BUILDING RECONSTRUCTION USING A STUCTURAL DESCRIPTION BASED ON A FORMAL GRAMMAR

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ABSTRACT:

The automatic reconstruction of roofs and buildings has been an important research topic during the last years. This paper elaborates on the automatic and semi-automatic reconstruction of roofs from aerial laser scan data. Two approaches are considered in detail. First, a program has been developed, which segments laser scan data into planar patches, labels them according to their adjacency, and sets up a region adjacency graph. Then, simple roof shapes are found as sub-parts of complex roofs by finding sub-graphs in this region adjacency graph. Second, we developed a formal grammar to describe complex roof face layouts. The goal is to identify complex roof structures as words derived using this formal grammar. This also has the potential to enforce acquisition generalisation, since structures which cannot be expressed using the grammar will be omitted. We describe our approach and present first results for two data sets of different point density.

1. INTRODUCTION

1.1 General Remarks

Three-dimensional city modelling is a very active research topic in recent years, with applications in the simulation of noise and electromagnetic waves, city planning, and tourism. Since the manual reconstruction is very labour intensive, it is worthwhile to develop automatic or semi-automatic reconstruction processes. In this paper, especially roofs are considered, with the goal of recognising and reconstructing roof shapes.

To this end, we present a program which recognises simple shapes being part of complex roofs, based on laser scan data. We show first results using two scenes of varying point density of approximately one point and 20 points per square meter, respectively. Using those scenes, points are segmented into planar patches which are then used to recognise simple roof shapes. No classification into vegetation, ground, or roof faces is done beforehand.

In the second part of the paper, we address formal grammars which are developed to recognize complex roofs based on simple roof primitives. Thereby, the usefulness and limitation of the grammar for the purpose of describing buildings will be demonstrated.

1.2 Related Work

In the past, there have been numerous approaches to reconstruction buildings, some of which are covered in this paragraph. Overviews are given in (Baltsavias, 2004, Brenner, 2005).

First, there are approaches which include existing structural information, for example, existing ground plans, into the reconstruction process and to use predefined volumetric models with simple roof shapes. Brenner (1999) uses the information from ground plans, from which simple primitives are used for the reconstruction. This approach is limited by the complexity of roof shapes, since the possibilities to form complex roofs is limited by the set of available primitives.

Lafarge et al. (2006) also start with simple primitives, based on rectangles, which are placed based on a digital surface model, using a Markov chain Monte Carlo simulation. In the following, the rectangles are merged to obtain ground plans, which are then additionally subdivided along height jumps. From this, the final roof reconstruction is obtained.

Vosselman (1999) and Suveg & Vosselman (2004) extract the outlines of buildings from laser scan data, using a Hough transform. This way, ground plan and jump edges are detected, which are then used to model the buildings.

A hierarchical modelling concept is introduced in (Fischer et al., 1998). They use a 'is-part-of' hierarchy of primitives to split up buildings. The primitives themselves are specialised using a 'is-a' hierarchy, e.g. 'connectors' and 'terminals' for the building parts. This hierarchy has been chosen to obtain a link between 2D and 3D primitives on all levels of the reconstruction chain.

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However, only buildings can be obtained which fit the available connector / terminal scheme.

Of course, all approaches which are based on laser scan data are susceptible to certain problems. Erroneous reconstructions may result since smaller objects like chimneys or windows lead to false measurements or holes. Also, the detected outline of the building may be erroneous due to vegetation which overhangs the roof surface. Moreover, a low point density can lead to an error in segmentation, since small surfaces contain too few points.

In order to overcome such problems, a strong model can support segmentation, since the model is able to bridge missing data or to replace wrong segmentations. One such approach is to use formal grammars.

Prusinkiewicz & Lindenmayer (1990) present L-systems, which are grammars developed to simulate the growth of plants. Later, such an approach has also been used in the context of road and building reconstruction (Parish & Müller, 2001). In contrast to facades, which are limited by their extents and are thus more amenable to split grammars, roofs can be described by a growth-like process, as expressed by L-systems.

Other grammar-based approaches are shape and split grammars. Shape grammars operate by detecting and replacing simple shapes directly (Stiny et al., 1972). They were developed to reproduce shapes and sculptures under the aspect of mathematical aesthetics, using derivation rules. Split grammars do not grow an object, but rather partition it successively into smaller units. They were introduced by Wonka et al. (2003) to subdivide facades into subparts which are described by predefined primitive shapes. A second grammar, called the control grammar, is used to assign attributes during the derivation process.

Müller et al. (2006) combine the modelling of (coarse) volumetric primitives with the generation of (detailed) facades. Using a grammar called CGA shape, large city models can be generated artificially down to a very detailed level, which is demonstrated by a virtual reconstruction of ancient Pompeii.

In order to explore possible interpretations based on given measurement data, Monte Carlo techniques are often used. Thus, a huge number of proposals is hypothesized, which are then verified using the available measurement data. Methods used include Markov chain Monte Carlo (MCMC) or reversible jump Markov chain Monte Carlo (rjMCMC), which is able to generate models of varying dimensions. For example, Dick et al. (2004) use rjMCMC to reconstruct buildings from multiple images, whereas Mayer & Reznik (2005) use MCMC to detect windows in facades.

2. DETECTION OF ROOF TYPES

A program has been developed to detect simple roof sub-shapes based on laser scan point clouds. The program works in four steps, similar to the approach of Verma et al. (2006). First, planes are detected, second they are segmented, third a region adjacency graph (RAG) is set up, and fourth, roofs are found as subgraphs of this RAG. These four steps are described in the following.

1. Plane detection.

First, the normal vector for each point is calculated by using a random sampling consensus (RANSAC) approach. The points in a local neighbourhood are used to estimate a plane and thus to obtain a normal vector. This can also be done using principal component analysis. However, using RANSAC has the advantage that it will also yield correct normal vectors in the vicinity of sharp building edges. Subsequently, planes are extracted from the point cloud, again using a RANSAC approach. Points are only added to the consensus set if they are close to the plane and their (local) normal vector, determined in the first step, is similar to the normal vector of the plane. To increase the possibility of success, the whole point cloud is divided into grid cells and each tuple of seed points is drawn from one grid cell only.

2. Segmentation.

As a result of the plane detection step, there are some patches that do not connect but were extracted as one patch because they have the same plane equation. Using region growing, connected regions are obtained.

3. Construction of the RAG.

In this step, the adjacency relations of each segmented region are found and abstracted into a graph. Patches that have too few points or are too small in size are removed beforehand in order to avoid unreasonable results. Then, to judge if two patches are adjacent, their intersection line equation is calculated, and the points in the two patches are rotated until their link line is parallel to the x-axis. After the rotation, the envelope boxes of both patches are calculated. If the distance of the two boxes along the y-axis is smaller than the given distance tolerance, the number of points which are in the buffer of the link line are calculated. The buffer size is equal to the given distance tolerance. If enough link points are found, the two patches are considered as one pair of adjacent patches. For each adjacent patch pair, additional relations are computed such as if their angle is concave or convex, if they have the same slope angle, and if their intersection line is horizontal. The relations of each adjacent pair are attached to a graph edge which is set up between the nodes which correspond to the adjacent planes in the segmentation. After searching all adjacent patches, the RAG is obtained.

4. Matching of simple roofs.

The simple roof types to be detected are translated into RAGs and saved as templates. All possible sub-graphs of the RAG derived from the process above are matched against the templates. If one sub-graph fits one template graph, the patches belonging to the sub-graph are saved as one result of this template. The constraint conditions are used to discard unreasonable sub-graphs and also can accelerate the matching process.

All roof type templates are described in a template file, which contains for each roof the following pattern:

```
Roof type name
{
node1 node2 isConcave isSlopeEqual isLinkLineHorizontal
node1 node3 isConcave isSlopeEqual isLinkLineHorizontal
.....
},
```

where isConcave, isSlopeEqual and isLinkLineHorizontal are flags which indicate if the dihedral edge is concave, if the corresponding planes have the same slope, and if the intersection line is horizontal, respectively. Figure 1 shows an example of segmented roof planes and the two-, three- and four-plane roofs which can be found as substructures in the central hipped type roof.
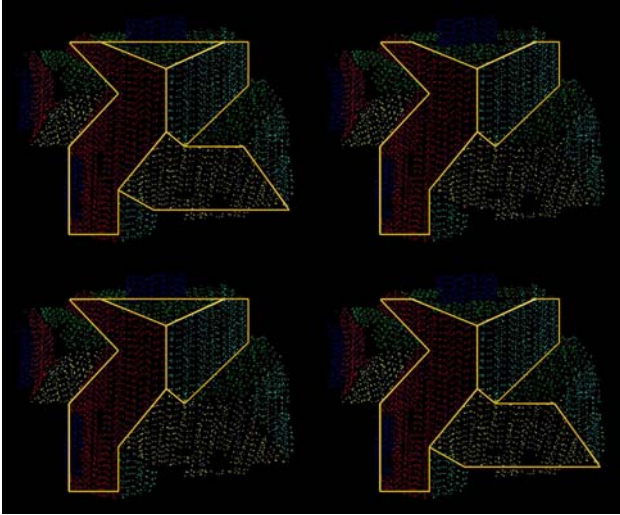

Figure 1: Simple roof structures found in a hipped roof (upper left): gable roof (upper right), three-plane hipped roofs (lower row)

3. GRAMMAR BASED ANALYSIS

In order to reconstruct roofs despite measurement errors and missing data, a formal grammar can be used which uses the results from the planar segmentation. As additional information, the basic shapes found by the RAG analysis are used, where always the most complex subshape is selected.

3.1 Formal grammars

In general, a formal grammar G consists of a 4-tuple (N,T,P,S). N is a non-empty, finite set containing the set of nonterminals, T is a non-empty set of terminals, P is the set of production rules, and S is the start symbol. In each derivation step, a production rule is applied which replaces a nonterminal symbol by a string of terminal and nonterminal symbols. Terminal symbols cannot be replaced.
Formal grammars can be subdivided into context sensitive and context free grammars, the latter of which have the property that the left hand side of the production rules contain a single nonterminal symbol only.

3.2 Description of roofs using a formal grammar

We decided to use a context free, attributed grammar. Grammar derivation rules are accompanied by rules and conditions concerning the attributes. 'Roof' is used as start symbol, 'eaves height' g being the accompanying attribute.

Basic roof shapes correspond with nonterminal symbols, which can be derived from the start symbol in the first derivation step. In our first approach, we selected five basic roof shapes as shown in Fig. 2. We believe that a large percentage of real-world roofs can be built from those shapes and appropriate connections between them.
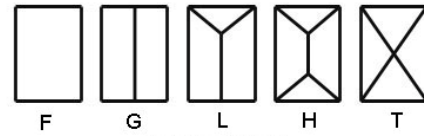

Figure 2: Basic roof shapes

Which rules of the grammar can be applied depends on the attributes associated with the symbols. A flat roof is described by the length and width and the eaves height. A gable roof additionally uses the ridge height r and the distance δg of the ridge to the eaves edges. Thus, a gable roof is not required to be symmetric.

In addition to the attributes concave/convex, same slope, and horizontal intersection line, presented in the previous section, the following attributes were defined:

- Parallelism of opposing edges and to ridge lines
- Right angles of the outer edges of the roofs
- Labelling of eaves- and gable walls
- Percentage of the individual roof sides.

When basic shapes are connected along an edge, the position of the joining points along the edge is expressed as a relative percentage (Fig. 3). The edges are enumerated for each basic shape, so that eaves walls and ridge walls can be distinguished. For example, in Figure 3, left, the enumeration is chosen such that a and c are eaves walls, whereas b and d are ridge walls.
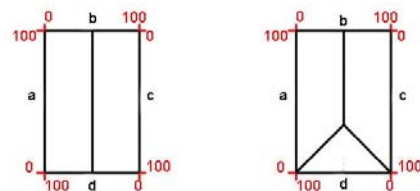

Figure 3: Percentage of individual roof sides

When several basic roof shapes are to be combined, a connector is required between them (Fig. 4). Three connectors have been identified so far (Fig. 5). These are to be selected according to the attributes of the roof shapes which they connect.
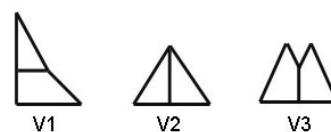

Figure 4: Connected roof shapes

Figure 5: Connectors

In order to select the appropriate connection, the first criterion is the type of the roof side which is to be connected. If this is a gable wall, this yields different possibilities than an eaves wall. For example, at a ridge wall, if the connected shape has identical roof plane equations, the roof patches can be merged. Otherwise, or in case the second primitive is flat, there is a jump edge between them. The attributes are used to distinguish the different cases.

$$S = D \;\rightarrow\; G \;\rightarrow\; GVD \;\rightarrow\; G1VG2 \;\rightarrow\; G1V1G2$$

G.1.e=D.e   D.a=G.2.b   G.1.r=G.2.r
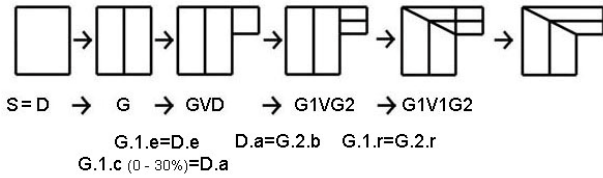
G.1.c (0 - 30%)=D.a

Figure 6: Derivation of an L-shaped roof.

For example, to construct an L-shaped roof, the derivation is as shown in Fig. 6. The start symbol is the general roof, D, which holds the eaves height as an attribute. This is then replaced by a gable roof, which additionally holds the ridge height. On an eaves side (here, side c of G.1), a second roof is attached using a connector V, which again starts as a general roof D. This roof is connected from 0 – 30% at side c of G.1. The eaves heights of both building parts are identical in this case.

In the next step, the roof is identified as a gable roof and side a of the general roof is modified into side b of the gable roof G.2. Since the ridge heights are found to be identical (G.1.r = G.2.r), connections V1 or V2 (Fig. 5) may be used. Which one is actually chosen depends on the result of the planar segmentation. The connection (in this case V1) modifies the existing roof shapes (in this case, G.1). In the final step, adjacent roof surfaces are merged if they belong to the same plane.

3.3 First results

In this section we show first results regarding two data sets of different point density. The first data set was taken at approximately one point per square meter, the second at 20 or more points per square meter. For both cases, we show the results of the planar segmentation and the found subshapes, and compare this with what can be obtained using the grammar.

One point per square meter: Fig. 7 shows a part of this data set together with manually marked roof surfaces.
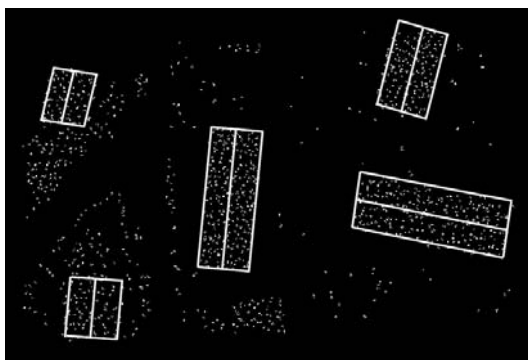

Figure 7: Roof shapes of scene one (marked manually).

Using the planar segmentation of section 2, the result in Fig. 8 is obtained. The gable roofs are found correctly, but

additionally, spurious surfaces lead to the identification of hipped roofs which are not present in the scene.
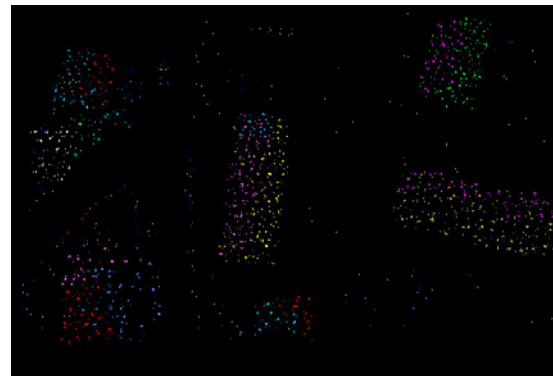

Figure 8: Planar segmentation of the example from Fig. 7.

Due to this oversegmentation, the grammar will reconstruct a hipped instead of a gable roof, because it starts with roof with the most complex shape.

20 points per square metre: Fig. 9 shows the results for the dense data set, again with manually marked roof surfaces. Compared to the previous example, this scene contains much more complex roof shapes.
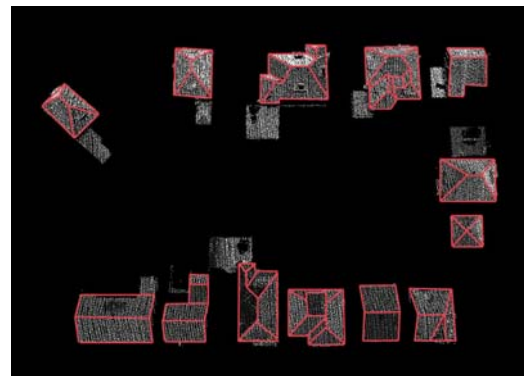

Figure 9: Roof shapes of scene two (marked manually).

For this data set, the planar segmentation yields quite good results, as shown in Fig. 10. Clearly, the reason for this is the high point density.
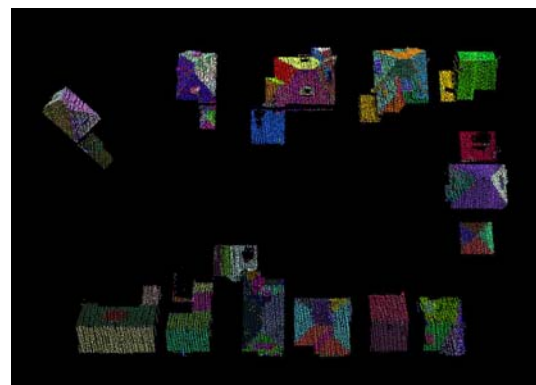

Figure 10: Planar segmentation of the example from Fig. 8.

Based on this segmentation and the results found from the analysis of the RAG, the grammar is manually applied.

All the simple roof shapes can be reconstructed using our grammar based approach. Also, results for more complex roof shapes are promising.

Problems occur since there are only a limited number of basic shapes which are not sufficient to model all roofs present in this scene. Also, flat roofs, which are part of a more complex roof, are currently not handled since planes with a jump edge between them are not detected as being adjacent. Jump edges are also not included in the grammar yet, so that the roof in Figure 11 (right) will not be reconstructed correctly.
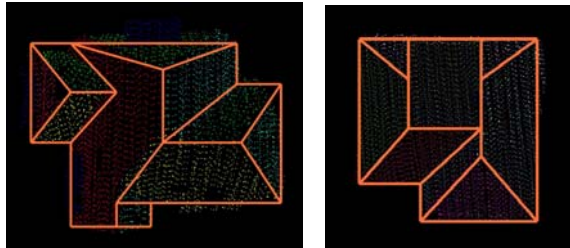

Figure 11: A roof shape which can (left) and cannot (right) be expressed using our grammar.

4. CONCLUSION

In this paper, we have described our first steps towards a grammar based reconstruction of building roof shapes. First, we used a planar segmentation followed by an analysis of adjacent regions to find simple subshapes. Then, we described our formal grammar which is used to express valid roof types. We analysed several roofs and commented on the method and its limitations, using two datasets of different point density.

Using the data set of low point density, we experienced problems in the planar segmentation step. Since our grammar based approach uses the segmentation results, it also yields wrong results.

In contrast, using the data of high point density, a good planar segmentation is obtained. Then, relatively complex roofs can be reconstructed using the grammar (Fig. 11, left). However, the grammar still cannot express all the roof shapes present in the second scene. To render this possible, more basic shapes and rules have to be added. Nevertheless, it is also the goal of the grammar based approach to provide a certain acquisition generalization by providing only a well-defined, limited amount of expressiveness.

5. OUTLOOK AND FUTURE WORK

Our main goals are to extend our approach to more complex roof shapes and to automate the reconstruction process. Our first step will be to integrate jump edges into the region analysis and into the grammar. Then, we will add more basic shapes and rules, based on an analysis of a larger built-up area.

Up to now, the selection of rules has been carried out manually. We plan to develop this towards a hypothesize-and-test approach, for example using rjMCMC to generate samples. Using the scan data, a data-driven rjMCMC approach should be feasible, as in (Ripperda & Brenner, 2007). Also, the grammar-based reconstruction currently builds on top of the segmentation results only. Thus, height data is used only indirectly. We plan to couple the grammar more tightly to the original scan data as well.

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