3D-City Models:
Automatic and Semiautomatic Acquisition Methods

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Abstract

3D-city models are becoming an important tool for town planning. Photogrammetry appears to provide the only economic means to acquire truly 3D city data. The paper discusses the current status of automatic and semiautomatic acquisition method. Research in automatic methods for building extraction being increasingly intensive in the last few years has lead to promising results, however, still lacks the performance needed for practical applications. Semiautomatic acquisition methods rely on the ability of the operator to intelligently interpret and select the required information and appear to be ripe for practical implementation.

Contents

1 INTRODUCTION

Three dimensional (3D) city models are becoming an important tool for planning. Though city management needs a large variety of spatial information, most of which is administrative,

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reference to space is needed in nearly all queries to a city management system. Reference to two-dimensional city maps with various kinds of themes, including height of topography, roads or pipes, appears to be available. However, the need for 3D structure of buildings has evolved rapidly in the last years. Applications are transmitter planning of phone companies, micro climate investigations, analysis of air pollution, noise emission, or architectural design. This demand is confirmed by the OEEPE Survey on 3D City Models by the European Organization for Experimental Photogrammetric Research (OEEPE, cf. Fuchs et al. 1998): 95 % of the participants mention 3D building data to be of most interest within city models, followed by information about traffic networks (about 85 %) and 3D information about vegetation (about 75 %). At the same time the communication between producers and users of 3D city data should be improved, as 'Every second producer has requests to provide other objects or information than he is presently producing and three out of four users would like to have other city data than already available'.

Photogrammetry appears to provide the only economic mean to acquire truly 3D city data. This holds for both techniques available today, stereo evaluation of aerial images and the use of airborne laser range data. Photogrammetry inherently measures three dimensional thus in principle is able to fulfill the requirements.

However, there are quite some problems in establishing 3D city data:

- Data acquisition in photogrammetry has been triggered by the past requirements for planimetric information of buildings.

- Current geoinformation systems cannot handle truly 3D data. The height of buildings often is just taken as an attribute, which of course is a first step in establishing a 3D city model.

- There is no commonly accepted model for the object 'building'. Due to the great variety of 3D building forms this is already true for two dimensional descriptions of the ground plan, much more this holds for 3D descriptions with the multitude of possibilities for generalization.

- The diversity of applications of 3D building data hinder an agreement on a specification which developers of data acquisition systems could rely on.

Nevertheless, the obvious needs and the technical challenge have triggered intensive research in 3D building acquisition.

The goal of this paper is to describe and evaluate state of the art in 3D building acquisition. Due to the high costs of 3D data acquisition in general, which is due to the higher amount of data and the need for generating topologically consistent data, automatic procedures appear to be the only way to satisfy the needs of the users. Based on examples we will show the potential of currently available methods and demonstrate the difficulties of fully automatic techniques. We therefore also describe and evaluate semiautomatic systems w. r. t. their use in practice. They rely on the ability of the operator to intelligently interpret and select the required information and appear to be ripe for practical implementation.

2 BUILDING MODELS

Any acquisition method requires as prerequisite a building model. This may be sufficient for manual data acquisition, and can be found in map specifications, as e. g. in the object catalog of the German topographic cartographic information system ATKIS. Automatic systems in addition need an image or appearance model, i. e. a model how the objects appear in the data, be it aerial image or laser range data. These image models reveal additional difficulties during specification.

2.1 The Complexity of Buildings

Buildings reveal a huge variety. We only refer to the exterior boundary of buildings not their interior structure. Even with this restriction the diversity of forms is very large, moreover, any fixation of structure will motivate architects to invent new elements, hitherto not seen. However, on may always restrict to a limited level of detail. Visualization may use texture mapping techniques to compensate for lack of details (cf. Fig. 1).

Building models mean the representation used for describing the form of buildings, not the actual description, thus correspond to mathematical models, which describe rules of a certain kind, in contrast to digital elevation models, which refer to a specific description of the object.

One may distinguish between different models:

- parametric models. Parametric models describe the form by a usually small but fixed set of variable parameters. The structure of the building is fixed. These parameters allow to vary the form, and may also refer to position and orientation of the building. As an example take a gable roof (cf. Fig. 6) whose form may be described by length, width and two heights. Four additional parameters may specify the spatial location and the orientation. Classical building forms are houses with flat roof, gable roof or hip roof. Assumptions about certain properties, e. g. edges or surfaces to be horizontal or vertical or to be symmetric may be established to reduce the number of specifying parameters. Also L-shaped buildings could also be described this way. However, this mode of extension is limited due to the a priory fixation of the number of parameters.

- generic models. Generic models allow for variation in the structure of the building, thus need to be able to specify the internal structure generally requiring a set of geometric parameter which is not fixed in number.

We may distinguish two important subclasses of generic building models all of the being in use:

- prismatic models assume the building to be specified by a polygonal ground plan, vertical walls and a planar, usually horizontal roof. Thus the structure of the building is quite limited, the number of parameters is given by the number of edges of the ground plan.

- polyhedral models assume the building to be bounded by planar surfaces. Obviously this is a quite general model, just excluding curved surfaces. Similar to prismatic models, one could require the walls to be vertical or certain symmetries to hold.

Both models do not take into account the internal structure of buildings which are constructed and perceived as agglomerates of parts. This is the reason why an additional subclass of generic models is used:

- CSG-models. Models from constructive solid geometry allow the composition of complex models from simple parts. The simple parts, also called primitives, usually are parametric models. The composition of primitives can be performed by the union, the intersection of the difference of the corresponding volumes. As the type of primitives is not limited, thus may also contain objects with curved surfaces, such as cylinders or tori, the flexibility of modeling is very high. A boundary representation of an object may be uniquely derived.

All models mentioned so far allow to describe the form of the object. This may be sufficient for visualization. For GIS data acquisition thematic attributes may be important. The semantics of the objects may be added as attribute, however, complex buildings represented as polyhedra prevent a simple attributation, while CSG-models allow to specify the semantics of each primitive.

hier Fig 1, 7.5 cm hoch

Figure 1: shows one image (section) out of 6 and the automatically derived texture mapped 3D model, from Baillard et al. 1999

2.2 The Appearance of Buildings in Aerial Images

Automatic procedures need to know the appearance of buildings in the sensor data. They work on the original gray level (or color) images (cf. Fig. 1 left) or on derived image features (cf. Fig. 2 right), which are points, straight lines or homogeneous areas.

There are basic properties of such image data, which have to be taken into account when analyzing the images and which prevent simple solutions:
- the loss of one dimension in images causes indeterminism about the form of the objects
- occlusions by the objects them self or by other objects cause lack of information.
- other objects or object parts lead to additional data which are not immediately relevant
- the image features cannot be extracted reliably, due to image noise, low contrast, limited modeling, disturbing objects etc.
- the data contain no semantics about the object.
hier Fig. 2, 7.5 cm hoch

2.3 Buildings in Digital Surface Models

Airborne laser range data leading to Digital Surface Models (DSM) appear to solve these problems. Advanced automatic stereo techniques (cf. Baillard et al. 1998, Bignone et al. 1995, Fratkin et al. 1999, Jaynes et al. 1997, Schlüter 1998) specialized to urban scenes have been developed for this same reason.

In both cases, one has the advantage of having 3D data which are easier to analyze with respect to buildings (cf. Weidner/Förstner 1995, and the citations mentioned above). DSM actually show nearly no occlusions, of course for the price of additional flying costs.

The extraction of DSM features is as involving as the extraction of image features. This especially holds for DSMs from airborne laser range data, as their resolution is limited and the regular DSM results form a usually quite complicated interpolation process of the irregularly

Figure 2: shows an image (section) and the corresponding image features

spaced 3D points. Errors in navigation data may lead to rugged edges.

In all cases also these data contain no semantics.

3 ACQUISITION STRATEGIES

Data acquisition consists of using the sensor data for deriving geometric and possibly semantic descriptions of the imaged scene. There are several strategies which we will sketch here in order to explain the developments in research.

3.1 Difficulties of Automatic Image Interpretation

Interpretation consists in the detection, the structuring, the geometric reconstruction and possibly the semantic attributation of the objects. The situation is technically different in intensity images and in surface models (range images). In all cases the semantics is derived from the observed intensity, color or geometry using the object and the appearance models (cf. Lang 1999).

Detection of buildings can rely on simple attributes which distinguish buildings from non-buildings: In DSM this might be the relative height and the size of regions with heights larger than the surrounding (cf. Weidner/Förstner 1995). In images the situation is much more complicated due to the loss of the third dimension. Lang (1999) uses corner points, i. e. feature points with long neighboring image edges for initiating stereo reconstruction of corners of buildings. Taking the projection into the image into account, rectangles formed by image edges are an efficient way to setup hypotheses (Nevatia et al. 1999). Bayesian networks appear as a promising tool for qualitative recognition of buildings in aerial images (Kulschewski 1997, 1999, Nevatia et al 1999).

Structuring of the the data is the most complicated part, in case generic models are used. Structuring essentially is setting up the neighborhood relations, i. e. the topology between

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the different parts of a building. This process consistently is performed in 3D (e. g. Baillard et al. 1999a/b, Chen/Murai 1998, Fischer et al. 1998, Fradkin et al. 1999, Haala et al. 1998, Haala/Hahn 1995, Henricsson 1998, Jaynes et al. 1997, Lang 1999, Maas 1999a/b, Moons et al. 1998).

Geometric reconstruction, given the structure, is a comparably simple task. It may rely on the points and edges extracted in all images simultaneously and use a bundle adjustment. This is state of the art also in the Computer Vision area, and allows to give quite realistic estimates on the precision of the extracted 3D geometry.

Semantic attribution can be as simple as labeling a face as being a roof or a wall or as complicated as deciding on the use of a building, which may be even derivable only taking into account the wider context in the image. Most systems do not address this part of interpretation. In Fischer et al. 1998 the semantics of building parts refers to the type of roof structure.

3.2 The Role of Knowledge

Deriving a building description from images in addition requires a well defined building model and interpretation process. In terms of artificial intelligence this is required knowledge.

There are at least three dimensions this knowledge has: Object models, image models derived from the object and the sensor models, and the process knowledge. None is commonly accepted.

This results in a set of hitherto unsolved problems:

- For each type of building model, being dependent on the application, and for each class of data (imagery, DSM) with a choosable resolution there exist many paths from the data to the building description.

- Combining two or more data sources naturally reduces the amount of knowledge necessary. Using more than two images allows to overcome the problem of occlusions, thus the need to predict these parts using model knowledge, at the expense of more complicated processing (Baillard et al. 1999a/b, Fischer et al. 1998, Fradkin et al. 1999, Lang 1999, Moons et al. 1998, Noronha/Nevatia 1997). On the other hand integration DSM with ground plans of buildings due to the complementarity or the data sources requires much less model knowledge, appears comparably straight forward and leads to an efficient procedure (Haala et al. 1998).

- Machine learning techniques are the only way to overcome the conflict of needing huge amount of model knowledge and of being unable to perform this modeling by hand. First experiences show the feasibility of theses techniques (Englert 1998).

The two examples shown below will demonstrate the use of knowledge.

3.3 The Role of Interaction

The difficulties in structuring and semantic attribution lead to low success rates of the automatic systems. The reported success rates (e. g. in Nevatia 1999) refer to very special conditions. Often also the number of samples investigated is much too low, observe the relative accuracy of a success rate derived from from N samples is 1/sqrt(N), thus 100 samples lead to success rates being uncertain to 10 %. Moreover, evaluation complex building structures is a conceptual problem already in 2D (cf. Ragia/Förstner 1999). Agreeing on and generating reference data is very difficult. Self diagnosis, e. g. in the sense of traffic light programs indicating success (green), failure (red) or uncertainty (yellow) would help, but due to the complexity of the methods is far beyond current knowledge.

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It can be doubted that automatic systems can achieve success rates comparable to human operators within the next few decades.

Having the operator in the loop allows quick and efficient solutions:

- The operator anyway needs to specify the task and to check the result. Specification is to be done by the user, checking is difficult, especially as missing details cannot be detected by the system.

- Structuring and semantic attributation can be performed by the operator, detection and geometric reconstruction can be performed by the system. Topological structuring is the explicit goal of the CC-Modeler (Grün/Wang 1998), structuring and partial semantic attibutation is the explicit goal of the system ObEx (Gülch et al. 1999).

- Generalization can be performed, if necessary

- Automation may be integrated stepwise following the efficiency of the automatic procedures. Goal would be to accept an automatic procedure only in case the total costs actually decrease, either through increase of speed or through increase of reliability.

4 EXAMPLES FOR ACQUISITION METHODS

Two examples want to illustrate the techniques for automatic building extraction. Both use multiple images from which the orientation is assumed to be known.

4.1 Two Automatic Approaches

4.1.1 Oxford's Approach

The first one, developed by the Visual Geometry Group in Oxford aims at a polyhedral description of buildings (cf. Baillard et al. 1999a, b).

They start with extracting 2D straight line segments (edges) in the image (cf. Fig. 3 left). Using a line matching algorithm they derive 3D edges (cf. Fig. 3 right) from in this case 6 images. The line matching algorithm (Schmid/Zisserman 1997) not only exploits the geometry of multiple views but also the intensity information in the images to overcome the splitting of the edges as to be observed in Fig. 2 right. Starting from the 3D edges they use the intensity information on both sides of the image edges to find the optimal orientation of a half plane passing through the 3D edge, shown in Fig. 4 for a small subsection. Prolongation of these half planes and intersection leads to complete roofs. Assuming vertical walls, texture mapping with the image intensities leads to a photo realistic view (Fig. 5).

Another result has already been shown in Fig. 1.

Observe the continuous use of domain specific knowledge about buildings: The straight edges of the polyhedral model motivate the image edge extraction procedure. Using the perspective model of the images trigger the matching algorithm. The half plane model takes into account the different orientation of neighboring sides of polyhedral faces. Their intersection defines the edges of the polyhedron.

4.1.2 Bonn's Approach

The second approach has been developed jointly by the Institutes for Computer Science and Photogrammetry at Bonn (Fischer et al. 1998).

They aim at a CSG-description of buildings, where the primitives are building parts, representing either end parts of basic buildings or connecting parts between pairs of basic buildings, both parametric models.

They start with a feature extraction leading to image points, image edges and image regions as shown in Fig. 2 right. Then corners are looked for in all images, which are promising for 3D reconstruction. The reconstructed 3D corners are classified with respect to typical building corners (cf. Fig. 6). These 3D corners, shown in Fig. 7 for two different buildings, lead to hypotheses of building parts (cf. Fig. 8). A 3D analysis of the bundling yields situations where a) neighboring corners belong to the same building primitive (Fig. 8 middle), fixing some of the parameters of these primitives and b) neighboring corners linking different but compatible building primitives, fixing parameters common to both primitives (Fig. 8 right). The height of the ground plan of the buildings, not derivable from the available 3D corners, can be taken from a Digital terrain model.

Observe, none of the approaches stores the used knowledge explicitly. This is typical for an early stage of development in a field.

4.2 A Semiautomatic Approach

Semiautomatic systems aim at taking the advantage of both, the operators skills to interpret the data and the machines skill to efficiently handle large amount of data. The goal is to increase performance of purely operator driven systems by inclusion of automatic techniques. Of course the classical tools from interactive photogrammetric and cartographic systems, such as snap functions, topology building etc. can be used to advantage also when acquiring truly 3D data.

In the case of digital photogrammetric systems two types of processes are unique:

- Extraction of geometric features, especially straight image segments, help measuring in the image, thus reduce the operator's task to pointing at the correct image feature or to provide accurate enough approximate values.

- Image matching techniques enable automatic measurement of heights of selected points by finding corresponding points in two or more images,

- Matching corresponding image and model features allows automatic determination of model parameters. E. g. in case a building primitive represented parametrically needs to be adapted to the image content, the wire frame model of the primitive may be projected into the images and the projected lines may be compared with the extracted image lines in order to optimally determine the parameters of the model.

Several systems have been developed in the last years (cf. Brenner/Haala 1998, Grün/Wang 1998, Lammi 1998, Veldhuis 1998, Vosselman 1999), some of which are discussed in this volume.

We want to give a few details of our system ObEx for semiautomatic object extraction. It was developed in the past years (Lang/Förstner 1996, Englert/Gülch 1996, Müller 1998, Gülch et al. 1999). The key properties of the system are:

- It can handle aerial images and DSM
- It can handle single and multiple images
- It is a one-eye stereo system, thus interaction takes place in one image
- It uses a wire-frame cursor for data acquisition, which is much easier to handle than point cursors
- It leads to a CSG-description of the object

Besides basic tools of an interactive system it contains automatic image analysis tools:
- Automatic measurements of heights
- Automatic determination of parameters of primitives

The last feature reduces the number of necessary interactions for acquiring data to a minimum, e. g. three points in one of the images for measuring a building with a saddle roof, namely the two gable points and a point at the ground.

Figures 9 and 10 show an example. The 3D model in Fig. 10 right is derived from the single aerial image Fig. 10 left using the known height of the ground. Observe, the 3D model contains overhanging parts.

We only integrated automatic modules if they really increased efficiency, which we controlled by extensive practical tests.

We have found it convenient to compare acquisition times in seconds per primitive, as more complex buildings usually consist of more primitives than simple buildings.

In the table you find acquisition times of different projects during the last years (taken from Gülch et al. 1999). We now can reach a speed of appr. 20 sec./primitive. This is comparable both to classical photogrammtric techniques, and to the other techniques available.

Version	Project	Details	Compl.	Prim.	Sec/P.	Remark
-1995 Hase	Diff. areas	Suburb-Urban	medium	249	**124.8**	Basic version
1996 Hase+	Oedekoven I	Suburb	high	5499	**86.4**	CSG
1996 Hase+	Frankfurt I	Downtown	high	549	111.5	CSG, one image only
1996 Hase+	Rostock	Urban	high	371	149.6	CSG and non-photogrammetrist
1997 ObEx0.7.1	Oedekoven III	Suburb	high	525	**70.0**	Slider for height measurement
1998 ObEx0.8.2	Oedekoven-SD.	Suburb	medium	29	**41.0**	Automated form adaption
1998 ObEx0.8.7	Frankfurt II	Suburb	high	3907	**40.9**	Automated form adaption
1999 ObEx1.0	Oedekoven	Suburb	high	62	**20.3**	Copying and guided adaption alone

Table 1: Development of acquisition times and the relation to the the involved new functionality (Compl.:=complexity, Prim.:=# of primitives in the data set, Sec/P.:=seconds per primitive).

5   CONCLUSIONS

Automatic techniques for building extraction have evolved rapidly in the last years. They show great potential for generating 3D city models of high fidelity. Up to now are not reliable enough to be used alone. Most of the automatic techniques only work in areas without or little vegetation. Occlusions due to vegetation will even more increase the need for operator assistance.

Semiautomatic systems could make intensive use of these methods, in case their kernels are made stable and equipped with a reliable self diagnosis. Then a further increase in efficiency could be achieved and lead to a surpass of classical system.

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Imaging, Heijen, The Netherlands, 1999
CVIU: Computer Vision and Image Understanding
CVPR: Computer Vision and Pattern Recognition
ECCV: European Conference on Computer Vision
IAP: International Archives of Photogrammetry and Remote Sensing

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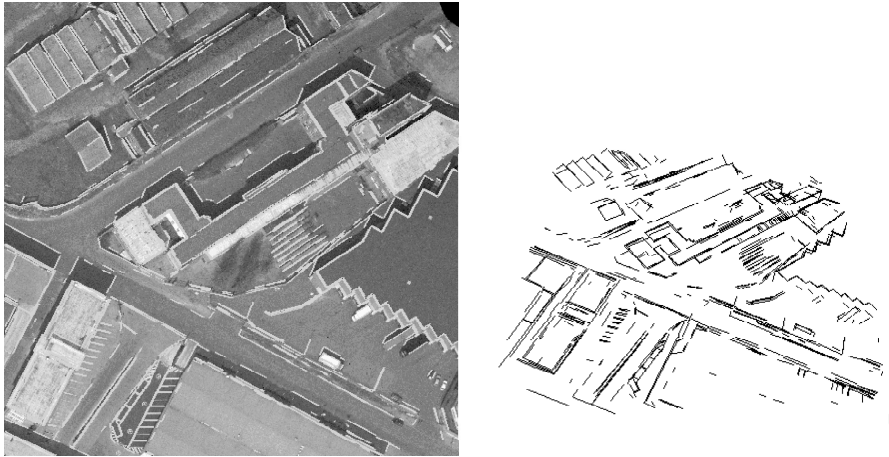Figure 3: shows one of six aerial image sections with the extracted edges

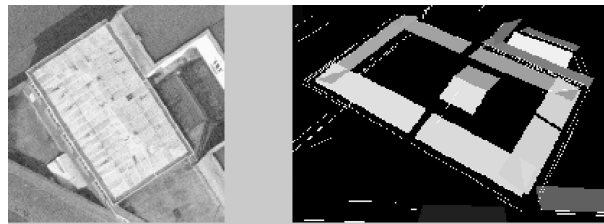Figure 4: shows the reconstruction of half planes

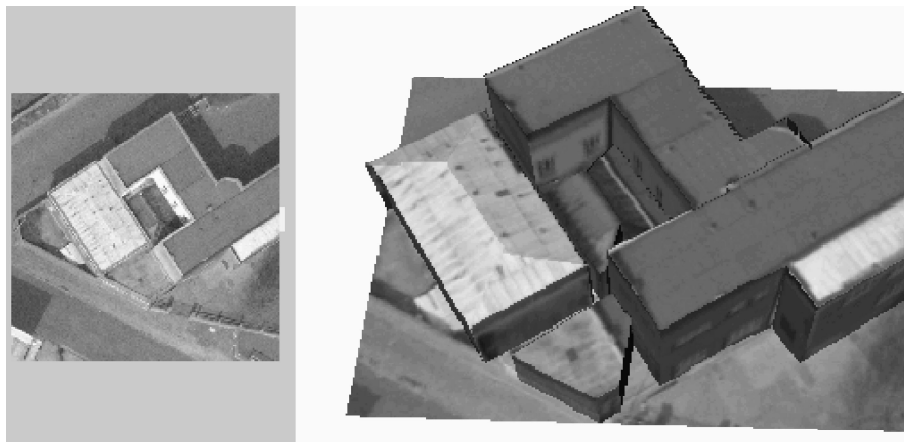Figure 5: shows one image section and the texture mapped 3d model

Figure 6: shows the corner classes of four types of buildings

flat roof   prismatic roof   gable roof   hip roof
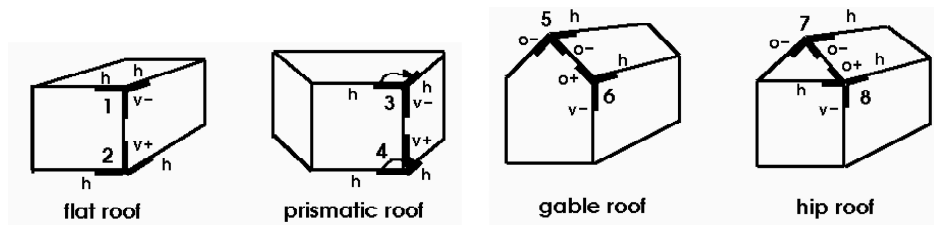
Figure 7: shows the reconstructed corners of two buildings

Marked
Feature Aggregates

Reconstructed
3D Corners
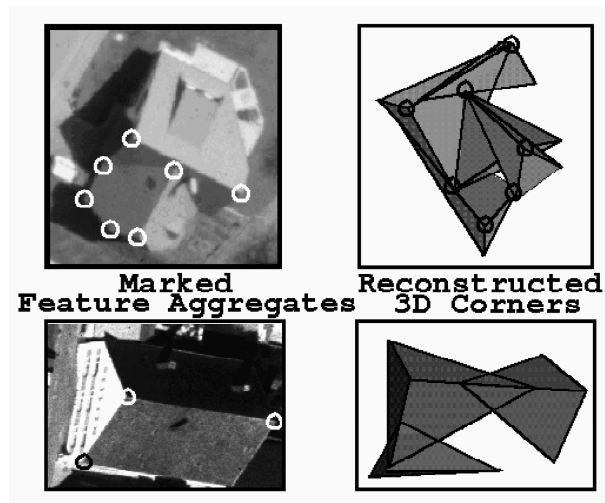
Figure 8: shows the process of 3D grouping of the corners

Corners
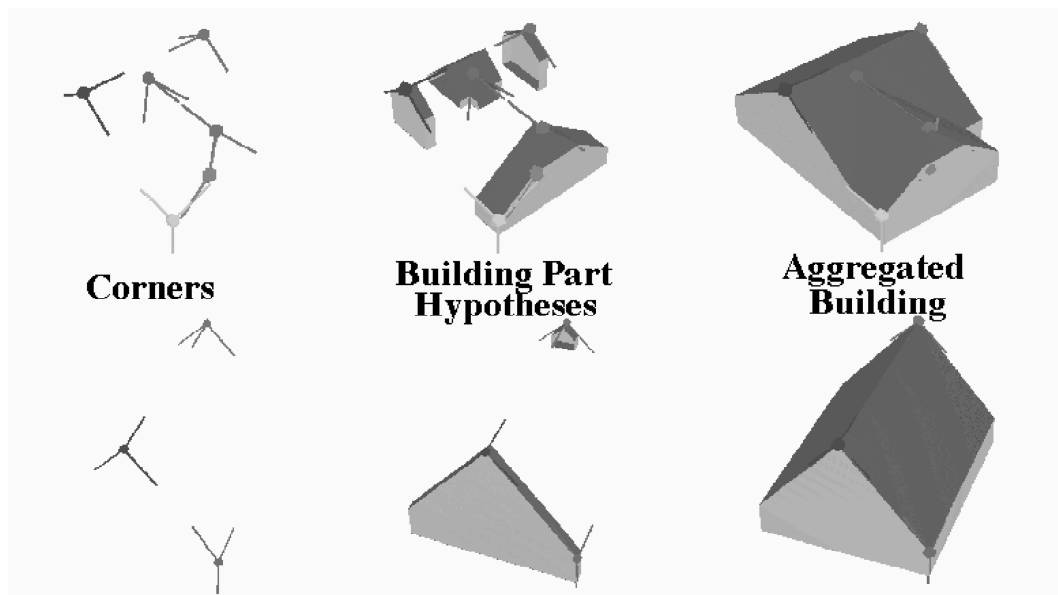
Building Part
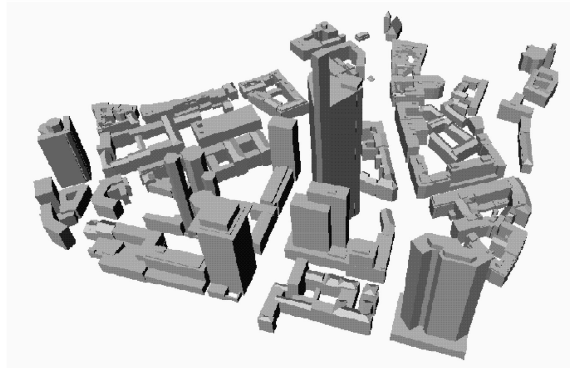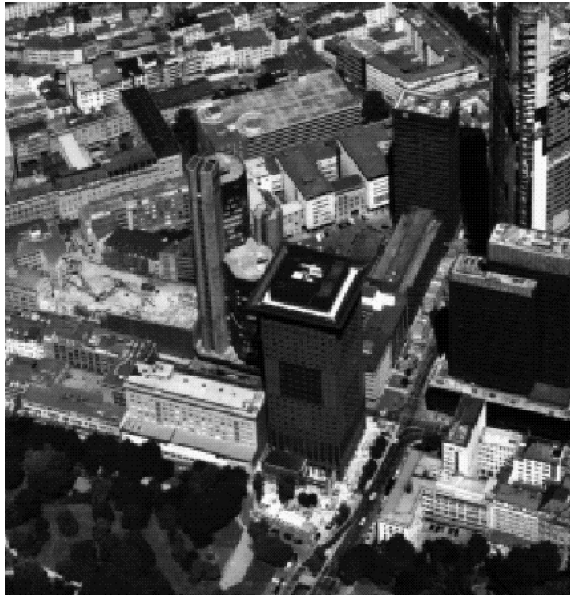Hypotheses

Aggregated
Building

Figure 9: shows the section of a single aerial image

Figure 10: shows the textured 3d model