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Automation in Building Reconstruction

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ABSTRACT

Automated methods for reliable 3-D reconstruction of man-made objects are essential to many users and providers of 3-D city data. Manual 3-D processing of aerial images is time consuming and requires the expertise of qualified personnel. Therefore, the necessity to interpret, classify and quantitatively process aerial images in a semi- or fully automatic mode and to integrate the results into CAD- or spatial information systems is more urgent than ever.
This paper describes current research activities at ETH Zurich in automated 3-D reconstruction of buildings. Two conceptually different approaches to building reconstruction are presented: TOBAGO and ARUBA. The first approach is semi-automatic and aims at the automatic structuring of manually measured 3-D point clouds to generate CAD models of complete buildings. It is geared towards a reliable and flexible procedure which has a large potential to be useful for professional practice. The second approach aims at fully automatic detection and reconstruction of buildings. This automatic system relies on hierarchical hypothesis generation in both 2-D and 3-D. To achieve this we have developed novel methods for feature extraction, segment stereo matching, 2-D and 3-D grouping, color and object modeling, and geometric reasoning.

1. INTRODUCTION

Many applications in city and regional planning, architecture and monument preservation, environmental engineering, telecommunications, (virtual) tourism, real estate, delivery business, etc. require 3-D data of cities and towns in structured form, so-called "city models" or "cybercity". Since city models are requested by different users with a great variety of different expectations, a city model, in general, may include many components as outlined in Figure 1. We distinguish geometric, radiometric and attributive data. The priority of these categories varies with the application. Figure 1 indicates, how the geometric and radiometric part of a "hybrid" city model can be generated from a variety of data sources (aerial and terrestrial images plus map information). Buildings constitute a crucial part of any city model. The whole of all building roofs generates a "roof landscape". For complete photogrammetric building extraction a combination of aerial and terrestrial images would be required. Aerial images serve for the determination of roofs and DTM data, while terrestrial images would be used to connect the facades to the roofs and to provide for facade pixel data. Alternatively, the location of facades could be taken from digitized cadastral maps or even from data produced with mobile mapping systems.
There are several basic techniques available to produce the required data:

5. Scanning of maps
6. Laser scanning from aerial platforms
7. Photogrammetry

Conventional data, as represented in plans and maps, is essentially 2-D, and very often, at least in parts, outdated. Laser scanners produce Digital Surface Models (DSM), which are unstructured, smoothed and not easy to interpret. The relevant information (buildings) has to be first extracted from this data, before it can be used any further. Photogrammetry represents an appropriate technology to solve the task at hand. It is inherently 3-D, geometrically accurate, and produces complete and actual results. Project parameters like image scale, camera constant, type of film (B/W or color), overlap, flight date, etc. allow for optimal adaptation to the project specifications. Modern instruments for data processing (Analytical Plotters and Digital Stations) open possibilities to automate, at least in parts, the data acquisition procedure. GIS and CAD-systems can be either integrated or interfaced.

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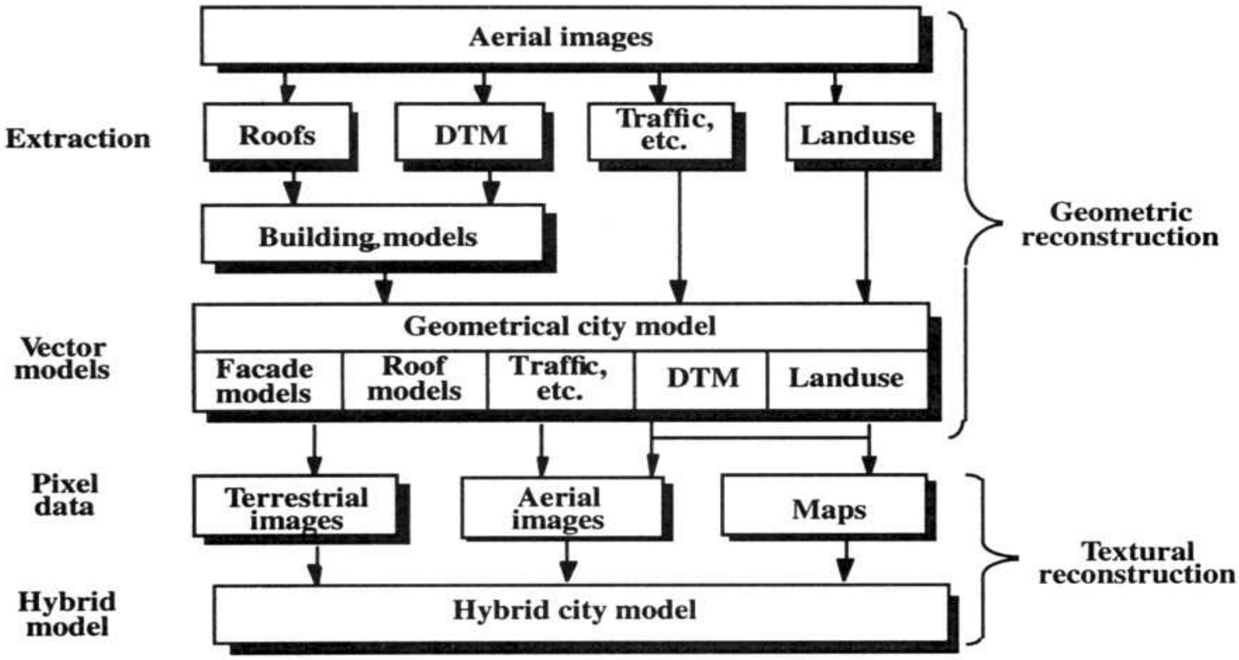

Figure 1: Generation and components of the geometric and radiometric parts of a hybrid city model.

Building extraction from images has become a key issue in research and practice lately. Using photogrammetry and computer vision the task consists in transforming 2-D image information, contained in aerial photographs, into 3-D structured vector data of buildings, as shown in the example of Figure 2. The huge volume of data, which has to be generated, requires to automate this transfer process as far as possible.

Many different approaches to building extraction have been developed in the meantime, some of them more practically, others purely scientifically oriented. Overviews of the state-of-the-art are given in Gruen, et al. (1995, 1997) and IAPRS (1996). In the next chapter we will make some basic comments about extraction methodologies. In our own group we have developed two reconstruction techniques: TOBAGO[8] and ARUBA[9]. They will briefly be described in the subsequent chapters.

[8] TOBAGO: **To**pology **B**uilder for the **A**utomated **G**eneration of 3-D **O**bjects from Point Clouds.
[9] ARUBA: **A**utomatic **R**econstruction of Sub**U**rban **B**uildings from **A**erial Images.

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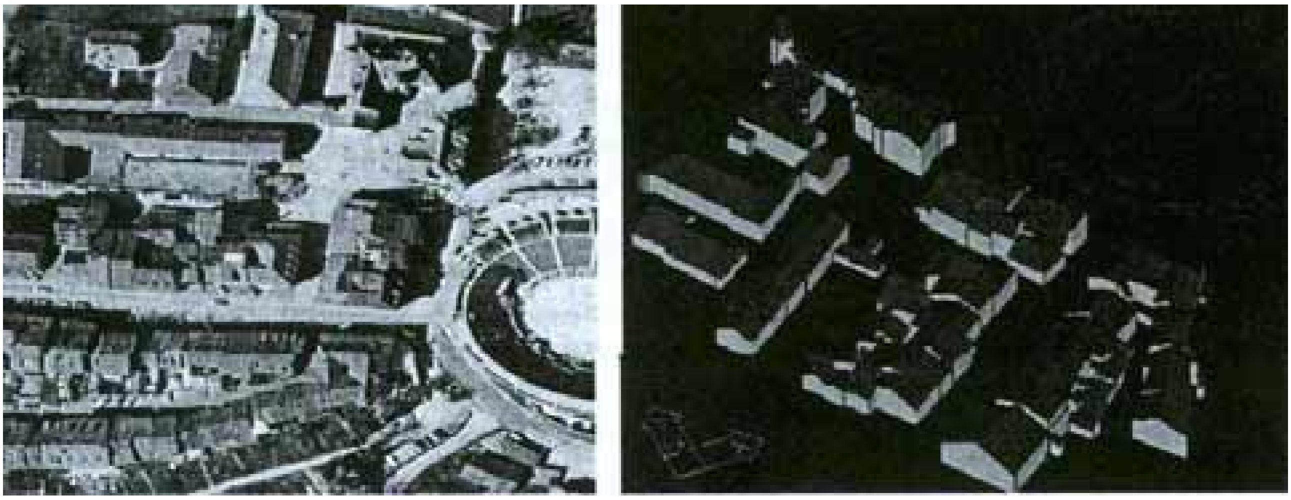

Figure 2: Aerial image and derived 3-D models of buildings (Avenches, central town).

2. METHODOLOGY IN BUILDING EXTRACTION

Building extraction consists of three steps: detection, reconstruction, and attributation. Detection refers to the process of finding a particular building in as many images as are used for further processing. Detection does not necessarily require the knowledge of the building outline, but, as a minimum requirement, should be able to produce image windows, containing the outline. Reconstruction generates the 3-D geometric description of the building at the required resolution. Attribution designates descriptive elements to the building, including the type of building (apartment house, school, church, factory, etc.), a clear definition of parts of building (chimney, dormer window, balcony, door, window, etc.), or other required information.

This sequence detection-reconstruction-attributation could even define a processing strategy and in fact is usually equivalent with the processing sequence and represents very often, but not always, a path towards increasing complexity.

At the detection level cues like color and DSM data have proved to be particularly valuable (Sibiryakov, 1996). They are used to separate in a first step man-made objects from vegetation and other natural features and then to distinguish buildings from other anthropogeneous objects, like roads, bridges, etc. Good success has been reported with isolated houses. Complex urban structures, as they exist in European old towns, still widely resist this approach.

In reconstruction we encounter a great variety of methods, depending on the type of building, level of required detail, number of images, kind of image cues and image primitives used, and utilized external and a priori information, level of automation and operator interference. There is recently a clear trend towards the use of multiple (>2) images, color cues, early transition to 3-D processing, and use of geometrical constraints. The complexity of buildings ranges from cube-shaped flat roof boxes to very complex structures with even non-planar geometrical elements. The level of detail is clearly application-dependent and goes from the joint representation of full building blocks through cube-type single height approximations of individual buildings up to a very detailed modeling with all ridge, gable and eaves points and maybe even the inclusion of chimneys, dormer windows and the like. Image cues may involve texture, color, shadows, reflection properties. Image primitives include points, double- and triple-legged vertices, linear elements, homogeneous regions. External information may come from additional sensors, DTMs, DSMs, scanned maps and GIS-resident data.

A priori information includes preknowledge about the building, its geometry and functionality (right angles, parallel/straight lines, etc.), the sensor geometry (camera models), the sun position, and the like.

The level of automation in reconstruction extends from zero (complete operator measurements and structuring) to conceptionally full automation.
For details about reconstruction techniques the reader is referred to IAPRS (1996), Foerstner, Pluemer (1997), and Gruen et al. (1997). Model-based extraction is very often referred to. This is not a very helpful terminology since any kind of information extraction from images requires the use of some sort of model of the feature or object. However, there are different kind of models utilized (parametric, generic, functional, special) and models are used at different levels of complexity (e.g. a signalized point versus a full house).
In a building extraction, as in image analysis in general, there exist two fundamentally different approaches: bottom-up and top-down. Bottom-up is a data-driven strategy, which extracts in a first step image primitives, groups them to higher level entities, and through the process of hypothesis generation and verification, builds up the complete objects. The main problem here is the instability and ambiguity of the segmentation process at the lowest level. At the higher level of object aggregation techniques from artificial intelligence, such as constraint-based reasoning, uncertainty reasoning with Dempster-Shafer, probabilistic relaxation, Bayesian reasoning, constraint satisfaction networks, semantic networks, blackboards, etc. are used.
The top-down approach, which is model-driven, usually starts with hypotheses about the scene and tries to verify their existence by compatibility checks with the existing image data. Indispensable to this technology are object models, often used in explicit form. In essence, the object data structure inferred from the image(s) is matched to the model data structure (Haralick, Shapiro, 1993). While this concept has a certain justification in robotics and navigation, where the environment might be of reduced complexity, we encounter big problems in building extraction, because here the scene knowledge is of purely generic type and the computational expense for hypotheses verification is prohibitively high.
In the more recent approaches of building extraction we see elements of both strategies used together in an interrelated manner. This seems to be the right way to approach the problem.
Other current trends in building extraction include the following aspects:

- multi-image approaches
- multi-cue algorithms
- fusion of various information sources
- Digital Surface Models (DSM) for detection and reconstruction
- derivation of DSMs by laser scanners
- generic roof modeling by decomposition into parts
- use of a priori knowledge from maps and GIS
- semi-automated reconstruction techniques

Since it would go far beyond the scope of this paper to describe all available approaches in reconstruction we will restrict ourselves to the methods that have been developed by our own group and which have reached already a certain level of maturity.

3. TOBAGO AND ARUBA - NEW METHODS FOR BUILDING EXTRACTION

At the Swiss Federal Institute of Technology (ETH) in Zurich the Institute of Geodesy and Photogrammetry (IGP) and the Communications Technology Laboratory (IKT) have started a joint project, which aims at developing novel, reliable and geometrically precise image analysis methods towards the Automation of Digital Terrain Model Generation and Man-Made Object Extraction from Aerial Images (AMOBE), compare Henricsson et al. (1996). The topics of the research focus on 3-D metric and integrative aspects of aerial image processing, in particular on methods for a semi-automated and fully automated extraction of man-made objects (buildings, bridges, roads, etc.). Our

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research has so far concentrated on the high quality 3-D reconstruction of buildings, mainly because of their importance for generation and photorealistic visualization of 3-D city models.
For the semi-automated and automated extraction of buildings we have developed three different approaches, as depicted in Figure 3. Here we present two of these: TOBAGO and ARUBA. The first approach is semi-automatic and aims at the automatic structuring of manually measured 3-D point clouds to generate CAD models of complete buildings. TOBAGO has been developed with the idea in mind to have a method which is fast, robust and safe enough to be used in a practical, professional environment. The second approach aims at fully automatic 3-D reconstruction of buildings. It is still an academic approach. The automatic system relies on hierarchical hypothesis generation in both 2-D and 3-D. To achieve this we have developed novel methods for feature extraction, segment stereo matching, 2-D and 3-D grouping, color and object modeling, and geometric reasoning. The rule-based approach presented in Willuhn, Ade (1996) has not been further developed and is therefore not included here.

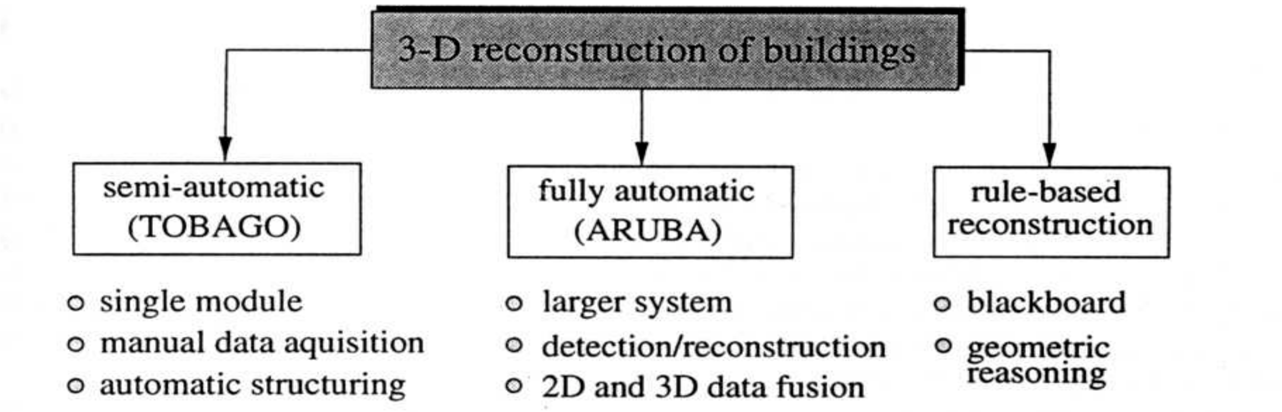

Figure 3: Different approaches for building reconstruction in the project AMOBE.

3.1 TOBAGO - a topology builder for the automated generation of building models from 3-D point clouds

This approach presents a strategy and methodology for an efficient generation of even very complex building models. It has two relevant features. First of all, the interpretation capability of the human operator is incorporated in a rigorous way and, secondly, generic roof models are explicitly used in the reconstruction process. Thus, the approach consists of two major components: manual photogrammetric data acquisition and automated structuring. Data acquisition involves measuring manually a 3-D point cloud for each roof unit from aerial images. The points can be measured in an arbitrary sequence. However, each roof must be separated from the others. A "roof unit" is a completed point cloud, which represents either a full roof or a part of a more complex roof, which can be managed by the roof models of the model catalogue. Given a 3-D point cloud and ground points, the complete CAD model of the building is automatically generated using the structuring software TOBAGO.
The first step is data acquisition, which involves measuring the emerging roof structures, such as eaves, gable and ridge points. The points belonging to a single roof unit are measured in an arbitrary sequence, thus producing a 3-D point cloud. Although trained operators tend to measure the points in a particular order, the TOBAGO software can handle arbitrary sequences of point measurements. Using this technique, several hundreds of roof units can be measured in one day. During data acquisition, the operator is responsible for the interpretation of the scene. The operator not only identifies the location of single roofs but also defines, which roof parts should be reconstructed. Hence, with this technique it is possible to acquire, for example, only the main structures of a roof. However, dormer windows, chimneys, and other more detailed roof parts can also be acquired.

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The TOBAGO software essentially solves the automatic structuring of 3-D point clouds. The concept of structuring is based on a functionality-related view of a roof. A roof is thus considered to consist of a number of points, each of which serving a certain functional purpose. The main components of the method are shown in Figure 4. The first step of structuring is a simple classification procedure. Using only the height coordinates of the 3-D points, a set of height classes is constructed. Building construction rules and the expected accuracy of the point measurements are used to set a suitable tolerance for this clustering.The classifier determines for each roof point j a class Ω_k, if

$$Z^k_{Max} - \sigma_S < Z_j \leq Z^k_{Max} \qquad (k = 1, \dots ,K)$$

Z^k_{Max} is the largest Z-coordinate in class Ω_k. Z^1_{Max} is selected such that $Z^1_{Max} = Z_{Max}$.

σ^2_S is determined by the variance σ^2_B derived from building tolerances and the accuracy of the photogrammetric interpretation and measurement σ^2_M as $\sigma^2_S = \sigma^2_B + \sigma^2_M$.

In practice σ_S is introduced based on empirical evidence. We have used σ_S = 0.3 m with good success in the projects discussed later in this paper.

Subsequently to the Classifier a Parser (K-Parser) is activated which determines the type of roof, based on the number of ridge points. For that we use a catalogue of roof models (compare Figure 4). Currently this catalogue contains 6 categories (classes) of roof types, distinguished from each other through their number of ridge points (flat roofs and roofs with one, two, three, four, five and six ridge points). This catalogue has been set up considering specific roof types in Switzerland. The given models of Figure 4 do not represent the full catalogue, they only stand for some typical examples. The catalogue is by nature always incomplete, because we use the concept of generic modelling. Therefore, it is a priori not even clear, which models cannot be handled in each class. Thus, the catalogue of tested models is growing with every project.

The K-Parser not only indicates the class a particular roof belongs to, but also determines through the examination of the ridge points' topology the type of roof within each class. This examination is coupled with procedures for blunder detection (non-consistency checks), which allow to signal problem cases. These cases are assigned to a "Rejection Class" and must be examined interactively.

In essence, the K-Parser delivers the connecting edges of the ridge points and decides about the type of parser which is used in the next processing step.

In a third step another parser (G-Parser, a geometric parser) is activated, which determines the complete roof structure, including also gable and eaves points. This G-Parser derives the detailed topology of the individual roof within a particular roof class.

The G-Parser operates with "constraint-based reasoning" techniques, exploiting geometric criteria, such as parallelism and orthogonality of straight lines. These criteria do not have necessarily to be fulfilled strictly. A tolerance parameter for deviations from parallelism and orthogonality can be selected.

We usually apply a value of ± 4◦. The parsing is performed in 2-D in the X,Y-plane.

The algorithmic details of the whole procedure are described in Dan (1996).

Both parsers, the K- and G-Parser, are able to detect blunders in the data and signal deficiencies in the configuration of points. As shown in Figure 4, those roofs which cause problems are collected in a file "Rejected Data" and further treated as explained in the following.

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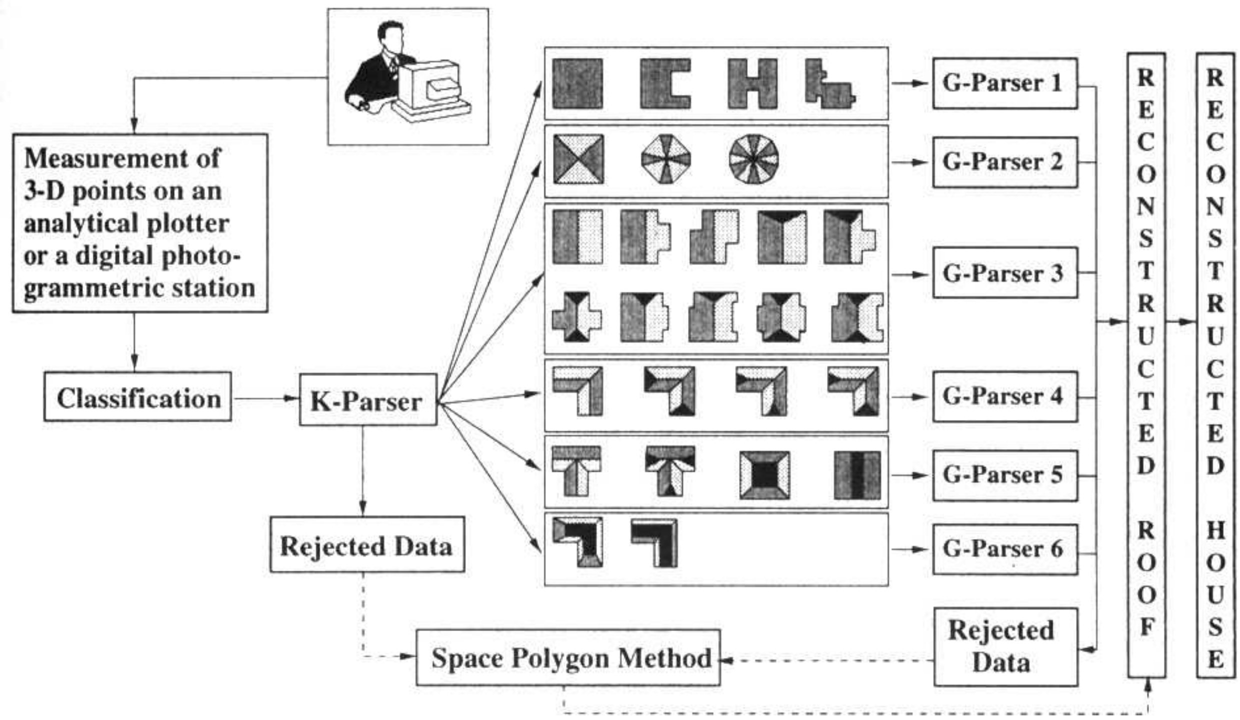

Figure 4: Structuring process of a point cloud into CAD-compatible 3-D roof models and complete buildings.

The TOBAGO software has been applied to several data sets. Our experience with the algorithm is overall positive, however, failures do occur under certain circumstances. These failures are mostly detected by any one of the two parsers. Four situations may lead to data rejection:

1. The roof is not included in the model catalogue
2. Large measurement errors (gross errors) occur
3. Missing 3-D points due to overlooking by the operator
4. Irregularities on the objects, such as acute or obtuse angles

These errors can be corrected by respectively: (1) extending the model catalogue, (2) correcting (re-measuring) erroneous 3-D points, (3) manually introducing missing 3-D points, and (4) combining the TOBAGO software with alternative methods. An alternative method for structuring 3-D points is the "Space Polygon" method. It is based on structured measuring of the 3-D points according to a predefined rule - the virtual connection line between consecutively measured 3-D points must always define a physical roof edge. This is a mode quite familiar to photogrammetric operators. This alternative approach is also suitable to solve problem (1). Often, rejected point clouds can be successfully reconstructed using this alternative method.

3.2 Results of pilot projects

The TOBAGO approach has been tested in several pilot projects (Avenches, Olten, Zürich-Bellevue, Zürich-Limmat, Chur, Oerlikon), the statistics of which are presented in Table 1.

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Project	Total number of roof units	Structured by point cloud method	Structured by space polygon method
Avenches	218	218	-
Olten	194	194	-
Zürich-Bellevue	1191	1044	147
Zürich-Limmat	855	853	2
Chur	597	357	240
Oerlikon	492	446	46
Total	3547	3112	435

Table 1: TOBAGO statistics for six pilotprojects.

For each project the table indicates the number of roof units which could be structured by either the point cloud method or, alternatively, the space polygon method. The term "roof unit" is being used in order to indicate that in case of very complex roof structures the roof is decomposed by the operator into roof units, which individually can be handled by the topology builder.

Out of a total of 3547 roof units 88 % could be handled by the point cloud method. Every project was measured by a different operator, ranging from a totally inexperienced student to a well-trained photogrammetric operator. According to our experience, given a minimum of stereomodel measurement experience, the main factor determining the performance is the degree of familiarity of the operator with the concept of automated structuring and the manageable roof models of the catalogue. With a person well familiar with the catalogue one may expect on the average 700 or more roof units to be generated per day. We believe, that with an experienced operator, roof units can ultimately be generated at an average rate of 0.5 minutes/ unit. This includes interpretation of the scene, measurement of the point clouds, structuring and necessary corrections.

The procedure of fitting roof models to 3-D point clouds can be executed on-line. The average time for the structuring of one roof unit is 5 msec on a Sparc20. This allows the operator to check each point cloud interactively and to remeasure individual points or activate the space polygon method, if necessary. Also, visualizations can be generated in quasi real-time and used for on-line quality control.

3.3 ARUBA - an automatic approach for building reconstruction

The automatic reconstruction of buildings requires many components, such as camera models, image processing, matching, texture and color modeling, geometric processing and reasoning, as well as object modeling. In ARUBA we use color aerial photography. With this imagery primarily building roofs can be reconstructed. Vertical walls are added afterwards by projecting the eaves of the roof down to an existing DTM, thereby generating a complete building. The main features of our strategy for 3-D building reconstruction are:

1. Separation of building detection and reconstruction
2. Use of multiple, overlapping color images
3. Early transition to 3-D data (DSM, 3-D edges)
4. Generic object modeling directly in 3-D
5. Combination of 2-D and 3-D processing

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One of the important strategic issues is the separation of building detection and reconstruction. The fact that each region of interest may include only one building simplifies the automatic reconstruction to a large extent. Preliminary work has been done by our group to automatically detect man-made objects in a single color aerial image (Sibiryakov, 1996 and Henricsson et al., 1996). The approach is shown in Figure 5 and consists in detecting elevation blobs from the DSM and combining this information with color analysis. A rigorous combination of blobs and color clusters allows the software to separate blobs stemming from man-made objects from those of natural objects (e.g. trees). Although impressive results have been presented for detecting buildings in a single aerial image, the approach is not yet fully automatic. We currently use a human operator to either verify/correct the automatic detection results or to manually mark a rectangular window enclosing the same building in all four images.

ARUBA utilizes multiple (>2) images. Multi-photo geometries are advantageous in providing redundant information and improving the accuracy of the reconstruction. Further, it has been shown (Henricsson, 1996) that combining color attributes with edges leads to vastly improved results over the use of either alone.

Assuming that overlapping images are available, 3-D information such as a DSM and 3-D edges can be extracted. Because 3-D information is available, object reconstruction can be done in 3-D, right from the beginning. Whenever 3-D features are incomplete or entirely missing, additional (more complete) 2-D information should be used to infer the missing features and structures. This further means that the mutual interaction of 2-D and 3-D procedures is required at all levels of processing. This interaction is important since neither 2-D nor 3-D procedures alone are sufficient to solve the problems.

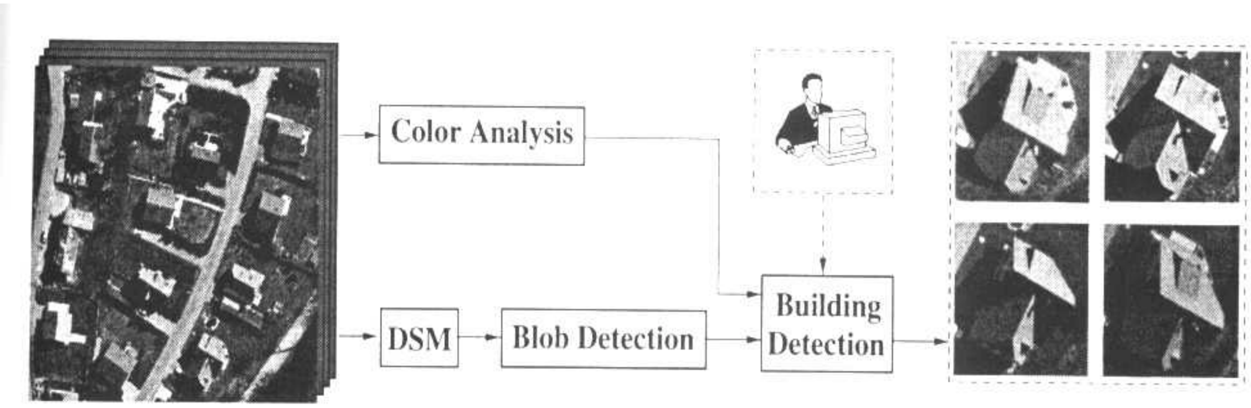

Figure 5: Our approach to automatic building detection. The method effectively combines color analysis with information extracted from elevation blobs in the DSM.

To reconstruct roofs of a general class of buildings, we propose the concept shown in Figure 6 that relies on hierarchical hypothesis generation in both 2-D and 3-D.

For details we refer to Henricsson (1996). The general assumption is that a complete roof consists of a set of planar parts which mutually adjoin along their boundary. Based on this assumption, we use a generic 3-D primitive (denoted as 3-D patch), which is roughly planar and encloses a compact polygonal 2-D enclosure with similar photometric and chromatic attributes. In a first step, straight 2-D edges from one image are matched in the other images, thus producing a small number of 3-D segments. These 3-D segments are then grouped to hypotheses of planes. The object boundary of each plane hypothesis is then found by extracting 2-D enclosures employing a novel grouping technique, which is based on similarity in proximity, orientation, and photometric and chromatic region attributes. The most evident and consistent set of planar roof hypotheses is finally selected based on simple geometric criteria. Vertical walls are added afterwards by projecting the eaves of the roof down to a DTM. The final result is a complete CAD model of the roof and its vertical walls, including 2-D contours, 3-D segments, 3-D planes and their topology.

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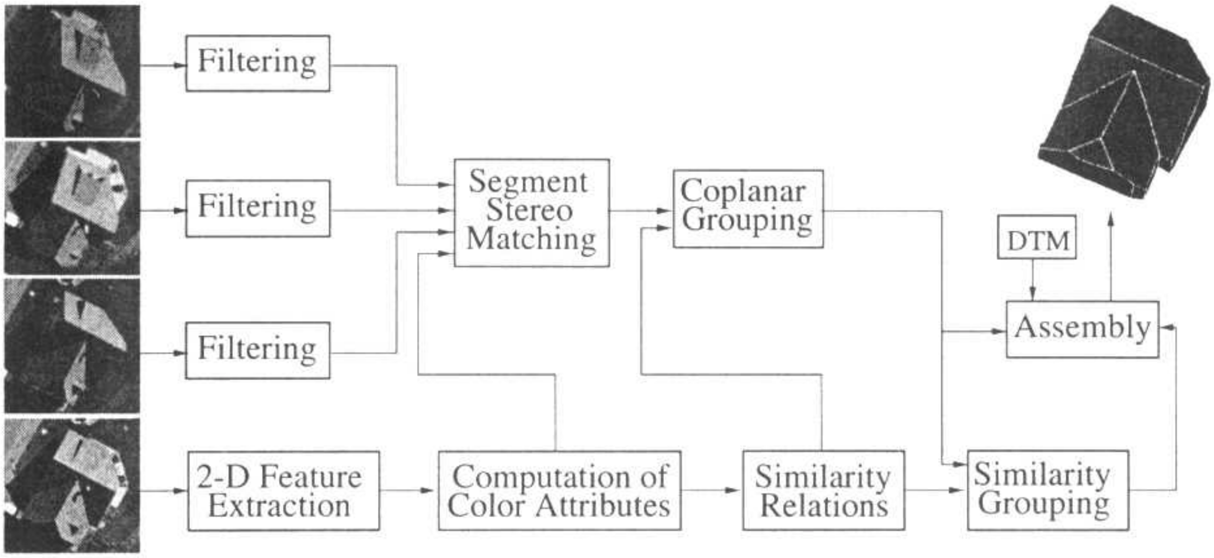

Figure 6: The ARUBA system for fully automatic 3-D reconstruction of buildings.

3.4 A test example

For testing of the ARUBA approach we selected the residential scene from the Avenches data set (Mason et al., 1994). One of the four images is shown in Figure 7A.
This high precision photogrammetric data set has the following characteristics: 1:5 000 image scale, vertical aerial photography, four-way image coverage, color imagery of size 1800x1800 pixels, geometrically accurate film scanning with 15 microns pixel size, precise sensor orientation, and accurate ground truth including DTM and buildings. The ground truth data of the buildings (shown in Figure 7B) was manually acquired by an experienced operator at an analytical plotter. This data forms the input for the TOBAGO data software and also serves as an important component to qualitatively and quantitatively evaluate the results of the ARUBA reconstruction.
Figure 7C shows the results of the fully automatic system (ARUBA). Eleven of the thirteen roofs have been reconstructed, ten of them with a high degree of accuracy and completeness. The algorithm fails to reconstruct two buildings. The lower of the two is under construction (covered with blue plastic sheets). The upper house is complicated because a group of trees cast large shadows on the right roof part. Due to these shadows the algorithm fails to extract the corresponding plane. Figure 7D shows the corresponding results of the semi-automatic (TOBAGO) approach. All thirteen buildings have been reconstructed. Notice that detailed structures, such as dormer windows, have also been reconstructed. Complex roofs have to be decomposed by the operator into simpler roof units, which can be found in the catalogue. For example, the building in the lower right corner of Figure 7B consists of four roof units.
The two approaches to automated 3-D reconstruction of buildings pursue the same primary goal - accurate 3-D reconstruction of buildings. However, the means used to achieve this goal are indeed different. In general, ARUBA is a complex system of visual processing modules, while TOBAGO is a single module that solves the structuring of a complete set of 3-D points, thereby leaving the more complex interpretation task to the human operator.
The TOBAGO software is a semi-automatic approach where the operator must manually measure the 3-D points at an analytical plotter or a photogrammetric station in stereo mode. In the current version of the ARUBA system the operator is only asked to mark a rectangular window enclosing the same building in all four images, i.e. a simple task that can be executed by an unskilled operator. On the other hand, the setting of parameters in the ARUBA system requires knowledge about the single

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modules. A further difference is the required input data. TOBAGO requires a stereo image pair, whereas the ARUBA system needs four overlapping images in order to do robust segment stereo matching. Color or false-color infrared images are favorably used in the ARUBA approach to reduce the ambiguities in the interpretation.

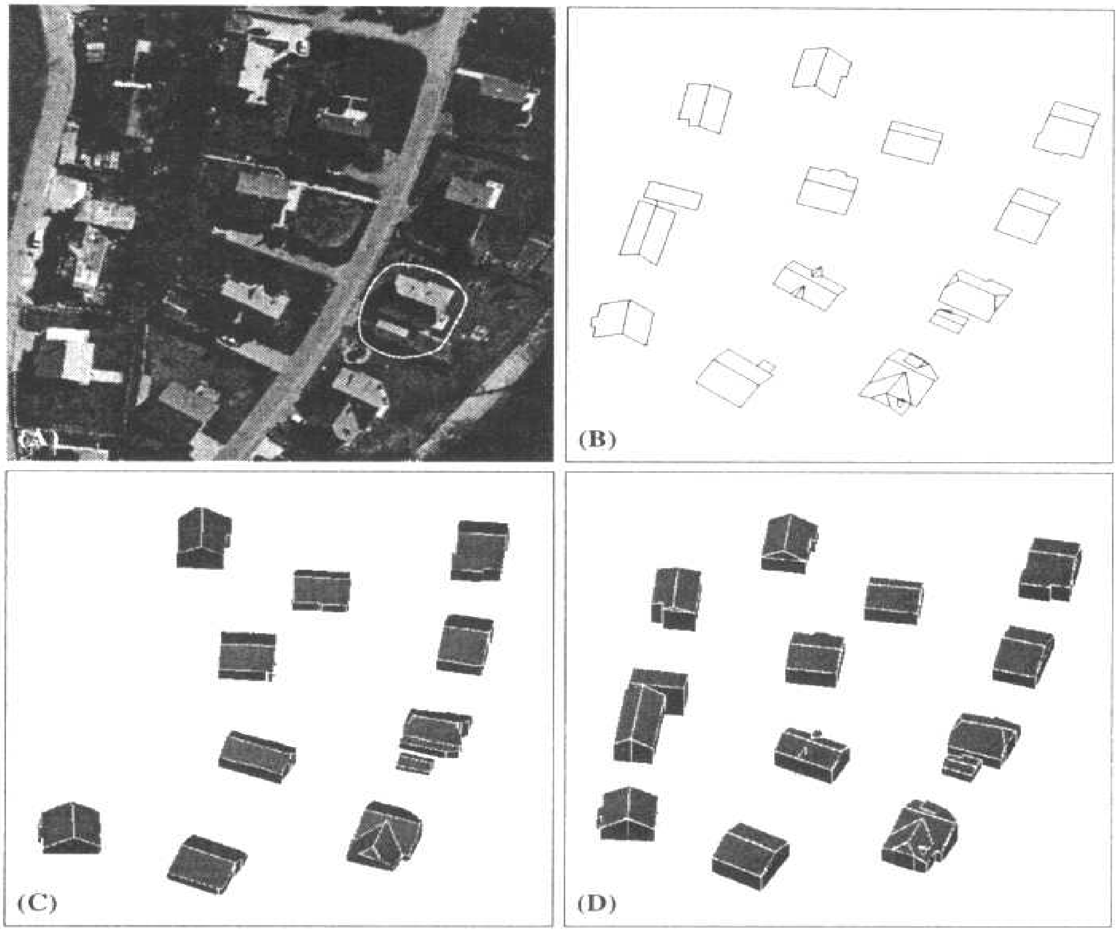

Figure 7: The results of 3-D reconstruction. (A) an original color image, (B) ground truth data, (C) fully automatic 3-D reconstruction using the ARUBA system, and (D) semi-automatic 3-D reconstruction using the TOBAGO software. The ground points (building heights) were manually set for the results in (D), whereas in (C) the DTM was used.

4. CONCLUSIONS

In this paper we have presented two operational approaches for automated 3-D reconstruction of buildings from aerial images. The semi-automatic approach (TOBAGO) is considered operational for practical use, whereas the system ARUBA shows the performance level of today's fully automatic procedures.

The TOBAGO software is essentially a tool for structuring given 3-D point clouds. The output is in standard (AutoCAD) format, which directly supports the visualization of the reconstructed scene. The method is fast, reliable, and flexible with respect to the level of detail. The approach requires complete and accurately measured 3-D points, a building model catalogue, and the ability of the operator to interpret the scene and to subdivide complex roofs into manageable roof units. With this technique we can reconstruct up to seven hundred roof units per day, or even more, depending on the complexity of the scene and the ability and experience of the operator.

The presented ARUBA system for fully automatic building reconstruction is well suited for reconstructing the major parts of the roof - the detailed structures may be extracted in a second step. The approach makes effective use of much of the available 2-D and 3-D information present in several images of a given site. The final result is a complete CAD model of the roof and its vertical walls, including 2-D contours, 3-D segments, 3-D planes and their topology. Geometric, photometric and chromatic attributes and stereo information about contours and their flanking regions are effectively combined.

For a hybrid 3-D city model, not only the automated reconstruction of buildings is important but also near real-time, photorealistic visualization. The use of photorealistic texture enhances the perceived detail even in the absence of a detailed geometric model.

This building data can be combined with data on Digital Terrain Models, roads, squares, water bodies, trees, general land use, property and administrative boundaries, etc. to full 3-D city models.

If required, such a CAD-based system may be amended by a data base management system to form a Building Information System (BIS). This in turn can be integrated into a multimedia environment for optimal user-friendliness.

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