantics of the topographic objects, left: lakes, right: road network

It is based on a constrained Delaunay triangulation using all points of the DTM (mass points and structure elements) and the polygons of the topographic objects of the 2D GIS data (section 3.1). The linear structure elements from the DTM and the object borders are introduced as edges of the triangulation, the result is an integrated DTM TIN.

Then, certain constraints are formulated and are taken care of in an optimization process (section 3.2). In this way, the topographic objects of the integrated data set are made to fulfill predefined conditions related to their semantics. The constraints are expressed in terms of mathematical equations and inequations. The algorithm results in improved height values and in a semantically correct integrated 2.5D topographic data set.

A basic assumption of our approach is that the general terrain morphology as reflected in the DTM is correct and has to be preserved also in the neighbourhood of objects carrying implicit height information. Therefore, any changes must be as small as possible. A second assumption is that inconsistencies between the DTM and the topographic objects stem from inaccurate DTM heights and not from planimetric errors of the topographic objects.

3.1 Non-semantic data integration

As mentioned in section 1.2 there are several approaches for the integration of a DTM and 2D topographic GIS data based on a TIN. Because Lenk's approach has some advantages, we use a variant of his algorithm. First, a DTM TIN is created using the DTM mass points and the structure elements in a constrained Delaunay triangulation. Second, the heights for the topographic objects are derived using the height information of the TIN by interpolating a height value for each object point. Next, the points of the polygons representing the topographic objects are introduced into the TIN by re-triangulating the neighbourhood of the objects. Here, the Delaunay criterion is not re-established. Then, the object lines are considered as constraints. This is done in such a way, that the intersection points between the object polygons and the edges of the DTM TIN (Steiner points) are introduced as new points. The edges of the DTM TIN and the lines of the object polygon are split.
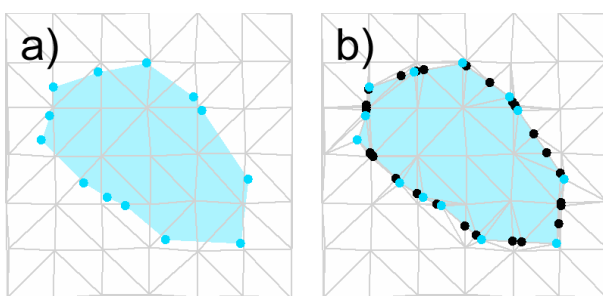

Figure 2: Integration of a DTM and an object "lake", a) original DTM TIN and object "lake", b) integrated data set

Figure 2 shows an example of the integration of a DTM and an object "lake" of a 2D GIS data set. The original points of the bounding polygon of the lake are shown in light blue. After the integration, the intersection points between the DTM TIN and the object polygon are new points of the integrated data set (Figure 2b, coloured by black).

Another example is given in Figure 3. A road is an object modelled by lines (Figure 3a, black line) which is buffered using an attribute "road width". First, all intersection points between the middle axis and the DTM TIN are estimated

(Figure 3a, light grey points of the centre axis). This is done because every triangle has a different inclination and the middle axis should be best fitted to the terrain represented by the initial DTM TIN. After buffering the left and right side of the road contain as much points as the centre axis. Then, the object is triangulated in such a way that the cross sections situated at the points of the road centre axis border the triangles of the object TIN. Thus, it is garanteed that for a profile a change in slope is allowed. The bordering polygon is then introduced using the variant of Lenk's algorithm (Figure 3b).
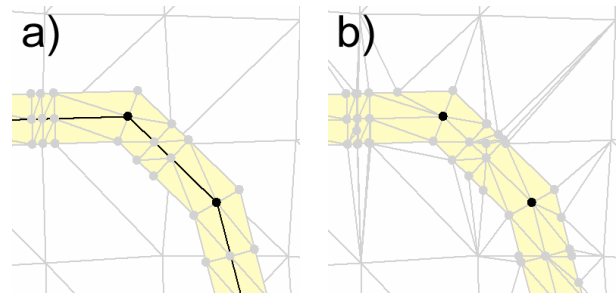

Figure 3: Integration of a DTM and an object "road", a) original DTM TIN and object "road" after buffering, b) integrated data set

3.2 Optimization process

As mentioned, there are topographic objects of the 2D GIS data which contain implicit height information. Within the integrated data set these objects have to fulfill certain constraints which can be expressed in terms of mathematical equations and inequations. To fulfill these constraints or to achieve semantic correctness, the heights of the DTM are changed. Up to now the horizontal coordinates of the polygons of the topographic objects are introduced as error-free.

The heights of the topographic objects are estimated within an optimization process which is based on a least squares adjustment; these values are unknown parameters. The heights of the corresponding part of the DTM are introduced as direct observations for the unknown heights at the same planimetric position. Equality constraints are introduced using pseudo observations. Thus, a Gauss-Markov adjustment model is used and the adherence to the constraints is controlled via weights for the pseudo observations. Furthermore, inequality constraints are introduced. The resulting inequality constraint least squares adjustment is solved using the linear complementary problem (LCP) (Lawson & Hanson 1995; Heipke 1986; Fritsch 1985; Schaffrin 1981).

3.2.1 Basic observation equations: The heights which correspond to the topographic objects of the 2D GIS data and the heights of the neighbouring terrain are introduced as:

$$0 + \hat{v}_i = \hat{Z}_i - Z_i \tag{1}$$

The height Z_i refers to the original height, the value $\hat{Z}_i$ denotes the unknown height which has to be estimated.

In order to be able to preserve the slope of an edge connecting two neighbouring points P_j and P_k of the DTM TIN (one of the two points is part of the polygon describing the object, the other one is a neighbouring point outside the object) and thus to control the general shape of the integrated TIN additional observation equations are formulated:

$$Z_j - Z_k + \hat{v}_{jk} = \hat{Z}_j - \hat{Z}_k \tag{2}$$

3.2.2 Equality and inequality constraints: Each class of object representation (see Table 1) has its own constraints which will be derived in the following.

Horizontal plane: Heights of objects which represent a horizontal plane must be identical. This means, that points P_l with a height Z_l and planimetric coordinates X_l, Y_l situated inside the object boundary (see Figure 4a, black points) must all have the same value $\hat{Z}_{HP}$ which has to be estimated in the optimization process. These height values lead to the following observation equation:

$$0 + \hat{v}_l = \hat{Z}_{HP} - Z_l \tag{3}$$

Additionally, the heights of the bounding polygon points of the topographic objects must be identical to the height of the horizontal plane. The height difference between the unknown object height and the calculated height is used to formulate an additional pseudo observation (see Figure 4a, dark grey points):

$$0 + \hat{v}_m = \hat{Z}_{HP} - Z_m\left(X_m, Y_m, Z_u, Z_v, Z_w\right) \tag{4}$$
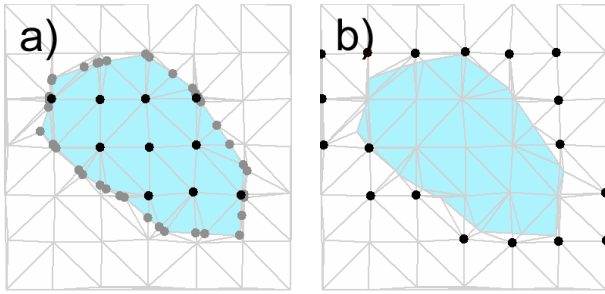

Figure 4: Equality and inequality constraints of an object "lake"

The neighbouring terrain of the horizontal plane is considered using the basic observations (1) and (2) (see section 3.2.1). If the object represents a lake it is necessary to use a further constraint which represents the relation between the lake in terms of a horizontal plane and the bank of the lake whose unknown height values $\hat{Z}_i$ have to be higher than the height level of the lake:

$$0 > \hat{Z}_{HP} - \hat{Z}_i \tag{5}$$

It is set up for all points marked in black in Figure 4b.

Tilted planes: The objects treated in this paper which can be composed of serveral tilted planes are elongated objects. In longitudinal direction these objects are not allowed to exceed a predefined maximum slope value s_{Max}:

$$s_{Max} \geq \left| \frac{\hat{Z}_n - \hat{Z}_o}{D_{no}} \right| \tag{6}$$

The example in Figure 5 shows a road which is modelled by lines and then buffered using the attribute "road width" of the GIS data base. Here, $\hat{Z}_n$ and $\hat{Z}_o$ are the unknown height values

of successive points P_n and P_o in driving direction of the road (Figure 5a). D_{no} is the horizontal distance between these points.
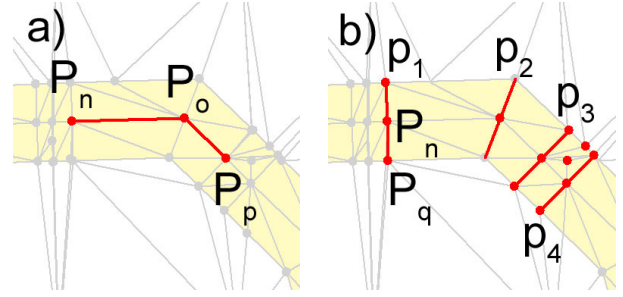

Figure 5: Equation and inequation constraints of an object "road"

In addition, the difference between two successive slope values which is comparable to the vertical curvature of the object is restricted to the maximum value ds_{Max} (Figure 5a):

$$ds_{Max} \geq \left| \frac{\hat{Z}_n - \hat{Z}_o}{D_{no}} - \frac{\hat{Z}_o - \hat{Z}_p}{D_{op}} \right| \tag{7}$$

In case of a road, the points P_n, P_o and P_p are successive points of the middle axis of the object.

Assuming a horizontal road profile in the direction perpendicular to the middle axis the height values of corresponding points must be identical:

$$0 + \hat{v}_{nq} = \hat{Z}_n - \hat{Z}_q \tag{8}$$

The values $\hat{Z}_n$ and $\hat{Z}_q$ represent point heights of the centre axis and the left or the centre axis and the right side of the buffered object (Figure 5b). These constraints are introduced for all cross sections whose centre point results from the intersection between the DTM TIN and the object centre axis (Steiner points). Those cross sections whose centre points are original points of the object middle axis are not used to form this kind of constraint because in the original points the road may show a change in horizontal direction and slope (Figure 5b, profile p_2). Consequently the cross section is not horizontal.

Finally, the points of any two neighbouring cross sections and the points in between have to represent a plane:

$$0 + \hat{v}_r = \hat{a}_0 + \hat{a}_1 X_r + \hat{a}_2 Y_r - \hat{Z}_r \tag{9}$$

In Figure 5b the points of the neighbouring profiles p_3 and p_4 as well as the red point in between represent a point P_r of equation (9). These points have to represent a plane with the unknown coefficients $\hat{a}_0, \hat{a}_1, \hat{a}_2$. X_r, Y_r are the planimetric coordinates of point P_r, $\hat{Z}_r$ is the height of P_r which has to be estimated. A special case is the treatment of the points of a cross section involving an original object point of the 2D road centre axis. As an example let's consider the profile p_2 of Figure 5b. Equation (9) is set up twice, once for the horizontal profile p_1 and the centre point of profile p_2 (and any point in between), and again for the horizontal profile p_3 and the centre point of profile p_2 (and any point in between). After the optimization process the intersection line of the two neighbouring planes can be

calculated. This straight line represents the non-horizontal profile p_2.

3.2.3 Inequality constrained least squares adjustment:

The basic observation equations (section 3.2.1) and the equation and inequation constraints (section 3.2.2) have to be introduced in the optimization process which is based on an inequality constrained least squares adjustment. The stochastic model of the observations (basic observations and equation constraints) consists of the covariance matrix which can be transformed into the weight matrix. Assuming that the observations are stochastically independent, the diagonal of the weight matrix contains the reciprocal accuracies of the observations. To fulfill the equation constraints the corresponding pseudo observation has to have a very high accuracy and the corresponding diagonal element of the weight matrix has to be large. The possibility to solve the optimization process, i.e. the semantic correctness of the resulting integrated data set depends on the choice of the individual weights. The algorithm is formulated as the linear complementary problem (LCP) which is solved using the Lemke algorithm (Lemke, 1968). For more details see Koch (2003), the LCP is explained in detail in Lawson & Hanson; 1995; Heipke, 1986; Fritsch, 1985 and Schaffrin, 1981.

4. RESULTS

The results presented here were determined using simulated and real data sets. Two different objects were used - a lake which can be represented by a horizontal plane and a road which can be composed of several tilted planes. The simulated data consist of a DTM with about 100 height values containing one topographic object. The heights are approximately distributed in a regular grid with a grid size of about 25 meters.

The real data consist of the DTM ATKIS DGM5, a hybrid data set containing regularly distributed points with a grid size of 12,5 m and additional structure elements. The 2D topographic vector data are objects of the German ATKIS Basis-DLM. Three different lakes were used bordered by polygons. The objects are shown on the left side of Figure 1.

4.1 Simulated data

In case of a lake, the basic observation equations (1) and (2), the equation constraints (3), (4) and the inequation constraint (5) are used. The unknown lake height is identical to the mean value of the heights inside the lake. This is true if the neighbouring heights outside the lake are higher than the mean height value, i.e. if the inequation constraints (5) are fulfilled before the optimization begins. It is also true if neighbouring heights outside the lake are somewhat lower than the mean height value and equation (3) has a very high weight. Here, equation (3) was given a weight of 10^6 times higher than all other observations. Equation (4) had a rather low weight because the heights are not original heights of the DTM.

After the optimization process the equation and inequation constraints are fulfilled, and thus the neighbouring heights outside the lake are higher than the estimated lake height. All heights inside the lake and at the waterline have the same height level; the integrated data set is consistent with the human view of a lake.

If some heights outside the lake are too low and the heights of the bank have a high weight, the lake height is pushed down. Then, the heights outside are nearly unchanged, consistency is again achieved.

The second simulated data set represents a road with five initial polyline points. The maximum height difference is 6 m, the road length is 160 m and the width is 4 m.

The investigations were carried out by using different weights for the basic observation equations (1), (2) and the equality constraints (8), (9). Furthermore, the inequation constraints (6) and (7) were used. Equation (1) was considered for all points of the bordering polygon, the points of the centre axis and the points outside the object which are connected to the polygon points. Equation (2) represents the connections to the neighbouring terrain. Using the same weight for all observations results in a road with non-horizontal cross sections and differences to the tilted planes. After the optimization process the inequation constraints are fulfilled and the maximum differences between the initial DTM heights and the heights of the integrated data set are in an order of half a meter.

Using higher weights (10^6 times higher than other weights) for the basic equation (2) and the equation constraints (8) and (9) leads to horizontal cross sections and nearly no differences to the tilted planes. The maximum differences between the initial DTM heights and the heights of the integrated data set are somewhat bigger than the differences before.

If just the equation constraints (8) and (9) have a high weight, the equation and inequation constraints are fulfilled exactly. However, compared to the results before, the terrain morphology has changed considerably.

The results show, that a compromise has to be found between fulfilling the equation constraints and changing the terrain morphology. Using a higher weight of 10^6 leads to fixed observations, i.e. the equation constraints are fulfilled exactly. But, the terrain morphology is not the same as before.

4.2 Real data

The real data sets representing lakes consists of three ATKIS Basis-DLM objects with 294 planimetric polygon points. The DTM contains 1.961 grid points with additional 1.047 points representing structure elements (break lines). The semantically correct integration was carried out by using the same equations as in the simulations and high weights for the equation constraints (3) and for the basic observation equation (1) (10^6 times higher than other weights).

The number of basic observations and equation constraints is 2.754; 533 parameters had to be estimated and the number of inequation constraints is 530. The results show, that all constraints were fulfilled after applying the optimization. The differences between the estimated lake heights and the initial mean height values are very small. The first mean height value is reduced by 2 mm and the second one by 4 mm. The third lake is 3,7 cm lower than the original mean height value which is caused by a higher number of heights at the bank which did not fulfill the inequation constraint (5).
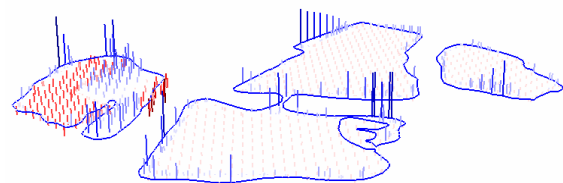

Figure 6: Residuals after the optimization process, blue: terrain is pushed down, red: terrain is pushed up

Figure 6 shows the residuals after the optimization process. The blue vectors correspond to adjusted height values which are

lower than the original heights. Red coloured vectors refer to heights which became higher. The figure shows that most of the heights inside the lakes became higher. Most of the points which became lower are situated at the border of the lakes. Nevertheless, a big part of the differences of the left lake became lower, too. Here, one of the data sets seems to be coarse erroneous. The maximum differences between the original heights and the estimated heights are -1,84 m and +0,88 m, respectively. The right side of Figure 7 shows the result of the semantically correct integration with respect of the results without considering the semantics of the lakes (Figure 7, left). The semantically correct integrated data set shows that all constraints are fulfilled. The height values inside the lake and at the water line have the same level. The terrain outside the lake rises. Summarized, it could be stated that most of the residuals are rather small in respect of the vertical accuracy of the DTM of half a meter. The estimated lake heights are nearly identical to the mean values of the heights inside the lakes, the constraints are fulfilled exactly.

5. OUTLOOK

This paper presents an approach for the semantically correct integration of a DTM and 2D topographic GIS data. The algorithm is based on a constrained Delaunay triangulation and a least squares adjustment taken into account inequality constraints.

First investigations were carried out using simulated and real data sets. The objects used are lakes represented by a horizontal plane with increasing terrain outside the lake and roads which can be composed of several tilted planes. The results which are based on the use of different weights for the basic equations and equation constraints are satisfying. All predefined constraints can be fulfilled but a compromise between fulfilling these constraints and changing the terrain morphology has to be found.

In the future the impact of blunders has to be investigated because height blunders or big differences to the equality and inequality constraints may cause a non-realistic change of the original height information of the DTM.

Furthermore, the planimetric coordinates of the topographic objects were introduced as error-free. This may cause a erroneous height level of the topographic objects. Also the horizontal accuracy of the GIS objects has to be considered.

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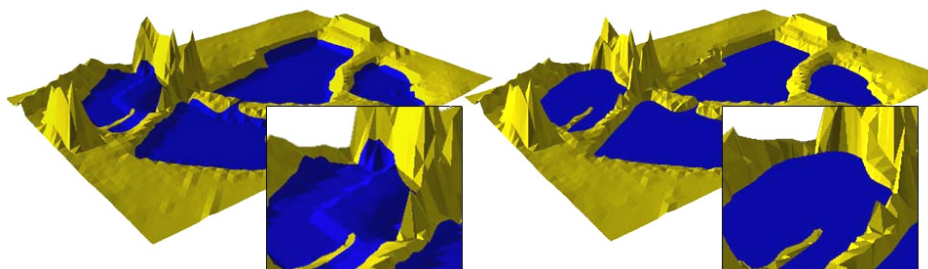
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Figure 7: Results of the integration process, left: non-semantic integration, right: semantically correct integration