Extraction of 3D objects from aerial photographs[1]

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ABSTRACT *There is an increasing request for 3D data on city objects of all kinds for urban design, confirmed by a recent European wide study on 3D city models. To acquire 3D information in urban areas still is costly, only automated or at least semi-automatic methods appear feasible in the long run to reach the cost-effectiveness, necessary for a broad application. This paper presents a semi-automatic system for 3D building acquisition from various sensor data, mainly, however, from stereo pairs of digitized aerial images. The operator is supported by various automated modules. Very complex buildings can be modeled by a combination of volumetric primitives. The system does not require stereo-viewing and is such suitable also for non-photogrammetrists. The output of the process are 3D volumetric primitives, ready for further analysis in CAD systems or for visualization purposes in combination with automatically extracted texture. We present results from the acquisition of 3D building information in a suburban area and the centers of two cities and give more details on the acquisition times and the quality of the derived data.*

1. Motivation

Urban areas are the living place for more than 50% of the world population. Urban management requires up to date information on all type of city objects, like buildings, traffic networks, public utilities etc. Most data of this type is currently available in 2D or 2.5D. Three-dimensional information on buildings appears to be urgently necessary for all types of city planning, regional planning and architectural planning. Many buildings are nowadays constructed in built-up areas and the neighborhood must be taken into account for planning purposes. Simulations on sound emission, air pollution or micro-climatology require 3D object information. The mo-

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bile phone industry needs 3D city models for the simulation of wave propagation for transmitter placement, i.e. cellular network planning. Links can be established to building information or facility management systems. We can distinguish between simulation/analysis on one hand side and visualization/animation on the other hand side. Simulation puts usually higher requirements on the level of detail and the accuracy of e.g. building data, whereas visualization usually puts lower constraints on the quality of the 3D objects. Those facts and the great variability of objects forces any acquisition method to be extremely flexible. The cost for the acquisition of 3D data are still high, hindering so far a regular request for 3D information. On the other hand, the users requirements are not always known or at least diverse. In addition to that there is a storage problem: currently available Geographic Information Systems (GIS) can store 3D information in a 2.5D representation only, whereas CAD systems offer full 3D capabilities, but usually lack possibilites to combine graphic and non-graphic information, e.g. from a cadastral data base.

In an ongoing OEEPE[2] survey on '3D City Models' [4] producers and users of city object information were in a first phase interrogated on the current state-of-the art and future needs for 2.5D and 3D information in urban areas. The results of this first phase of the study, based on the input from 55 participants from all over Europe, were presented on a Workshop at the University of Bonn in October 1996 ([3]). The participants of the first phase are, evenly distributed, from firms, administrations/governmental agencies and universities. 41 of the participants are producers of city data, 21 are users and 7 are both, producer and user. The major tasks are mapping, surveying, photogrammetric service, environmental analysis, telecommunication and research.

The analysis of the returned questionnaires confirmed the usage and the increasing interest and the increasing demands on the availability of 3D city information of all types. The following extract of results is interesting in this context (the complete analysis with all details can be found in [4]):

- All types of 3D-city objects required by the users are provided by at least some of the producers. 50% of the producers are requested for the near future to produce other type of data and 75% of the users would like to have other data available, than they currently have in use. There is obviously a deficit in the mutual knowledge about the availability of 3D city data.
- Major objects of interest for (producers/users) are buildings (95 %/95 %), traffic network (90 %/76 %) and vegetation (78 %/71 %). Major reason for not producing or using 3D data are the high costs. Some producers have no data sources (e. g. images) available, and some users are in lack of city data.

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[2] The "Organisation Européenne d'Etudes Photogrammétriques Expérimentales" is a European intergovernmental organization, established in 1953 and has at present thirteen European countries as members. The aim of the OEEPE is to improve and promote methods, performance and application of photogrammetry by carrying out mutual co-operation, investigation and research, in particular of an experimental and application oriented nature.

- Participants were asked on the request or need of city data in the near future. 3D buildings and traffic network data are of significant interest now and highly requested in future. This holds for all, firms, administrations and universities. Vegetation data is urgently needed as well. In 2.5D these data are requested by producers from administrations and by users from all type. Firms and universities would like to have vegetation data in 3D. Public utility data seems also in the near future only requested in 2D.

- Data sources of the producers are aerial images (76%), map data (54%) and classical surveying methods (46%). Aerial (terrestrial) range data are only used by 20% (5%) of the producers, but these producers process several 1000 km^2/per year.

- The degree of detail for building data provided by the producers fits to the demands of the users. Detailed roof structures and garages are of highest interest. In general it can be observed, that the demands of most users are currently lower than the possibilities of some of the producers.

- The usual representation for buildings is a boundary vector representation or a 2.5D vector representation with footprint and building height or a 2.5D raster representation. Only few producers and users apply 3D volumetric representations, most probably due to the lack of software tools to handle those data.

The definition of resolution, precision and accuracy as well as the structure of specification of 3D data is an unsolved problem. In addition to that we can observe a lack of well defined data exchange formats. In the first phase of the study no information on the production process nor on the production rates where interrogated. The study is thus not a complete market analysis. It has, however, successfully provided deep insight into the current status of acquisition and usage of 3D city information on an European level. There is a definite need for a denser communication between producers and users of 3D city data, and in a second phase of the test an empirical comparison on currently used 3D acquisition methods will be performed.

We will focus in the following on the acquisition of 3D building information in urban areas, as one of the most required city object types. To acquire 3D information on buildings still is costly, even with conventional photogrammetric tools, only automated or at least semi-automatic methods appear feasible in the long run to reach the cost-effectiveness, necessary for a broad application in large scale mapping. An overview on some currently developed automated and semi-automated methods for the extraction of buildings and roads from aerial or space imagery can be found in [5].

This paper presents a system for 3D building acquisition from various sensor data, mainly, however, from stereo pairs of digitized aerial images. We must be aware of the fact, that sensor data only provide access to the geometry and the physics of a building, allowing to derive the 3D shape and infer some of the semantics of its parts. The large variety of buildings up to now prevents automatic systems to yield successful data interpretation on larger data sets. Sensor data are projections, thus only show a specific portion of the scene. This projection leads to various defects, like the missing depth in images, occlusions and local deformations of the 3D shapes. Applied methods have to be able to deal with those problems.

2. Semi-automatic building acquisition

To reliably perform or complete the 3D reconstruction from sensor data we propose **semi-automatic procedures**, related to early work done at SRI [10]. Previous work on semi-automatic procedures at our Institute has been performed by [8]. Their approach has been extended using the Constructive Solid Geometry (CSG) [6] for the three-dimensional modeling of complex buildings [2]. This work has been done in cooperation with the Institute of Computer Science III, University of Bonn.

In the semi-automatic approach the operator is providing the interpretation step, supported by various automated modules. We model buildings as a combination of volumetric primitives, following the CSG principle. Constraints on regularities and symmetries are incorporated in the primitives. By boolean operations of this primitives very complex building structures can be reconstructed, if required. Those can be buildings with polygonal foot prints and detailed roof shapes. Higher degrees of details may contain canopies, dormers, oriels, chimneys, and overhanging eaves. The orientation data of the images are supposed to be known. The operator performs a form and pose adaption of a selected building model in one image and selects homologous points in the other image(s) to get the absolute height. The system does not require stereo-viewing and is such suitable also for non-photogrammetrists. No specific photogrammetric hardware is required, like in Analytical Plotters or Digital Photogrammetric Workstations. The output of the process are composites of 3D volumetric primitives and 3D world coordinates for the corner points. In addition to the geometric acquisition a module for the extraction of texture from one or more images provides fully automatic photo-realistic texture mapping on the 3D object surfaces for visualization and animation. Visual representation is a valuable tool for conducting exploratory data analysis.

In the following we describe the procedures and stages in the work-flow and give the links where information on the object structure derived by automated procedures can be used to advantage.

2.1 Work-flow and connection to overall strategy

The 3D acquisition process for buildings (cf. Figure 1 and 4) is based on the assumption that the interior and exterior orientation data of the images are known. First, in the navigation phase the operator may zoom down into the aerial image, and focus the interest on a particular building in one image. This step can be replaced by an automated building detection based on the analysis of a digital surface model, if available, or in combination with an automated 3D reconstruction of parts (cf. also 2.4). The modeling phase is performed by a semi-automatic

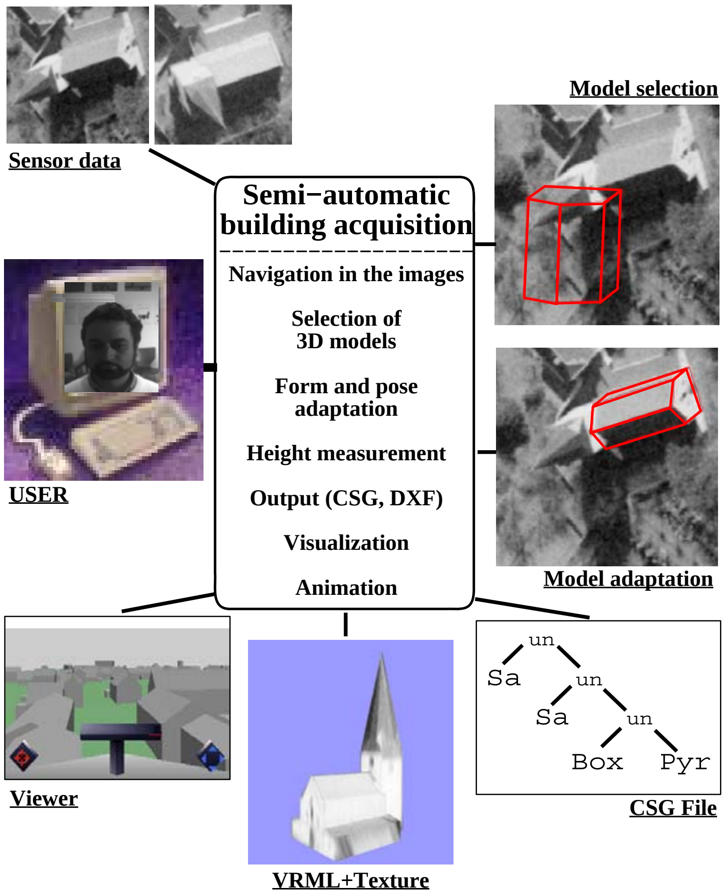

Figure 1: 3D building acquisition from stereo aerial images. The user can navigate in complete aerial images, by zoom and roam functions. Models are selected and the modeling of the CSG primitives is done in monocular mode resulting in a binary tree structure. At least one homologous point has to be measured to get the absolute height. As output DXF or VRML formats are available combined with texture information for visualization and animation.

form and pose adaptation of selected 3D parametric models. This step can be substantially speeded up, if the type of parametric model or even the approximate parameters are already known, up to a simple confirmation of an automatically derived form and pose of the building (cf. also 2.4). One homologous point has to be measured in the images in order to compute 3D world coordinates. This single step has not to be performed manually if the automated reconstruction of parts has been successful. The result of the building acquisition process is a 3D building description, which can also contain several buildings. For further data analysis and visualization a boundary representation (B-rep) is derived.

In the following we describe the Constructive Solid Geometry applied to 3D building acquisition, we briefly specify the supporting tools and describe then the automated tools for the form and pose adaptation. An extended description of the current system can be found in [2] and [1].

2.2 Constructive Solid Geometry

Within this approach buildings are reconstructed by combining a series of 3D atoms, so-called CSG primitives (short: primitives), until the complete building has been modeled. For the combination of primitives different commutative and distributive CSG operations are provided: union, intersection, and difference. As primitives we are using box, chock, cone, cylinder, half-chock, pyramid, and tetrahedron (cf. Figure 2) and three combined primitives: saddle-back roof building, hip roof building, and lop-sided saddle-back roof building. This combined primitives substantially speed up the acquisition process, due to the large number of buildings corresponding to those types of models. A parameterized description of these combined primitives can be found in [8].

2.3 Semi-automatic pose and form adaption of models

The degree of generalization determines which details of a building are reconstructed, e.g. if chimneys have to be modeled. The choice of the degree of generalization has to be made by the operator. The modeling process results in a CSG tree, whose interior nodes contain operations and the leaves contain instantiated primitives and attributes, e.g. form and pose parameters. There are several possibilities to describe and acquire a building. The operator has the freedom of choice to determine the construction of the CSG tree.

During the modeling phase the operator has to choose a primitive which will be projected as a wire frame model (with removed hidden lines) into the focussed image region, adapt the parameters of the wire frame model by clicking with the mouse onto its edges and pulling them to the correct size of the modeled building part. These steps have to be repeated for each primitive until the whole building is described. All these adaptations are performed in monocular mode.

During the adaptation process the system supports the operator by diverse tools. A 3D rendering of the currently acquired building description is used to check for completeness and correctness. The inheritage of parameters of the previously acquired primitive allows efficient acquisition in areas with similar building types, like

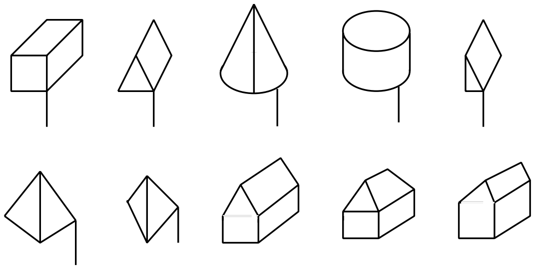

Figure 2: Primitives (with flagpole): box, chock, cone, cylinder, half-chock, pyramid, tetrahedron. Combined primitives: saddle-back roof building, hip roof building, and lop-sided saddle-back roof building.

row houses and reduces the need for homologous point measurements of primitives belonging to the same building. This is even more valuable in flat terrain. The flagpole principle allows the operator to efficiently adjust primitives above ground level, like canopies, dormers, smoke stacks, chimneys, etc. All primitives (except the combined ones) are equipped with a pole along which they are moved up or down by the operator in order to adjust their height above ground. The height of the lower end of the flagpole is the ground height inherited from the previously acquired primitive.

Reduction of interaction can be provided by the following automated modules:

- Docking of primitives. Describing a building by the combination of primitives or combined primitives requires a precise "docking" of the primitives. This docking is supported by matching and gluing facilities. The former allows to match at least two edges of different primitives and the latter matches and glues exactly two faces of different primitives together. These functions are based on a user-defined radius (cf. Figure 3) and are thus extended to three dimensions. The matching and gluing are performed automatically with already instantiated primitives and even with invisible lines, respectively faces. This enables the operator to dock the current primitive easily to neighboring primitives.
- Line extraction for the acquisition of prismatic building models. For the extraction of prismatic building models, i.e. buildings with a polygonal ground plan and a constant height the operator simply has to identify automatically extracted straight line segments in the image belonging to the ground plan, instead of measuring the vertices. The intersections of lines are automatically calculated. With a manual definition of the height of the building and the measurement of one homologous point in the other image the prismatic building model can be reconstructed in 3D.
- Multi-image matching and fine-tuning by clustering techniques. The measurement of homologous points for single primitives can be replaced by an automated matching procedure. It is based on automatically extracted straight line segments in multiple images. The lines of the form and pose adapted parametric building model in one image (cf. above) are compared to the extracted line segments in the other images. Robust pose clustering techniques ([12], [11]) are used to determine the height in 3D. In a final fine-tuning step, a robust spatial resection, using all line segments in all images provides an optimal fit of the selected model to the image data. More details can be found in [8], [7].

Before storing the corresponding CSG tree of a 3D building description, the operator may add useful knowledge to the building description. This extended CSG structure can be further analyzed by a conversion to Drawing Interchange File (DXF) format for standard CAD systems. An interface to the Virtual Reality Modeling Language (VRML) and OpenInventor formats link this output to the visualization tools of various platforms and the World Wide Web (WWW).

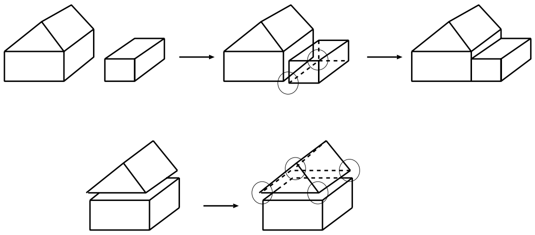

Figure 3: Automatic matching process of two edges (first row) and automatic gluing process of two faces (second row). The circles show the user-defined radius of a sphere, where matching and gluing is performed.

2.4 Integration of further automated modules

There are different information sources on buildings available, distinguishable in type, cost-effectiveness, scale and resolution with images being the major data source. Laser scanners are on the threshold of becoming an economical alternative at least for moderate accuracy requirements. But also digital cartographic databases can provide useful information, like footprints or attribute data registers. We have additional tools at hand and in development (cf. figure 4 and [1]), that can, through automation, speed up the acquisition process further, if the sensor data is suitable for the task.

With the analysis of Digital Surface Models (DSM) it is possible to detect and reconstruct prismatic and parametric building models up to a certain complexity, limited by the resolution of the DSM data, derived from image matching or laser scanning. Even change detection in several DSM's or in combination with a cartographic data base are possible. The detected and extracted models and their parameters can be used as input for the automated reconstruction by parts to derive generic roof structures from multiple images patches or as input for the semi-automatic acquisition described above. The reconstruction by parts can be triggered by the operator and provide models and parameters for user validation and acceptance.

From successfull applied automated procedures described above we expect a substantial reduction for (a) the modeling time, by preliminary form adaption and measurement of homologous points for (b) the local navigation by a preliminary selection of primitives and for (c) the global navigation by a guided navigation through the project area and a focusing on each building. Having more than two images available we further expect an improvement in accuracy and the reliability of the model and homologous point measurement.

3. Three-dimensional building models in extended areas

We present results from the acquisition of 3D building information in extended areas with the semi-automatic method and give more details on the acquisition times and the quality of the derived data in 3.4. Two projects have been performed

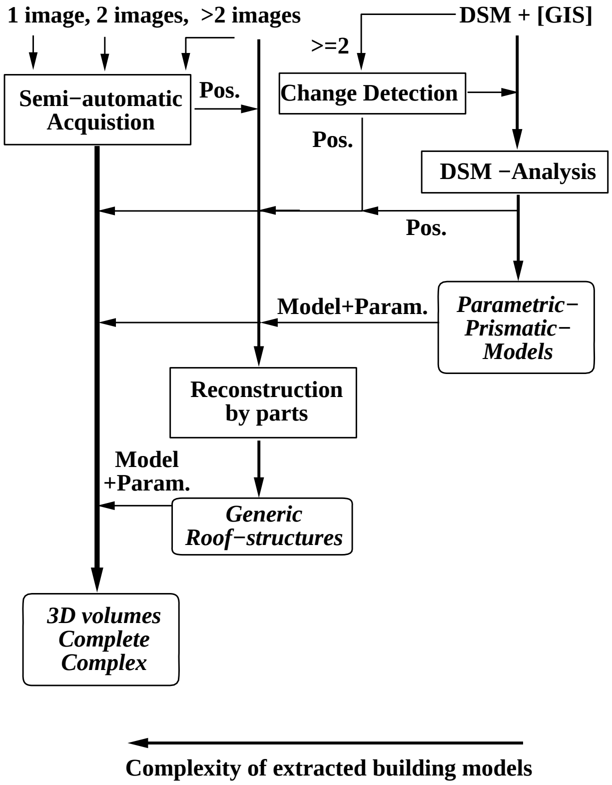

Figure 4: Automated modules and strategy for incorporation. Selection depending on task and availability of data.

with stereo pairs of digital aerial photographs in the sub-urban area OEDEKOVEN near Bonn, Germany and in the center of ROSTOCK, Germany with expert- and non-expert operators. In downtown FRANKFURT/Main, Germany the 3D building shapes where extracted from one tilted aerial photograph and known ground heights only, which demonstrates the flexibility of this system.

3.1 Suburban area OEDEKOVEN

The test field Oedekoven has been chosen to acquire data for the first phase of the OEEPE study on 3D city models (cf. above). The image scale of the B/W aerial imagery is 1:12000, the focal length is 153 mm. A stereo pair had been digitized with a pixel size of 12.5 μm in the image or 15 cm on the ground. The scene of about 3 km^2 had been divided into two parts for two operators. The task was to acquire detailed roof and building structures, which refers to a very low level of generalization. 1870 building aggregates (CSG trees) have been extracted with an average amount of 2.9 primitives per CSG tree resulting in 5499 primitives. As primitives occurred 55% boxes, 0.5% chocks and half-chocks, 31% saddle-back roof buildings, 2.5% hip roof buildings, 10% lop-sided saddle-back roof buildings, and 1% others. There are single buildings, building groups, garages, churches, farms, and plants. An optional texture extraction process fully automatically provides each 3D face with the texture from one of the images, if visible there (cf. figure 5). Figure 6 visualizes a small subset of the acquired buildings. The terrain between

Mean (Median) time/primitive [seconds]	Oedekoven		Rostock		Frankfurt	
Modeling time	(44)	47.8	(81)	94.1	(73)	76.0
Local navigation	(2)	10.3	(8)	54.2	(4)	10.7
Global navigation, organization		28.3		1.3		24.8
Gross time		86.4		149.6		111.5

Table 1: Average acquisition times per primitive of project OEDEKOVEN (5499 primitives), project ROSTOCK (371 primitives by non-expert user) and project FRANKFURT (549 primitives from 1 image and heights only). For the modeling and the local navigation the (Median) values are given for comparison.

the buildings is automatically triangulated from the measured ground heights of the buildings.

3.2 Urban area ROSTOCK

A part of the city center of Rostock (cf. figure 7) had been acquired by a non-photogrammetrist after four hours! training only. In our experience is not possible with such a short training time on any existing analytical or digital photogrammetric system to get the same output. The image scale is 1:12500, the focal length is 153 mm. A stereo pair had been digitized with a pixel size of 21 μm in the image or 26 cm on the ground. 74 building aggregates consisting of 371 volumetric primitives where extracted. This amounts to 5 primitives/building aggregate, which is higher than in the suburban area Oedekoven. Selected parts of the 3D model where provided with automated texture mapping (cf. figure 8). The acquisition time was prolongated by the poor images quality which is visible in the relatively poor texture quality.

3.3 Downtown FRANKFURT/MAIN

The dowtown area of Frankfurt/Main was extracted from one tilted aerial image only (figure 9), and the ground height of the buildings. The pixel size was 21μm, the focal length 30.5cm and the flying height 850m. All together 549 primitives were extracted forming 77 building aggregates. This results in an average of 7.1 primitives/building aggregate, which is, as expected, highest for all three projects. The gross time for the extraction of the complete area shown in figure 10 was about 17 hours. From the aerial image, texture was extracted automatically and mapped to the 3D faces. A subset of the whole model is given with texture rendering in figure 11. A horizontal view (figure 12) and a close-up view from below (figure 13) demonstrate the animation potential of photo-realistic 3D data.

3.4 Performance

The gross and net **times for data acquisition** are given in table 1. The gross time contains the modeling time, the internal navigation and the external navigation and organization. The times per building primitive are given as mean values, where available also as median values. The **modeling time** contains the form adaptation, the specification of operations, the measurement of homologous points and for complex buildings a 3D visualization. The **local navigation time** contains the navigation through the pyramid and the selection of primitives. The **global navigation and organization** covers the navigation through the project area, checks of completeness, editing and 3D visualization.

We can give the following comments to the figures provided in table 1:

- Oedekoven:
    - The average gross time of this test is about 25% shorter compared to an earlier version of the system [9] tested on comparable image material, but with much less buildings. The higher performance here is in addition combined with a more detailed building acquisition and texture extraction. One of the operators was inexperienced, but reached the same performance for the modeling as the experienced operator, after one week training only. This shows the potential of this system, for usage as a modeling tool by a non-expert in practice.
    - Due to some very complex buildings the mean value for the modeling (47.8 seconds) is higher than the median value (44 seconds). Independent from the complexity of the building i.e. the amount of primitives in a CSG tree we are observing a more or less constant modeling time per primitive. The short local navigation time of 10.3 seconds per primitive (median time 2 seconds) indicates the near optimality of this acquisition step. The global navigation and organization (28.3 seconds) covers the navigation through the project area, checks of completeness, editing and 3D visualization.
- Rostock:
    - The average gross acquisition time per primitive is with ∼150 seconds double as high, than in the case of Oedekoven. It must be noted that the operator was a non-photogrammetrist with an extremely short training time of four hours only and in addition hampered by a quite poor image quality and large pixel size.
    - The average modeling time is influenced by some difficult primitives, as indicated by the lower median time of 81 seconds compared to a mean value of 94 seconds. The median time for local navigation (8 seconds) indicates a good performance as well, hampered again by some few difficult cases, that increase the average time (54 seconds) dramatically. The global navigation time is much lower, as there was only a limited area to deal with and no other operators were involved.
- Frankfurt:
    - The average gross acquisition time per primtive is higher than in Oedekoven, but the major difference is in the modeling time. This was to be expected, as only one image is available, and the effects of occlusions are substantial due to the high rising buildings.

- The median value for the local navigation is with 4 seconds less than half of the average time and thus comparable to the other projects.

The **accuracy** of the system depends on many factors, like image scale, pixel size, orientation, film processing, scanning, selection and measurement of models and homologous points, the definition uncertainty of building corners, and the generalization level. A preliminary accuracy check of few buildings in the project OEDEKOVEN based on the differences of measured roof point coordinates and ground truth yielded an external accuracy of $\sigma_{X,Y} \approx 25$ cm and $\sigma_Z \approx 35$ cm. This corresponds to the accuracy of analytical photogrammetric methods. Further, more extended investigations are planned in the second phase of the OEEPE study on 3D city models.

4. Conclusions

We have presented a system for the efficient acquisition of 3D building information with a high degree of detail in urban and suburban areas. The system is applicable for the initial acquisition as well as for regular updates of 3D building models. The system has been tested on extensive scenes with several thousands of extracted primitives. We rely on the human operator to solve the interpretation, but we supply various automated tools that support the interaction. It has been confirmed that also non-photogrammetrists can use the system after very short training time, due to the monoscopic viewing and the developed user interface. No specific photogrammetric hardware is required. With stereo imagery, the accuracy results are, after first investigations, on the level of standard analytical photogrammetric techniques. In contrast to analytical photogrammetry, the quality of the derived products is increased by automated texture extraction from one or several images. The system is very flexible in handling single images as well as multiple imagery. An empirical accuracy check over an extensive scene is in preparation. Several additional automated modules are in development and testing for further speed up of the data acquisition to reach cost-effectiveness for applications in urban design and urban civil engineering.

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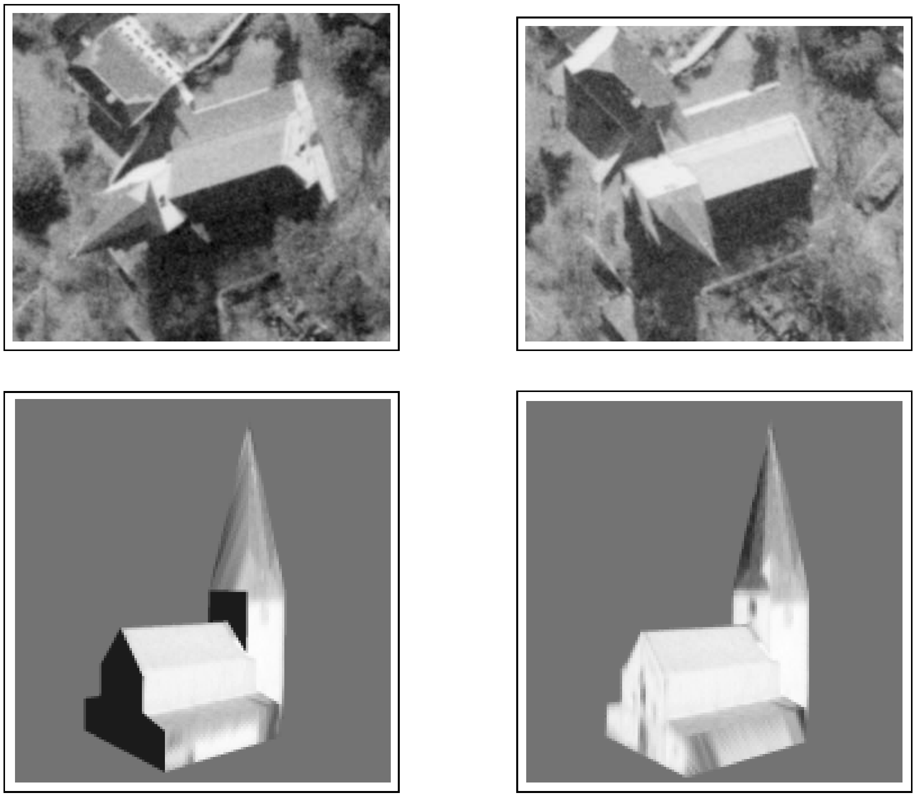

Figure 5: Automatic texture mapping of 3D faces in the project OEDEKOVEN. Upper row: left and right image patch. Lower row: texture extracted from right image and texture extracted from both images

Figure 6: A visualized part of the acquired extensive scene OEDEKOVEN.

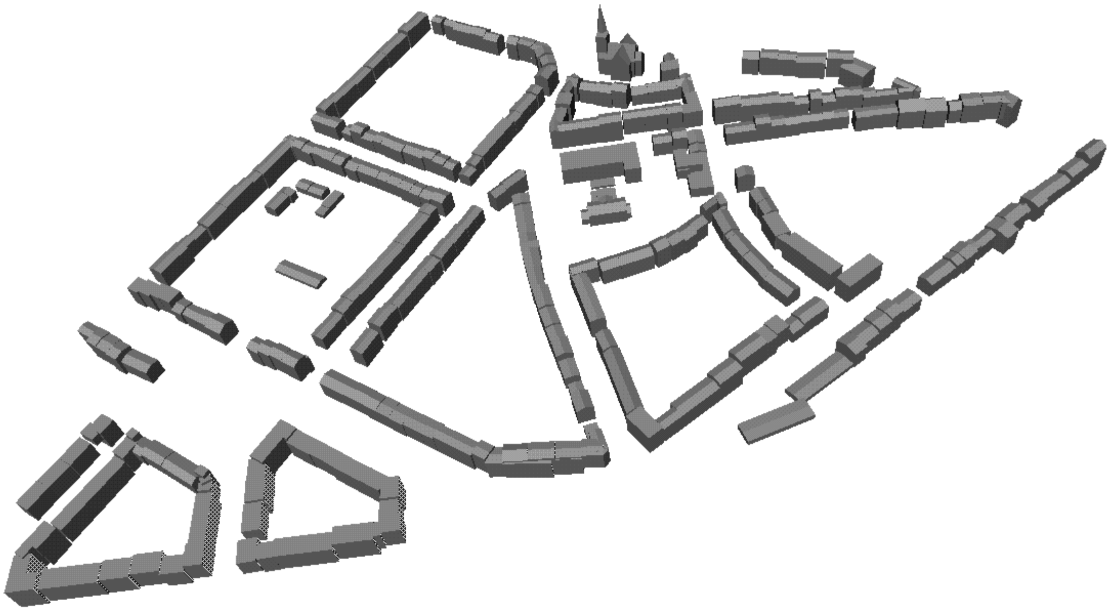

Figure 7: A visualized part of the acquired scene ROSTOCK. Acquisition time ~15 hours. Data by S. Bartel, Uni Rostock

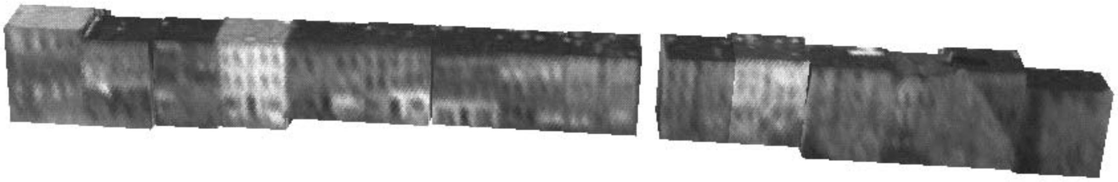

Figure 8: Automatic texture mapping of a row of houses in Rostock.

Figure 9: Large scale aerial image over FRANKFURT. Data by StadtVermA Frankfurt and Digital Affairs Computergrafix.

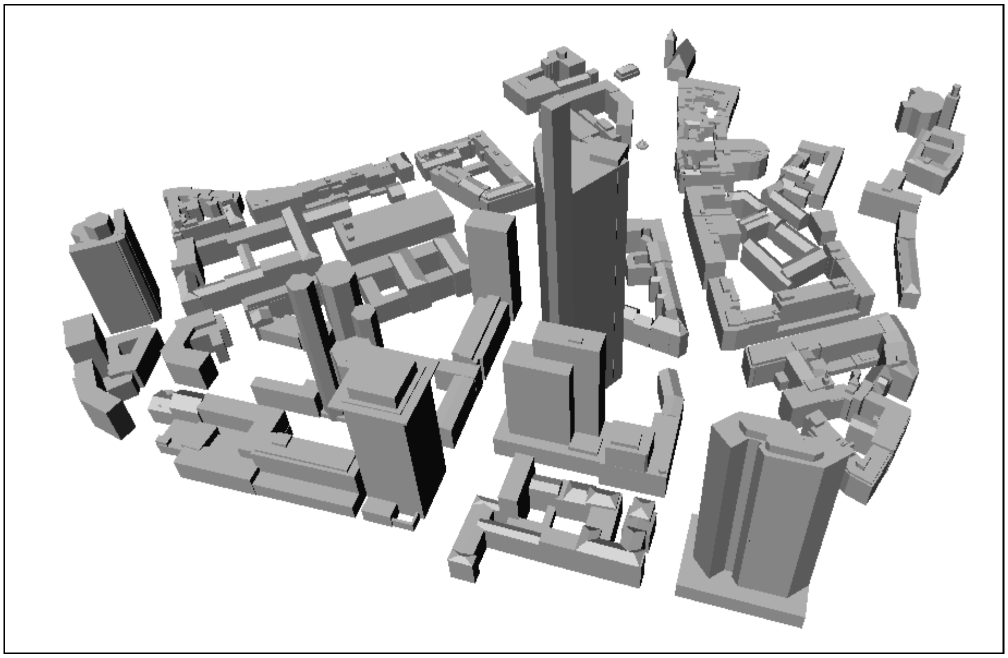

Figure 10: Acquired scene FRANKFURT. Acquisition time ~17 hours.

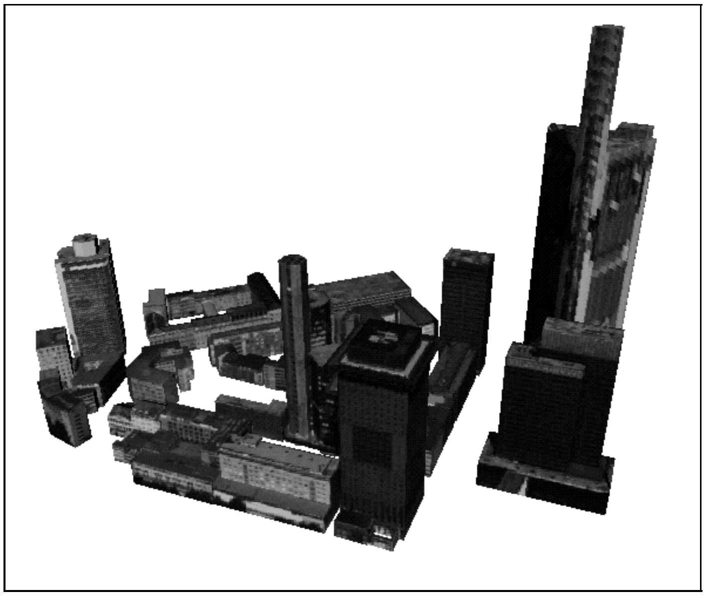

Figure 11: FRANKFURT: Subset with 103 primitives. Acquisition and automated texture extraction in $<$ 5.0 hours.

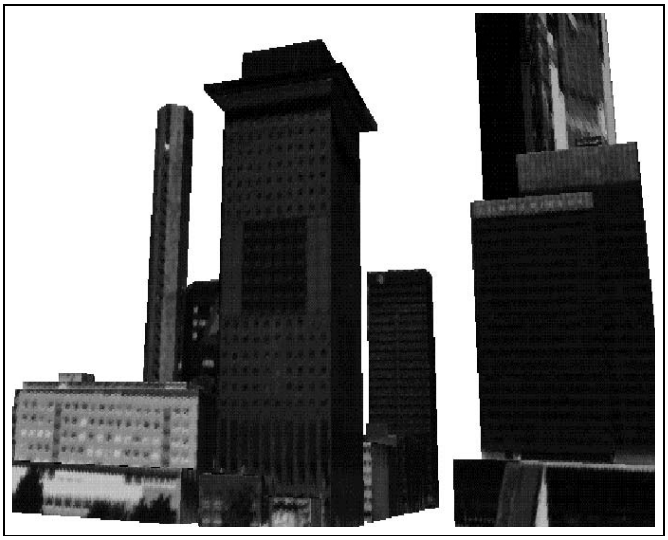

Figure 12: FRANKFURT: Automatic texture mapping and horizontal view.

Figure 13: FRANKFURT: Detailed view from below.