3D Topography acquisition
Literature study and PhD proposal

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RGI 3D Topo – DP 1-4
Status: definitive

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1. Introduction

1.1. Background

This PhD-project is part of a bigger project, called 3D Topography, which covers the entire geo-information process on 3D data, from data collection, modelling and analysis (in an explicit data structure) to visualization and interaction (with emphasis on virtual reality interaction). This research is funded by the Bsik Programme Space for Geo-Information, and carried out by a consortium of project partners. Research activities will be done at the OTB department of TU Delft (Peter van Oosterom, Friso Penninga and Edward Verbree) and EOS at ITC Enschede (George Vosselman and Sander Oude Elberink). Besides these research groups, the consortium also consists of TD Kadaster and AGI Rijkswaterstaat, as they produce relevant data sets for this project. Oracle and NedGraphics complete the consortium with their knowledge and strength to implement research results into products.

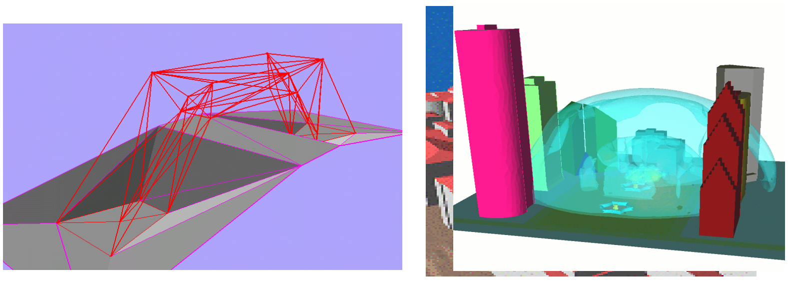


Figure 1 Result of acquisition (left), modelling (middle) and analysing 3D Topography (right).

Acquisition of the topographic data in general can be divided in multiple steps. After data collection, raw data has to be transformed, interpreted, filtered, classified, combined and/or generalized in order to get topographic information. Photogrammetric and terrestrial techniques used for the production of national topographic databases are very labour-intensive and (thus) expensive. Acquiring 3D topographic information is even more complicated. 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. 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]. Two main streams can be distinguished among them: the image-based approach and the laser altimetry-based approach. Some of them use additional information, like 2D GIS data, in one or more steps of their methods.

1.2. Goal

The first goal of this report is to give an overview of 3D reconstruction methods published in the past 10 years. This topic has been described in the first part of the report:

Part 1: Literature study on State of the art 3D Topography acquisition techniques.

An additional goal is to describe research effort that still has to be done in the field of automated 3D topographic data acquisition. This effort will eventually be translated in a detailed Phd proposal 'Acquisition of 3D topography' and carried out by the author of this report. The research activities described here will connect to the other activities carried out in the "3D Topography" project, especially to the research activities at TU Delft.

Part 2: PhD Proposal Acquisition of 3D topography.

1.3. Structure

In chapter 2 a global overview of the literature used in this report is given, followed by a detailed literature description in chapter 3, answering the first research question. Chapter 4 will present a rough version of the Phd research work to be carried out at ITC in the RGI 3D Topography project.

2. Literature

2.1. Platforms of relevant literature

Literature study has been carried out to get an overview on the state-of-the-art techniques of 3D data acquisition. Because this research topic is relatively new, most of the literature has been found in presented papers, rather than in books.

2.1.1. Journals

Presented by Elsevier, ScienceDirect contains a long list of science technology full text and bibliographic information. Besides online reference works, handbooks and book series ScienceDirect contains a journal collection of over 2,000 titles. In this report we used ScienceDirect to select papers from the following Journals:

- Computers, Environment and Urban Systems
- International Journal of Applied Earth Observation and Geoinformation
- International Journal of Geographical Information Science
- ISPRS Journal of Photogrammetry and Remote Sensing

2.1.2. Proceedings

Many of the papers have been presented at ISPRS events, or ISPRS-related events. At these events presentations are grouped into sessions. Relevant papers can be found in sessions like “Building reconstruction”, “Object extraction”, “Mapping”, depending on the choice of the organising committee and the presence of a sufficient number of related papers to fill the session.

Congresses:

- XIX ISPRS Congress, 2000, Amsterdam, The Netherlands
- XX ISPRS Congress: Geo-Imagery Bridging Continents, 2004, Istanbul, Turkey

Symposia:

- Photogrammetric Computer Vision, 2002, Graz, Austria

Workshops:

- “3-D reconstruction from airborne laserscanner and InSAR data”, 2003, Dresden, Germany
- “Laser scanning 2005”, Enschede, The Netherlands

Others:

- Workshops on Automatic Extraction of Man-Made Objects from Aerial and Space Images, 1999/2001/2003, Ascona, Switzerland
- WSCG '98 : the 6th international conference in Central Europe on computer graphics and visualization, 1998, Plzen-Bory, Czech Republic.

- International Conference NATSCAN "Laser-Scanners for Fores and Landscpae Assessment – Instruments, Processing Methods and Applications, ISPRS working group VIII/2, 2004, Freiburg im Breisgau, Germany.

Most of the proceedings of recent ISPRS events are available online at:
http://www.isprs.org/publications/archives.html

2.1.3. Books/Manuscripts/Theses

The following books and theses have been used to quote or to get inspired.
PhD theses: [Brenner, 2000], [[Rottensteiner, 2001], [Sithole, 2005], [Stoter, 2004], [Suveg, 2003].
Msc thesis: [Simonse, 2000]

Book: Large-scale 3D Data Integration, edited by S. Zlatanova and D. Prosperi.

2.2. Related fields

To prevent specialising too much in an early stage, it is wise to look around in adjacent working fields. Several working fields deal with (parts of) 3D Topographic data acquisition. Among others:

- Photogrammetry
- Computer vision
- GIS technology
- Surveying
- Urban planning
- Industrial engineering
- Environmental engineering
- Architecture
- …

Although the technical terms and ideas about object reconstruction might differ between these fields, integration of knowledge is likely to improve the quality of this research project.

2.3. Mind map

To relate interesting papers to research topics, a mind map has been made, see Figure 2. Mind mapping is one of many ways to visualise small details without losing the big picture. The mind map used here is in a simple tree-structure and is under continuous construction. The left-hand side of the figure is supposed to be related to, but not subject of, the acquisition of 3D Topography. The right-hand side covers the literature discussed in this report.

Figure 2 Overview relating literature to research topic.

3. State-of-the-art 3D acquisition techniques

3.1. Introduction

In this chapter an overview is given of object reconstruction techniques, based on a literature study. Object reconstruction can be split up in two main activities: object detection and object reconstruction. Object detection can be seen as a preparation step before the geometric reconstruction. Object detection can be done manually where operators determine the corner points of an object, or can be done (semi-) automatically based on assumptions about the shape, size, colour, texture etcetera of the object. Besides geometry semantics has to be added to the object. Two main streams can be distinguished: the image-based reconstruction approach (see 3.2) and the laser altimetry-based approach (3.3). Some of them use additional informationand, like 2D GIS data (3.4) or aerial images (3.5), in one or more steps of their methods.

3.2. Image based approach

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 [Vincent 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]. Many researchers have tried to improve the automation of object recognition and reconstruction from images. Some approaches need the manual measurements of object points, like in [Fu and Shan, 2004] and [Zlatanova et al., 1998]. They focus on finding topology and reconstructing the building automatically. [Henricsson and Baltsavias, 1997] combine matching of planar patches in multiple images with spectral properties along the patches' boundaries. [Suveg and Vosselman, 2004] and [Pasko and Gruber, 1996] use 2D maps to reduce the complexity of the object reconstruction by introducing the simplicity of the map. Further improvement of the reliability of the result can found in restricting the shape of roof models. [Rottensteiner, 2001] describes a semi-automatic approach, where the operator can select CSG primitives from a database, and the software fits the primitive in a feature based matching procedure in the images. [Suveg and Vosselman, 2004] automate the selection of CSG primitives by determining the best fit of the building models corresponding to the building partitions.
Major disadvantage in the automatic reconstruction using aerial images is the complexity in suburban and densely populated urban regions in general due to connected buildings, shadows and occlusion situations [Henricsson and Baltsavias, 1997].
Despite the great research effort and the introduction of digital cameras, providing higher radiometric resolution, fully automatic model reconstruction based on images is still a problem hard to solve.

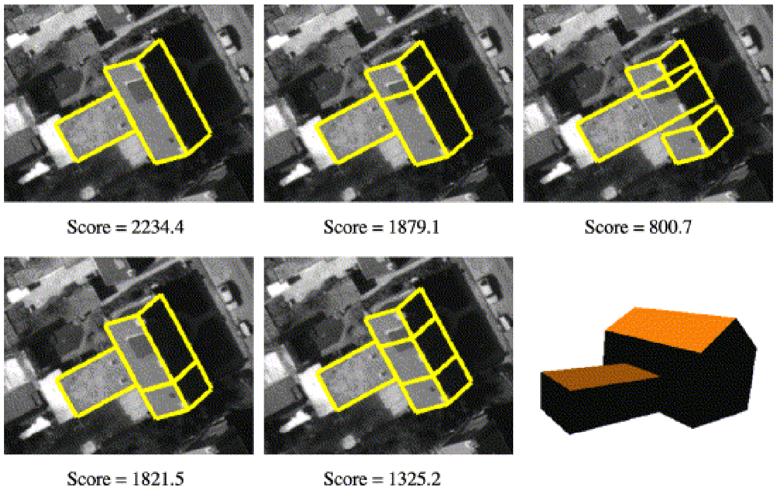


Figure 3 Building models corresponding to possible partitioning schemes and the 3D model of the best building model, [Suveg and Vosselman, 2004].

3.3. Point cloud based approach – without 2D maps

Originally being used as a powerful technique for the acquisition of data for digital terrain models, airborne laser scanning is meanwhile often referred to as a tool for adding the third dimension to GIS data, and to acquire data for a wide range of 3-D object modelling tasks [Maas, 2001].
The point densities obtained by airborne laser scanner systems are increasing rapidly. 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 many 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].

3.3.1. Vosselman, 1999

In [Vosselman, 1999] an approach is presented which is based on the detection and outlining of planar faces in dense height data. Planar faces have been detected by Hough-based plane extraction. In a connected components algorithm fragmented planes have been connected.

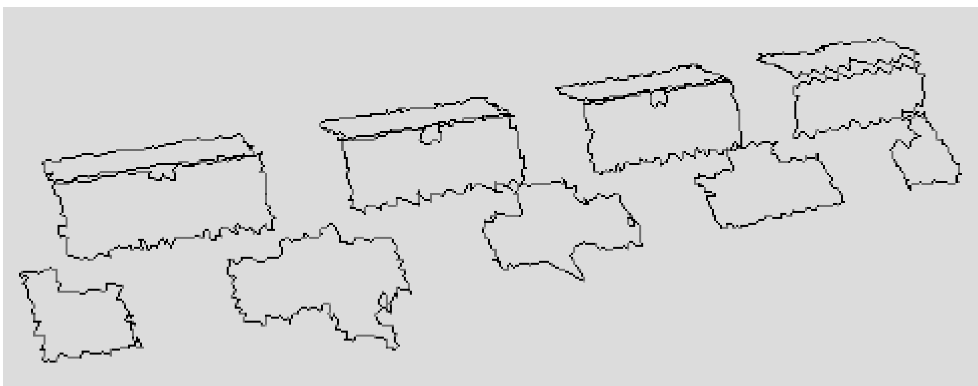


Figure 4 Roof faces detected by clustering and connected component analysis.

Ridges and valleys are detected by intersecting adjacent planes. Outlines of extracted planes are modelled as straight lines, restricted to be parallel or perpendicular to the main building orientation. In an iterative way outlines of the buildings are determined from the outlines of the planes.

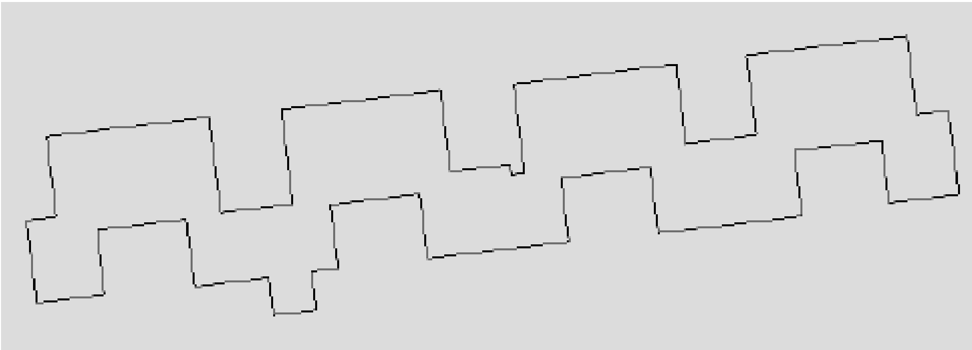


Figure 5 Extracted building outline.

After the reconstruction of the edges, they are merged to form the outlines of the roof faces. Finally, the model is completed by a reconstruction of the walls.

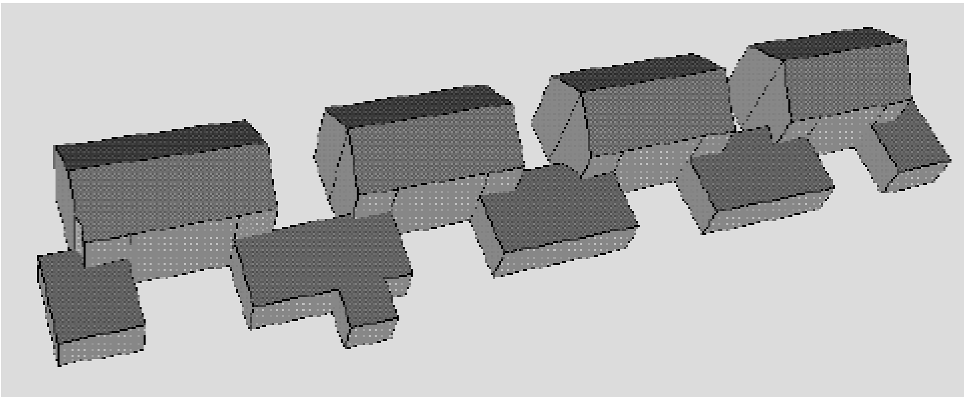


Figure 6 Results for four "two under one roof" type of houses.

3.3.2. Rottensteiner and Briese, 2002 & 2003

[Rottensteiner and Briese, 2002] present an approach where object points are separated from terrain points using an interpolation technique that creates a surface model (DSM) from a point cloud. Building regions are extracted by thresholding and texture analysis. In extracted building regions planes have been reconstructed and grouped to build 3D models. In a model adaptation step reconstructed models can be refined.

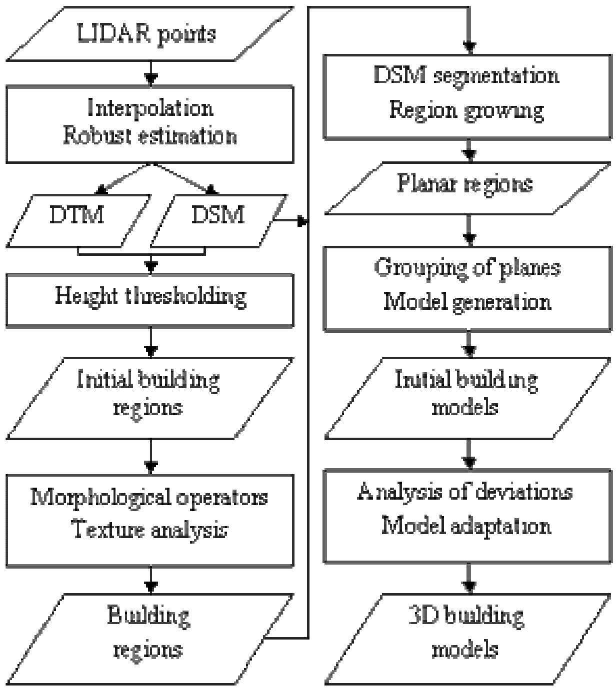


Figure 7 Work flow for building extraction from LIDAR data (source [Rottensteiner and Briese, 2002]).

The structure of the roofs is correctly resembled, but the intersection lines of neighboring roof planes are not yet computed correctly.

[Rottensteiner and Briese, 2003] improved the approach mentioned above by analysing the roof segments, looking for an intersection, a step edge, or both an intersection and a step edge.

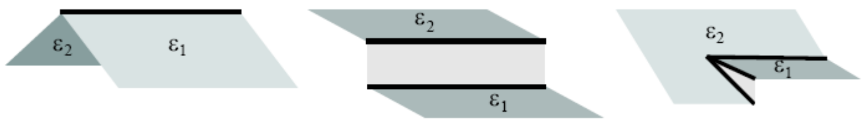


Figure 8 Mutual relations between two planes "1 and "2. Left: intersection. Centre: step edge. Right: intersection and step edge.

Also, geometric constraints on the consistence of buildings are proposed by performing an overall adjustment including available sensor information, parameters of the planes and vertices. Geometric constraints can be applied on lines, planes or combinations of them. Examples are restricting an object line to be horizontal, or two planes to be perpendicular.

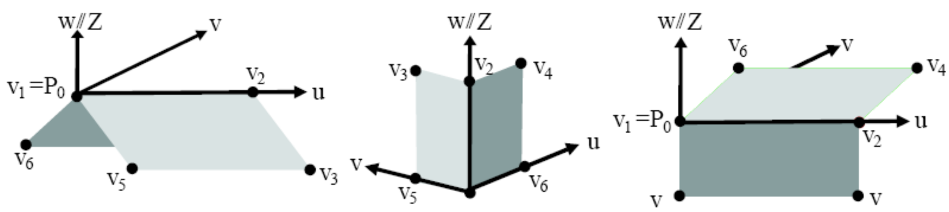


Figure 9 Three possible geometrical constraints between two planes "1 and "2. Left: a horizontal ridge. Centre: two orthogonal walls. Right: a horizontal eave.

3.4. Point cloud based approach using 2D maps

The use of an additional source of information can improve the reconstruction process, especially in terms of time and reliability. In this paragraph we will discuss the advantage of using both laser data and 2D maps, in 3.5 we will focus on the synergy between laser data and aerial images.

Although most of the papers in this field discuss the reconstruction of *buildings*, [Haala et al., 1998], [Brenner, 2000], [Vosselman and Dijkman, 2001], [Overby et al., 2004], [Hofmann, 2004] and [Schwalbe et al., 2005], there are some authors handling the reconstruction of *other topographic objects*, like roads in [Vosselman, 2003] and [Hatger and Brenner, 2003], roads and lakes in [Koch, 2004], or unclassified break lines [Briese, 2004].

3.4.1. Haala, Brenner and Anders, 1998; Brenner, 2000

[Haala et al., 1998] describe a method that combines height data provided by airborne laser scanning and existing ground plans of buildings in order to enable an automatic data capture by the integration of these different types of information. A building is represented by a general polyhedron, i.e. it has to be bounded by a set of planar surfaces and straight lines. The assumption has been made that the coordinates of the given ground plan are correct and the borders of the roof are exactly defined by this ground plan. The reconstruction is constrained by the assumption that:

- all walls defined by the ground polygon lead to a planar roof face of variable slope,
- all eaves lines have the same height.

The reconstruction consists of four major steps:

1. subdivision of the ground plan into rectangular (2D) primitives,
2. selection of a three-dimensional primitive for each 2D rectangle based on analysis of the interpolated raster DSM,
3. estimation of the parameters for each 3D primitive,
4. merging of all 3D primitives in order to obtain the model of the entire building.

[Brenner, 2000] refines this approach by integrating the DSM in the process of finding the roof structure, rather than being used for measurement only. This integration step has been done by detecting planar faces from the DSM, using random sampling consensus (RANSAC). These planar faces are accepted or rejected in a rule-based approach. Finally, the roof is built from the primitives that have been accepted, closing any gaps that have been caused by the deletion of unexplainable regions.

3.4.2. Vosselman and Dijkman, 2001

[Vosselman and Dijkman, 2001] focus on the extraction of the roof faces and the generation of 3D building models by combining the extracted roof faces with the ground plans. Two strategies are discussed, where the first four steps are the same:

1. split the dataset into smaller parts (segments),
2. apply 3D Hough transform to the points of each part separately,
3. the planar faces need to be merged over the bounds of the segments, and if possible extended,
4. final determinations of the plane parameters follow from a least squares adjustment using all points that are assigned to a plane.

The two strategies now follow their own path:

The first strategy focuses on the refinement of the ground plan partitioning, which can be done by splitting a segment if evidence is found for the presence of an intersection line of two adjacent planar faces or a height jump edge between two such faces. The final steps of constructing the 3D model of a building consist of splitting and merging the ground plan segments until there is a one-to-one relationship between the segments and the roof faces.

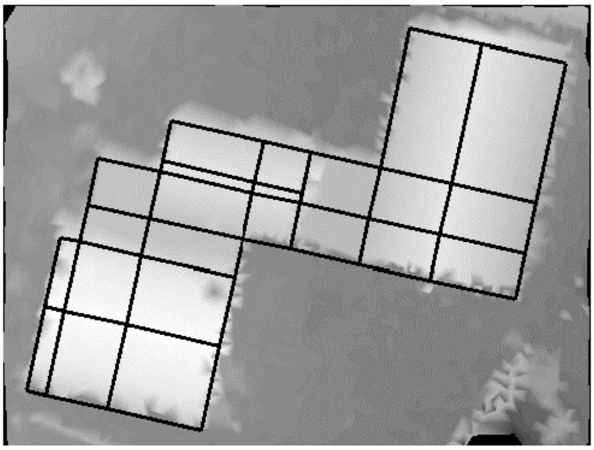


Figure 10 Refined segmentation after splitting segments at positions of intersection lines and height jump edges.

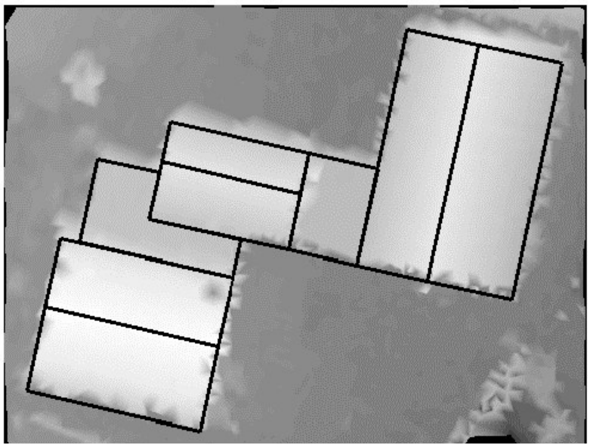


Figure 11 Final partitioning after merging segments assigned to the same planar faces.

In order to preserve more detail in the model, another reconstruction strategy has been explored [Vosselman and Dijkman, 2001]. In this strategy the authors start with a relatively coarse 3D building model that is derived by fitting shape primitives to the original segments of the ground plan. By analysing the clouds of points that do not correspond to this model, refinements are estimated.

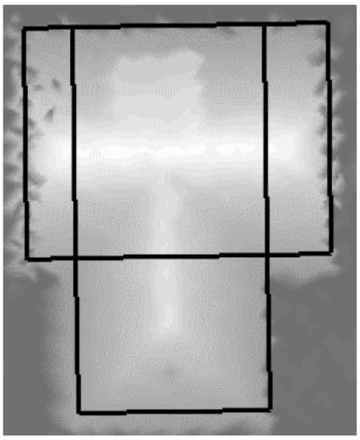


Figure 12 Building with two hip roofs and a dormer.

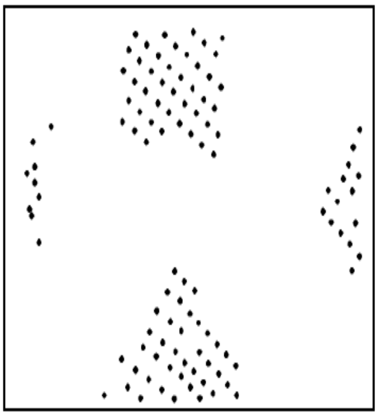


Figure 13 Clusters of points that do not fit the initial model.

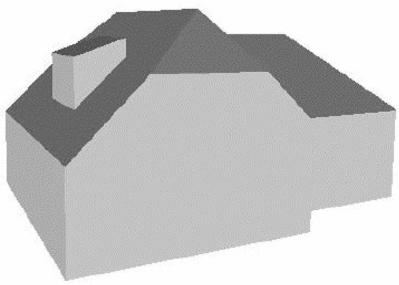


Figure 14 Reconstructed model.

Figure 15 Photograph of the building.

3.4.3. Hofmann, Maas and Streilein, 2002 & 2003, Hofmann, 2004

In [Hofmann et al., 2002] first both the laser data and the topographic data have been transformed into raster format, in order to extract buildings from laser data. In an object based segmentation procedure laser scanner data has been transformed into house segments and roof segments. Together with the topographic map these segments have been analysed and classified in a GIS environment.

After this building extraction step in raster-based datasets, building reconstruction will be performed using laser data in a TIN structure [Hofmann et al., 2003]. The parameters of every TIN mesh are mapped into a triangle-mesh parameter space, which is then analysed by cluster analysis techniques. Both the utilisation of a 2-D parameter space (containing only triangle-mesh slope and orientation) and a 3-D parameter space (containing all three plane parameters) are described and tested. By cluster analysis and available knowledge on possible roof shapes, significant planes are derived from triangle parameter space. This procedure can be compared to the Hough-transformation based technique proposed by (Vosselman and Dijkman, 2001). Main difference is that Vosselman and Dijkman work on unstructured point clouds and generates an entry plane in a 3-D Hough space for every point, where Hofmann's approach is based on a point cloud in a TIN structure, where every TIN-mesh produces one entry in a 3-D parameter space.

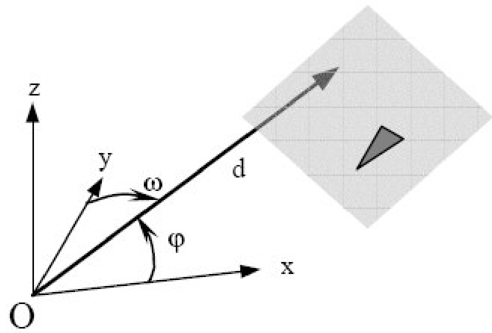


Figure 16 Triangle parameters φ slope, ω orientation and d minimal distance of the triangles plane to the origin O.

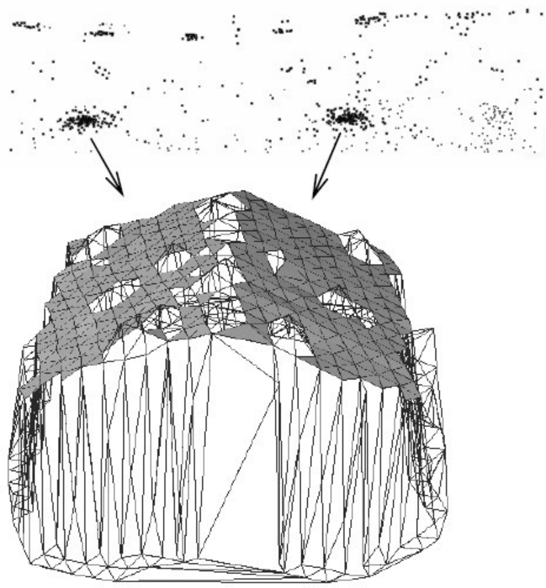


Figure 17 Association of parameter points to roof faces.

First, cluster analysis will segment the TIN structure into clusters. Then region growing is performed to group TIN meshes belonging to roof faces. Roof faces are intersected in three steps: to find dormers, to intersect ridges and to intersect sides and bottoms. The finishing part is adding walls to the building model. The lower edge of the wall is derived form the DTM of the building's surrounding. The lowest point is chosen in order to please the eye in visualisations where also the terrain model is included [Hofmann, 2004].

3.4.4. Schwalbe, Maas and Seidel, 2005

Buildings are extracted from the laser data by taking polygons from a 2D cadastral map and overlay the laser data with the polygons including a buffer of 5 meter [Schwalbe et al., 2005]. For every building one segment has been extracted.

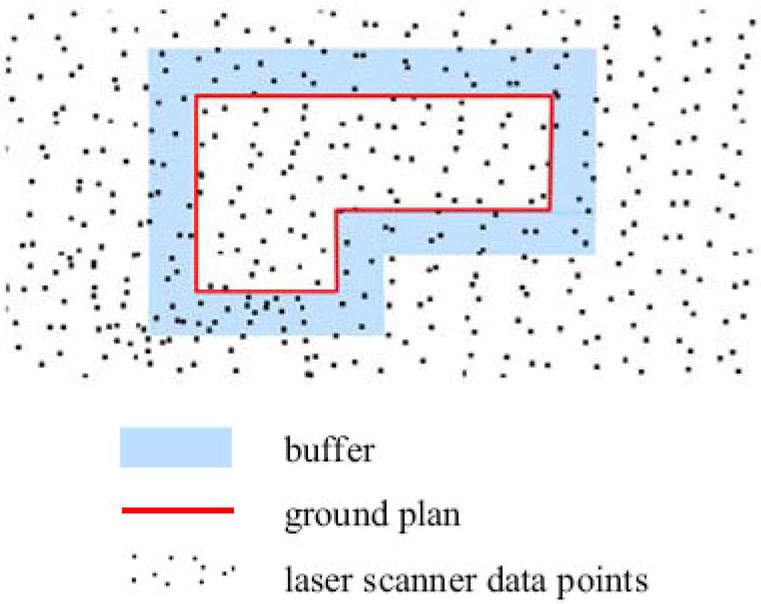


Figure 18 Segmentation with ground plan plus buffer.

Ground points are eliminated by performing a height threshold. Building orientation can be obtained by using either the laser data (with histogram height bins) or the GIS data. Then segmented points have been projected on two orthogonal planes, along and perpendicular to the main building orientation. Robust straight line detection in projection planes provides the inclination roof faces.

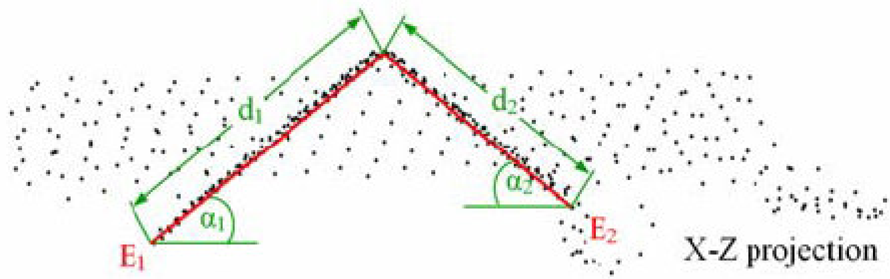


Figure 19 Lines representing roof faces.

Planes are intersected to finish the roof model. Walls have been added, using a similar approach as [Hofmann, 2004].

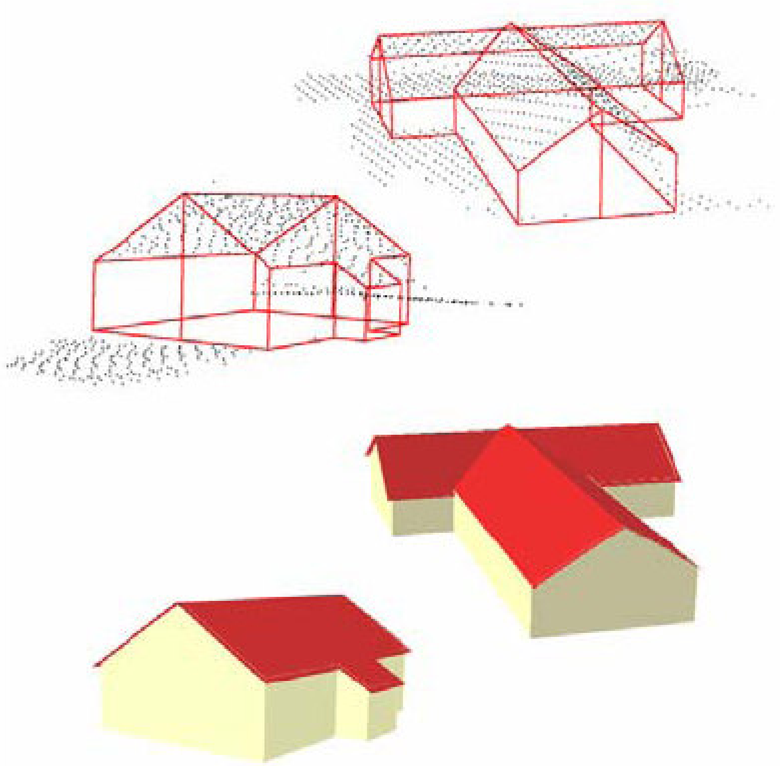


Figure 20 Reconstructed buildings.

3.4.5. Vosselman, 2003

Besides buildings other topographic objects like roads and trees are important features in 3D city models. [Vosselman, 2003] describes several algorithms and procedures developed for the 3D reconstruction of streets and trees from airborne laser altimetry data in combination with a cadastral map. Using the boundaries of cadastral objects and knowledge about smoothness of streets, the laser data is processed into realistic street models.

In a two-step procedure laser points are selected that fall inside street parcels. These two steps are first a mask operation, followed by a point-in-polygon operation.

Morphological filters have been used to remove points on cars, trees and other objects on the street. Segmentation based filtering is needed to remove points below street level, e.g. on water surfaces. On the remaining laser points constrained Delaunay triangulation has been performed to create a rough street model. Combining constrained Delaunay triangulation when integrating 2D GIS data with laser data has also been described by [Stoter and Oosterom, 2005].

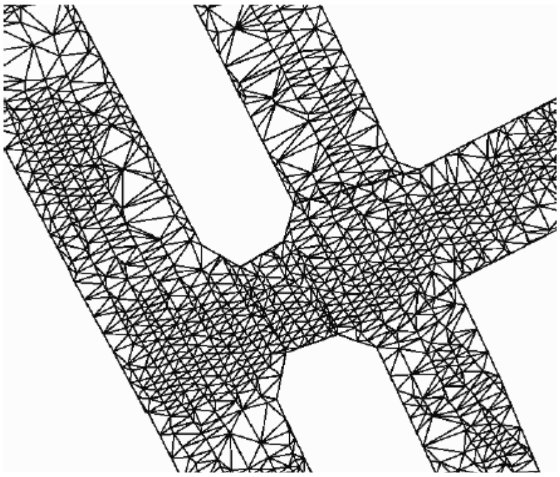


Figure 21 Constrained triangulation of the combined map and laser points within the streets objects. The varying point densities are due to occlusion of the street level by trees, cars and buildings.

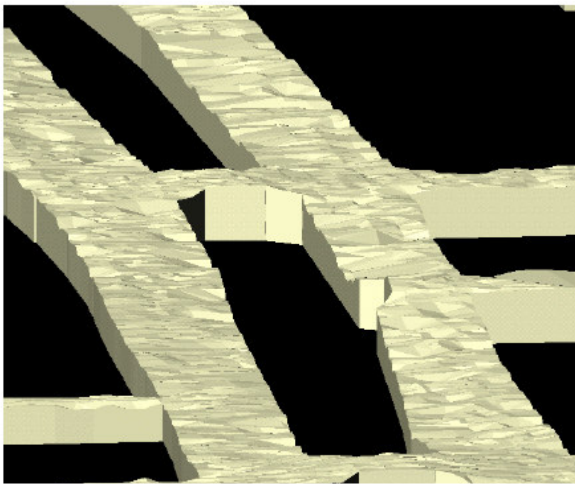


Figure 22 Original laser points combined with map points. The heights of the map points are inferred from the nearest laser points.

Additional knowledge about street models has been used in a constrained polynomial fitting to remove the noisy character of the rough model.

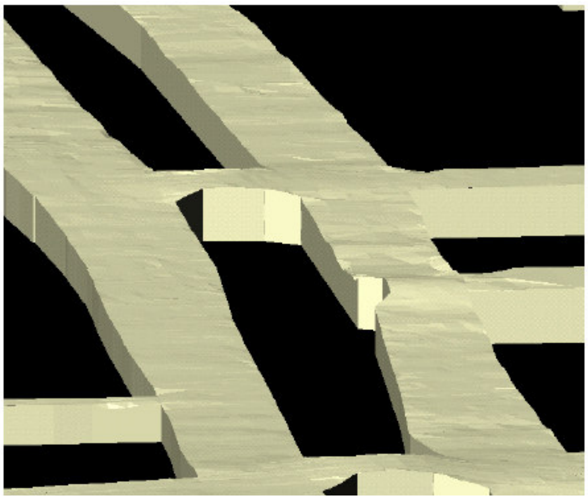


Figure 23 Road surface estimated by 2nd order polynomial fitting to near laser points.

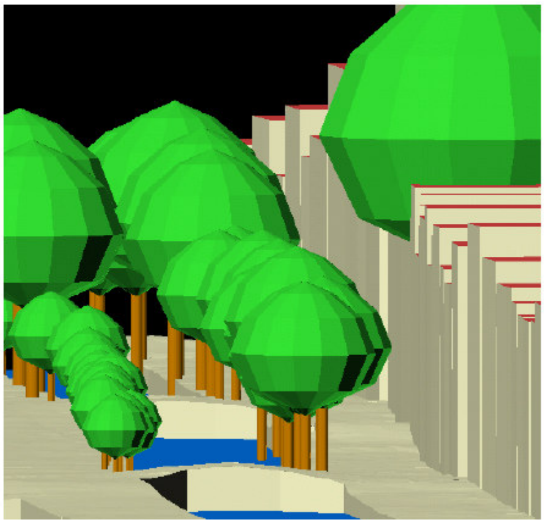


Figure 24 Street level view of the 3D model.

The laser data used in [Vosselman, 2003] was, with its 1 point per m^2, dense enough to determine the tree locations. In this dataset the locations of the trees were detected by determining the local maxima of the laser points within the road and water parcels that are 5 or more meters above the ground level.

3.4.6. Koch, 2004

When integrating GIS data and height data, discrepancies between the two data sets arise. Different acquisition, processing and modelling techniques introduce mismatches between the two representations of the same world. [Koch, 2004] recognizes these discrepancies, and describes an algorithm to correctly integrate DTM and topographic data.

The algorithm is based on a constrained Delaunay triangulation. The DTM and the bounding polygons of the topographic objects are first integrated without considering the semantics of the objects. Topographic objects that are represented by a line, but actually have a certain width, are buffered which results in a surface representation.

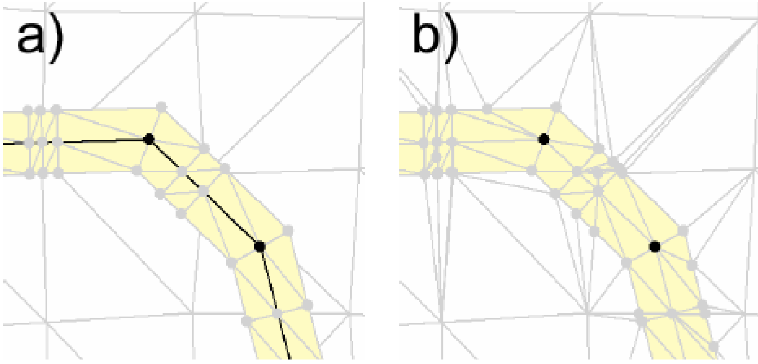


Figure 25 Integration of a DTM and an object "road", a) original DTM TIN and object "road" after buffering, b) integrated data set.

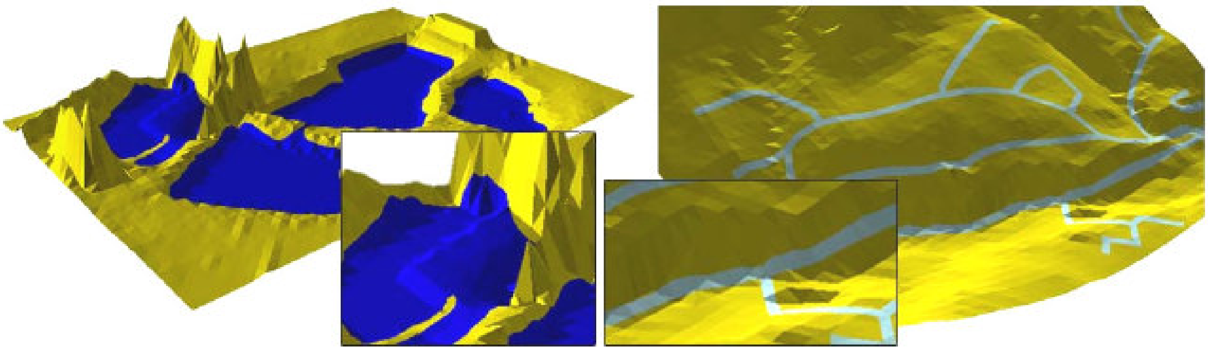


Figure 26 Results of the integration of a DTM and a 2D vector data set without considering the semantics of the topographic objects, left: lakes, right: road network.

After this step the semantics are introduced. Like in [Vosselman, 2003] heights within certain polygons have to fulfill conditions belonging to that object. For example, the object "lake" has to be represented by a horizontal plane. Neighboring objects will probably contain heights that lie above "lake" level. Least square adjustments on DTM points within the polygon "lake" have been used to fulfill the horizontal plane condition, where at the same time heights of neighboring points are restricted to have heights above lake level.

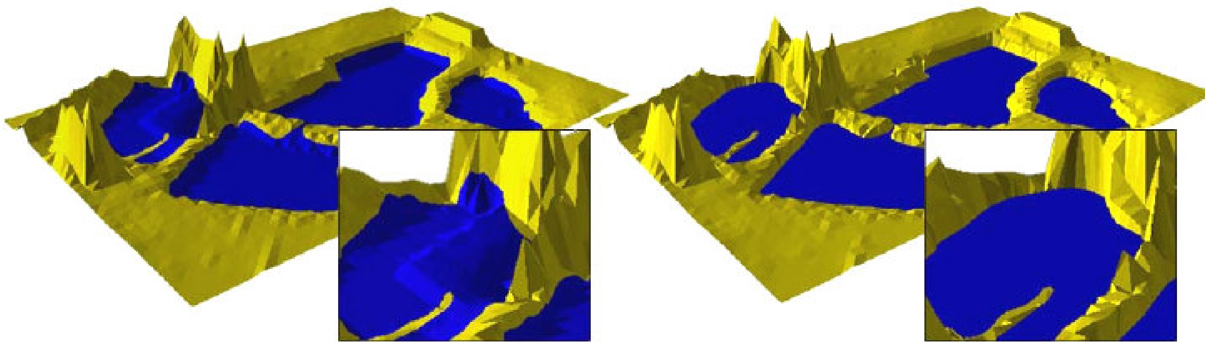


Figure 27 Results of the integration process, left: non-semantic integration, right: semantically correct integration.

The author describes several object types and their semantic rules.

3.4.7. Overby, Bodum, Kjems and Ilsøe, 2004

Whereas the previous authors focus on point densities of multiple points per square meter, [Overby et al., 2004] aim to describe a reconstruction approach using less dense laser data, i.e. one point per square meter or less. The reconstruction procedure can be split up in the next steps:

1. roof polygons are generated using airborne laser scanning of 1x1 meter grid and ground plans (footprints) extracted from technical feature maps,
2. plane extraction by 3D Hough transform,
3. merging planes belonging to one 'real world' plane,
4. producing intersection lines by intersecting all planes that are within a pre-specified minimum distance,
5. overlapping faces are removed if these are not represented by any points of the point cloud,
6. removal of degenerate parts of mesh and filling up the holes, merging parallel adjacent faces.

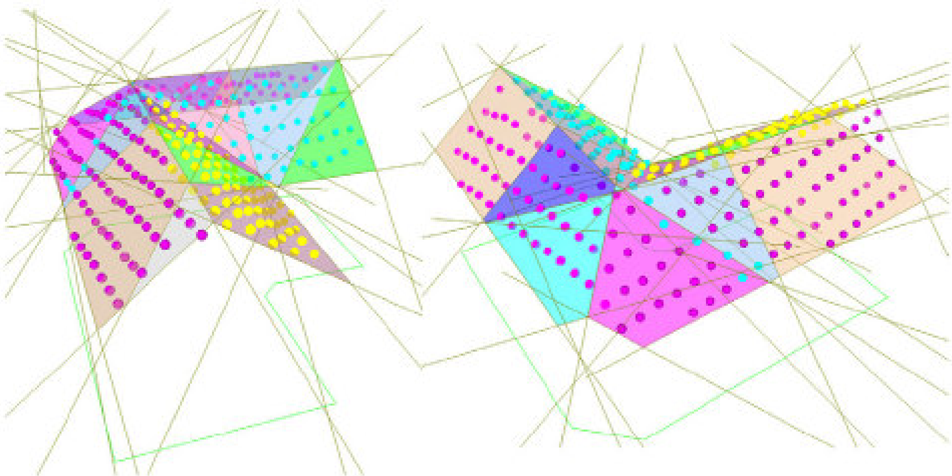
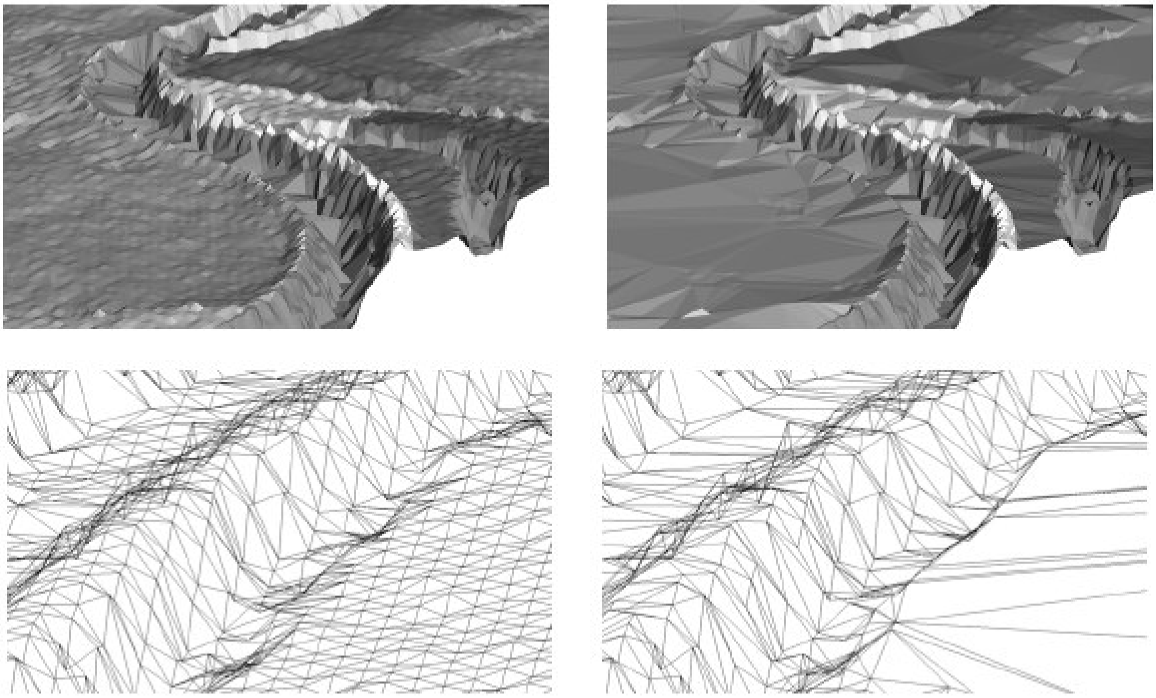


Figure 28 Roof faces generated by intersecting planes and filtering.

3.4.8. Stoter, Penninga and Van Oosterom, 2004

In [Stoter et al., 2004] the authors focus on the generalisation of integrated height and 2D GIS models. First a description is given on the integration of height data with topographic features, using a confirmed or refined constrained TIN technique. They further process this model by filtering superfluous height data. Also, topographic features have been generalized by removing so-called 'non-characteristic' nodes. Doing so, data reduction can be achieved of more than 70%, without losing characteristic features.



3.5. Airborne laser scan data combined with aerial images

Many authoritative researchers predict that the future of object reconstruction will consist of intelligent fusion of laser data and aerial images. [Ackermann, 1999] predicts that the systematic combination of digital laser and image data will constitute an effective fusion with photogrammetry, from a methodical and technological point of view. Obviously, data fusion - preferably from a laser scanner and a digital camera integrated on a common platform - will merge the advantages of both types of sensors [Maas, 2001]. Future research will therefore focus on the integration of these data sources [Vosselman and Suveg, 2001]. [Brenner, 2005] also mentions that costs of fusing data from different sources might decline in the future, since combined sensor platforms are used anyways. Indeed, laser scanning data can be considered to be complementary to conventional digital image data in many aspects. While laser scanner data is well structured and well suited for automated processing, the resolution and interpretability of panchromatic or multispectral image data is superior. Planes can easily be reconstructed from laser data. It is, however, difficult to accurately determine the location of height jump edges between planar faces. In contrast, the location of edges is something that can be done accurately in images. The determination of planes from imagery is, however, more difficult [Vosselman and Suveg, 2001].

3.6. Modelling, surface and object representations

Some parts of the 3D reconstruction are independent of the data source. In this paragraph the following topics are highlighted: surface representation, object models.

Data modeling is an abstraction activity in that the details of the values of individual data observations are ignored in favor of the structure, relationships, names and formats of the data of interest, although a list of valid values is frequently recorded. The data model should *not only define the data structure, but also what the data actually means (semantics).***Source: Wikipedia.org**.

One way to represent the terrain given by a set of surface points is to construct a Delaunay Triangular Irregular Network (DTIN). In [Verbree and Oosterom, 2003] a surface reconstruction method has been described, based on the Delaunay Tetrahedronised Irregular Network (DTEN), which tessellates the 3D-space with non-overlapping, adjacent, tetrahedrons. Their Surface TIN (STIN) approach relies on the assumption that the position of the “observer” is known. In case of airborne laser, that is the position of the laser sensor. Within the STIN method the Z-value of the target points is taken into account along the position of the observer and the observation lines. The surface is created and derived within a Tetrahedronised Irregular Network (TEN) in three dimensions. This method lines up with all kinds of Data Dependent Triangulations (DDTINs). The STIN method is capable to reconstruct surface out of a given point cloud in 3D as long as the location of the observer is known.

The assumption that the location of the observer is known might run into practical problems in strip overlapping areas and areas that needs multiple acquisition positions to overcome occlusions. Object detection might be a preparation step, to implement this STIN method in 3D acquisition.

When the boundary is modelled by a set of triangles (3D-TIN) it will simplify the explicit modelling of the interior. A polyhedron described by a set of polygons is an example of an implicit representation of the interior. Only when the boundary is confirmed to be valid the interior is believed to exist. The TEN models the interior of the object explicit by a set of tetrahedrons [Verbree et al., 2005].

The geometry of objects can be described by boundary representation, constructive solid geometry (CSG) or spatial enumeration (i.e. voxels) [Brenner et al., 2003].
The object models can be generic or specific [Brenner et al., 2003]. Simple generic objects are parametric descriptions where the general form is fixed but geometric parameters can be adjusted.

[Brunn and Weidner, 1997] discriminate three kinds of building models: parametric, prismatic or polyhedral. In the definition of [Brenner et al., 2003] these are all generic object models. Parametric models are used for simple buildings, which can be described using a few parameters. For the reconstruction of these parametric models assumptions has been made that the buildings are separate from each other and that the ground plan of the building is a rectangle. Complex buildings and blocks of buildings are described using prismatic models, which constitute the second group. These models are based on generic knowledge about the buildings. The first fact used is that the ground plans of buildings or building blocks are sets of closed polygons. Furthermore, neighbouring straight lines of the buildings' outlines and therefore neighbouring edges of the polygons are likely to be orthogonal. The outline of a building also may be formed by several polygons, e.g. representing court yards. In cases where parametric and prismatic models fail, [Brunn and Weidner, 1997] introduce polyhedral models.

3.7. Conclusions on literature study

Major disadvantage in the automatic reconstruction using aerial images is the complexity in suburban and densely populated urban regions in general due to connected buildings, shadows and occlusion situations [Henricsson and Baltsavias, 1997]. Laser altimetry provides reliable and detailed 3D data, which to a certain extend can be processed (semi-)automatically into 3D information. The use of an additional source of information can improve the reconstruction process, especially in terms of time and reliability. When using 2D maps information becomes available for object detection and outlining in laser data. Due to possible discrepancies between the two data sets, combining has to be performed with care.

[Stoter et al., 2004] processed the point cloud in the way that non-characteristic points were removed in order to simplify the model. [Vosselman, 2003] and [Koch, 2004] use polynomial functions to fit through the point cloud to generalise and improve the visualisation of the model. The point density of laser data is important for reconstruction strategy and the degree of detail of the reconstructed model. When using high density laser data, the reconstruction can be more data-driven. With low density data knowledge about the shape of the object has to come from constraints, assumptions or generalisations.

In the overlapping area between data acquisition, modelling and storage of 3D data there is a variety of topics that are linked to several working fields, e.g. GIS, computational geometry, photogrammetry. Due to different definitions of technical terms, readers might get confused when one author describes "modelling" as a way to represent the terrain (like in TIN/TEN modelling), where another author means the determination of geometric shape of one or more objects (e.g. gable roof, hip roof, function fitting). As long as the reader is aware of possible differences in the language, the problem is manageable.

4. PhD proposal: Acquisition of 3D Topography

4.1. Background

This PhD proposal will focus on the development of efficient methods for the acquisition of 3D topographic information. In chapter 3 of this report an overview is given on the state-of-the-art acquisition techniques of 3D topography. In the final version of my PhD proposal, to be published in february 2006, a summary and conclusions of the literature study will be given here.

4.1.1. Data input

Laser altimetry provides reliable and detailed 3D data, which to a certain extend can be processed (semi-)automatically into 3D information. The use of an additional source of information can improve the reconstruction process, especially in terms of time and reliability. When using 2D maps information becomes available for object detection and outlining in laser data. Due to possible discrepancies between the two data sets, combining has to be performed with care.

4.1.2. Context

This PhD project will be carried by Sander Oude Elberink, promovendus at ITC in Enschede. George Vosselman (EOS, ITC) is his promoter; Peter van Oosterom (OTB, TU Delft) will be his co-promoter. As mentioned in § 1.1 this PhD research is embedded in a larger research project, called 3D Topography. The main goal is *"to force a breakthrough in the use of 3D Topography by structural embedding of 3D methods and techniques in the Geo-ICT work field."*

In this paragraph special attention will be given to the other PhD research projects, performed by Friso Penninga and Edward Verbree. This has been done to be able to tune all research activities at both ITC and TU Delft.

The following 4 tasks have been extracted from the PhD proposal from [Penninga, 2004].

1. *Theoretical TIN/TEN Track:*
   This track will focus on the logical design of the data model, input/output functions and data formats (joint research effort Edward Verbree and Friso Penninga).
2. *Topographic Track:*
   This track will focus on the design and prototyping of a method to create a 3D topographic model by combining current 2D topographic products with 3D topographic and height data sets. Some results in this area are available from earlier research of Edward Verbree (research effort Friso Penninga).

3. *Technology Track:*
   This track will focus on the implementation in a geo-DBMS environment of data structures and algorithms as designed in the Theoretical Track, the creation of input/output functions and design of true 3D analyses (joint research effort of Edward Verbree and Friso Penninga).
4. *Advanced TIN/TEN Track*
   This track will focus on issues like modelling temporal aspects in the TIN/TEN model, creating and testing different spatial indexing techniques, multi-scale representations, multi-representation, etc. (research effort Edward Verbree).

It is obvious that in particular task 2 "Topographic track" is closely related to the PhD research described in this report. Whereas TU Delft focuses on the theoretical conditions of 3D Topographic models, will ITC adapt this model and focus on the actual combination of the two input data sets. Also, the acquired 3D Topography has to support the requirements of task 3 "Technology track". Regular meetings between researchers at ITC and TU Delft will further fine-tune both research activities.

[Verbree et al., 2005] have restricted the 3D Topography project to the so-called boundary representations of real-world objects, while they discussed properties of several 3D topological models. Among them, preferences are given to the 3D-Triangulated Irregular Networks (3D-TIN). This kind of representation operates with the simplest primitives (triangles) ensuring planarity and simple consistency check operations. It is easy to validate an object and it is relatively straightforward to represent the interior of the object as a Tetrahedronized Irregular Network (TEN).

4.2. Research problem

4.2.1. Ad hoc solutions

Most of the 3D models have been acquired on an 'ad hoc' basis, making it suitable for the local situation. To be able to establish structural 3D methods and techniques in the Geo-ICT working field, it is necessary to focus on the global solution. Further automation of this process requires the production of general rules and conditions for 3D data acquisition.

4.2.2. Semantics

Little research has been done on the semantically correctness of the 3D model. 2D semantics of the map generally will not be enough to be valid in 3D.

4.2.3. Point density and generalisation

The point density of the data, especially of the height data, is a crucial parameter for the level of detail of the reconstructed (roof) surfaces. Higher density means that more (and more detailed) objects can be reconstructed. On one hand, it is advisable to use as many points as possible to reconstruct objects in detail. Especially when using low density datasets like AHN (1 point per 16 m^2) to reconstruct buildings, it is essential to use as many points as possible, only to estimate the rough shape of the roof, e.g. is it flat or gable. The question is if the number of observations is enough to estimate the shape of the object (and its quality parameters). Geometric constraints can be used to decrease the number of unknowns.

Figure 29 Building object in 2D, overlaid with laser points (left). Two possible shapes in 3D: flat roof (middle) and gable roof (right).

But on the other hand, from a data provider's point of view it is desirable to aim for a uniform 3D dataset, independent of the exact number of points lying on the object. Until now, there is a lack of transparent decision making rules for the level of detail of reconstruction on a global (national) level.

Figure 30 Building object in 2D, overlaid with denser laser data (left). The more laser points, the more details can be reconstructed (middle and right).

4.2.4. 3D Map users

A 3D map is not just a special version of a 2D map. Not only the features are extended to 3D, the users can change their point of view to look at the data. 3D Topography will be stored in a digital format. Data users have software to explore, visualise and analyse 3D Topographic data. Although these assumptions look obvious and straightforward, it has big consequences for the semantics of the map. Because users can see the third dimension of the map data:

- Height information at **the object surface** has to be acquired. This is the most interesting part for many users, because it adds height information to existing map data.
- 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/necessary (at viaducts, bridges, overhanging objects 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, scratches to indicate height differences at banks and dikes. If the user really can explore the third dimension some of these objects will become superfluous. And to use a metaphor: "If one can hear and understand the television reporter, one does not need his subtitles anymore."

4.3. Objectives

The main objectives are:

- to set up integration rules and conditions to select, combine and process the input data
- to produce a semantically and geometrically correct 3D model
- to model and to implement knowledge about building shape, geometric constraints and topographic constraints
- to produce quality parameters for every reconstructed object
- to visualise the quality of the reconstructed objects
- to start with a coarse dataset (input as well as output) and finish with a highly detailed 3D topographic dataset

4.4. Results

These objectives have been set up, to be able to produce the following results:

1. Acquisition of 3D topographic data from 2D GIS data and laser altimetry data
2. Production of an algorithm for a complete and semantically correct 3D surface and object reconstruction

4.5. Research questions

Conclusions of the literature overview and research problem can be translated in research questions. Answering these questions will fill the gap between what allready has been done by others, and the desired results of this project as stated in 4.4. The questions have been divided into three groups: input data, modelling strategy and quality assessment.

4.5.1. Input data

- *What is the influence of the density of the input data on the level of detail of reconstruction?*
- *What is the influence of the density of the input data on the strategy (data driven or model driven) of the reconstruction?*

4.5.2. Modelling strategy

- *Which other parameters influence the choice between a data driven and a model driven approach?*
- *Can a data driven approach be combined with a model driven approach?*
- *How to select suitable laser points for adding height information to a certain object?*
- *Which processing steps have to be applied to the selected laser points in order to get a semantically, geometrically and visually correct model?*
- *What is the best way to model surface knowledge?*
- *How can one integrate building shape knowledge into the reconstruction process?*
- *How to deal with conflicting reconstruction conditions?*

4.5.3. Quality assessment

- *How to deal with incomplete parts in reconstructed models?*
- *Which parameters are suitable for quantifying and visualising the quality of the reconstructed objects?*

4.6. Procedure

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, height differences in grasslands and infrastructure. Laser data and 2D map data will be integrated and processed in a rule-based approach. For groups of objects rules for reconstruction are being set-up. These rules have to ensure the geometrical, topological and semantic correctness of the 3D map.

Rules can be set up to fulfil several sorts of conditions:

- to select parts of the laser data
- to decide which processing steps of the data will be taken
- to define constraints for the 3D shape of the object
- to define constraints for neighbouring objects
- to define accept criteria for the reconstructed model

The reconstruction algorithm will be built following two strategies:

1. **Coarse-to-fine**: Starting with rough object reconstruction, analysis of the residuals will refine the model bit by bit. Also improving the density of laser scan data during the research project will allow us to follow this coarse-to-fine approach. Although the modelling part of the coarse data set will be based on real 3D primitives, the combination of airborne laser data with 2D map data may not be sufficient to correctly model topographic objects in 3D. This is because parts of the objects will be occluded in aerial images as well as in airborne laser scan data. Where in the beginning the 3D gaps will be filled with synthetic data (interpolated, extrapolated, and assumptions), we will refine this method by using higher density airborne and terrestrial laser data together with additional data sources like 2D maps, and maybe also images.

2. **Semi-automatic to automatic**: research experience during this project will be implemented to improve the automation of the algorithm, bit by bit.

In the following scheme an overview is given of the proposed processing steps. Before data processing will start, rules and conditions will be set-up for each object (or object group) to be reconstructed. These rules will provide input parameters for the first four steps of the reconstruction process, as indicated with the red arrows in Table 1.

Table 1 Schematic overview of 3D reconstruction.

Step	2D Map data	Laser altimetry data
1	Group objects (4.6.1)	Registration (4.6.2)
2	Selection (segmentation, grouping, filtering, outlining) (4.6.3)	
3	Modelling (shape or function fitting) (4.6.4)	
4	Semantically correction (4.6.5)	
5	Storage, distribution, visualisation (4.6.6)	

4.6.1. Grouping objects

Combining laser data with 2D map data can be done in several ways. For each 2D object laser data can be found to upgrade that object from 2D to 3D. Doing so, conflicts may arise at borders of the object with neighbouring objects. Therefore, it might be more efficient to first group 2D objects, and upgrade the whole group. For example, road segments can be grouped in 2D because it is likely that the road segments will have a continuous shape. This can be done by grouping objects with the same object code, see Figure 31a. The first 3 numbers of the code indicate the specific type of object. The fourth number indicates if an object is visible (0 or 3) or not visible (2). For some object parts it is necessary to contact the height data in order to check if they belong to the same group, see Figure 31b.

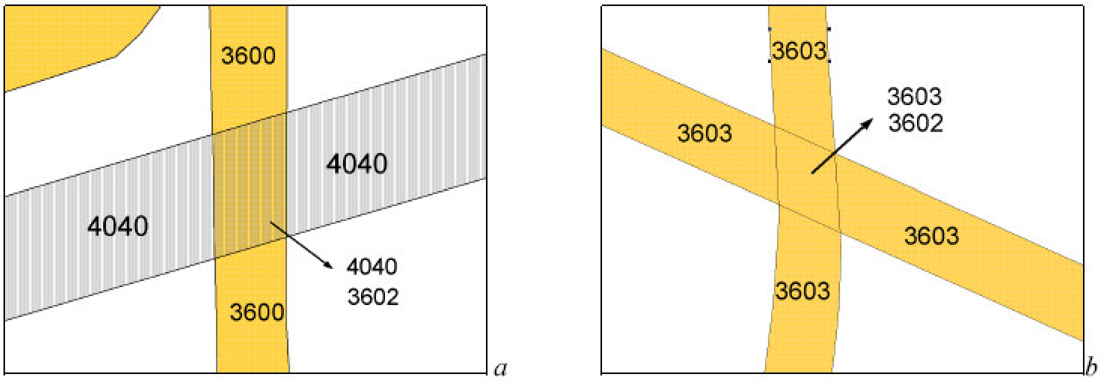


Figure 31 Viaduct with object codes per object. A) Object can be grouped according to codes. B) Height information is needed to group objects and to determine the path of the road (source: [Simonse, 2000])

4.6.2. Registration

To combine laser data with GIS data the data has to be in one and the same coordinate system. In this project registration of laser data means the positioning of the point cloud, including removing all systematic errors. It is to be expected that data providers already performed this step in a calibration and strip adjustment procedure.

4.6.3. Selection

In this step 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 simplest way 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 an object, e.g. one laser point can lie on a chimney instead of the roof, or on a car instead of the street. The first step of the selection is segmenting the point cloud, according to the rules and conditions of the object (group).

4.6.3.1. Segmentation

To extract 3D information of an object from the point cloud, the laser data has to be processed. This processing often involves the recognition of specific geometric shapes or more general smooth surfaces [Vosselman et al., 2004]. In this step segments (i.e. groups of points) will be made, based on parameters like connectivity, planarity, smoothness etc. Segmentation techniques can be based on region growing, split and merge or clustering techniques [Brenner et al., 2003] and [Vosselman et al., 2004]. Characteristics of the grouped 2D objects will be used to define the segmentation strategy, e.g. segments on man made objects may be clustered purely based on planarity, whereas segments on natural objects might be clustered by connectivity.

4.6.3.2. Outlining

Outlines of the 3D objects have to be determined from the outlines of the 2D map and the outlines of the selected segments. Rules and conditions will act as referee when discrepancies arise between the outlines of the map and of the laser segments. The positions of the outside walls of the building from the map are known up to some uncertainties due to map inaccuracy and generalization, extensions of the roof faces beyond the wall location, small registration errors and more [Vosselman, 2002].
This step includes the so-called partitioning of building segments.

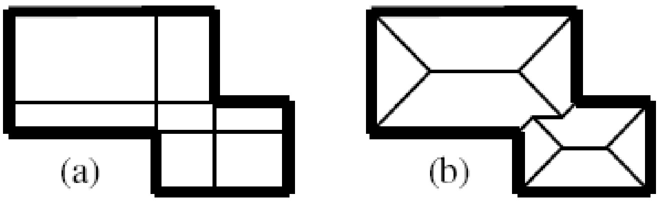


Figure 32 Segmentations of ground plan by (a) extension of lines at concave corners or (b) intersecting planes through the eaves, assuming horizontal eaces at one height and the same slope for all roof faces (source [Vosselman, 2002]).

It can be expected that when using higher density laser data, outlines from laser data will become more and more detailed and reliable. In a (semi-) automatic procedure outlines of the laser segments will be combined with the outlines and partitions of the map.

4.6.3.3. Grouping/filtering

Segments are combined or removed according to the characteristics of the topographic object. E.g. for highways: only laser data points lying in same local plane will be used for further processing. Laser points lying on cars, trucks, traffic signs, etc will be excluded.

4.6.4. Modelling

In this step selected laser points will be further processed in order to remove the noisy character of the laser data, to generalize the shape of the object, and, doing so, to prepare a more realistic view in the end product. For each object group different strategies will be set-up. Again using the highway example: because a high way needs to be smooth, laser points will be the smoothened in the determination of a polynomial function to model the highway, similar as [Vosselman, 2003] described to model city streets.

4.6.5. Semantically correction

Implicit height information of objects will be added to the model. Examples have been described by [Koch, 2004]: a lake represents a horizontal plane, and all height values of the lakes' area must be the same, the neighbouring banks, however, have to be higher than the water. To give another example, the slope of a road along and across the road direction must not exceed a certain maximum value [Koch, 2004].

Other constraints for neighbouring objects can be:

- No topographic objects other than "air" are allowed to exist above a highway at a distance smaller than a certain threshold.
- Although neither laser points nor map data may be available underneath viaducts and crossovers, constraints in the model may fill the gap and connect two parts on the highway in 3D.

For all objects in a certain neighbourhood, neighbouring rules are sorted (from hard to soft), probabilities will be given to them, and solved in a least squares adjustment.

4.6.6. Storage, distribution, visualisation

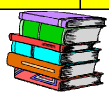
After acquisition of the 3D topographic data, data has to be stored in a database. Topological and consistency checks will be performed before final storage in the database. This step will be further tuned with the other project researchers at TU Delft, see also 4.1.2.

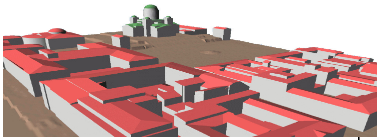
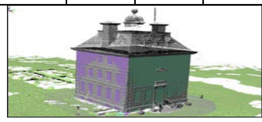
4.7. Time schedule

The time schedule contains five major steps, based on the source data used at that time.

1. Literature study: to get familiar with the project goals, datasets and environment. This results in a literature overview in December 2005, but will continu untill the end of the research project.
2. AHN & TOP10NL: Development of algorithms for the production of (relatively course) 3D Topopraphy by the integration TOP10Vector with the AHN4. The goal is to assign height descriptions to all objects in the topographical database TOP10vector.
3. Dense laser data & large scale 2D map: The goal is to improve automation in recognition and reconstruction of buildings.
4. Airborne and terrestrial laser data: Integration of airborne and terrestrial data for detailed modeling of buildings. Goal: visualization and production of indoor and complex topography.
5. Completion of PhD thesis.

Table 2 Time schedule

Year	2005	2006				2007				2008				2009		
Phd-quarter	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Literature study																
AHN & TOP10NL																

Higher density laser & large scale 2D map																
Airborne & terrestrial laser data																
Completion PhD thesis																

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