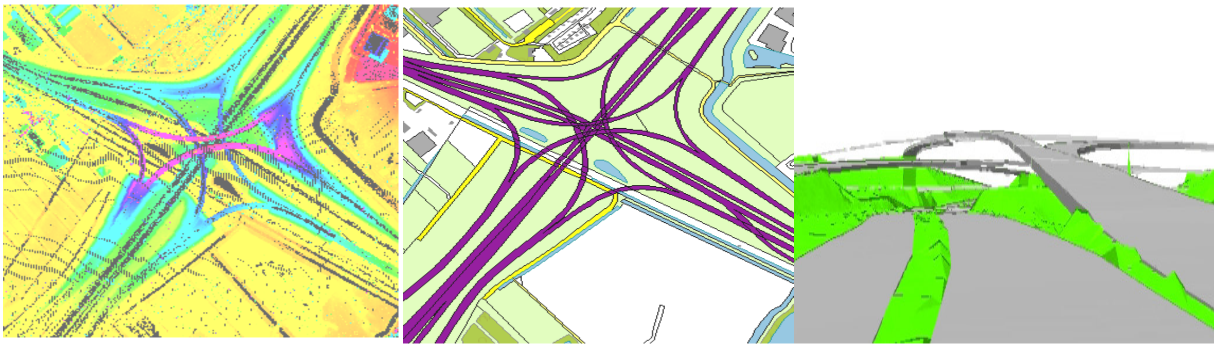
Acquisition of 3D topography by fusing lidar and map data



RGI project 011 3D Topography
Report: DP 3-1

Sander Oude Elberink
February, 2007

Second version ("95%").

ITC

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Preface

This document presents an overview on the developed methods to acquire 3D topographic information by combining laser and map data. It covers the work performed at ITC in 2006 as part of the RGI project 3D Topography. The document is written for project members, students and other researchers, who are familiar with basic photogrammetric terms. In the appendix, two technical papers are presented, who may require some more technical background.

Special thanks for Stefan Flos, who commented on the very draft version of the report.

We hope you will enjoy reading this report and that it may be useful for further activities in the 3D Topography project.

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February 2007
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1. Introduction

1.1. Background

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.

In 3D topographic databases it should be possible to store multiple topographic features on different height levels at one and the same 2D location (e.g. tunnels and flyovers). In figure 1 it is shown that this junction of two highways needs up to four height levels at one location.

Figure 1 Complex 3D infrastructural object "Prins Clausplein", The Hague. Source: BeeldbankVenW.nl

1.2. Goal

This report describes the methods to acquire 3D Topography by fusing laser scanner data and 2D topographic map data. We describe the steps to acquire 3D topographic information, focussing on the reconstruction of road objects, including complex situations as shown in figure 1.

The focus is on the method to combine laser data with map data. Input data and results have only been presented to verify the method.

The report should be a source of information for:

- students doing research on fusing laser scanner data and maps
- interested persons from Survey and Mapping agencies
- project members of RGI project 011: 3D Topography

1.3. Assumptions

In this report the fusion of two specific data sources have been described: topographic map **TOP10NL (1:10.000)** and the Dutch national height model **AHN**. The working of the algorithms has been presented using these two data sources. However, the algorithms are produced to be flexible to use other data sources. The most important input requirements for using the algorithms are:

- Topographic map consists of closed polygons;
- Polygons have been classified into topographic classes;
- Laser data has been aligned in the same coordinate system as the map;
- Laser data is preferable an unfiltered point cloud.

This makes the program to a certain extent independent to the input data source. In particular, we did not use the semantic information from the topographic map TOP10NL, because it would narrow the possibilities to use the program with other topographic map data.

1.4. Structure

In chapter 2 the background of 3D Topography and potential 3D object features and their representations are discussed. Chapter 3 handles the pre-processing steps concerning both lidar and map data. In chapter 4 we describe the approach to fuse lidar data with the map data. This is a crucial step in the automatically 3D reconstruction process. The actual conversion from 2D to 3D has been written in chapter 5. Results of the 3D reconstruction of two complex highway interchanges “Prins Clausplein” and “Knooppunt Waterberg” are shown and discussed in chapter 6.

2. Background

2.1. 3D topography

There are many definitions and interpretations on both the terms “3D” and “topography”. In this section we shortly describe what is meant with 3D topography in this research.

2.1.1. The object space is 3D

When we speak of 3D topography, we mean topographic features which boundaries are defined by a closed polygon through 3D (x,y,z) points. Each topographic feature has a 2.5D surface description, but can additionally contain vertical walls. Multiple topographic features can cross each other on one location at different height levels.

2.1.2. No 3D simplexes

3D objects are based on a combination of multiple 0D, 1D, and 2D simplexes. No volumetric instances (like tetrahedrons) have been used at the moment. Each 2D polygon from the map will be converted to a 3D triangulated surface description, containing planar triangles for visualisation.

2.2. Acquisition of 3D Topography

Conversion from 2D map data to 3D models has been performed by adding heights to the existing 2D map. The underlying principle is to use the laser points inside each polygon. This can be done with a point-in-polygon algorithm. Outliers like cars and small objects already have been removed in the filtering step. Through these laser points a plane has been fitted to calculate the height of the boundaries. Each boundary is connected to at least two polygons, so it will be 3D reconstructed at least twice. Constraints will decide how to handle discrepancies between multiple 3D representations. And then, depending on the class, laser points may be inserted to the surface, which will be triangulated to visualise the 3D surface.

2.3. Topographic classes

In this chapter we discuss the main characteristics of four important topographic classes: terrain, roads, water and buildings. For every class we describe the consequences of describing it in 3D.

2.3.1. Terrain

In this project we define terrain as the collection of ground features, like grasslands, agricultural fields, etc. Here, water surfaces, buildings and roads do not belong to the class terrain. In general terrain polygons can be described with a 2.5D representation, meaning that at a certain location there is only one height value possible. To include the possibility for a real 3D representation, we also allow terrain features to have more than one height value at the same location. This is the case when there is a (vertical) step edge in the surface. Boundaries have been determined in 3D, and laser points inside the polygon have been added to correctly capture the shape of the terrain.

Figure 2 The 3D shape of terrain features is valuable for dikes, which are important objects in (e.g.) water management.

2.3.2. Roads

In 3D topographic databases it should be possible to store multiple topographic features on different height levels at one and the same 2D location (e.g. tunnels and flyovers). In Figure 1 (chapter 1) it was shown that a complex junction of two highways needs up to four height levels at one location.

For cartographic reasons, we add a certain thickness to the roads. The default value is a thickness of 1.0 meter. When visualising the 3D model in situations like in Figure 1, the “flying” road objects looks more real with a certain thickness, than without.

2.3.3. Water

Water is a special kind of object in 3D. In reality the water object is volumetric feature. The surface can be generalised to a horizontal plane. In this research the volume underneath the water surface has not been modelled, because it can not be reconstructed by using laser altimetry and map data. Constrains to each of the water objects is that the boundary and its surface has the same height, resulting in a horizontal polygon. Companies interested in the volumetric representation can integrate bathymetric information for the shape of the bottom of the water object.

Figure 3 Water objects are generally flat.

2.3.4. Buildings

Reconstructing buildings is a challenging task in modern photogrammetry. To correctly capture the 3D shape of buildings, one has to reconstruct roofs, dormers, walls and details on or at the building. This challenge will be part of the PhD research in 2007 and 2008, and will not be represented in this report.

At the moment Top10NL and AHN are not suitable for reconstructing buildings. There are too few laser points, and buildings in TOP10NL are too generalized. The shape of reconstructed models as shown in Figure 4 is far from reality. Details cannot be reconstructed correctly.

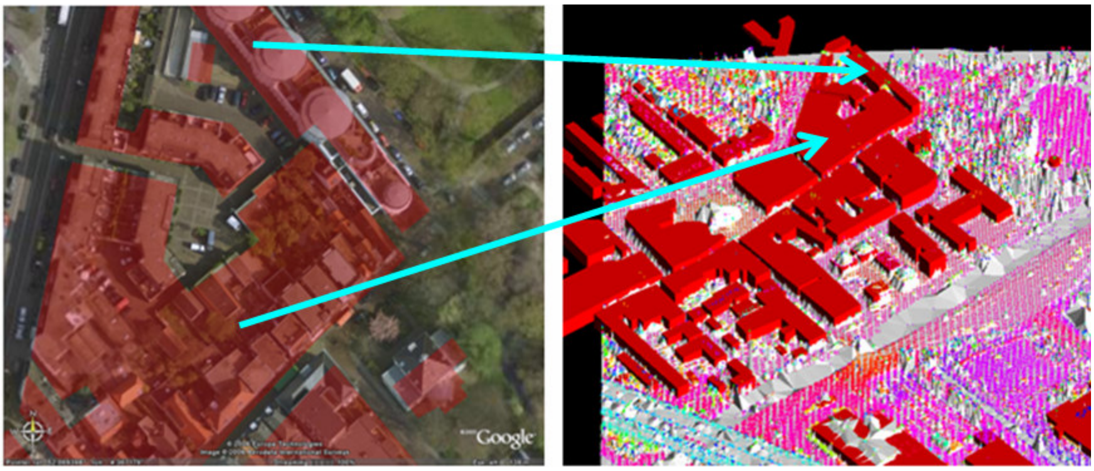


Figure 4 Building polygons overlaid on image (left), blocks of buildings displayed with laser points (right).

3. Data properties

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.

3.1. TOP10NL

TOP10NL 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.

3.2. AHN

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. As one can see in the right part of Figure 5, there are some black parts in the area, meaning that there were no reflected pulses from the surface. This happens at water surfaces, and at large parts of some highways. This type of asphalt greatly absorbs the laser pulse. Our program should deal with varying laser point density.

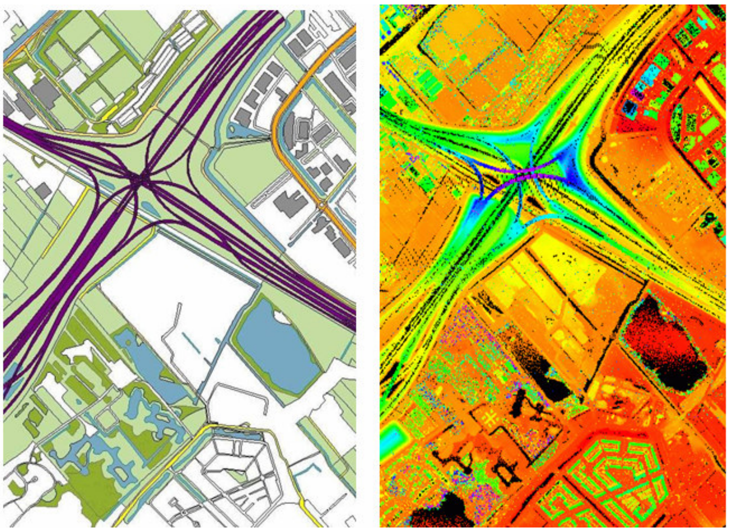


Figure 5 Topographic map (left) and laser data (right) of Prins Clausplein.

3.3. Filtering laser data

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.

By requiring a minimum segment size, all points on small objects will be left without a segment number after the segmentation step and can be easily removed. After removing these points, we have got a filtered pointcloud, see Figure 6.

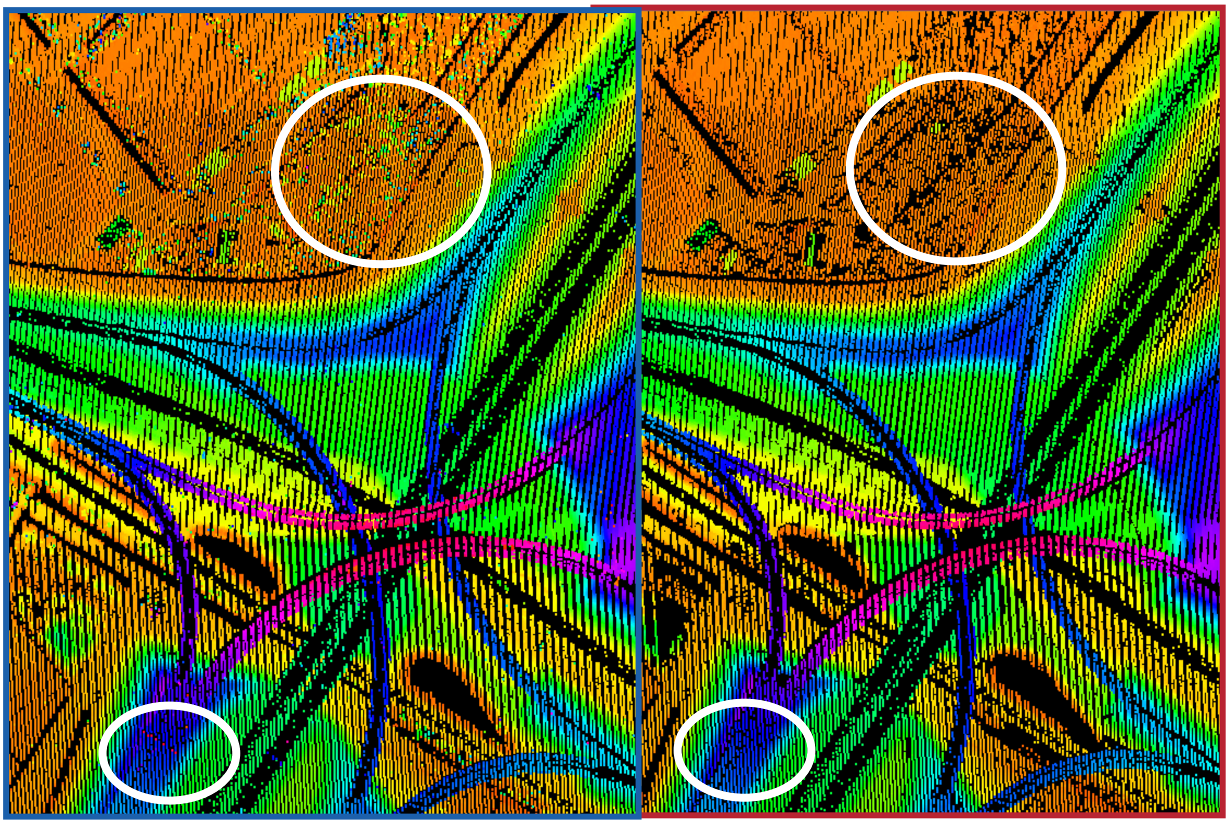


Figure 6 Original pointcloud (left), filtered pointcloud (right).

4. Data fusion

4.1. Introduction

As we have seen in 2.2 the underlying principle for 3D reconstruction is to use the laser points inside each polygon. This can be done with a points-in-polygon algorithm. This can be seen as a simple data fusion process. What if there are no or incorrect points in a polygon. This chapter explains that for complex situations some more knowledge has to be added to the process. In this chapter solutions will be given for situations like:

- "no-points-in-polygon";
- "wrong-points-in-polygon".

When there are less than 8 laser points in a polygon, it is regarded as too few points too reliably fit a plane through these points. Actually one needs 3 points to fit a plane. To reduce the influence of a single laser point in the plane determination, we safely set the minimum number of points on 8.

4.2. Problems with fusion

Fusing laser data with map data is more than co-registration of the datasets into the same coordinate reference system. A simple points-in-polygon operation can be used to connect points with map data, but operation will definitively cause problems at real 3D situations. In this section we discuss the problems and the solutions to fuse lidar with map data. Figure 7 shows an orthogonal projection of laser data on the map data. Map data has been represented by yellow lines describing the outlines of the polygons. The filtered pointcloud is colour coded.

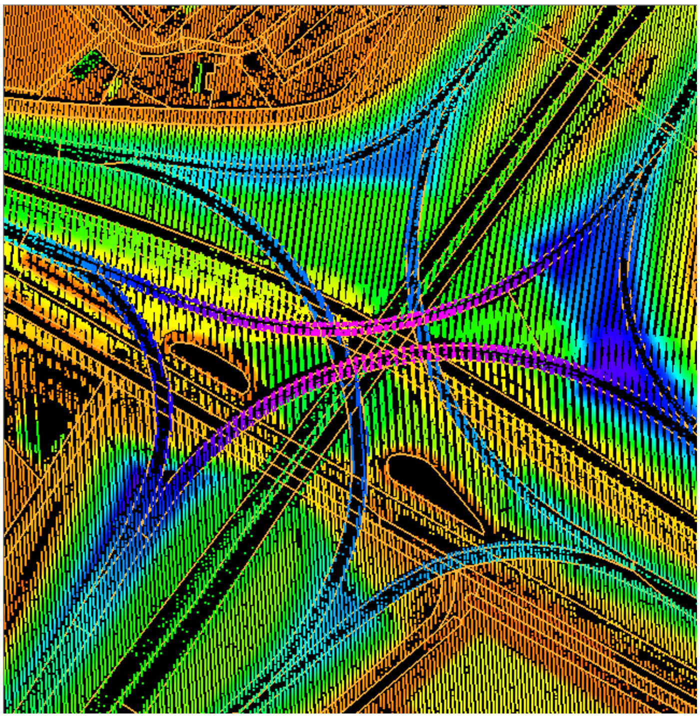


Figure 7 Overview on lidar and map data at Prins Clausplein.

When looking at a complex infrastructural object, the following characteristic problems may occur:

- P1. Road features at the top level show large horizontal distortions in the map. Roads are usually mapped from orthophotos. In a complex situation like this, the DEM used for orthophoto production neglects the height of the higher features, resulting in a horizontal displacement. These displacements can easily rise up to 5 meter. This means that not all corresponding laser data will be found by performing a points-in-polygon operation. Knowledge has to be added to correctly fuse laser data with the topographic polygon representing the object. This problem is a wrong-points-in-polygon situation.
- P2. Laser points will be reflected on all road levels. Due to the large across track scanning angle it is possible to acquire height data at different levels at the same horizontal location. Although in the segmentation step these points will not be grouped into the same segment, large segments can be found each at different height levels. This problem is a wrong-points-in-polygon situation.
- P3. Problems arise when handling polygons with only a few points, due to the size of the polygon or due to the surface material of the object feature resulting in a low point density. This problem is a no-points-in-polygon situation.

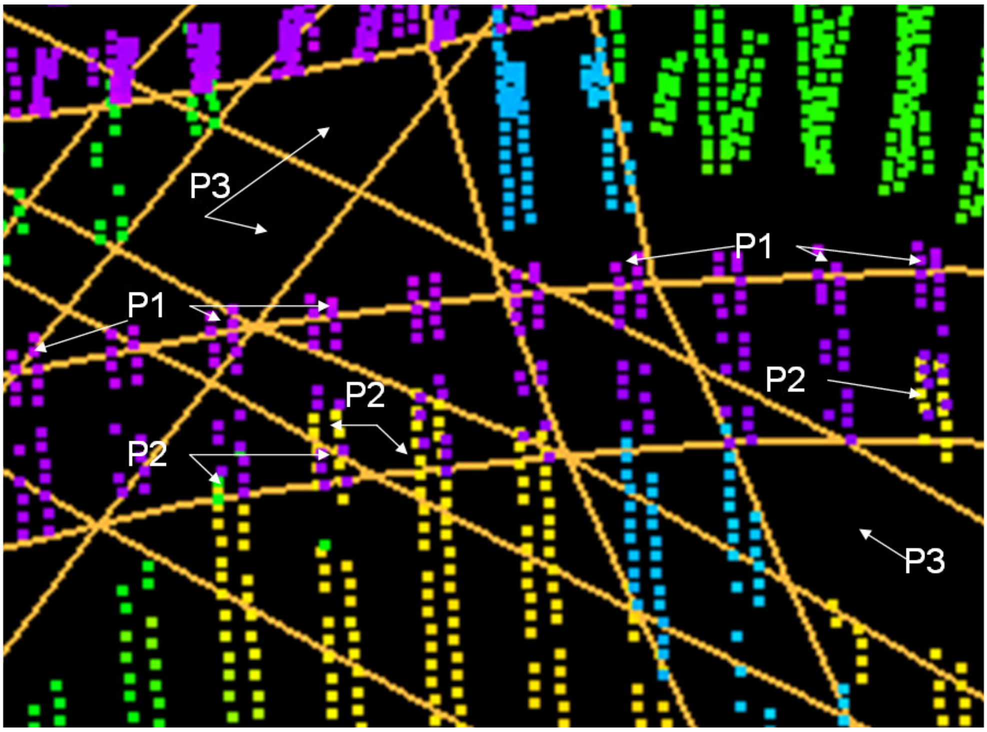


Figure 8 Three sorts of problems mentioned above (P1, P2, P3) when fusing lidar and map data.

Our aim is to reconstruct all topographic road features in 3D. 3D roads can intersect or they can cross each other at different height levels. This implies topological changes compared to the 2D case where all crossing roads are connected to each other and thus intersect in 2D. Our knowledge is that the 3D shape of roads should be an object with a smooth surface. There should be no height and slope discontinuities between adjacent road polygons. But, looking at the problems in Figure 8, we will get a long list of incorrect results if we do not add this knowledge to our program. For clarity reasons, we want to point out some problems that will occur when ignoring knowledge modelling in the road reconstruction process.

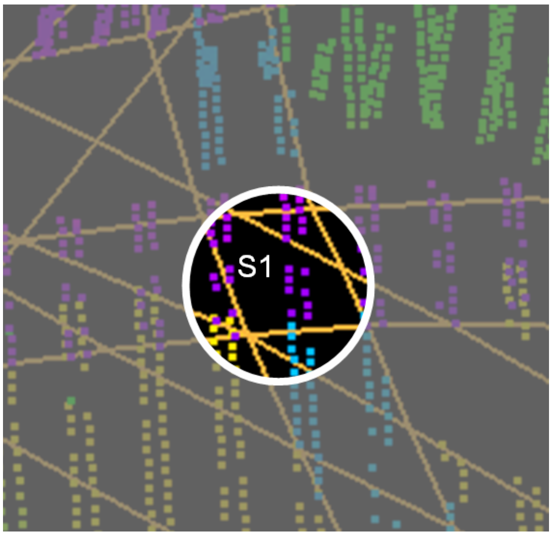


Figure 9 Situation 1 (S1) This polygon should be modelled at three different heights, but only contains laser points on the highest level, and one laser point on the intermediate level, and no one the lowest level.

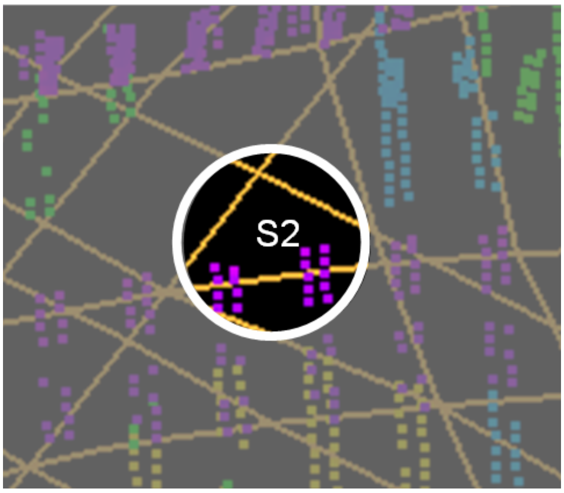


Figure 10 Situation 2 (S2) This polygon only contains laser points on the highest level; but in reality it should contain only points of the lowest level. This polygon will be wrongly placed at the highest level.

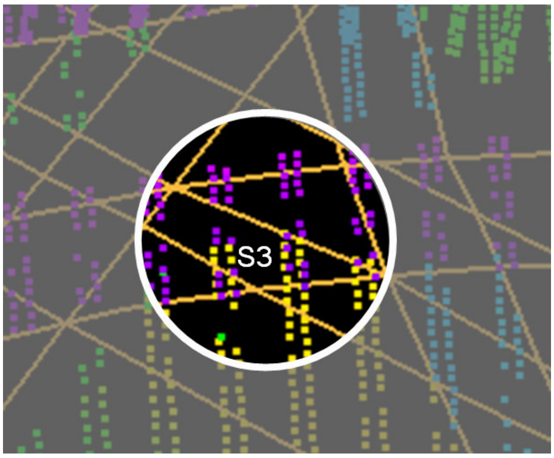


Figure 11 Situation 3 (S3) This polygon contains more points on the lowest level then on the highest level, but in reality there is no road polygon on the lowest level. This road polygon will be wrongly placed at the lowest level.

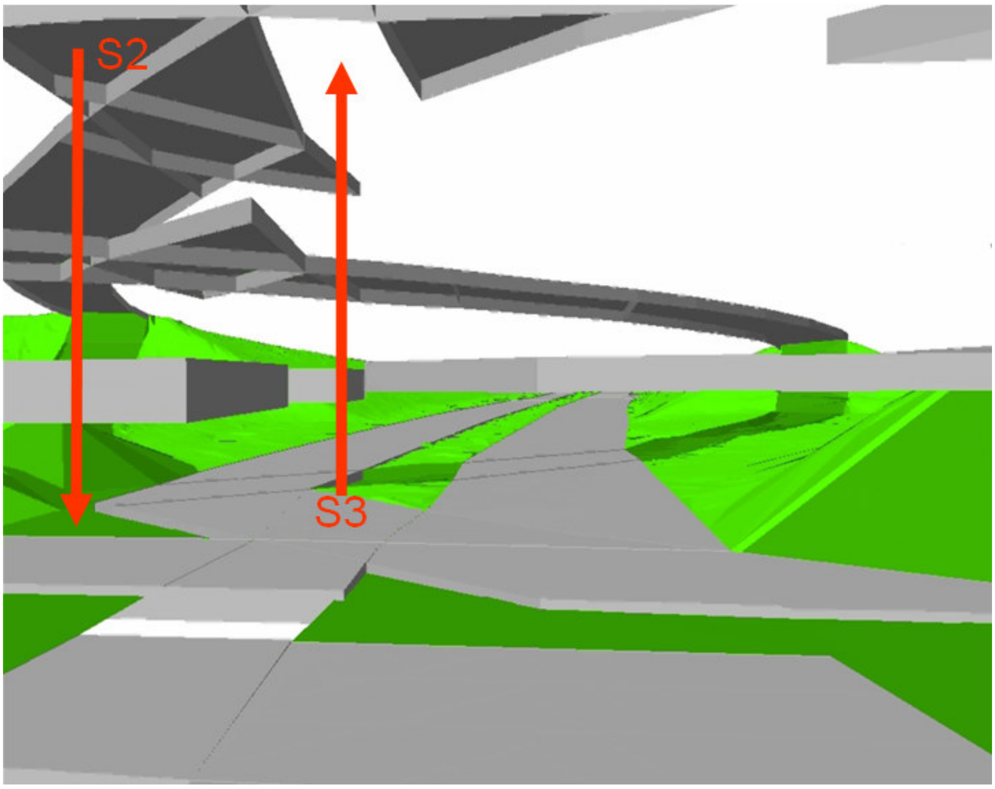


Figure 12 Wrong laser points in polygon causes incorrect 3D results.

For some polygons we could overcome the problems of having no laser data by connecting them to its neighbour, but as we can see in Figure 12 situation 2 and 3 need more knowledge to reconstruct correctly.

To overcome these problems we do not want to reconstruct small road parts individually. We choose to first connect the small road parts to each other if they belong to the same road. Then corresponding laser points are selected that belong to the road. By performing this step correctly, we are able to connect road parts without laser points to other road parts which have laser points (S1 and S2). But even more important is the removal of false laser points, like situations S2 and S3.

4.3. Combined merging algorithm and laser data selection

Our approach is to merge road polygons that belong to one and the same road and select the accompanying laser points. We start with selecting seed polygons and then grow through the graph of all adjacent road polygons. Together with the growing of the polygon the corresponding laser point set also grows, starting from a seed segment. The largest laser segment in the seed polygon is taken as seed segment. In the following sections the combined merging algorithm will be described in more detail.

4.3.1. Map growing algorithm

The map growing algorithm is based on a Hough transformation technique to find the correct direction of growing. Starting from a seed polygon we use the graph to see which polygons are connected to the seed. These neighbouring polygons are candidates for merging with the seed polygon. If the candidate polygon fits into this direction the polygon has been added to the growing polygon. To see if the candidate polygon can be merged, we check if the candidate lies in the growing direction of the seed. Once a seed has been grown, we speak of a growing polygon. In our program we take large polygons (more than 100 meter in length) as seed polygons. The assumption is that this road part covers enough laser points, and this road part has got enough length to give a direction to search for.

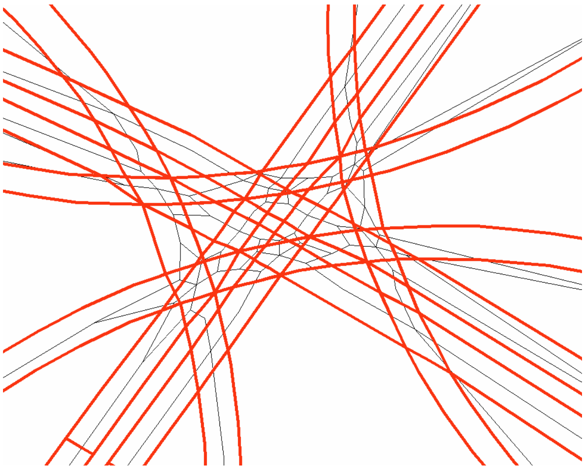


Figure 13 Map outlines (red lines) and adjecent graph representation (black lines).

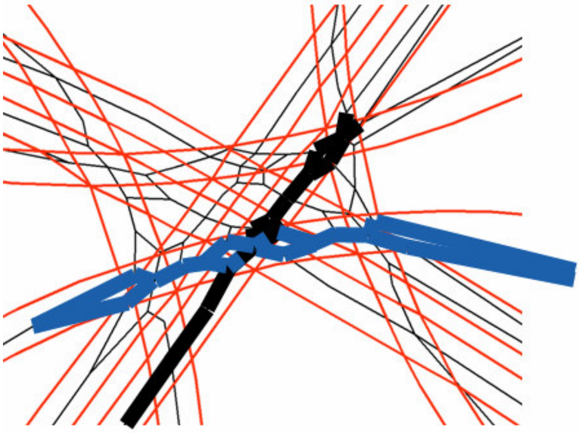


Figure 14 Growing algorithm should find connecting road parts.

2D coordinates of the nodes of the road polygons are being labelled with the direction of line segments between two consecutive nodes. The direction of two consecutive nodes is a measure for the direction of the road. This label is taken as artificial z-value. To get more input points for more reliable direction estimation, points were inserted into the edges of the polygons at every 3 meter.

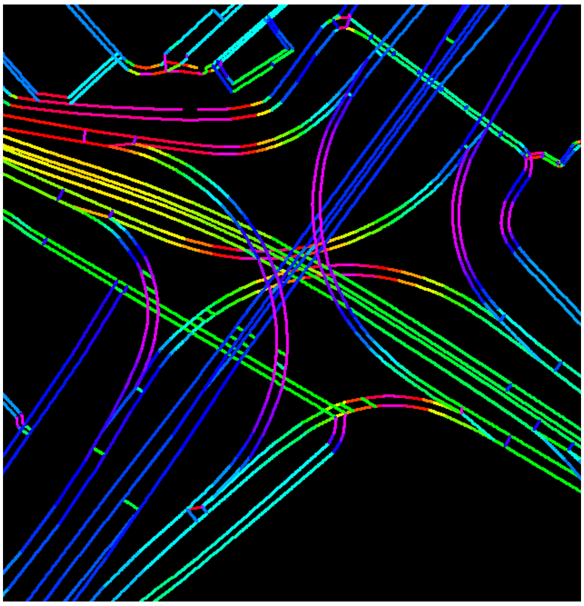
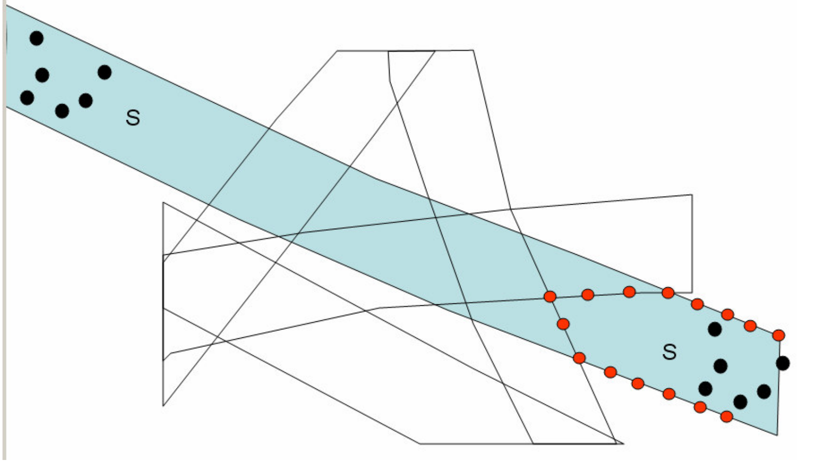


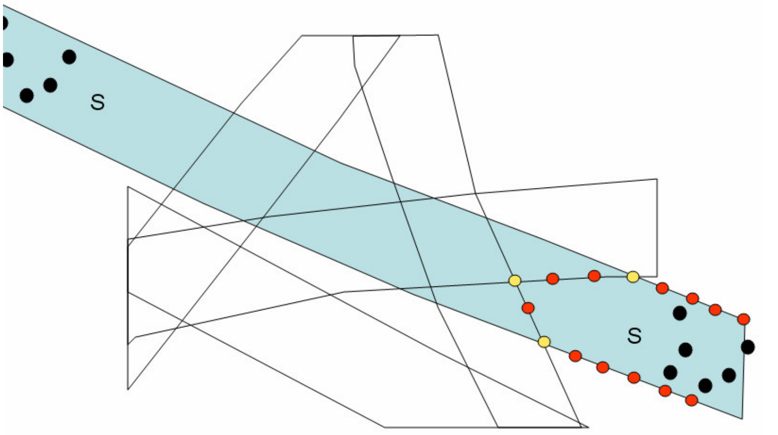
Figure 15 For every map point its direction has been calculated. Here, direction has been visualised as colour.

Only points have been selected that are within a radius of 25 meter of the common edge with the candidate polygon. To eliminate false directions at corner points, only points which lie in a straight line (180 +/- 10 degrees) with its two neighbours, are taken into account. These pseudo 3D points are taken as input in the Hough transformation. A plane is fitted in Hough space, in order to calculate the direction of the road at any place, but specifically at the centre point of the candidate polygon. If a line through this centre point with the calculated direction intersects with the common map line segment, the candidate polygon will be added to the growing polygon.

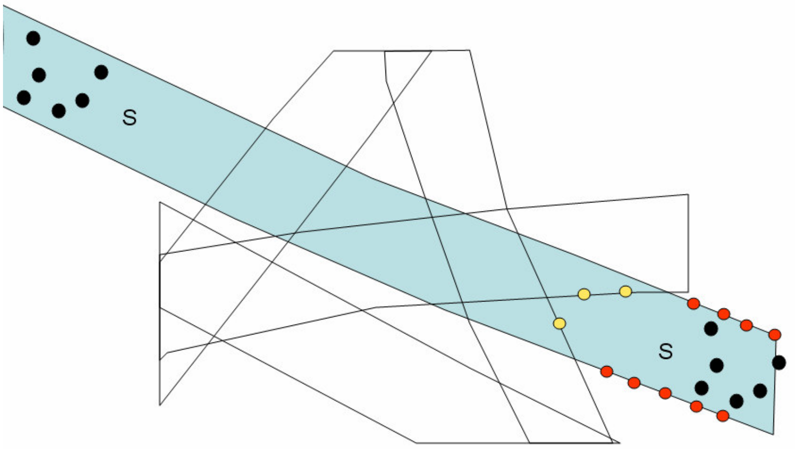
This algorithm continues for all seed polygons until there are no more candidate polygons for the growing polygon, or the growing polygon has merged with another seed polygon. In the next figures, the working of the map merging algorithm is described visually.



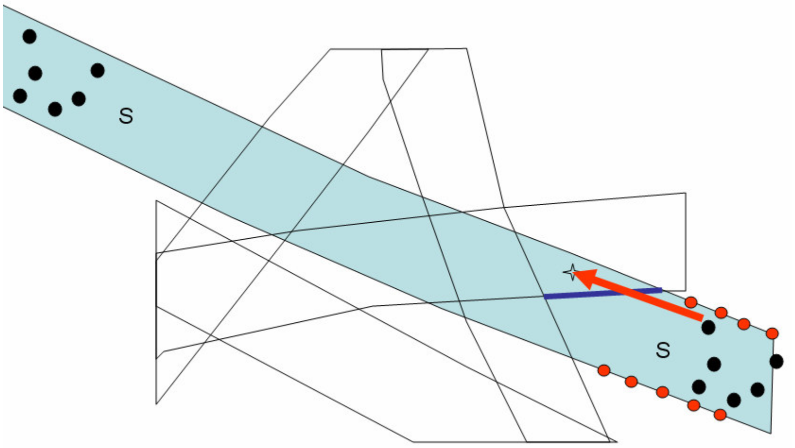
Large polygons will be taken as seeds, here indicated with the letter S. Black points are laser points. Red points are map points along the boundary.



Map points that do not lie in a straight line with its neighbours will be removed. Points shown in yellow. The direction of the other points will be taken as pseudo Z-value and taken as input for the Hough transformation.

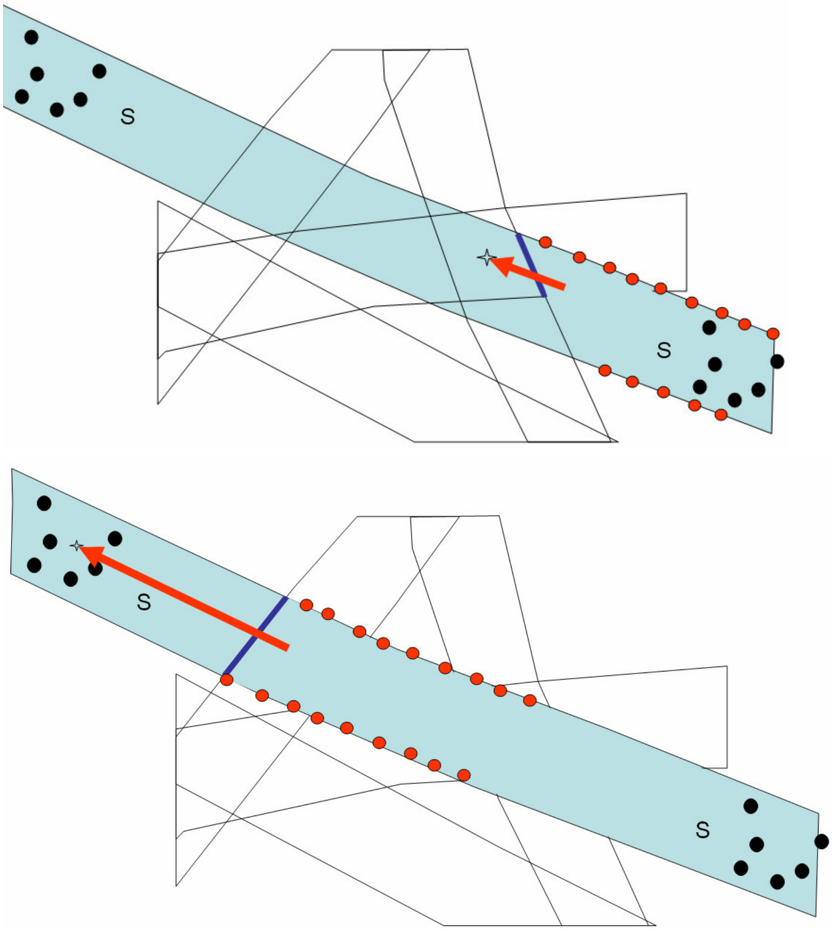


The best plane in Hough space will fit to points with similar direction, here shown in red.



The reconstructed plane will give us the local direction of the road. Direction is displayed by the red arrow. If the line through the middle point of the neighbouring polygon (indicated with a star) intersects with the common boundary (shown in blue), then this polygon will be merged with the seed polygon.

Laser points will be added to the grown polygon. This step will be described in 4.3.2.



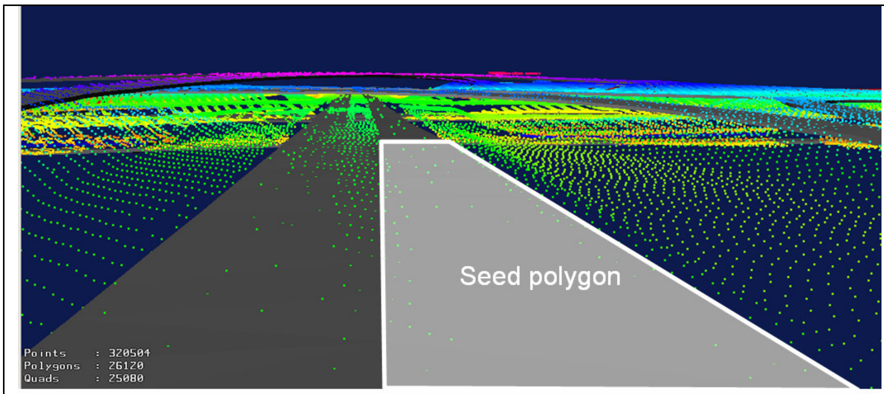
The potential polygon will be added to the seed polygon; from now on called the growing polygon.

The process repeats until there is no more potential polygon to merge with, or when the growing polygon has merged with another seed polygon.

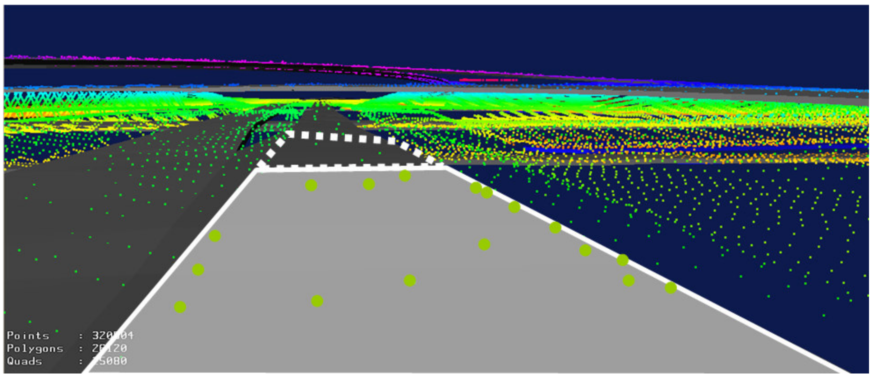
Figure 16 Visualisation of one seed polygon, growing from right to left.

4.3.2. Assigning laser points to merged road parts

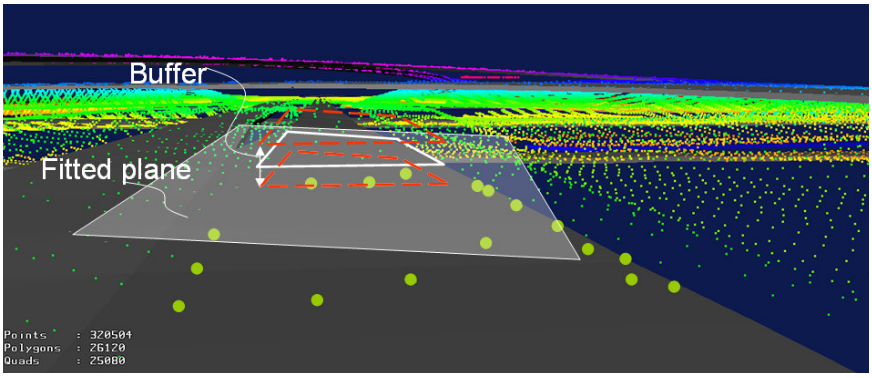
Adding laser points to the road polygon is an activity that will be done in every iteration step of the map merging algorithm as described in the previous section. Laser points in the growing polygon are added to the laser point set if they have the same segment number as available in the growing laser point set or if they are near the plane fitted through the nearest large laser segment in the polygon. This step is important because it selects only laser points that belong to the growing road. Doing so, we can grow underneath several other highways, merging all small road polygons without laser points, and connect to the other side of the interchange where we have enough laser points on the road. To visualise the working of this step, we will introduce the next figures. Laser points are shown, superimposed on a 3D model of the road. This model actually is the final result of our reconstruction method (and further explained in chapter 5 and 6); here we only use the model to visualise the assigning of laser points to the growing map polygons.



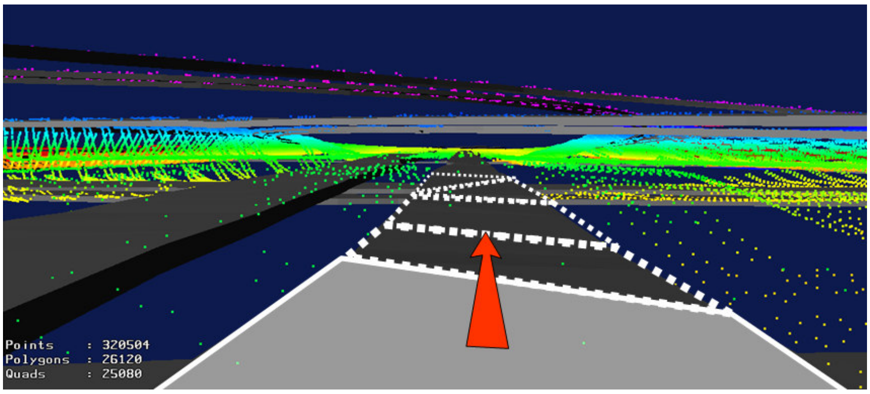
A seed polygon is chosen automatically to grow and merge with neighbouring road polygons.



Laser points in adjacent polygon are added if they are in the same segment as the biggest nearest laser segment in the seed polygon, here shown in large green dots.



And laser points have been added if they are within a certain distance (1.5 meter) from a fitted plane through the largest laser segment.



This process continues as long as the map polygon growing algorithm works. Note that in this approach we will discard laser points on other height levels. This is the solution for problems as mentioned in section 4.2.

Figure 17 Laser growing algorithm as part of the polygon growing algorithm.

Compared to a simple points in polygon our approach performs better with selecting the right laser data. We can see this in Figure 19. Small polygons of a bicycle tunnel are merged together, and correct laser points have successfully been found. Laser points on higher roads will be not assigned to the lower roads, so during the reconstruction only the right laser points will be used. The reconstruction process itself will be described in chapter 5.

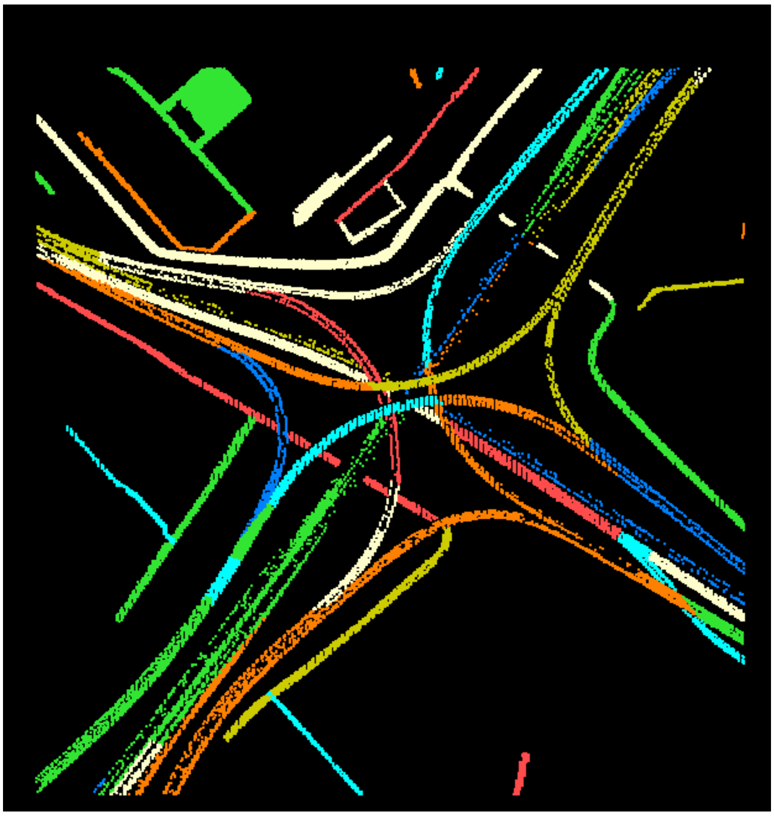


Figure 18 Results after merging algorithm. Laser points have been colored by polygon number.

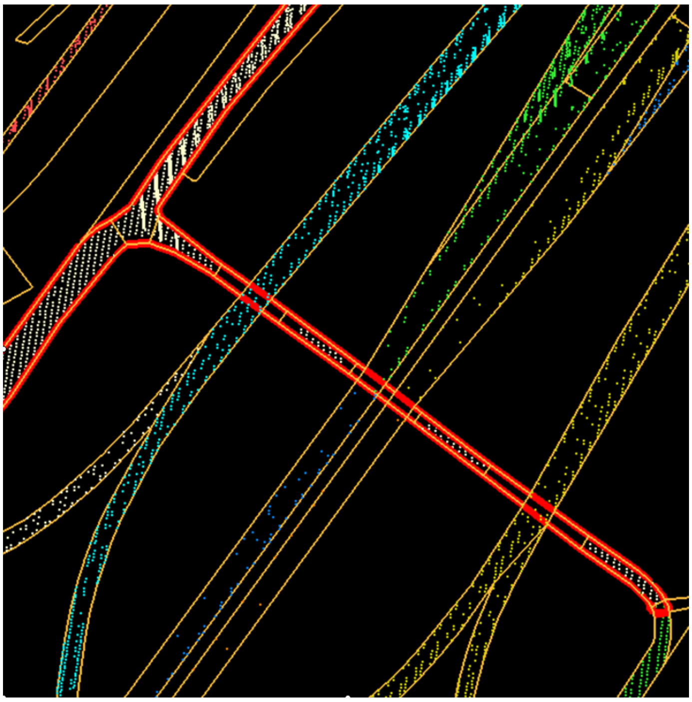


Figure 19 Polygons of small tunnel merged together. Accompanying laser points are shown in white.

5. 3D Reconstruction process

5.1. Overview

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.

In this research we recognise and model height discontinuities between objects that are adjacent in a 2D topographic database.

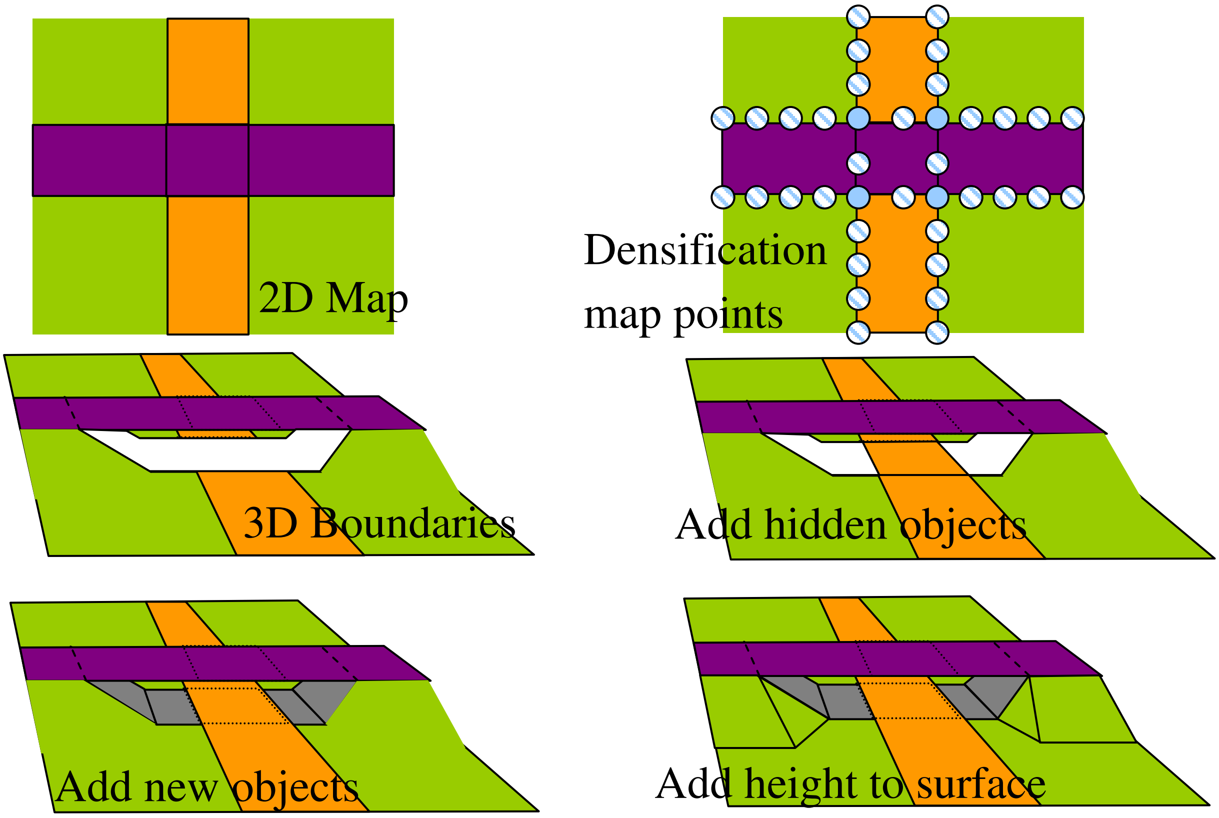


Figure 20 Overview of process from 2D to 3D.

5.2. 3D Boundaries

As shown in Figure 20, 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 boundaries, 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. Every map point belongs to two or more polygons. In each of the neighbouring polygons laser data is selected to calculate the height at the map point. In chapter 4 it was shown which laser points belong to the polygon. In the actual reconstruction step, only laser points are selected in a certain radius around the object points, see Figure 21. By calculating multiple heights at every map point, height discontinuities can be detected and modelled. Several constraints have been introduced to get a topological correct model, see (Oude Elberink and Vosselman, 2006).

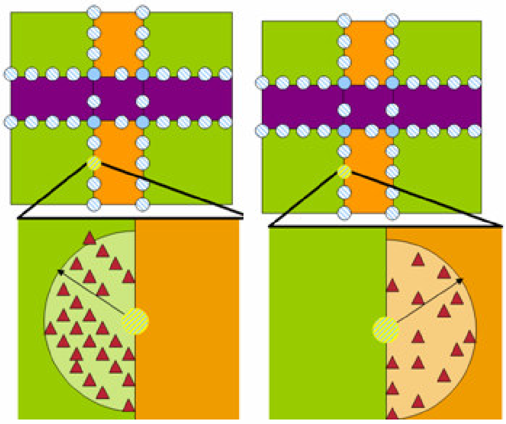


Figure 21 Calculation of map point height, from grass land (left) and road object (right).

5.3. 3D Surfaces

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 terrain objects show some relief at its surface. Laser points lying on the terrain (i.e. not on buildings, roads, trees, water) are used as nodes in the surface TIN model. To get a smooth surface at road objects, map points at road boundaries have been used to generate a constrained TIN model, without adding laser points lying on that road. Trees and buildings have not been modelled in this part of the research project.

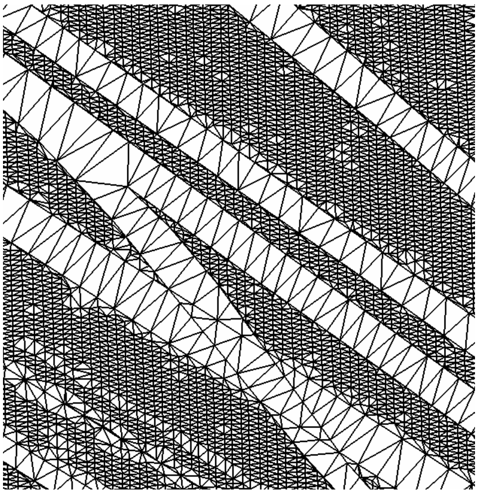


Figure 22 Constrained TIN model with roads and grass land.

5.4. Quality aspects

In this section we describe several quality aspects of the 3D model. The quality of the result depends on the quality of the input, and the processing steps to come to the result. We will discuss issues like geometric accuracy (both horizontal and vertical), reliability, and describe at which steps in the process is space for quality improvement. Quality of the 3D reconstructed models has not been tested in practice; this section handles the theoretical quality aspects.

5.4.1. Boundaries

Our algorithm does not change the horizontal position of the input topographic data. The horizontal position of boundaries has been determined in the map production process, by means of operator assisted photogrammetric measurements.

Height of boundary points has been determined by the height of a plane fitted through at least 8 laser points near the boundary point. The plane has been fitted in a least-squares fitting algorithm. The accuracy of this object point can therefore be divided in two groups: influence of quality of laser points, and a contribution due to interpolation uncertainties[1]. We assume that the segment-based filtering was performed correctly, and that all remaining laser points actually lie on the surface.

A practical manner to estimate the quality of laser altimetry data for a certain area has been described in (Oude Elberink et al., 2003). The authors describe several sorts of error sources in the chain of data acquisition and compute their influences when looking at a certain area. In this section we focus on the laser point noise and the systematic error for a group of points. Knowing that the program at least takes 8 laser points, the influence of laser point noise will be reduced by at least a factor $\sqrt{8} \approx 3$. Assuming that the average airborne laser point noise is about 10 cm, the contribution due to laser point noise is in the order of 3.5 cm. Systematic errors of this group of laser points consist mainly of GPS/INS errors and strip adjustment errors. Looking at the experiences described by (Oude Elberink

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[1] It even can be called an extrapolation error because the object point generally lies on the outside of the group of laser points.

et al., 2003) we can roughly take an estimation of 7 cm for our situation. More precise value can be computed after performing a strip adjustment to the laser data. Preferably, quality descriptions will be delivered together with the laser data.

Interpolation errors are harder to predict, because they depend on whether the local situation between the laser points and the object point can be represented by a planar surface. Looking at the construction of road objects, the assumption that the laser points and the 3D boundary lie on a planar surface is quite correct. But, as we have seen in chapter 3, situations exist with large areas with no laser data. In that cases a plane has been fitted through points that might lie 15-25 meters from the object point. If there are less than 8 points in a radius of 25 meter, then the height of the object point will be interpolated through its neighbouring object points. Doing so, we showed that we can bridge gaps of more than 70 meter without laser points. In these cases interpolation errors are closer to 1 meter than 10 cm.

The boundary of terrain objects can show larger distortions because the terrain near the boundary might not be correctly represented by a plane. If the terrain object connects to a road object, then the common boundary will be taken from the laser points on the road object[2], resulting in a better determination of the boundary.

Geometric and topologic constraints have been introduced to narrow the possibilities for 3D reconstruction. These constraints improve the reliability of the model, because it integrates object knowledge with data driven approach and therefore introduce data-independent information. Improvement of the vertical accuracy of boundaries can be made by increasing the point density of the laser data. This will decrease the size of gaps with no laser points, and it can decrease the radius around an object point for selecting laser data to fit a plane through. The latter will reduce the interpolation error in rough areas.

5.4.2. Surfaces

Quality of average heights of surface patches mainly depends on the systematic errors in the laser data for that area. For large areas this means that only the block error is of major influence. If the acquisition has been done under normal conditions, the systematic height error for large areas is in the order of 5 cm.
Locally the height variation is larger, because of the influence of a single laser point uncertainty, and the local terrain variations that could not be covered in the laser data.

Local height accuracy can be improved by using higher laser point density data. Then, the triangulated surface will represent the shape of the terrain with more detail, resulting in a more realistic model.

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[2] This constraint holds if the difference is less than 1.5 meter. If the difference is more, it is expected that the road object and terrain object are on different height levels, and do not connect in 3D.

6. Results of 3D acquisition method

6.1. Interchange “Prins Clausplein”

Interchange “Prins Clausplein” is a challenging infrastructural object to reconstruct. The presence of four height levels of highways causes many obstructed views, and many small road polygons. This results in several gaps in the laser data. Additionally, due to the weak reflectance of some (low) parts of highways (asphalt absorbs laser pulses) point density decreases to 1 point per 100 m^2, and in extreme cases 1 point per 400 m^2. These are the main reasons why this interchange is a challenging object.

In the following we show several screenshots of the 3D reconstructed model. The model has been reconstructed automatically, without manual intervention or editing. The operator only has to tune some parameters, e.g. concerning the size of small objects to be filtered, the size of the seed growing polygon as explained in 4.3.

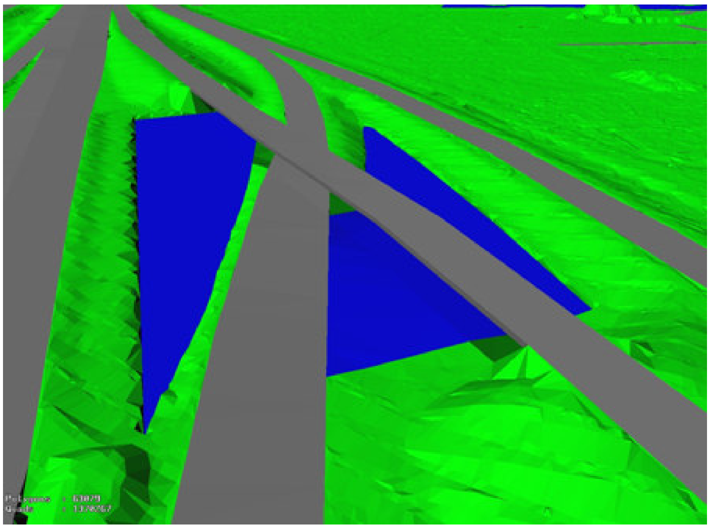


Figure 23 Simple interchange with lake objects.

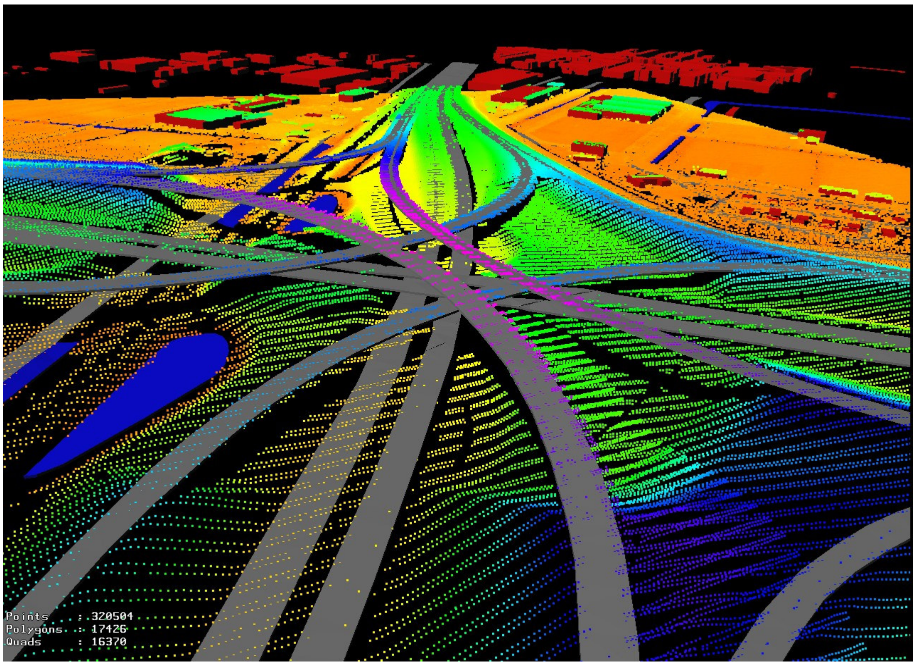


Figure 24 Laser points superimposed on 3D roads.

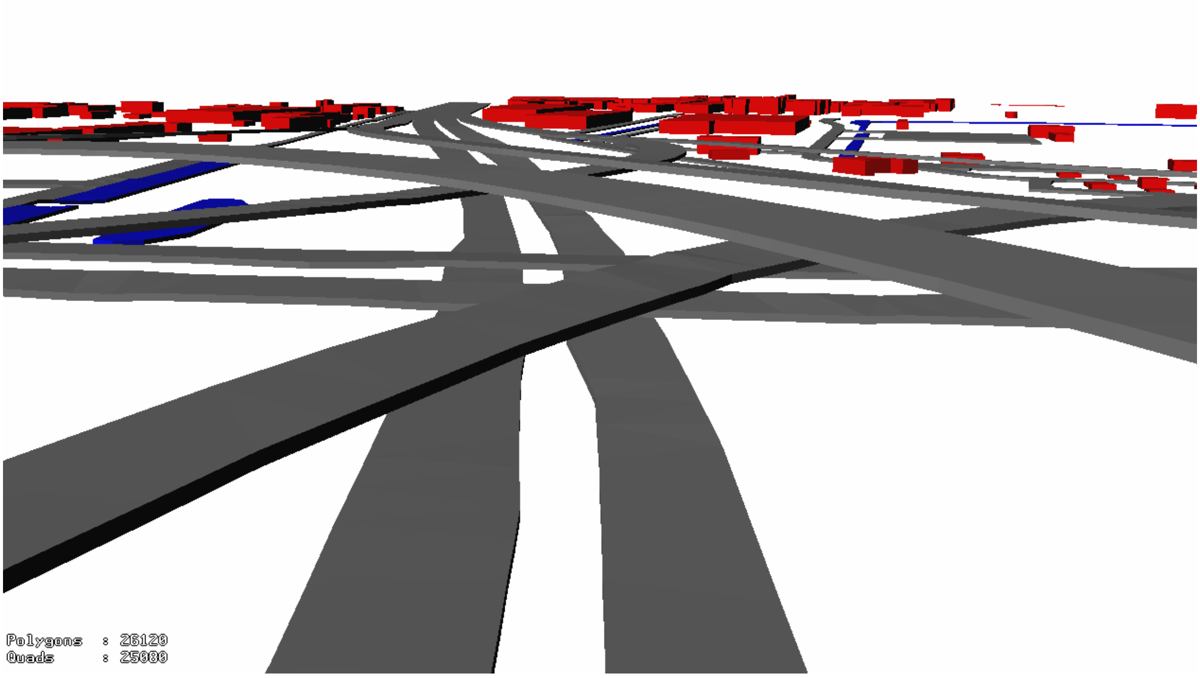


Figure 25 A closer look at four height levels.

6.2. Interchange “Waterberg”

In Figure 26 topographic map data and laser data are shown for interchange “Waterberg”, situated just a few kilometres north of Arnhem.

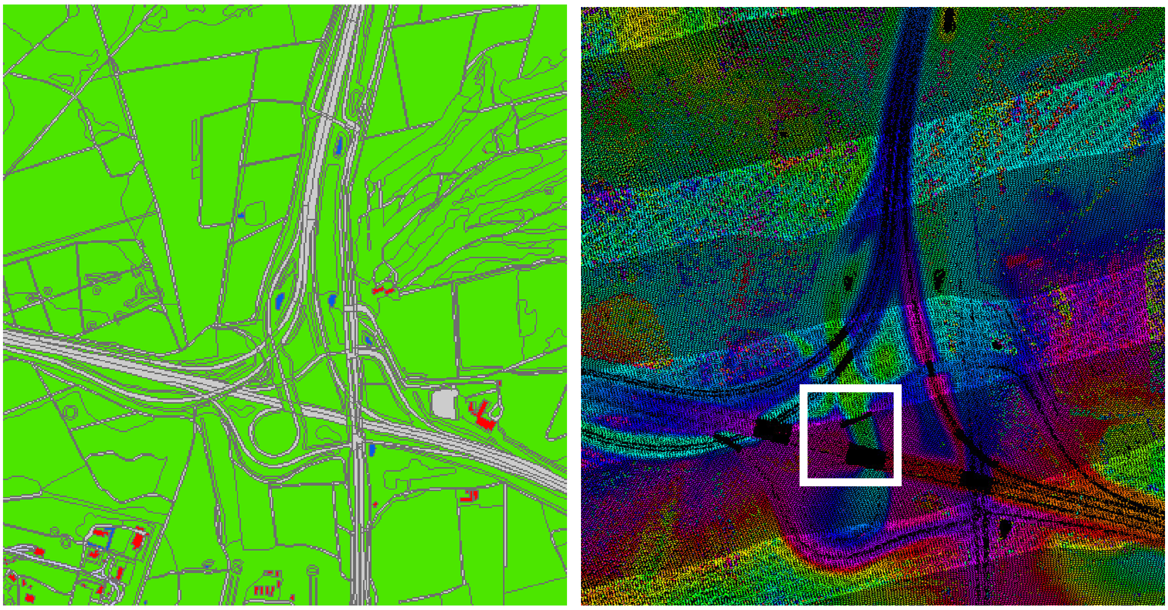


Figure 26 Input data sources of interchange "Waterberg"; topographic map TOP10NL (left) and AHN point cloud (right).

Remarkable in the laser data is the lack of laser points at interchanges, see Figure 27. These were filtered out by the flying company, on behalf of the Survey Department, who used the laser data for production of the AHN model. When processing the topographic map data, several sliver polygons caused problems by destructing the topologic relations. These sliver polygons were not visible at first hand, because they covered not more than 2 cm. These sliver polygons can easily be removed in software packages like ArcGIS.

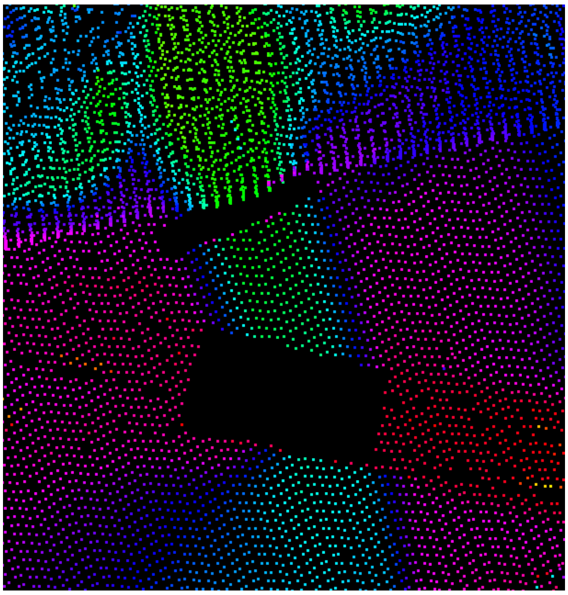


Figure 27 Lack of points on interchanges: some of the gaps cover more than 2000 m^2.

In the following several screenshots are shown for interchange “Waterberg”.

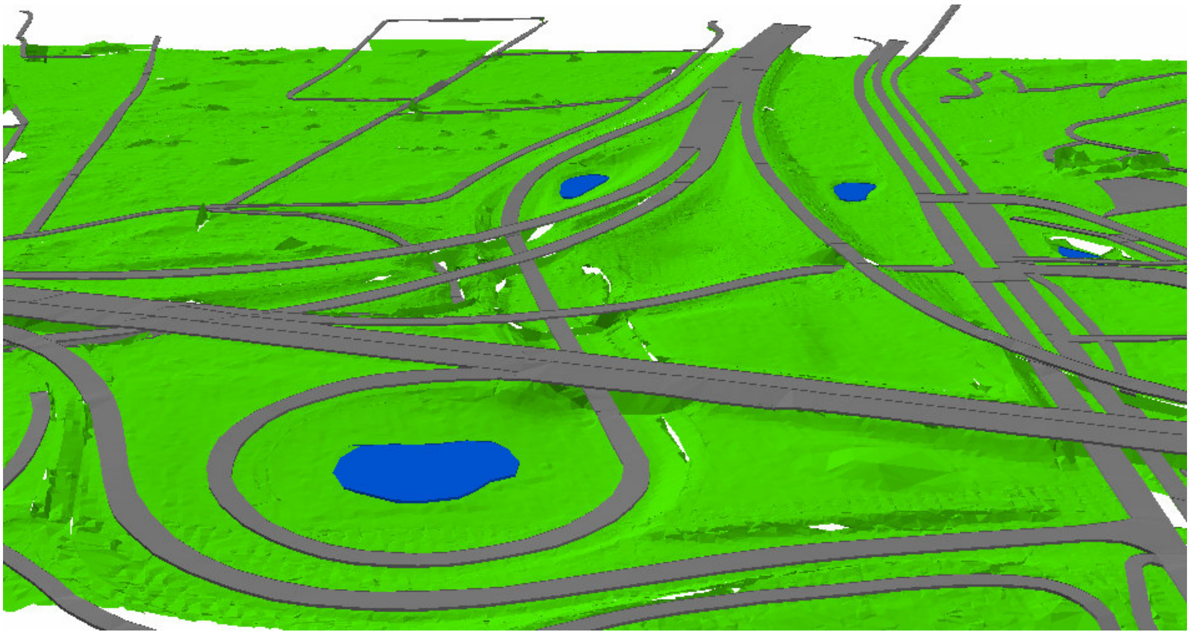


Figure 28 3D model of "Waterberg", looking northward.

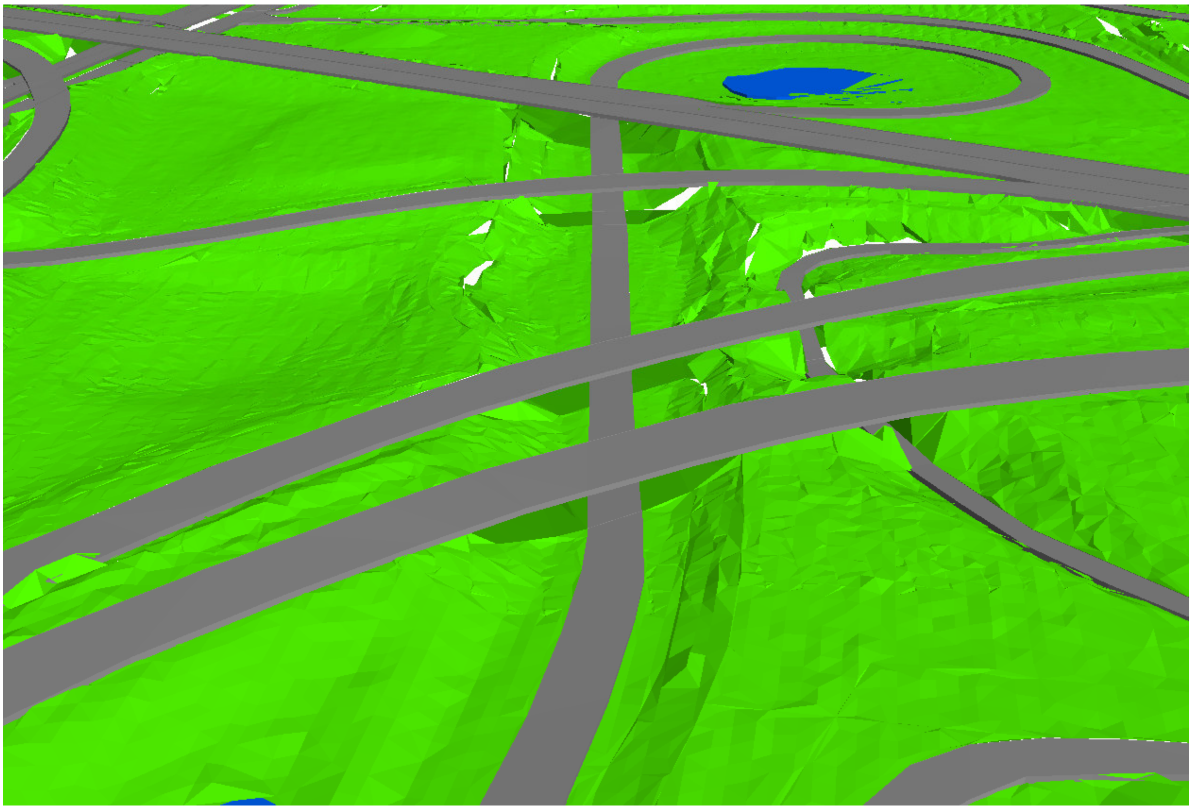
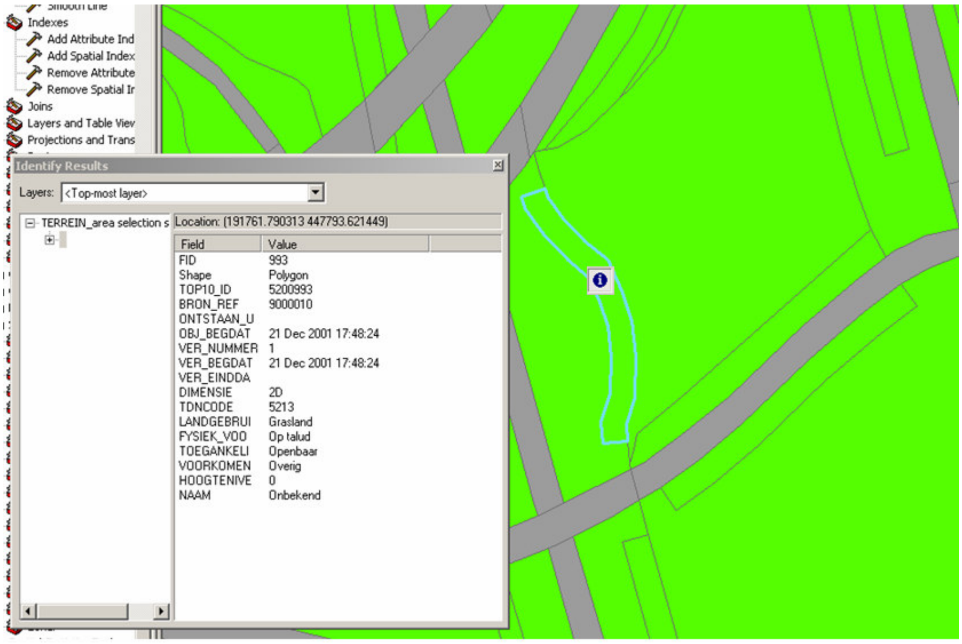


Figure 29 3D model of "Waterberg", looking southward.

At some locations in the terrain, gaps are visible in the 3D model. Most of these gaps are vertical gaps between two terrain polygons, as shown in Figure 30 and Figure 31. This happens when the height difference between the calculated heights from both sides of the boundary is larger than 1.5 meter. By default, this is the minimum value for recognising multiple height levels on topographic boundaries.



Location: (191761.790313 447793.621449)

Field	Value
FID	993
Shape	Polygon
TOP10_ID	5200993
BRON_REF	9000010
ONTSTAAN_U	
OBJ_BEGDAT	21 Dec 2001 17:48:24
VER_NUMMER	1
VER_BEGDAT	21 Dec 2001 17:48:24
VER_EINDDA	
DIMENSIE	2D
TDNCODE	5213
LANDGEBRUI	Grasland
FYSIEK_VOO	Op talud
TOEGANKELI	Openbaar
VOORKOMEN	Overig
HOOGTENIVE	0
NAAM	Onbekend

Figure 30 Terrain boundary within hilly terrain.

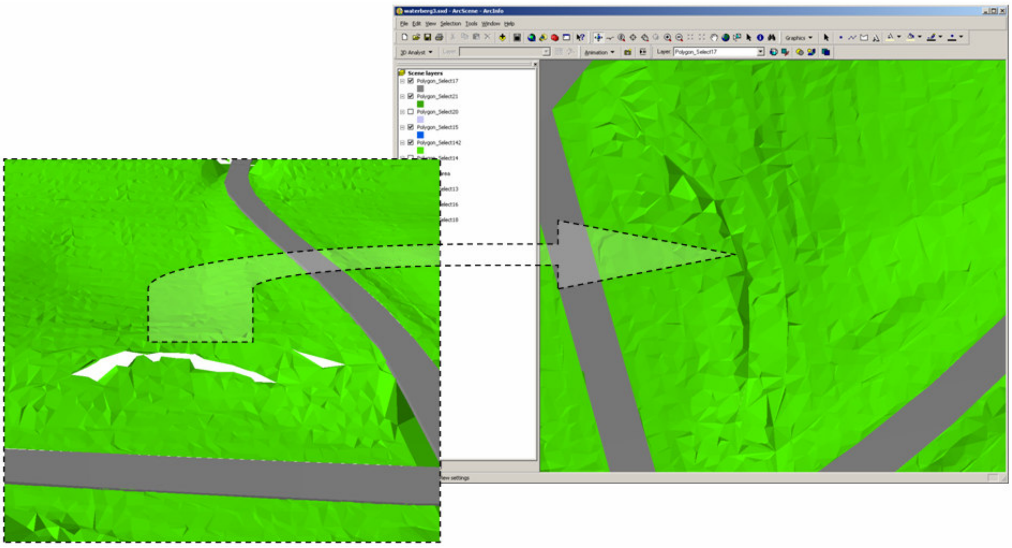


Figure 31 Oblique view on vertical gaps (left) and top view (right) on 3D model.

These kinds of failures can be avoided when removing these terrain-terrain boundaries by merging terrain polygons. One has to be sure that these polygons are on the same height level; this can easily be checked by the operator. Another solution is to adjust the constraints for these terrain-terrain boundaries. In Figure 32 the constraint of gluing two terrain boundaries together is set on 2.5 meter. For other topographic features it is still set on 1.5 meter.

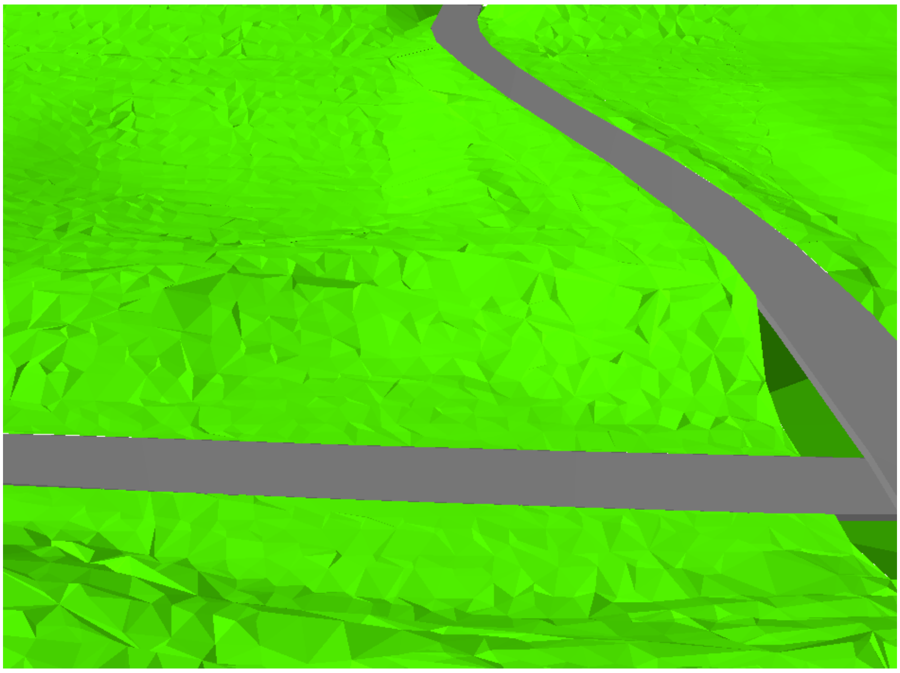


Figure 32 Boundaries between two terrain object are merged if the height difference is below 2.5 meter, instead of (default) 1.5 meter.

7. Conclusion and Future work

7.1. Conclusion

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. A combined map and laser growing algorithm has been developed to merge road polygons that are connected in 3D, and the accompanying laser points are assigned to that polygon. Occluded road parts are created automatically when two roads cross in 3D. 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.

7.2. Future work

Next, focus will be on the detailed reconstruction of buildings, by fusing higher point density laser data with large scale topographic maps. Reconstructing buildings is a challenging task in modern photogrammetry. To correctly capture the 3D shape of buildings, one has to reconstruct roofs, dormers, walls and details on or at the building. This challenge will be part of the PhD research in 2007 and 2008.

8. Literature

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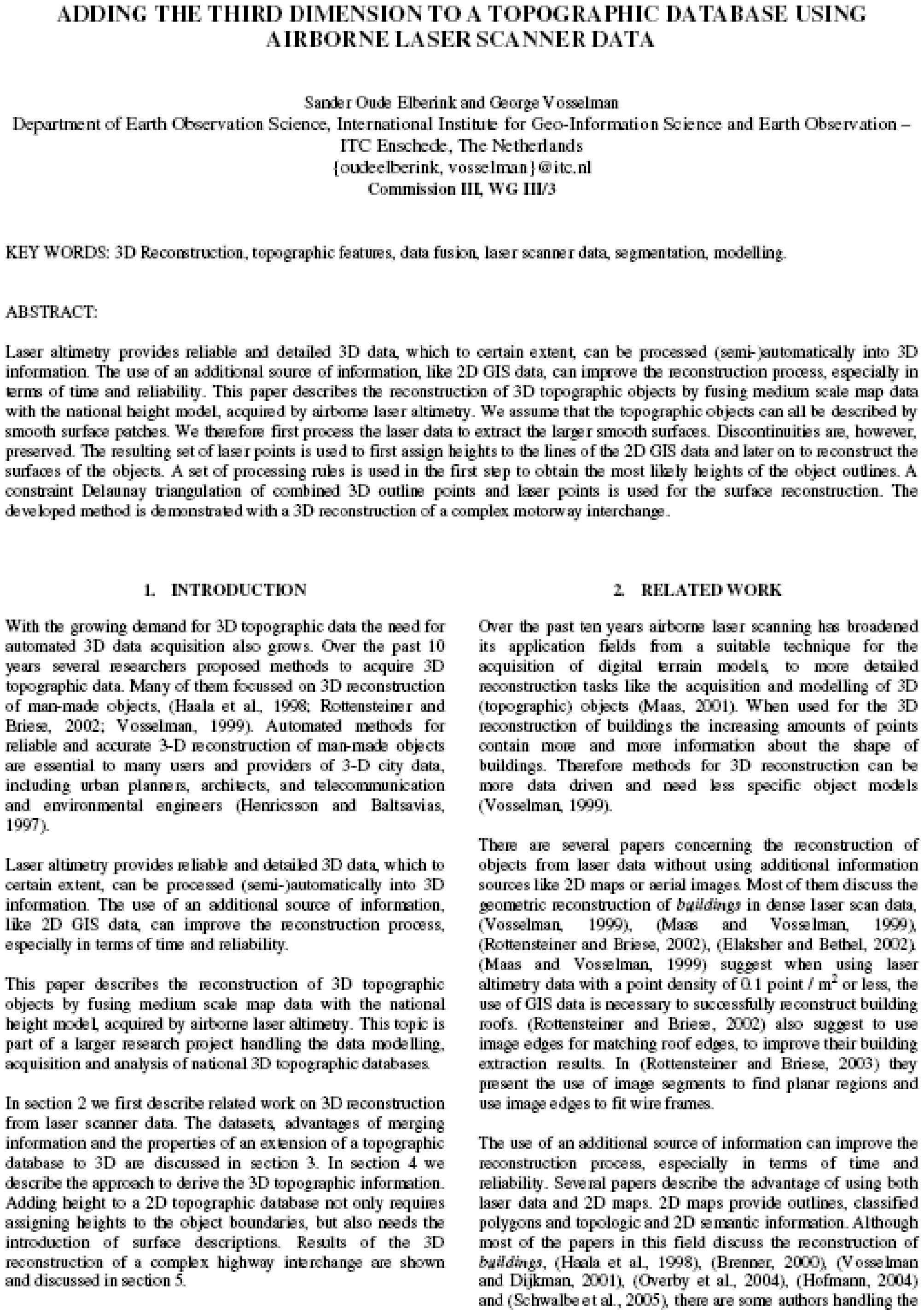
Appendix A: Adding the third dimension to a topographic database using airborne laser scanner data[3].



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

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KEY WORDS: 3D Reconstruction, topographic features, data fusion, laser scanner data, segmentation, modelling.

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

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[3] Presented at ISPRS symposium Commission III, Bonn Germany, 20-22 Sep 2006

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).

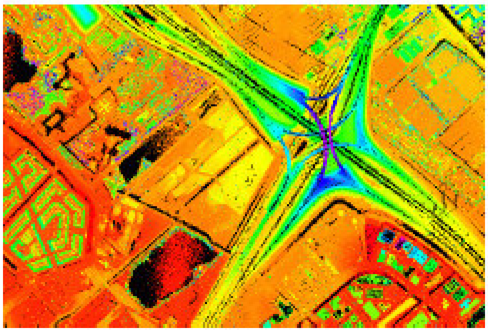


Figure 2: Colour coded AHN elevation data of the study area.

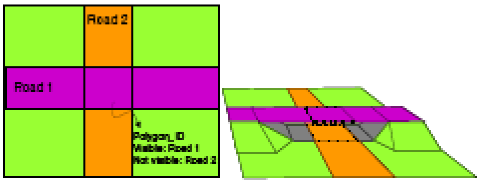
3.2 Data fusion

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.



a) b)

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.

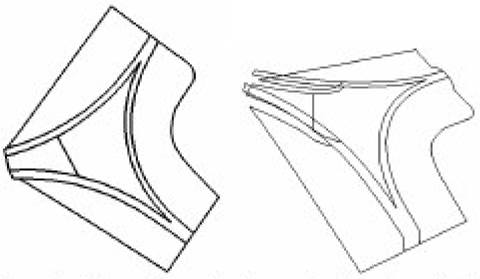


Figure 4: 2D map lines of a few road and meadow objects (left) and perspective view on the reconstructed 3D object boundaries (right).

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.

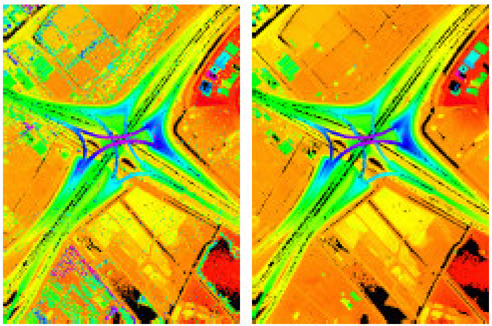


Figure 5: Laser scanner data before (left) and after (right) the removal of small segments. Black areas contain no laser points.

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.

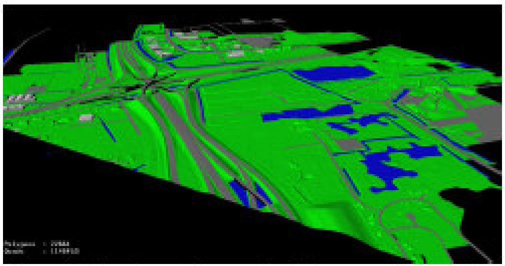


Figure 7: Overview of reconstructed scene with complex infrastructural objects.

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.

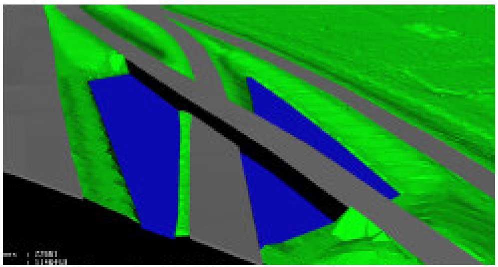


Figure 8: Reconstructed interchange, together with water and meadow objects.

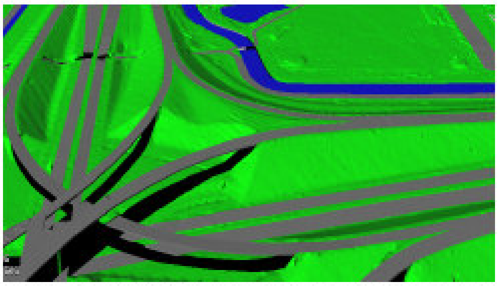


Figure 9: Result for the reconstruction of the body of the flyover, and the flying roads.

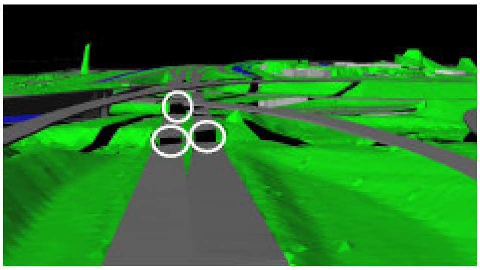


Figure 10: Holes due to hidden object parts and lack of suitable laser points. The white circles show the locations of three holes.

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.

ACKNOWLEDGEMENT

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Appendix B: 3D Modelling of topographic objects by fusing 2d maps and lidar data[4].

3D MODELLING OF TOPOGRAPHIC OBJECTS BY FUSING 2D MAPS AND LIDAR DATA

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KEY WORDS: 3D modelling, topographic features, data fusion, laser scanner data, segmentation

ABSTRACT:

In the past few years the number of applications that use 3D information of topographical objects increased rapidly. With the growing demand for 3D topographic data the need for automated 3D data acquisition also grows. Height information can be extracted from airborne or terrestrial acquisition methods, but can also be modelled as implicit semantic information. Adding height information to existing features is insufficient; additional features have to be acquired and existing features might get an extra dimension (surfaces can be converted to volumes, etc). The challenge is to produce semantical, geometrical and topological correct 3D topography. In this paper we describe the steps to acquire 3D topographic information. Special attention lies on the user requirements of 3D models. These requirements have been accomplished by information analysis at four major geo-information organizations in The Netherlands. The four cases describe the wishes and requirements for 3D data and modelling. The most important acquisition task is the modelling of 3D infrastructure and 3D building models. In this paper we will focus on the modelling of 3D infrastructure in general, and specially the reconstruction of hidden infrastructural object parts. The developed method will be demonstrated with a 3D reconstruction of the complex motorway interchange 'Prins Claus Plein' near The Hague, The Netherlands, with multiple infrastructural objects crossing each other at different height levels. Although the focus in this paper will lie on the modelling of 3D infrastructure, the presented 3D map includes the modelling of topographic features completely covering the terrain.

1. INTRODUCTION

In the past few years the number of applications that use the 3D information of topographical objects increased rapidly. Examples can be found in location based services, virtual reality tasks, visualisation for city planning, etcetera. These applications require 3D topographic input data. Acquiring 3D topographic information is even more complicated than 2D data.

With the growing demand for 3D topographic data the need for automated 3D data acquisition also grows. 3D data acquisition and object reconstruction is conventionally performed using stereo image pairs. Photogrammetry is a classic, accurate and operational approach for 3D data acquisition (Tao, 2005). However, the automated reconstruction of buildings using only aerial images as data source has been proven to be a very difficult problem (Suveg and Vosselman, 2004).

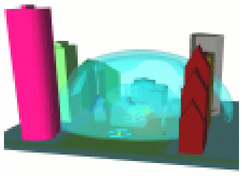

Figure 1 Example of a 3D modelling application.

The use of laser altimetry as data source for the (semi-) automatic reconstruction has been described by several authors (Brenner, 2000; Elaksher and Bethel, 2002; Maas, 2001; Vosselman and Dijkman, 2001), and shows great potential to reliable 3D surface modelling. Some of them use additional information, like 2D GIS data, in one or more steps of their methods.

Correctly combining height information with existing 2D maps has a great potential for a fast, accurate and highly automated acquisition of 3D maps. Several papers describe the advantage of using both laser data and 2D maps (Brenner, 2000; Haala et al., 1998; Hatger and Brenner, 2003; Hofmann, 2004; Koch, 2004; Rottensteiner and Briese, 2002; Vosselman and Dijkman, 2001). Topographic maps provide outlines, classified polygons and topologic and 2D semantic information. The purposes for integrating map data and laser data ranges 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 3D maps it should be possible to acquire multiple topographic features at one and the same 2D location (e.g. tunnels, flyovers, etc). Height information can be extracted from airborne or terrestrial acquisition methods, but can also be modelled as implicit semantic information. Adding height information to existing features is insufficient; additional features have to be acquired and existing features might get an extra dimension (surfaces can be converted to volumes, etc).

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[4] Presented at ISPRS Symposium Commission IV, Goa, India, Sep. 25-30, 2006.

When aiming for fully 3D models, the volume below and on top of the object surface has to be modelled. Not only does this mean that acquisition of multiple cartographic object types at one location is possible or necessary at interchanges, bridges etc, but it also means that vertical object planes have to be acquired. Existing 2D objects that indicate height information have to be revised. In [Penninga, 2005] a summary is given of some representations of height information: height contours, shadowing, hatches to indicate height differences at banks and dikes. If the user really can explore the third dimension some of these objects will become superfluous.
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.

The topic of this paper is twofold. Special attention lies on the user cases of 3D models. These cases have been accomplished by information analysis at four major geo-information organizations in The Netherlands. The cases describe the wish and requirements for 3D data and modelling, added with a list of scientific activities to fill the gap between the wishes and reality. These user cases have been highlighted in chapter 2. Second issue is describing one of the first research activities: the modelling of 3D infrastructure. In this paper, chapter 4, we will focus on the modelling of 3D infrastructure in general, and specially the reconstruction of hidden infrastructural object parts.

2. USER CASES

In our research project we defined and analyzed four user cases. Each user case represents the 3D model requirements of one specific organization to perform their 3D modelling and visualization tasks.

2.1 Survey department of Rijkswaterstaat

Rijkswaterstaat is responsible for the maintenance of national highways and waterways, including bridges, dikes and the navigability of canals. Geo-information of these infrastructural objects has been acquired at several scales, using several spaceborne, airborne, terrestrial and hydrographical measurement techniques. Rijkswaterstaat focuses on improving the acquisition, storage and distribution of their geo-information data. To successfully offer their web based geo information services and applications, Rijkswaterstaat is looking for the optimal production of 2, 2.5 and 3D geo-information. Their focus is on the large scale topography of infrastructural objects and the medium scale landscape modelling and visualization.

2.2 Municipality Den Bosch

Den Bosch aims for the production of a large scale 3D GEO database to inform citizens and to support other departments for real estate taxes, city planning, noise modelling etcetera. Their main motive for acquiring 3D data is to model and visualise the “as-is” situation. Den Bosch has many situations with multiple land use, like shown in Figure 2. At the moment they have to store these multiple classifications in multiple 2D layers, which makes it hard to perform 3D modelling and visualisation tasks.

Figure 2 Multiple land use at one location: buildings on top of a canal.

Their list with 3D model requirements starts with the modelling of shapes of buildings, followed by the possibility to store and analyse multiple objects on top of each other. Research activities have been determined in the field of semi-automatic reconstruction of buildings, using high point density airborne and terrestrial laser scanner data together with a large scale base map (scale 1:1000). These activities will be carried in 2007 and 2008.

2.3 Water boards

For the inspection and maintenance of regional dikes, bridges and waterways, the water board needs up-to-date and reliable geo-information. For several applications, e.g. when combining topography with hydrological, geological and geotechnical information, it is necessary to use full 3D topographic information. At the moment most of the water boards use large scale 2D base maps and high point density laser data separately from each other. Integration has been done visually by the user: information from one source can be used to better interpret the other. Requirements for a 3D model is that breaklines, e.g. on top and at the bottom of a dike, are modelled with high precision. Breaklines are important features for the condition (shape and strength) of dikes. The reconstruction of breaklines from laser scanner data has previously been described in (Briese, 2004). Our research activities are planned for 2007 and will focus on the integration of existing 2D maps and high point density laser scanner data, using a full 3D model data structure (e.g. a TEN structure), as described in (Penninga, 2005).

2.4 Topographic Mapping Agency

The Topographic Mapping Agency of the Dutch Cadastre produces national 2D topographic databases from scale 1:10.000 to 1:250:000. Users can be found in several public and private sectors in the Netherlands. To come to meet the growing 3D desires of the users, the Mapping Agency would like to implement the third dimension to their products. They participate in this research project by providing data and by helping to translate user requirements into research activities.

In the remaining part of the paper we will focus on the user case of the Topographic Mapping Agency as described in 2.4.

3. DATA PROPERTIES

The Topographic Mapping Agency aims to integrate the third dimension into their medium scale (1:10.000) topographic map, called the TOP10vector. In this chapter a description is given of the TOP10vector and the laser data set used in this project.

3.1 Topographic map

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 databases has been built 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 3.

Figure 3 The study area in the TOP10vector database.

One property of the TOP10Vector is that a polygon can have more than one classification, including the information whether this class is visible from above or not.

3.2 Laser data

The national elevation 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.
In the first step of data fusion it will be decided which parts of the laser data will be used to provide height information to which part of the 2D map. This is one of the most crucial steps in the automation of the reconstruction process. The easiest way to select the laser data is just to perform a points-in-polygon function, where the outlines of the grouped 2D objects act as polygons. In the ideal case this is enough to select the right points. However, in many cases not all laser points represent height information of the topographic object, but may indicate height of details of this object, e.g. a laser point can lie on a chimney instead of the roof, or on a car instead of the street. An important step of the selection is segmenting the point cloud, according to the rules and conditions of the object (group).

As described in more detail in (Oude Elberink and Vosselman, 2006), laser data has been filtered in a segment based approach to eliminate laser points on small objects like cars, light poles, traffic signs, and trees.

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.

4. APPROACH

4.1 Surface modelling

Some aspects of the 3D reconstruction are independent of the data source. Important examples are the type of surface representations and object modelling. One way to represent the terrain given by a set of surface points is to construct a Delaunay Triangular Irregular Network (TIN). In (Verbree and Oosterom, 2003) a surface reconstruction method has been described, based on the Delaunay Tetrahedronised Irregular Network (TEN), which tessellates the 3D-space with non-overlapping, adjacent, tetrahedrons. In this part of the research the surface is represented in a TIN structure; at a later stage a TEN structure will be used to be able to model volume objects.

4.2 Data fusion

Laser data and 2D map data are integrated and processed in an object-based approach. For groups of objects rules for 3D reconstruction are being set-up. These rules have to ensure the geometrical, topological and semantical correctness of the 3D map. Adding height information to existing 2D features is not sufficient; additional features have to be acquired and existing features might get an extra dimension. Examples are given showing the automated generation of additional polygons at real 3D objects like viaducts and flyovers. Road objects at those locations will be converted automatically from surfaces to volumes, in order to get realistic 3D data.

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.

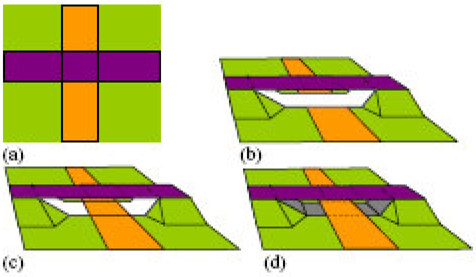

Figure 4 Creating new objects: interchange in 2D (a); height given to 2D features (b); connecting lower road parts (c); filling gaps (d).

Figure 4 illustrates four stages in the reconstruction process, starting with the 2D situation in (a) and ending with the 3D situation in (d). In (b) heights have been calculated at boundaries of visible objects, followed by the height determination of 'invisible' objects in (c). In the next part of this chapter we will describe the 3D modelling of existing object boundaries in 0, creating new parts that did not exist in 2D, but are necessary in 3D to get a tight surface model (4.4 and 4.5).

4.3 Modelling 3D boundaries

As shown in Figure 4a-b, 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 boundaries, 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. Every map point belongs to two or more polygons. In each of the neighbouring polygons laser data is selected to calculate the height at the map point, see Figure 5. Laser data has been filtered to remove small objects like cars and traffic signs. By calculating multiple heights at every map point, height discontinuities can be detected and modelled. Several constraints have been introduced to get a topological correct model, see (Oude Elberink and Vosselman, 2006).

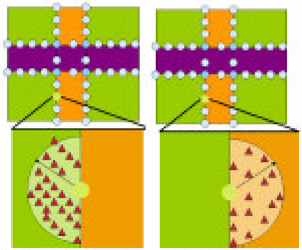

Figure 5 Calculation of map point height, from grass land (left) and road object (right).

In figure 6 results are shown for the modelling of 3D boundaries of a simple crossing. The 3D map points have been visualised as small red dots. Note that the density of map points is much higher in the 3D model than in the 2D map.

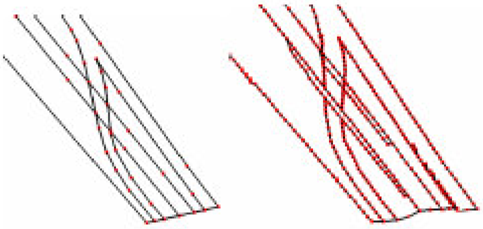

Figure 6 Oblique view on boundaries of crossing roads in 2D (left) and the 3D boundaries (right).

4.4 Connecting road parts

As we can see in Figure 4b gaps will occur when only modelling visible map features. Additional features have to be created under bridges and interchanges. The first step in filling the road gaps is the reconstruction of polygons marked as 'invisible', like in Figure 4c. Although it is likely that no laser points may be available, constraints in the model can fill the gap and connect two parts of the model in 3D. The modelling of the invisible polygons is accepted if the nodes successfully fit to potential neighbouring polygons. Successfully means that the reconstructed polygon is smooth and connect to neighbouring road parts. Planes have been fitted through laser points and 3D map points on those neighbouring road parts. At the centre point of the missing polygon, the height of each plane has been determined. If the heights of the planes at the centre point coincide within a certain threshold, the reconstructed polygon will be accepted. With this method also slanted 'invisible' roads will be reconstructed correctly.

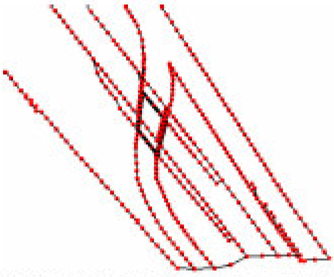

Figure 7 Polygon connecting two lower road parts, shown as bold polygon.

4.5 Completing surface model

After the previous step many other gaps remain at both sides of the 'invisible' polygons, as can be seen in Figure 4c. These can be filled by creating new polygons, which have the 2D shape (and topology) of the road polygons lying above them. The heights of the new nodes are determined by searching for map points at neighbouring polygons that lie on the ground surface. Doing so, these new polygons are connected to lower neighbouring polygons, like in Figure 4d.

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 terrain objects show some relief at its surface. Laser points lying on the terrain (i.e. not on buildings, roads, trees, water) are used as nodes in the surface TIN model. To get a smooth surface at road objects, map points at road boundaries have been used to generate a constrained TIN model, without adding laser points lying on that road. Trees and buildings have not been modelled in this part of the research project.

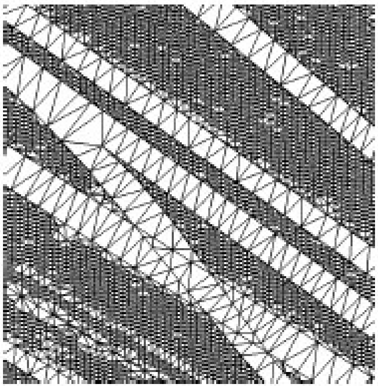

Figure 8 Constrained TIN model with roads and grass land.

5. RESULTS

5.1 Project results

In Figure 9 and in Figure 10 results are shown for the fusion of a medium scale topographic map (TOP10Vector) with laser data with a point density of one point per five m^2 (original dataset of part of the AHN). The developed method is demonstrated with a 3D reconstruction of the complex motorway interchange 'Prins Claus Plein', with multiple infrastructural objects crossing each other at different height levels.

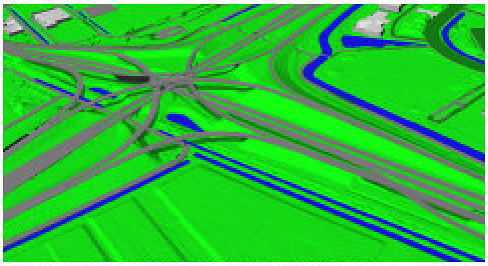

Figure 9 Reconstructed model of Prins Claus Plein.

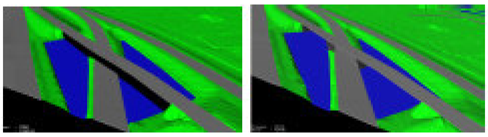

Figure 10 3D Modelling of existing polygons (left); with additional features (right).

The major disadvantage of the proposed method is the strong dependency on the quality of the 2D map. In Figure 11 five of many missing polygon edges are highlighted. Due to the lack of 2D edges, it is impossible to automatically reconstruct the accompanying 3D edges. In a later stage of the project a semi-automated approach will be introduced to be able to intervene in the reconstruction process.

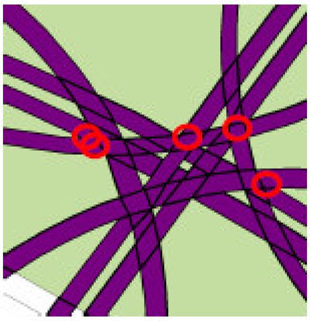

Figure 11 Several polygon edges missing in 2D map at complex interchange.

Another disadvantage is the possible time difference between the acquisition of the map data and in the laser data, resulting in two different recorded situations.

5.2 Applications

During the modelling of the scene the user can choose to derive several supplementary products. One side product can be a Digital Terrain Model (DTM), instead of a Digital Surface Model (DSM). Objects located above or on top of the surface can easily be left out when deriving a DTM from the laser point cloud. Doing so, this DTM excludes 3D objects like buildings, trees and interchanges but includes semantically correct break lines at topographic features; Figure 13 shows the DTM in which 3D objects have been filtered from the laser point cloud (Figure 12).

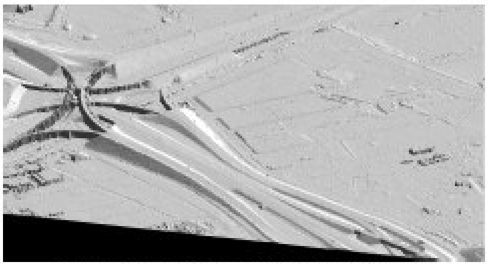

Figure 12 TIN of laser points at Prins Claus Plein.

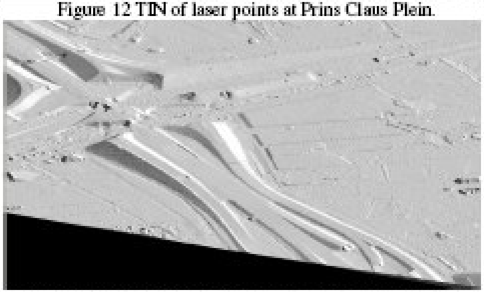

Figure 13 DTM of Prins Claus Plein, derived by filtering 3D objects.

Several producers of 2D topographic maps struggle with the implementation of the third dimension, as we have seen in user case 4 (chapter 2.4). One barrier is the increasing amount of data when adding laser points as nodes on the 3D surface, the other is the change of the products' topologic structure. The first step to implementation could be the determination of the height of map nodes, which can be derived from the 3D boundaries. By doing so, the topology of the map does not have to change, and the laser points have only been used to determine the height, but are not part of the end product. This 3D boundary product gives the user height information at nodes of the 2D map. However, when visualising 3D maps the 3D surfaces have to be triangulated. This implies a change of the topological structure of the product.

Several software packages can be used to further process 3D topographic objects. To give an eye-catching example, recently Google Sketchup became available for free, allowing basic handling and editing of 3D data for a large group of users. When exporting to Google Earth this 3D data can easily be visualised and distributed, as shown in Figure 14.

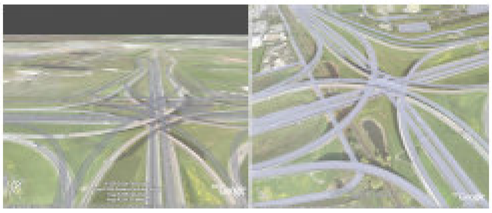

Figure 14 Road objects imported in Google Earth.

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. We've added missing polygons to hidden objects to get a tight surface model.

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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