ADDING THE THIRD DIMENSION TO A TOPOGRAPHIC DATABASE USING AIRBORNE LASER SCANNER DATA

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ABSTRACT:

Laser altimetry provides reliable and detailed 3D data, which to certain extent, can be processed (semi-)automatically into 3D information. The use of an additional source of information, like 2D GIS data, can improve the reconstruction process, especially in terms of time and reliability. This paper describes the reconstruction of 3D topographic objects by fusing medium scale map data with the national height model, acquired by airborne laser altimetry. We assume that the topographic objects can all be described by smooth surface patches. We therefore first process the laser data to extract the larger smooth surfaces. Discontinuities are, however, preserved. The resulting set of laser points is used to first assign heights to the lines of the 2D GIS data and later on to reconstruct the surfaces of the objects. A set of processing rules is used in the first step to obtain the most likely heights of the object outlines. A constraint Delaunay triangulation of combined 3D outline points and laser points is used for the surface reconstruction. The developed method is demonstrated with a 3D reconstruction of a complex motorway interchange.

1. INTRODUCTION

With the growing demand for 3D topographic data the need for automated 3D data acquisition also grows. Over the past 10 years several researchers proposed methods to acquire 3D topographic data. Many of them focussed on 3D reconstruction of man-made objects, (Haala et al., 1998; Rottensteiner and Briese, 2002; Vosselman, 1999). Automated methods for reliable and accurate 3-D reconstruction of man-made objects are essential to many users and providers of 3-D city data, including urban planners, architects, and telecommunication and environmental engineers (Henricsson and Baltsavias, 1997).

Laser altimetry provides reliable and detailed 3D data, which to certain extent, can be processed (semi-)automatically into 3D information. The use of an additional source of information, like 2D GIS data, can improve the reconstruction process, especially in terms of time and reliability.

This paper describes the reconstruction of 3D topographic objects by fusing medium scale map data with the national height model, acquired by airborne laser altimetry. This topic is part of a larger research project handling the data modelling, acquisition and analysis of national 3D topographic databases.

In section 2 we first describe related work on 3D reconstruction from laser scanner data. The datasets, advantages of merging information and the properties of an extension of a topographic database to 3D are discussed in section 3. In section 4 we describe the approach to derive the 3D topographic information. Adding height to a 2D topographic database not only requires assigning heights to the object boundaries, but also needs the introduction of surface descriptions. Results of the 3D reconstruction of a complex highway interchange are shown and discussed in section 5.

2. RELATED WORK

Over the past ten years airborne laser scanning has broadened its application fields from a suitable technique for the acquisition of digital terrain models, to more detailed reconstruction tasks like the acquisition and modelling of 3D (topographic) objects (Maas, 2001). When used for the 3D reconstruction of buildings the increasing amounts of points contain more and more information about the shape of buildings. Therefore methods for 3D reconstruction can be more data driven and need less specific object models (Vosselman, 1999).

There are several papers concerning the reconstruction of objects from laser data without using additional information sources like 2D maps or aerial images. Most of them discuss the geometric reconstruction of *buildings* in dense laser scan data, (Vosselman, 1999), (Maas and Vosselman, 1999), (Rottensteiner and Briese, 2002), (Elaksher and Bethel, 2002). (Maas and Vosselman, 1999) suggest when using laser altimetry data with a point density of 0.1 point / m^2 or less, the use of GIS data is necessary to successfully reconstruct building roofs. (Rottensteiner and Briese, 2002) also suggest to use image edges for matching roof edges, to improve their building extraction results. In (Rottensteiner and Briese, 2003) they present the use of image segments to find planar regions and use image edges to fit wire frames.

The use of an additional source of information can improve the reconstruction process, especially in terms of time and reliability. Several papers describe the advantage of using both laser data and 2D maps. 2D maps provide outlines, classified polygons and topologic and 2D semantic information. Although most of the papers in this field discuss the reconstruction of *buildings*, (Haala et al., 1998), (Brenner, 2000), (Vosselman and Dijkman, 2001), (Overby et al., 2004), (Hofmann, 2004) and (Schwalbe et al., 2005), there are some authors handling the reconstruction of *other topographic objects*, like roads in (Vosselman, 2003) and (Hatger and Brenner, 2003), roads and lakes in (Koch, 2004), or unclassified break lines (Briese, 2004). The purposes for integrating map data and laser data vary from improving the filtering process for DTM generation by explicitly modelling 3D breaklines (Briese, 2004) to rapid acquisition of 3D city models for virtual reality applications (Haala et al., 1998).

In this research we recognise and model height discontinuities between objects that are adjacent in a 2D topographic database. For modelling the surfaces of the 3D topographic object a point cloud segmentation algorithm is used. This algorithm preserves height discontinuities, but eliminates small objects like cars and traffic signs that should not be included in the 3D topographic database. Filtering algorithms are also used to select the correct laser points for modelling the object surfaces.

3. DATA PROPERTIES

3.1 Data sources

This research is a part of a project to develop methods for acquiring, storing, and querying 3D topographic data as a feasibility study for a future national 3D topographic database. Usage is therefore made of the current national 2D topographic database TOP10vector and the national elevation model AHN.

TOP10vector is a digital 2D topographic database for usage at a scale around 1:10.000. It has been built up in a fully coded object structure. The database is acquired from photographs in a 1:18.000 scale and has an accuracy of 1-2 m. Small buildings like houses, are stored in a different layer and are not shown in figure 1.

Figure 1: The study area in the TOP10vector database.

The national Height model of the Netherlands (AHN) has an average point density of 1 point per 16 m² or better and a height precision of about 15 cm standard deviation per point. In the standard production process the laser data has been filtered, removing buildings, trees and outliers. This filtered dataset will normally be interpolated to a regular grid, and delivered in grid sizes of 5, 25 and 100 meter. However, in this project the original, unfiltered irregular point cloud has been used in order to use as much information from the point cloud as possible (Figure 2).

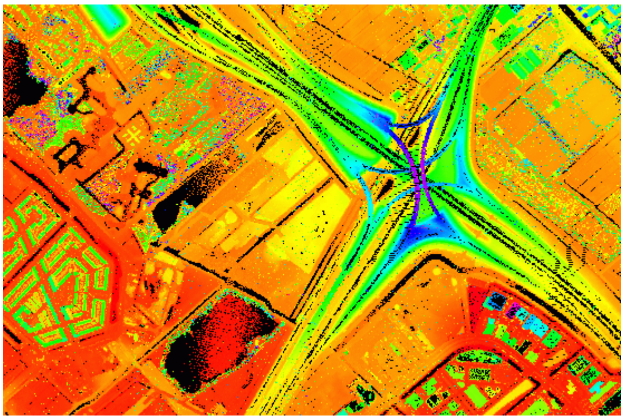

Figure 2: Colour coded AHN elevation data of the study area.

3.2 Data fusion

The existing topographic data delivers a large amount of topological and semantical information. Objects in topographic maps have been classified by human interpretation of aerial images. In this step the outlines, classification and semantics of topographical features are being stored for every object. We describe four different examples, showing how 2D map data can be used to better process the laser data:

1. Outlines. Although there might be small planimetric discrepancies between map data and laser altimetry data, the map data delivers information at object edges where there might be a change of class, resulting in break lines in the height data. Outlines can also be used as input for partitioning the 2D object (Haala et al., 1998), (Vosselman and Dijkman, 2001).
2. Classification in relation to individual laser points: Because the ground structure at the earth surface has influence on the characteristics of the returned laser pulse (Jutzi and Stilla, 2003), (Pfeifer et al., 2004), this class information will be used as input knowledge to further process the laser data.
3. Classification in relation to groups of laser points. Where the previous step focussed on the behaviour of individual laser pulses, the class information can be extended to groups of laser points. Lakes should be horizontal, roads should be smooth, and vegetated areas can show varying heights. Using the information that roads should be smooth in 3D, helps to determine filter parameters for road polygons, filtering out laser points reflected on small objects like cars, containers, traffic lights etc.
4. Semantics. One step further is the implementation of knowledge about an object in relation to its neighbouring objects. A good example is given in [Koch, 2004] where the object ‘lake’ has not only to fulfil internal constraints (the lake should be horizontal), but it also has to lie below its neighbouring objects. To give another example, reconstructing two intersecting roads should result in a smooth surface at the junction.

3.3 Features & representation

In the 2D map used in this project, road segments are represented by closed polygons. Its geometry has been defined by the coordinates of vertices and the topology. In the map implicit height information can be stored by adding ‘hidden’ objects classifications to polygons covering locations with multiple land use. Figure 3a shows that the middle polygon has two classification attributes: ‘visible road 1’ and ‘hidden road 2’. Figure 3b clarifies that adding height to 2D vertices is not enough to get a 3D model. At a certain point the terrain will connect the upper road with the lower road; part of the edges between terrain and road, which were connected in 2D do not connect to each other in 3D. This means that additional 3D edges have to be created for overlapping objects. Our task is to derive a method which automatically determines the location and shape of the interchange by adding laser data to map data. In the next chapter we describe a method, which integrates object knowledge into the reconstruction of 3D infrastructural objects.

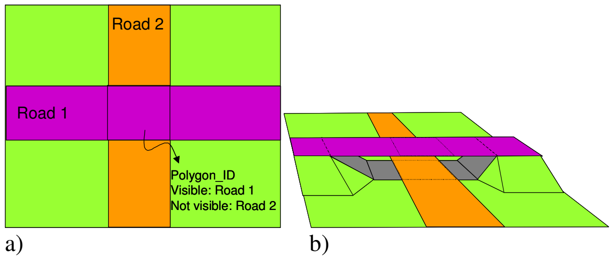

Figure 3: Fly-over in a 2D (a) and 3D representation (b).

4. APPROACH

4.1 Pre-processing 2D map

As shown in figure 3b, edges that are straight in the 2D map do not need to be straight in the 3D model. To correctly capture the shape of the infrastructural objects, the edges therefore need to be described by more points. For this purpose, points were inserted into the edges of the polygons at every 10 m. For all these points and the original map points the height needs to be determined from the laser data.

4.2 Segmentation

We assume that the topographic objects can all be described by smooth surface patches. The purpose of the point cloud segmentation is therefore to find piece-wise continuous surfaces that can be used to infer the heights of the topographic objects. Traditional filter algorithms that are used to produce digital elevation models often completely or partially remove objects like bridges and road crossings (Sithole and Vosselman, 2004). By segmenting a scene into piece-wise continuous patches and further classifying the segments this problem can be avoided (Sithole and Vosselman, 2005); (Tóvári and Pfeifer, 2005).

In our case, we do not perform a classification of the segments, but just use the segmentation results to eliminate laser points on small objects like cars, light poles, traffic signs, and trees. By requiring a minimum segment size, all these points will be left without a segment number after the segmentation step and can be easily removed.

For the segmentation of the point cloud a surface growing algorithm is used with some modifications that allow a fast processing of large datasets (Vosselman et al., 2004). The surface growing method consists of a seed surface detection followed by the actual growing of the seed surface. For the detection of seed surfaces we employ the 3D Hough transform. This transform is applied to the k nearest points of some arbitrary point. If the Hough transform reveals that a minimum number of points in this set is located in a plane, the parameters of this plane are improved by a least squares fit and the points in this plane constitute the seed surface. To speed up the seed detection, we do not search for the optimal seed (with most points in a plane and the lowest residual RMS of the plane fit), but start with the growing once an acceptable seed surface is found.

In the growing phase we add a point to the surface if the distance of the point to a locally estimated plane is below some threshold. This threshold is set such that some amount of noise is accepted. At the same time is also serves to allow for a small curvature in the surface. For a faster processing, the normal vectors of points are not computed and checked. The distance of a point to the local plane is the only criterion. If a point is accepted as an expansion of the surface, a local plane needs to be assigned to this point. In case the distance computed for this point was very small, no new local plane is estimated, but the plane parameters of the neighbouring surface point is copied to the new point. This strategy again serves a faster processing of the point cloud. Once no more points can be added to a surface, the seed detection is repeated. This process continues until no more seed surfaces are found.

4.3 3D reconstruction method

The first step of adding the third dimension to the map is to assign heights to the boundaries of all map objects. In many cases, two objects that are adjacent in 2D are also adjacent in 3D. In some cases, however, there will be a clear height difference for (a part of) the boundary that the objects share in 2D. Assigning the proper heights to the object outlines then requires the introduction of additional lines in the database (cf. section 3.3).

For each point in the map lines after the densification (section 4.1), the objects with boundaries containing this point are selected. For each of the objects around a point the height is derived from the laser points inside the object outline. For this purpose the segmentation results are used. First the k laser points that are nearest to the map point are selected. Next it is determined which segment number is most frequent among the selected laser points. A plane is fitted through the laser points of the most frequent segment number and the height of this plane at the location of the map point is taken as the boundary height. The usage of the most frequent segment number has proven useful in cases of a slight misregistration between the map and the laser data. In this case points of a high object may be located inside the boundaries of an adjacent low object or vice versa. A straightforward fitting of a surface to all laser points near the map point would then lead to errors. The selection of the points of with the most frequent segment number makes the height assignment more robust.

Once a height has been estimated for all objects around a point, it needs to be determined whether objects with similar heights should share the same 3D boundary point. A series of processing rules is used to make this decision:

- If a water and a meadow object are adjacent, the height of the meadow boundary point is set to the height of the water level. This ensures that the shores of water areas are horizontal (Koch, 2004).
- If there is a small height difference between two objects of the same type, a common 3D boundary point is used with the average height of the two objects.
- If there is a small height difference between a road object and another object, the height estimated for the road object is taken as the height of a common 3D boundary point. This

rule is used because the heights on (the very smooth) road surfaces can be estimated more accurately.

Figure 4 shows an example of a few road and meadow objects of a road junction. At the locations where the road surface is above the ground level, additional object lines are introduced to model the height difference.

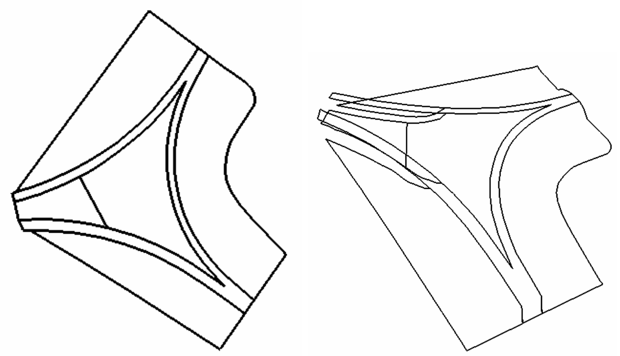

Figure 4: 2D map lines of a few road and meadow objects (left) and perspective view on the reconstructed 3D object boundaries (right).

4.4 Surface modelling

In the previous section laser data has been used to assign heights to the dense map points, which are situated on the object boundaries. Adding height to a 2D object not only means giving height to the boundaries of this object, but also to the surface of the object. Most of the objects show some relief at its surface, like structures on the roof of a building and height differences in grasslands.

To obtain a realistic surface model, a Delaunay triangulation was performed with the set of dense 3D map points combined with the set of laser points. However, road and water objects are triangulated without using the laser points. The motivation is that the resulting 3D road will be smoother, which can be seen as a generalization choice in 3D. Implicitly the laser points on the road segments already gave their height information to the map points, as described in section 4.3. In all triangulations the object boundaries have been added as constraints.

Morphological filtering has been applied to prevent unwanted spikes near edges between roads and meadow. These spikes are caused by misregistrations between the laser and map data, e.g. when laser points are located within meadow polygons but actually lie on upper roads of the interchange. These mistakes did not influence the height determination of the map points (in section 4.3), because a plane was fitted through a dominant segment of laser points. However, when adding individual laser points to the surface these errors show up as steep triangles in the TIN, and have to be removed. This filtering is performed for each object separately.

In 3D, road objects can be modelled as volume objects, instead of surface objects. At this moment we have added a fixed, predefined thickness of 1 meter, underneath the road surface to improve the visualisation at interchanges and flyovers. In the future terrestrial laser data will be integrated to be able to model the object parts which can not be seen from aerial laser and image data. For visualisation purposes the boundary representation has been converted to VRML 2.0 format.

5. RESULTS

Figure 5 shows the result of an important preprocessing step on the laser data: removing small segments from the point cloud. It can be seen that many small features like cars and bushes are being removed in this step.

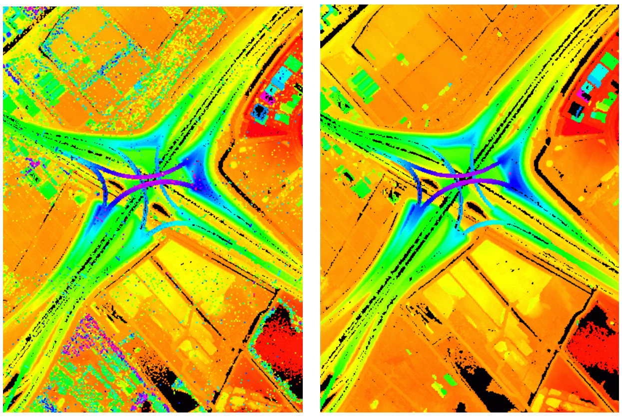

Figure 5: Laser scanner data before (left) and after (right) the removal of small segments. Black areas contain no laser points.

Note that on some parts of the roads even in the unfiltered data set only a few laser points return from the surface. This type of asphalt partly absorbs the laser pulse, resulting in lower point density on road objects. Only for small 2D road objects the low point density results in unreliable 3D reconstruction (cf. figure 10).

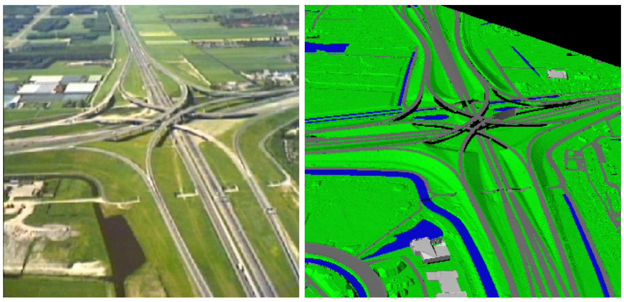

Figure 6: Aerial photograph of the motorway interchange (© Picture archive of the Ministry of Transport, Water Management and Public Works) and reconstructed model.

Figure 6 illustrates the motorway interchange on an oblique photograph (left) and as reconstructed model (right). As the picture is taken in 1983, a few objects have changed over time. In figure 7 the reconstructed model of the test region is shown. All objects have kept their classification type of the 2D map (cf. figure 1). For simplicity reasons, we choose to assign all objects to four classes: road (grey), meadow (green), water (blue) and building (light grey). The focus is on the reconstruction of infrastructural objects and the connections to the terrain. In the upper left part of the scene two large spikes show up. The selection of suitable laser points for plane fitting for the height determination of the map points has failed there. The reason is that the laser data ends a few meters behind those map points.

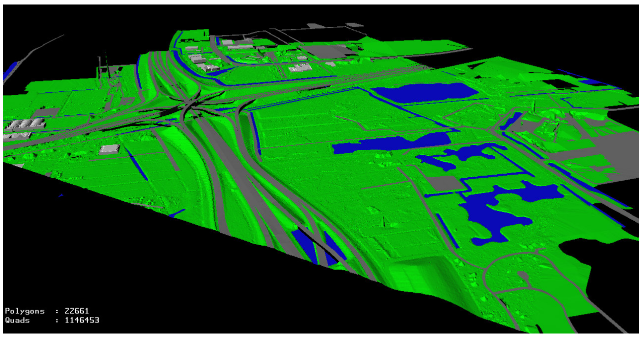

Figure 7: Overview of reconstructed scene with complex infrastructural objects.

In the next figures we will discuss this result in detail. Figure 8 & 9 show results for our reconstruction method. Water objects are horizontal and the neighbouring meadow objects connect to the water boundaries. The upper road in figure 8 is reconstructed above the water and the other road and connects to terrain at the correct position. Note that the black objects underneath the flyovers are still holes in the model. These holes will be filled up in a later stage, either in an integration process with terrestrial laser scanner data or by adding other information to the model. This information can be in the form of object knowledge: most of the holes can be filled up by interpolation between the two neighbouring objects.

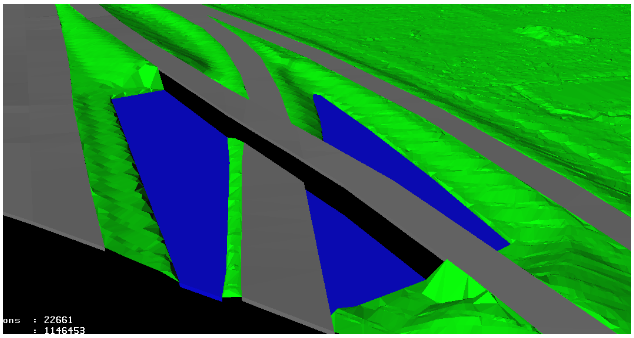

Figure 8: Reconstructed interchange, together with water and meadow objects.

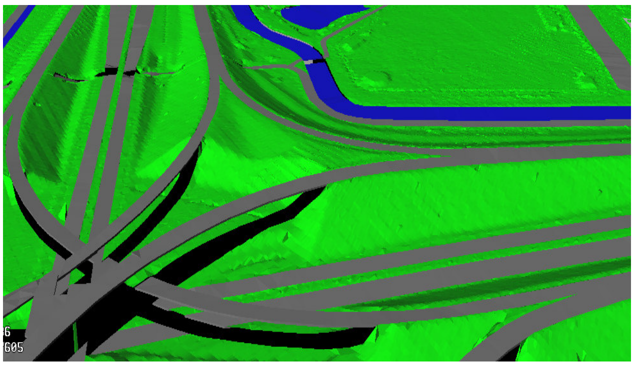

Figure 9: Result for the reconstruction of the body of the flyover, and the flying roads.

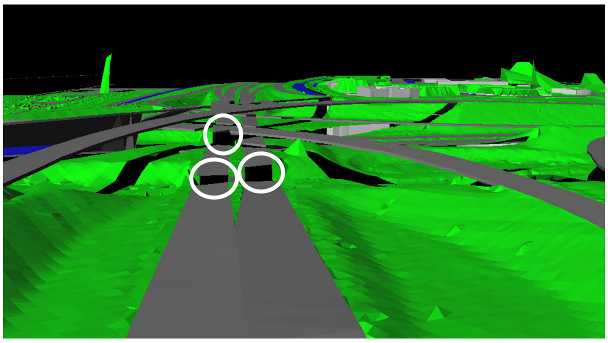

Figure 10: Holes due to hidden object parts and lack of suitable laser points. The white circles show the locations of three holes.

Figure 10 shows that some road object parts are missing on the lower region of the flyover. For some parts the reason is that there is a reconstructed road object on an upper level of the flyover, resulting in gaps at all lower levels. Another reason for missing parts is that the number of laser points may become too small to reliably fit a plane through these laser points, as we already have seen in figure 5. This means that the boundaries of these object parts cannot be determined in 3D. We decided not to add those unreliable parts in the model. Additional knowledge has to be put into the reconstruction process to constrain the connectivity between object parts, which represent the same real world object.

6. CONCLUSION & OUTLOOK

We have presented a method that recognises and models height discontinuities between objects that are adjacent in a 2D topographic database. A segmentation algorithm has successfully been used to connect laser points on smooth surfaces and remove small segments. First, the 3D boundaries have been determined by fitting planes to neighbouring dominant laser segments. Several connection rules have been applied to get a tight model at object boundaries. Several conditions have been applied to get horizontal lakes and smooth roads. At interchanges and flyovers additional boundaries have automatically been reconstructed to allow the reconstruction of 3D objects.

In the near future we will focus on how to add missing polygons to hidden objects. Knowledge about semantics and topology will be integrated with reconstruction method in order to overcome the lack of laser points on hidden objects. Together with other research partners we are working on the modelling of volume objects in a TEN data structure. This gives the opportunity to reconstruct 3D models with 3D primitives instead of with 2D surfaces. Next, focus will be on the detailed reconstruction of buildings, by fusing higher point density laser data with large scale topographic maps.

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