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Interactive modelling tools for 3D building reconstruction

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ABSTRACT

Fully automatic reconstruction of 3D city models is a topic of current research, while semi-automatic approaches are already applied for the acquisition of large databases. Examples for application areas are visualizations for architectural evaluation, town planning and city information systems as well as simulations for city climate, environmental evaluations and wave propagation. This paper reviews the available datasets and methods for efficient 3D reconstruction and some advancements that have been reported lately by the scientific community, focusing on interactive systems. Finally, the approach developed at the University of Stuttgart is presented and results of several projects are shown.

1. INTRODUCTION

Efficient acquisition of 3D city models or, more generally, man-made structures has been a topic of intense research for the past years. The great interest of the scientific community demonstrated for example during the two successful Ascona workshops (Ascona 1995, 1997) was driven by the obvious need to automate or to facilitate manual processes for capturing data efficiently.

It is still unclear what the main application areas for city models will be. Certainly there is a new, emerging field for 3D city information systems which need more geometric information than traditional 2D ground plans can provide. The scenarios discussed here include trip planning via the internet as well as enhanced guidance for pedestrians through personal digital assistants with built-in navigation systems that combine navigation and communication facilities with the presentation of tourist and commercial information. It is known that navigational skills of people rely heavily on the identification of landmarks. For this reason the user interface of navigation systems could be improved especially in urban areas by the display of 3D data, thus replacing the clumsy arrow symbols prevalent for example in today's car navigation systems.

More traditional fields include architecture and town planning, city climate and environmental research and propagation of sound or electromagnetic waves, the latter being important for planning the locations of telecommunication antennas.

Although in general all those potential application areas can benefit from reconstructed city models, they usually impose very different requirements on 3D data (see e.g. Weidner 1996). Three-dimensional information systems and architecture will need geometrically detailed and/or texture mapped photorealistic visualizations. On the other hand, visualization quality plays practically no role in climate, environmental or wave propagation research since the geometric models are used as input data for simulations only. The required accuracy might be high for architectural planning, lower for tourist information purposes, and still lower for simulations. For example, concerning telecommunications, relatively low accuracy requirements of better than two meters in position and height have been stated (Bahne, Rathgeber 1999). However, simulations usually take into account a larger area, and thus need a high area coverage whereas architectural planning often needs reconstructed models only in the vicinity of a planned building.

As is the case with every new and emerging technology, the specifications of the product (city model) have to be found in a dialog between producers and customers. In the area of city models for telecommunications, there have long been no exact requirements for the data to be captured, and the "specifications" were to reconstruct "as accurate as possible". However, this makes no sense, since choosing the proper method, buildings can be captured down to resolutions of centimeters or even millimeters. Rather, the classical engineering task is to be solved: to provide a system which meets

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the specifications in the most cost-efficient way, where cost-efficient means in this case a minimum amount of manual interaction. Of course, since there are different application areas, an incremental system would be desirable which allows to choose (and later extend) the reconstruction accuracy depending on cost limits or available data sources.

2. DATA SOURCES FOR BUILDING RECONSTRUCTION

Possible data sources can be classified as shown in figure 1. Satellite images are not yet useful for building reconstruction since the ground resolution is still in the order of several meters. In contrast, a minimum resolution of about 20-25 cm is considered to be useful for building extraction. Aerial images have been and continue to be the predominant data source for building reconstruction. Systems differ with respect to single image, stereo or multiple image measurement. Colour and multispectral aerial images have been used by several authors to discriminate between vegetation and man-made objects. Laser scanners are used to measure the surface geometry directly and are especially in dense urban areas the best choice to obtain digital surface models. Some are also able to measure surface reflectance (corresponding to the emitted laser wavelength) thus providing registered range and intensity data to facilitate object extraction (Hug 1997). Accurate extraction of features still suffers from the limited lateral resolution of laser scanners, which is often in the order of one measurement per square meter. However, helicopter based systems with higher resolutions of 5 or more measurements per square meter have been reported (Axelsson 1998) and used in the context of building extraction (Maas 1999a,b).

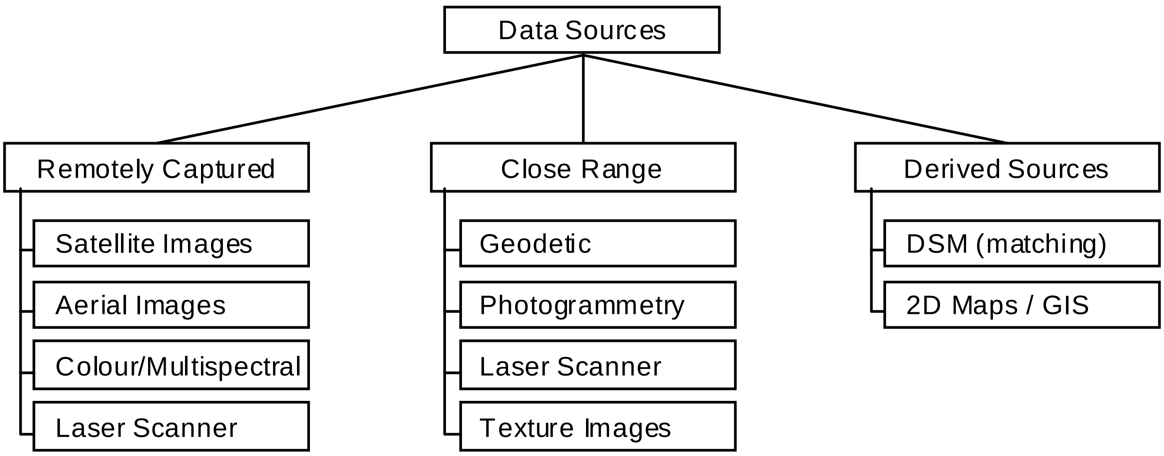

Figure 1: Classification of available data sources for building reconstruction.

Using aerial images and laser scanning, the roof structure (and often, building structure) can be reconstructed. In general, however, it is not possible to recover information about building facades due to steep observation angles and occlusions (although in some cases with multiple overlapping images it might be feasible). A standard approach adopted by several researchers is to approximate building walls by vertical planes defined by the eaves lines of the reconstructed roof and extend them downwards to some measured ground height in the vicinity of the building. Close range techniques have to be used in order to provide a more detailed reconstruction for facades.

A geodetic acquisition of the facade structure may be carried out, but in most cases it is more appropriate to measure photogrammetrically and use geodetic measurement for control point determination only. Close range photogrammetry packages are increasingly user-friendly (PhotoModeler 1999), and very accurate, texture mapped 3D models can be obtained. On the down side, due to the field work and necessary manual interaction the amount of time required is still substantial, leading to a production rate in the order of only a few buildings per day.

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Laser scanners are a powerful tool for capturing facades (Riegl, 1999), but it has to be noted that simply combining scans of individual buildings to obtain a city model is no sensible approach since one ends up easily with, for example, one million triangles per building, which makes a city model containing several thousand buildings prohibitively large. On the other hand, image interpretation in close range facade scans would be a promising approach.

Texture images can be included which do not contribute to the geometric reconstruction of the buildings, but improve the visual impression. The necessary rectification can be found manually by establishing point correspondences (Brenner, Haala 1998), or by determination of the exterior orientation (El-Hakim et al. 1998). New approaches try to find the proper rectification automatically from image analysis by extracting horizontal and vertical facade structures (Gülch 1997, van den Heuvel 1998).

Digital surface models (DSM) from image matching are included as “derived source” in this classification because they do not represent raw data. It is possible to recover the roof structure of buildings using image matching. However, problems frequently arise due to self-occlusion and at step edges (see e.g. Haala, Brenner 1997). Thus, the lateral dimension of buildings is usually not easy to extract from image matching DSM’s, especially in dense urban areas. Some authors have nevertheless used DSM’s from image matching as a means to detect the location of buildings (e.g. Haala 1994, Baltsavias et al. 1995).

Finally, 2D ground plans from Geo Information Systems (GIS) can be used as an information source. There are several advantages to this approach. Digitization is a process of interpretation, thus digital maps represent the most high-level information source among the possible sources described here. Also, geometry constraints imposed by 2D maps are strong, allowing for a fully automatic 3D reconstruction, and consistency between the provided 2D and reconstructed 3D datasets can be enforced. The problem with using 2D maps lies of course in their availability, actuality, completeness and quality. In case digital maps are not available, the effort required for manual measurement of 2D ground plans may be comparable to an interactive 3D building measurement using an efficient modelling tool.

3. DEVELOPMENT OF INTERACTIVE TOOLS FOR BUILDING RECONSTRUCTION

3.1. Advantages of semiautomatic tools

Practical photogrammetry still involves to a large extent the measurement of single points. Automated techniques like image matching, online-z, automatic target identification and measurement have found their way into commercial systems, however the basic primitive remains to be a point. In order to recover complex objects like buildings, the standard approach would be to:

1) measure points in two or more images
2) group points into meaningful subsets which describe the surface of the object.

In the case of buildings, a polyhedral building model can be described by vertices and planar faces where step 1) would measure all vertices and step 2) would group vertices into 3D polygons describing the boundary of each face. It is obvious that this method does not take advantage of many properties man-made objects exhibit, such as planar faces, vertical walls, constant eaves heights, symmetry and standard roof types. Consequently, more points have to be measured than are actually necessary to define a model of the building, which makes this approach time-consuming.

In a first attempt, research has concentrated on fully automatic reconstruction of building models from aerial images. In order to cope with the enormous amount of data present in aerial images, many techniques including extraction of higher level primitives, aggregation in 2D and 3D, spectral classification from colour and infrared images, and DSM’s for building detection have been used.

With the availability of laser scanner datasets, DSM's have become an increasingly important data source (Brunn, Weidner 1998, Maas 1999a,b).
Although the successful application of fully automatic reconstruction methods has been shown for some datasets, they have been found to be not stable and reliable enough for practical use (Grün, Wang 1998). In consequence, semiautomatic systems have been developed which are beneficial for several reasons:

- The rate of reconstructed buildings is 100% (with respect to the chosen model). Thus, semiautomatic systems can be used in large, practical projects which are important in order to make statements about their applicability
- They can serve as a testbed for automatic reconstruction algorithms, since it is much easier to evaluate an algorithm when parameters can be changed on-line than in the case where algorithm behaviour has to be inferred from the results of a batch job
- They can form the kernel of a system where fully automatic algorithms can be incrementally tested and (if proven to be successful) integrated.

3.2. Some tools reported recently

CyberCity Modeler (CC-Modeler), ETH Zürich. Following the fully automatic reconstruction approaches AMOBE (Henricsson et al. 1996) and ARUBA (Henricsson, Baltsavias 1997), the semi-automatic modellers TOBAGO (Grün, Dan 1997) and CC-Modeler (Grün, Wang 1998a,b) have been reported. The latter is based on measurement in aerial images and uses essentially two steps for building reconstruction.

In the first step, a structured point cloud is obtained using strictly manual point measurement. The cloud consists of all eaves and ridge points. Additional roof features like dormer windows can be captured as well by measuring single points. Structuring of points is enforced by two measures. First, a specific order has to be observed when points belonging to one building roof are measured. Second, each point gets a certain code by the operator according to some coding rules. This is accomplished by putting the measured points into different layers.

The second step consists of grouping the points into planar faces and the generation of roof and wall faces to obtain the building model. This step is fully automatic, although an interactive editing tool providing 2D and 3D views is available.

With respect to the strictly manual photogrammetric measurement of building models as outlined above, CC-Modeler essentially automates the grouping part (step 2), while the measurement of points remains to be manual. For measurement, the basic unit is a point rather than, for example, a volumetric primitive, and the overall procedure resembles more the traditional photogrammetric separation into point measurement and structuring which sets this method apart from the approaches of other groups described below. On the one hand, this makes it possible to use off-the-shelf standard photogrammetric software, and to obtain "photogrammetric" measurement accuracies. Also, the system is not constrained to any specific object model but rather all polyhedral structures can be handled. On the other hand, this approach can only reduce the amount of interaction necessary for structuring, while the measurement of points remains to be time-consuming.

CC-Modeler is available commercially, and its extension to a GIS for urban data management is discussed in (Grün, Wang 1999). Considering the reconstruction rate, (Grün, Wang 1998b) state that 500 roof units (a building roof may consist of several roof units) per day can be generated by an experienced user. In practical tests at Swissphoto Vermessung AG (Kersten, Cuche 1999), this could not be confirmed so far and rates between 5.3 and 20.7 roofs per hour (approximately 42 to 166 roofs per day) were reported.

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ObEx, University of Bonn. There is a long tradition in research for building extraction at the University of Bonn both in the semiautomatic and fully automatic field. Automatic extraction from aerial images (see e.g. Fischer et al. 1998) as well as from DSM's (Brunn, Weidner 1997) has been reported. Since several years, a semiautomatic system called "Hase", "Hase+" and "ObEx" has been developed and improved (Gülch et al. 1999). Buildings are modelled from a limited number of building primitives (flat-roof, pent-roof, hip-roof, saddleback-roof) using mono-mode measurement in aerial images. To that end, an operator selects the appropriate building primitive which is then displayed as a wire frame (hidden line) model in two or more aerial images. Using several mouse clicks, the operator can adjust primitive parameters like lateral dimension, position, orientation, ridge and eaves height. Besides this manual adaption, a so-called guided adaption is possible, which reduces the amount of mouse clicks necessary. A further reduction can be achieved using automated adaption, which uses image correlation and matching techniques to find some of the parameters fully automatically. This is reported to have a success rate of 50% to 90%. However, at each point during measurement, the operator is free to switch back to manual mode in order to correct false measurements.

Single primitives are combined in order to obtain complete building models using a constructive solid geometry (CSG) structure. Boolean operations *union*, *difference* and *intersection* are available, which allow to model complex buildings with non-rectangular ground plans. Also, copying of an entire CSG tree is possible, thus the structure of multiple identical buildings needs to be modelled only once.

Reconstruction times as low as 20.3 seconds per primitive have been stated in (Gülch et al. 1999), which would correspond to approximately 1400 primitives a day.

Stuttgart approach. In contrast to the previously mentioned systems, this approach uses DSM's and 2D groundplans as data sources for an automatic and/or semi-automatic reconstruction process (Brenner, Haala 1998). Aerial images can be used to facilitate the interpretation by a human operator during semi-automatic reconstruction, however they currently do not contribute to the measurement. The method and some results are described in the following sections.

4. THE STUTTGART APPROACH

4.1. Data Sources

DSM's of high quality with a point density of approximately one point per square meter are used. The datasets are obtained with the TopoSys laser scanner system (Lohr, Eibert 1995), although DSM's from image matching can potentially be used as well (Fig. 2). However, with standard image matching, there is usually a tradeoff between a good reproduction of step edges and the elimination of matching errors, as controlled by some smoothing parameter.

As discussed above, in most cases laser DSM's provide a better measurement at step edges. Nevertheless, it has to be noted that due to mixed point and interpolation effects, vertical building walls are still not strictly vertical in the data set and narrow streets do not reproduce very well. Also, laser scanners do have problems at surfaces with a high specular reflectivity or absorption like metal or slate roofs. Figure 3 shows a DSM from laser scanning (city of Heidelberg) with an orthoimage superimposed. The DSM consists of a regularized 1m x 1m raster and covers an area of approximately 1 x 2 km^2.

As a second data source, 2D ground plans are used. Frequently, these ground plans have already been acquired and are represented either in analog form by maps and plans or digitally in 2D GIS. An example for this kind of data is the digital cadastral map in Germany, which provides information on the distribution of property, including the borders of agricultural areas and the ground plans of existing buildings. At the moment the digital cadastral is built up as an area

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covering database, mainly by digitizing existing maps or plans. Currently, it covers 40% of the area of Germany. Alternatively, maps and plans can be digitized automatically (Frischknecht, Carosio 1997).

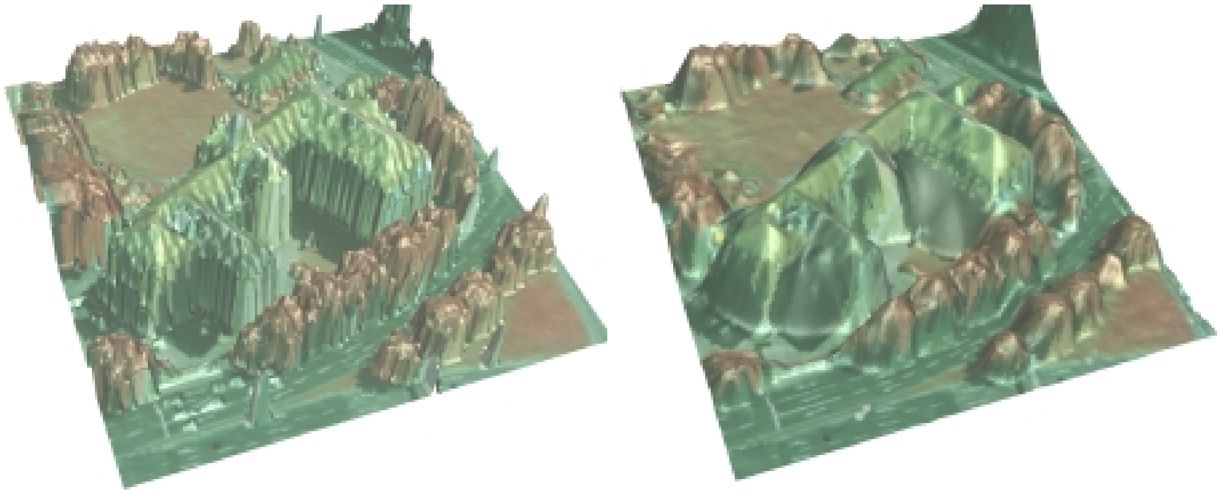

Figure 2: Comparison between a DSM from laser scanning (TopoSys scanner, left) and image matching (Match-T, right), shown as 3D visualization. Note that the laser scanner DSM appears to be much sharper.

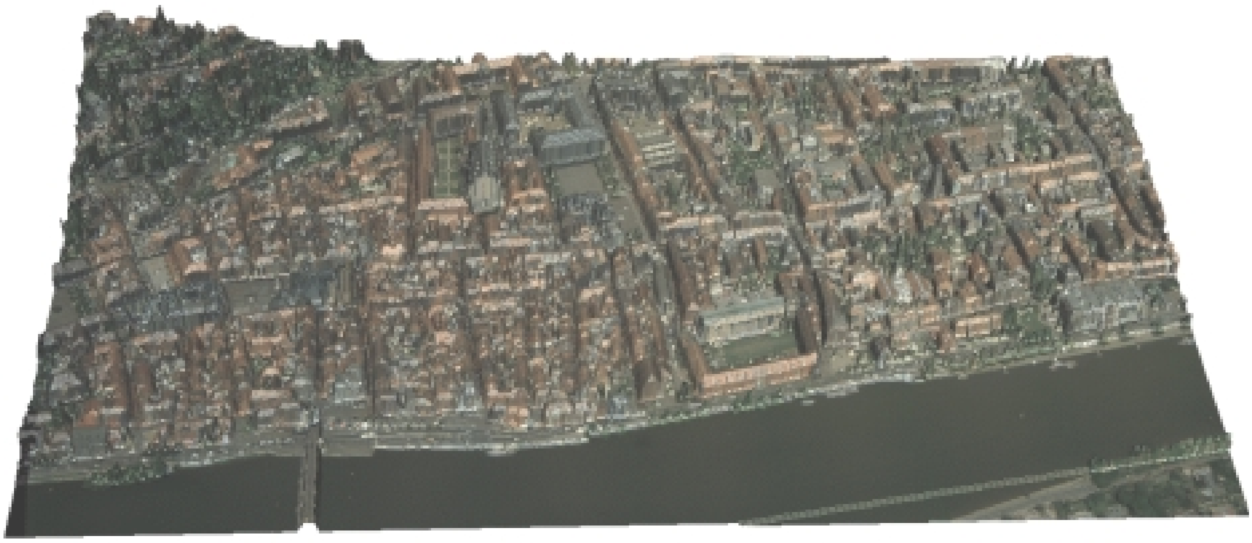

Figure 3: Laser Scanner DSM of the city of Heidelberg.

4.2. Automatic Reconstruction

The problem for any model based reconstruction algorithm lies in the selection of the appropriate model. On the one hand, it should be general enough to represent real world objects in sufficient detail. On the other hand, it should be specific enough to constrain the solution in order to deal successfully with noise or outliers. In the approach described here, the problem of reconstructing complex buildings is transformed into the problem of reconstructing its basic units (primitives). Each primitive can be one of a fixed set of parametric models. This simplifies the reconstruction process considerably.

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Figure 4 sketches the workflow of the reconstruction algorithm. Input data is on the left, output on the right and the flash icon marks the places where automatically derived data can be modified or amended. Processing starts by decomposing the ground plan polygon into 2D primitives (rectangles). Each 2D primitive is the footprint of a corresponding 3D primitive. The location, orientation, and size of the 2D primitive applies as well for the 3D primitive. What remains to be determined are the parameters of the roof, namely roof type (currently one of flat, gable and hip), height of the building and roof slope. A least squares estimation computes the best fit of the models to the given DSM. When several models are suitable, the one with the smallest residual is selected.

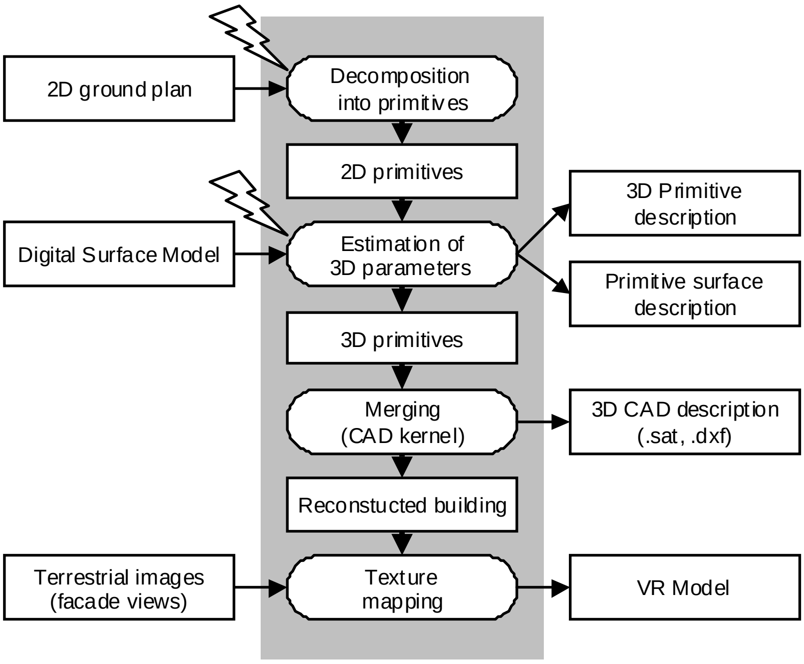

Figure 4: Workflow for the automatic and semi-automatic reconstruction algorithm.

After this step, the individually reconstructed primitives are overlapping 3D solids. They can be output in the form of either a list of solid descriptions or a list of planar faces. Most often it is desirable to find a building description without overlapping parts. As this is a standard CSG problem, a CAD kernel to perform the necessary merging (Boolean union) operations is used. Finally, a non-overlapping building description is obtained, which can be exported and converted into different CAD formats.

4.3. Semi-Automatic Reconstruction

Since the decomposition into 2D primitives uses only ground plan information, features in the 3D geometry of the building can only be detected if there is a corresponding hint in the ground plan. The basic assumption here is that each ground plan polygon segment defines one wall and one planar roof surface. Hence, a bay, dormer window or a small tower inside the building will not be reconstructed by the automatic algorithm.

For an effective visual control of the 3D reconstruction and to allow the manual refinement of building models, an editor was implemented. The tool allows to define, delete and modify 2D building primitives. Three-dimensional primitives are reconstructed instantly (using the same algorithms as those employed in the fully automatic reconstruction) when the user modifies the underlying 2D geometry.

We found it sometimes difficult for the operator to interpret a scene from a single data source like an ortho or stereo image. Thus, the editing tool supports the simultaneous display of 2D ground

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plans and primitives in an arbitrary number of images, like a scanned map, an ortho image or a greyvalue-coded DSM. Beside that, a 3D rendered display shows part of the DSM in the vicinity of the selected building and the current 3D building reconstruction.
Figure 5 shows a snapshot of the interactive editing tool with 2D and 3D display windows and the control panel. The user can directly modify 2D primitives in any window by mouse clicks and moves. Figure 6 shows an example of a building before and after manual editing. For this quite complex example, the automatic reconstruction solely based on the analysis of the ground plan (center image) is refined by manual editing of the 2D primitives (right image).

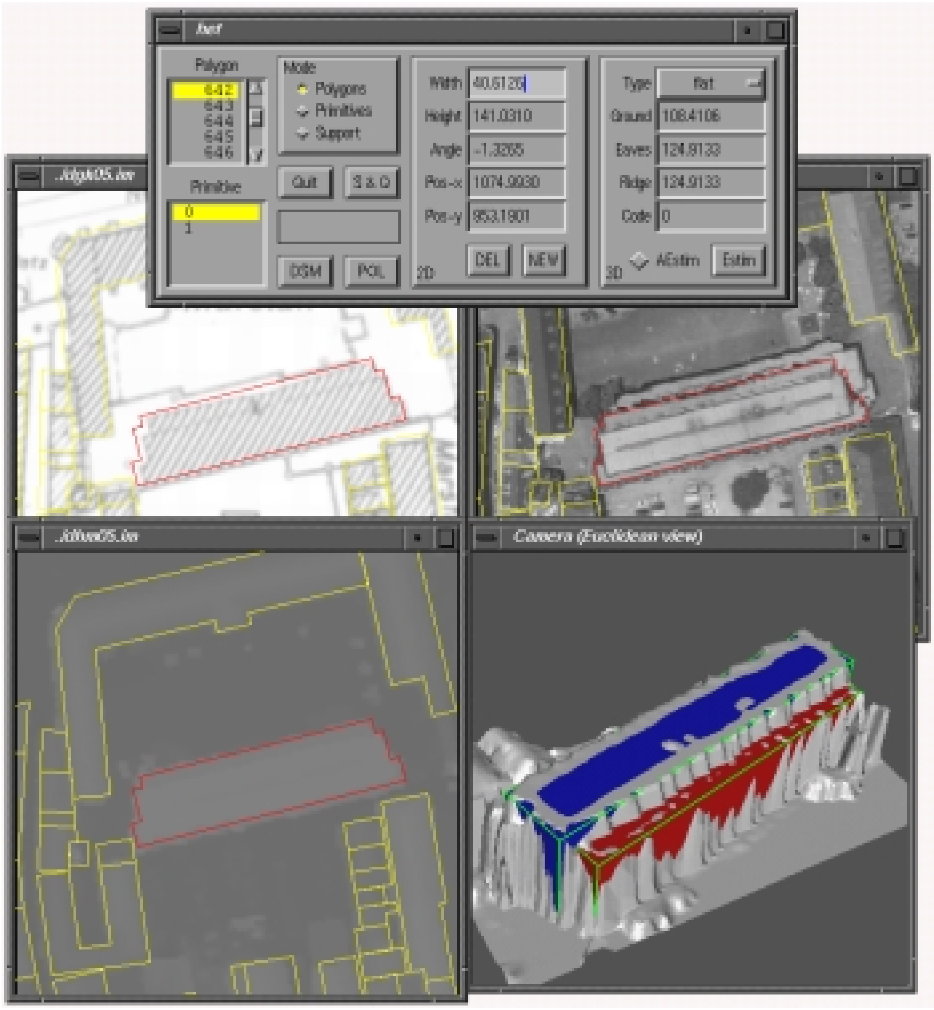

Figure 5: Interactive editing tool with map, ortho image, gray coded DSM and 3D view of DSM and reconstructed building.

4.4. Texture mapping

Using the described reconstruction scheme, effort and costs can be chosen depending on the application. When correct ground plans are available and all data is set up, a first 3D reconstruction is obtained fully automatically. This might be already sufficient for most of the buildings and many applications. In the next step, details can be added to the buildings using the editing tool during the semi-automatic verification and modification. Compared to other systems, however, reconstructed buildings are already available – there is no need to start „from scratch“.
The final step consists in adding texture maps to the building facades. Since real-world images embody a representation of object detail, it can be a substitute for missing geometric detail. To a

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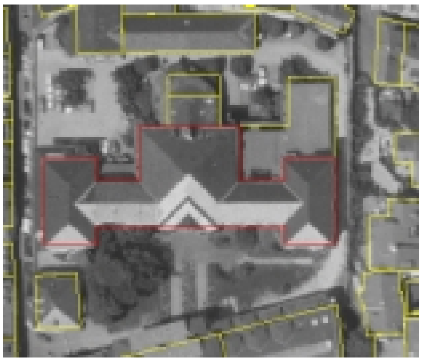
certain degree, non-planar surfaces can be represented by texture mapped planar surfaces without degrading the impression of viewing a 3D scene.



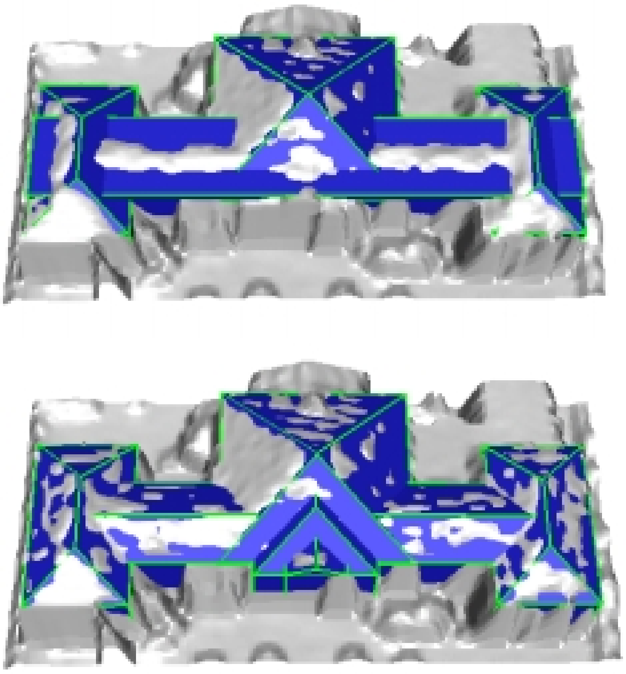


Figure 6: Ortho image (left) and reconstruction before (top) and after (bottom) manual editing.

Terrestrial images obtained by an inexpensive still video colour camera can be used. The images are rectified and mapped onto the corresponding building facade. At least four tie points between the reconstructed facade and the terrestrial image have to be measured interactively. Nevertheless, this method proves to be much faster than the standard approach of architectural photogrammetry, since building geometry is already defined.
The texture of building roofs can be taken from aerial images. Since the exterior orientation is known for aerial images, this step can be done fully automatically. Figures 7 – 9 show some texture mapped scenes from the Karlsruhe and Heidelberg data sets that have been processed so far.

Figure 7: Texture mapped scenes (Karlsruhe dataset, 200 buildings). Left: Scene with facade texture taken from terrestrial images, roof texture taken from aerial image. Right: Larger scene with roof texture only.

Figure 8: Automatically reconstructed buildings for the Heidelberg dataset (1400 buildings), with ortho image and roof texture from aerial image.

5. CONCLUSIONS

Nowadays, it seems that photogrammetry is the only means by which city models consisting of several thousand units can be acquired efficiently and economically. There is a general consensus among researchers that fully automatic systems, although promising results have been shown, have not reached an operational state yet. Several research groups have reacted accordingly by the development of semi-automatic systems which can be used as a testbed in which fully automatic modules can be integrated successively.
At the present moment, there is a certain lack of objective measures concerning reconstruction times, success rates and reconstruction quality, especially since a human operator is part of semiautomatic processes. As long as large-scale experimental investigations have not been performed, statements regarding these issues should be made (and read) carefully.
The systems described in this paper differ with respect to the data sources and measurement paradigms. *CC-Modeler* uses stereo measurement of points in aerial images, while *ObEx* and the *Stuttgart approach* measure building primitives using several (monoscopic view) aerial images or laser scan data and 2D ground plans, respectively. For the future, we envision a system which

- combines the possibility to measure complex primitives with the flexibility of single point measurement

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- allows the simultaneous use of all available data sources, including aerial and terrestrial images, aerial and terrestrial laser scan data and high-level information from GIS and thus integrates seamlessly roof, facade and probably even interior reconstruction
- recovers all appropriate data and images automatically during a modelling session for a specific building.

Figure 9: Same as figure 8, but using a different view and map background.

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