AUTOMATIC EXTRACTION OF BUILDINGS FROM LIDAR DATA AND AERIAL IMAGES

F. Rottensteiner*, J. Jansa

Institute of Photogrammetry and Remote Sensing, Vienna University of Technology, Gußhausstraße 27-29,
A-1040 Vienna, Austria - (fr,jj)@tuwien.ac.at

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ABSTRACT:

This paper is focused on two topics: first, it deals with a technique for the automated generation of 3D building models from directly observed LIDAR point clouds and digital aerial images, and second, it describes an object-relational technique for handling hybrid topographic data in a topographic information system. Automatic building extraction combining the mentioned data sources consists of three steps. First, candidate regions for buildings have to be detected. After that, initial polyhedral building models have to be created in these candidate regions in a bottom-up procedure. Third, these initial polyhedral building models have to be verified in the images to improve the accuracy of their geometric parameters. This paper describes the current state of development, the overall work flow, and the algorithms used in its individual stages. Intermediate results are presented.

1. INTRODUCTION

1.1 Motivation and goals

The great demand for 3D building models for various applications collides with the enormous costs of acquisition of these data at an appropriate level of detail. Quite some efforts have been spent in the past to automatically extract buildings from digital aerial images (Lang, 1999) or from digital surface models (DSM) derived from laser scanner data (Weidner, 1997). The most recent achievements in the field of automated acquisition of 3D building models are based on the integration of data from two or more sources in order to overcome the drawbacks of specific sensor types. For instance, a DSM is combined with existing 2D GIS data (Brenner, 2000) or with digital aerial images (Ameri, 2000). The trend towards combining data from multiple sensors for the automatic reconstruction of topographic objects is triggered by the fact that new sensor types such as LIDAR, SAR, and high-resolution space borne scanners, have become available. In the future, the task of data acquisition for topographic information systems (TIS) might be performed by "multi-sensor-grammetry" rather than by traditional photogrammetry. It is the goal of this paper to give a contribution to the development of this "multi-sensor-grammetry" by presenting a new method for the automatic creation of polyhedral building models in densely built-up areas by combining high-resolution LIDAR DSM and aerial images. Along with that method, an object-relational technique for storing large sets of building models in a TIS is described.

Automatic building extraction by combining DSM and aerial images consists of three steps (Ameri, 2000). First, building candidate regions have to be detected in the DSM. Second, initial polyhedral building models have to be created in the candidate regions by a bottom-up procedure using both the DSM and the aerial images. Third, the initial polyhedral building models have to be verified in the aerial images to improve the accuracy of their geometric parameters.

Our technique follows this three-step procedure. It is still work in progress and, thus, not all of its modules have already been finished. This paper describes the current state of development, the overall work flow, and the individual modules. Intermediate results will be presented for the modules already having been implemented.

1.2 Related work

1.2.1 Building detection from DSM: For that purpose, the points of the DSM have to be classified according to whether they belong to the terrain, to buildings or to other object classes, e.g., vegetation. Morphological opening filters or rank filters are commonly used to determine a digital terrain model (DTM) which is subtracted from the DSM. By applying height thresholds to the normalized DSM (nDSM) thus created, an initial building mask is obtained (Weidner, 1997; Ameri, 2000). The initial classification has to be improved in order to remove vegetation areas. In (Brunn and Weidner, 1997), this is accomplished by a framework for combining various shape cues in a Bayesian network. Our algorithm for building detection from DSM is based on the method of linear prediction presented in (Kraus and Pfeifer, 1998).

1.2.2 Generic procedures for creating polyhedral building models: The data driven generation of a polyhedral model starts by finding initial hypotheses for planar patches in object space. This has been performed by first reconstructing 3D line segments from aerial images and then finding tilted "half planes" delimited by these line segments (Baillard et al., 1999) or by grouping co-planar line segments supported by the results of a color-based segmentation of aerial images (Moons et al., 1998). Other possibilities are given by propagating the results of gray level segmentation of an aerial image to object space using a DSM (Ameri, 2000) or by a curvature based segmentation of the DSM, e.g. (Brenner, 2000). The initial planar patches having been found, neighboring patches are grouped (Baillard et al., 1999, Ameri, 2000). After that, the polygons delineating the borders of planar patches have to be

derived, which involves determining consistent intersections at the building vertices (Moons et al., 1998). Finally, the 3D polygons have to be combined in order to obtain consistent building models. At the building outlines, vertical walls have to be added to the model, and the floor has to be modeled. Parametric models which are typically used in model driven techniques for building extraction (Veldhuis, 1998; Rottensteiner, 2001) are used in a data driven context by (Brenner, 2000): the polygons delineating a building in a 2D map are split into rectangular regions. In each rectangle, the parameters of parametric models are determined using a DSM, and the model achieving the best fit is accepted.

1.2.3   Model verification by wire frame fitting: If an approximate object model exists, its (roof) edges can be back-projected to the images, where the model edges are matched with image edges. Thus, the accuracy of the model is increased considerably, especially with respect to the building outlines. Such model driven techniques are used for measurement of parametric primitives (Veldhuis, 1998; Rottensteiner, 2001). The method described in (Rottensteiner, 2001) is general enough to be applicable to any polyhedral model, and it is used in our work. Another technique for wire frame fitting of polyhedral models based on other observation equations is described in (Ameri, 2000).

1.2.4   Management of building data: In (Koehl and Grussenmeyer, 1998) and in (Grün and Wang, 1998), relational data base concepts for managing building models and DTMs are presented. By these concepts, the full power of standard relational data base systems can be exploited, especially with respect to semantic attributes. This advantage is contrasted by the fact that the data representing a single building are distributed over several tables. In order to perform an operation, an application has to construct the objects involved from these data. (Yang et al., 2000) use a relational data base system for managing building models, too, but in their system, the buildings are represented by binary large objects (BLOBs), and a tree-like structure is used for structuring the data by geometric criteria in order to increase access rates. The advantage of fast access is contrasted by the programming effort required to interpret the BLOBs and by the problems in exchanging data. The method described in our paper is also based on relational data bases and BLOBs. It is an expansion of the technique for the management of DTMs by (Hochstöger, 1996).
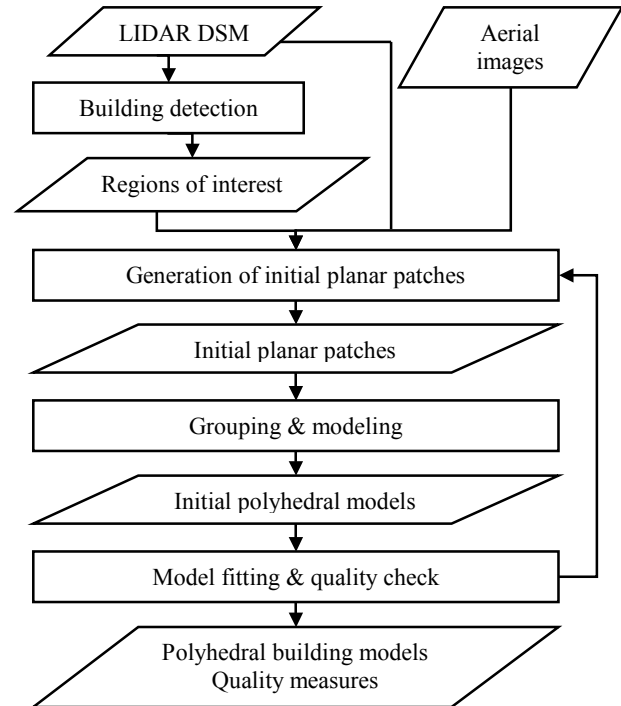
2.   WORK FLOW FOR BUILDING EXTRACTION

The work flow for our method for automatic building extraction is presented in Figure 1. First, building candidate regions have to be detected in the DSM by a hierarchical classification procedure of the LIDAR points. As a result, regions of interest for the geometric reconstruction of the buildings are obtained. In the subsequent processes, these regions of interest are treated individually. Building detection is described in section 3.

In the regions of interest, initial planar patches are reconstructed in object space by the results of a segmentation of the DSM, classifying grid points as being "planar". This segmentation can be improved by a segmentation of the digital images giving regions of homogeneous gray level or color distribution. Neighboring patches being co-planar have to be merged, and a further analysis of neighborhood relations gives hypotheses for lines of intersection and/or step edges. As soon as no more

hypotheses for grouping of planar patches can be found in the data, the resulting polyhedral model consisting of a conglomerate of intersecting (mostly: roof) planes is completed by adding vertical walls at the bordering edges of the planar patches not yet being neighbored by another plane and by adding a horizontal plane for modeling the floor. The creation of the initial polyhedral models is described in section 4.

Figure 1. Work flow for building extraction.

The initial polyhedral building models have to be verified in the

images by 3D-model fitting to improve the accuracy of their geometric parameters. The parameters having been determined, the models can be regularized by introducing hypotheses about planes being orthogonal to each other. The 3D-model fitting procedure is explained in section 5.

The feedback loop shown in Figure 1 indicates a coarse-to-fine strategy by which initially a model is created from the most salient structures found in the data. This initial model then guides further processing as additional data become considered and need to be "explained" by the model.

In all phases of building extraction, a close integration of 3D object and 2D image spaces is needed to improve the degree of automation, the reliability and accuracy of the results. Multi-view optical images are needed to cope with occlusions, ambiguities, and to get the 3rd dimension. On-line self-checking has to be performed in all stages of the extraction process.

3.   BUILDING DETECTION FROM LIDAR DSM

3.1   DTM generation from LIDAR data in urban regions

In (Kraus and Pfeifer, 1998), a method for linear prediction is proposed to separate vegetation from terrain points for the interpolation of DTMs from LIDAR data. The error distribution of the LIDAR heights is assumed to be skew with a strong bias towards off-terrain elevations. This assumption is used for

robust estimation in order to eliminate these points. After that, a classification of the LIDAR points is performed by thresholding the residuals. For LIDAR DSMs having high point densities, the algorithm has to be modified to work in a hierarchical framework because in densely built-up areas, it has to cope with relatively large blocks of houses which share the statistical behavior of steep hills rather than that of single outliers. The algorithm has to be applied to thinned-out data first to get an initial classification of terrain points. After that, iteration is continued starting from pre-classified data. In (Briese, 2001), this strategy has been evaluated for the generation of a high-quality DTM of a test site in the City of Vienna.

3.2 Detection of buildings by comparing DSM and DTM

Two digital elevation models of identical grid width are derived by linear prediction: a DTM is computed from the points classified as "terrain points" with a high degree of smoothing, whereas a DSM is computed from all points without smoothing (Figure 2a). An initial building mask is created by thresholding the height differences between the DSM and the DTM. This initial building mask still contains areas covered by vegetation, and some individual building blocks are not correctly separated (Figure 2b). A morphological opening filter using a small (e.g., 5 x 5) square structural element is applied to the initial building mask in order to get rid of small elongated objects and to separate regions just bridged by a thin line of pixels. A connected component analysis of the resulting image is applied to obtain the initial building regions. At this instance, regions smaller than a minimum area (e.g., 40 m^2) and regions at the border of the DSM are discarded (Figure 2c).
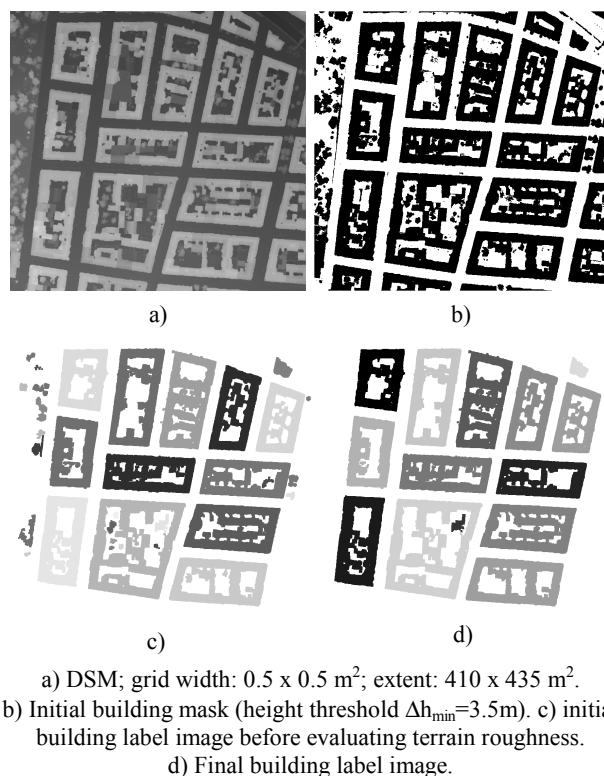
Some of the remaining regions correspond to groups of trees. They can be eliminated by evaluating a "terrain roughness" criterion derived by an analysis of the second derivatives of the DSM. In (Fuchs, 1998), a method for polymorphic feature extraction is described which aims at a classification of texture as being homogeneous, linear, or point-like, by an analysis of the first derivatives of a digital image. This method is applied to the first derivatives of the DSM using a large (e.g., 9 x 9) integration kernel. For each initial building region, the number of "point-like" pixels is counted. Regions containing more than 50% of pixels classified as being "point-like" (thus, pixels being in a neighborhood of great, but anisotropic variations of the surface normals) are very likely to contain vegetation rather than buildings, and they are eliminated.

The terrain roughness criterion is very efficient in classifying isolated vegetation regions, but it cannot find vegetation areas which are still connected to buildings. In a final stage of analysis, we try to eliminate such areas. By morphological opening using a square structural element, regions just connected by small bridges are separated. The resulting binary image is analyzed by a connected component analysis which results in a greater number of regions, and the terrain roughness criterion is evaluated again. Pixels being in regions now classified as containing vegetation are erased in the initial building label image. Thus, in vegetation areas originally connected to buildings, only the border pixels remain classified as "building pixels". Again, morphological opening helps to erase these border pixels. The resulting building label image only contains a small percentage of erroneously classified pixels in a few backyards (Figure 2d).

At a very coarse level of detail, a 3D city model can be derived by creating prismatic models from the boundary polygons of the

building regions using the average building heights computed from the DSM. An example for such a city model with a height accuracy of about ±5 m is shown in Figure 3.

Figure 2. Building detection in a test site in the City of Vienna. Original resolution: 0.1 m (in-flight) by 1 m (cross-flight).

a)   b)

c)   d)

a) DSM; grid width: 0.5 x 0.5 m^2; extent: 410 x 435 m^2.
b) Initial building mask (height threshold Δh_{min}=3.5m). c) initial building label image before evaluating terrain roughness.
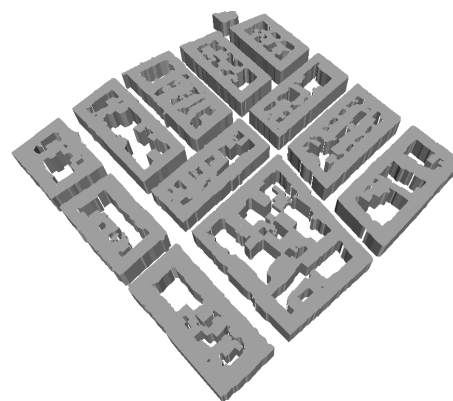d) Final building label image.

Figure 3. VRML visualization of prismatic models created from the boundary polygons of the building regions from Figure 2.

4. MODEL GENERATION

4.1 Generation of initial 3D planar segments

To start with model generation, initial 3D planar segments, their geometrical parameters, and their initial border polygons have to be found in the regions of interest. This can be achieved by generating a "segment label image" defined in object space with an appropriate grid width. Each pixel of that image is assigned the label of the planar segment it belongs to.

The framework for polymorphic feature extraction (Fuchs, 1998) is applied for the generation of planar segments, too. Just as described in section 3.2, the framework is applied to the first

derivatives of the DSM, this time using a small integration kernel of 3 x 3 pixels. Pixels classified as being homogeneous are surrounded by pixels having similar components of the normal vector, i.e., they are in a region containing co-planar points (Brunn and Weidner, 1997). The binary image of the homogeneous pixels is used for further processing (Figure 4a).

By applying a connected component analysis to this binary image, planar patches should be detectable. However, due to errors in the classification of homogeneous pixels, especially at the intersections of roof planes which are almost horizontal, the regions thus detected often turn out to be too large. Typically, this leads to L-shaped segments such as the one at the upper left corner of Figure 4a. In order to avoid these segmentation errors, an iterative strategy is applied for the generation of planar patches. The binary image of homogeneous pixels is morphologically opened using a square structural element before applying the connected component analysis. The geometric parameters of the planar patches thus detected are derived along with their r.m.s. errors from all points inside these patches. The height residuals are used to split the initial patches in case this appears to be necessary. The patches with the best fit, i.e., those with r.m.s. errors better than a certain threshold (e.g., ±10 cm) are considered to be seed regions for region growing. These seed regions are grown iteratively by adding neighboring pixels to a region if their distances from the original adjusting plane are below a certain threshold. In this way, the most relevant and best fitting planes are extracted from the DSM. After that, the plane parameters are updated, and the pixels already being assigned to a planar patch are erased in the binary images. The connected component analysis is repeated, and the parameters of the new planar patches are evaluated again. This procedure is repeated with a decreasing size of the structural element for morphological opening. Thus, smaller and smaller initial regions are found, and by only allowing well-fitting planes to grow, it is possible to split the regions corresponding to more than one roof plane because the r.m.s. error of the planar fit is a good indicator for the occurrence of such situations. Figure 4b shows the results of seed region generation for one of the buildings from Figure 2.
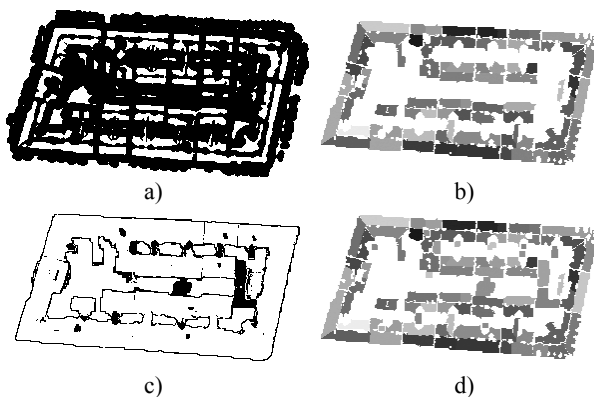

a) b)

c) d)

Figure 4. Creation of initial planar patches from a DSM in one of the building regions from Figure 2. a) Classification results of polymorphic feature extraction. White: pixels classified as "homogeneous". b.) Planar regions obtained by iteratively applying a connected component algorithm and region growing. c) Pixels not being consistent to a planar patch. d) Final segment label image.

A further analysis has to detect planes which cover too small an area for resulting in pixels classified as being homogeneous. We search for regions not being consistent with the planar regions

detected so far (Figure 4c). The borders of the buildings are typically found in that process, which is caused by laser points on the walls. Again, we get rid of these points by a morphological opening operation using a 3 x 3 square structural element, and a connected component analysis is applied to the resulting image in order to create additional planar patches. Figure 4d shows the final segment label image created for one of the building regions from Figure 2. The r.m.s. errors of planar adjustment varies between ±5 cm and ±15 cm for the segments corresponding to the "homogeneous" points. The segments having a r.m.s. error larger than ±10 cm possibly still correspond to more than one roof plane. In the planar regions created by the analysis of the originally inconsistent points, the r.m.s. errors vary between ±25 cm and ±5 m, which is caused by the fact that some of these regions still correspond to trees, whereas other regions also correspond to more than one roof plane. In the future, a further analysis will split these planar patches into smaller ones corresponding to even smaller planes in object space. This can be accomplished, e.g., by a height segmentation of the DSM in these regions. Another possibility for doing so is the integration of the information from the digital aerial images into the process of finding the initial planar patches. The digital images are also segmented based on the algorithm for polymorphic feature extraction, which results in a set of edge and point features and a set of patches of homogeneous gray levels for each image. The image segments could be considered in region growing, for instance by applying additional conditions with respect to homogeneity of gray levels at projected positions. In addition, the geometrical resolution of the segment label image can be increased considerably because the resolution of digital aerial images is still superior to the resolution of a laser scanner DSM.

4.2 Grouping planar segments to create polyhedral models

To derive the neighborhood relations of the planar segments, a Voronoi diagram based on a distance transformation of the segment label image has to be created (Ameri, 2000): each pixel inside the region of interest not yet assigned to a planar segment is assigned to the nearest segment. The distances of pixels from the nearest segments are computed by using a 3-4 chamfer mask. Figure 5 shows a Voronoi diagram of the segment label image from Figure 4d. From the Voronoi diagram, the neighborhood relations of the planar segments are derived, and the borders of the Voronoi regions can be extracted as the first estimates for the border polygons of the planar segments.
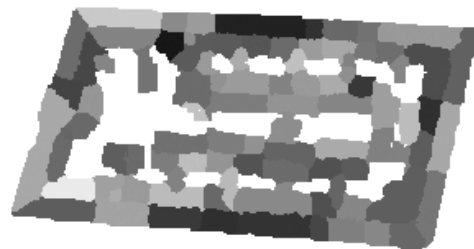

Figure 5. A Voronoi diagram of the label image in Figure 4d.

After deriving the neighborhood relations, neighboring planar segments have to be grouped. There are three possibilities for the relations of two neighboring planes (Baillard et al., 1999). First, they might be co-planar, which is found out by a statistical test applied to the plane parameters. In this case, they have to be merged. Second, two neighboring planes might intersect consistently, which is the case if the intersection line is close to the initial boundary. In this case, the intersection line

has to be computed, and both region boundaries have to be updated to contain the intersection line. Third, if the planes do not intersect in a consistent way, there is a step edge, and a vertical wall has to be inserted at the border of these segments.

After grouping neighboring planes, the bounding polygons of all enhanced planar regions have to be completed. (Moons et al., 1998) give a method for doing so and for regularizing the shape of these polygons at building corners. Finally, the completed planar polygons have to be combined to form a polyhedral model. Polygon sides not being intersections or step edges are supposed to be situated at the building outlines. Vertical walls and a floor have to be added to the model.
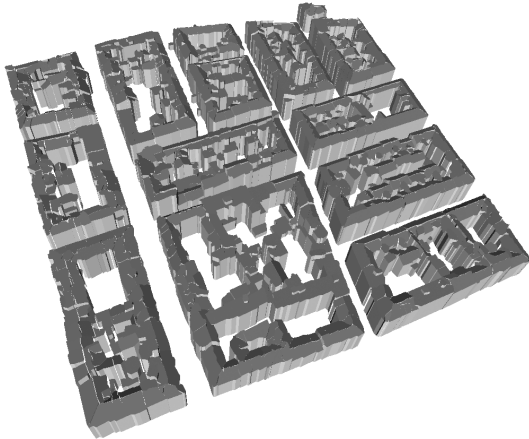

Figure 6. A VRML visualization of a model created from the boundary polygons of the Voronoi diagram in the test area from Figure 3.

The tools for grouping planes and for computing intersections and the positions of step edges have not yet been implemented. Figure 6 shows a VRML visualization of a 3D model created from intersecting vertical prisms bounded by the borders of the Voronoi regions with the respective 3D roof planes. The structure of the roofs is correctly resembled, but the intersection lines of neighboring roof planes are not yet computed correctly. However, the visualization shows the high potential of the method for generating roof planes from LIDAR data.

5. WIRE FRAME FITTING

The initial polyhedral model is back-projected to the images (Figure 7), where its edges can be matched with image edges. This is necessary in order to improve the accuracy of the building models, especially with respect to the building outlines. Our model fitting algorithm has first been used for automatic fine measurement of parametric and prismatic building models in a system for semi-automatic building extraction (Rottensteiner, 2001). It is based on the integration of object modeling by boundary representation (B-rep) and hybrid adjustment in the way it is realized in the adjustment package ORIENT (Kager, 1989). Each face of the B-rep corresponds to a set of "shape" ("GESTALT") observations, i.e., a set of points declared to be situated on the same surface (Kager, 1989), and the parameters of these surfaces have to be determined. In parameter estimation, the topology of the B-rep is represented by the fact that a building vertex gives support to at least three surfaces and by implicit geometric conditions imposed by a specific way of formulating the surface equations (Rottensteiner, 2001). Before matching is performed, the parameterization of the planes of the initial polyhedral models

has to be decided upon, and all "shape observations" and plane parameters which represent the building model in the reconstruction process have to be prepared.
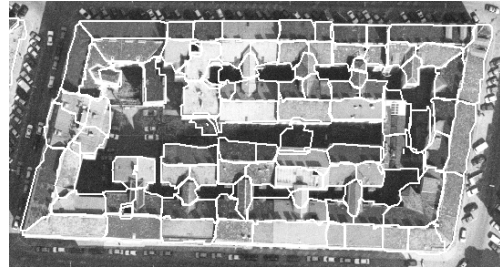

Figure 7. The roof polygons of the building in Figures 4 and 5 back-projected to one of the images (white). Approximate ground pixel size: 15 cm.

Model fitting is based on hierarchical feature based multi-image matching applying the scheme of hypotheses generation and verification (Gülch, 1994). Starting from the approximate values, the wire frame of the building is back-projected to the images. Straight image line segments are matched with the object edges. Whereas matching candidates for all object edges are searched for independently in all images, hypothesis verification is performed in an overall robust estimation process in a hybrid adjustment of the "shape observations" representing the object models, the heights of the points of the DSM, and the camera co-ordinates of image features. Robust estimation is applied in order to determine false matches between image and object edges. In a test project in the context of semi-automatic building extraction (scale 1:4500, six-fold overlap) the method has been shown to achieve results with an accuracy in the range of a few centimeters (Rottensteiner, 2001).

After model fitting, regularization hypotheses (e.g., orthogonal walls) can be created. A mapping between the type of regularization and the formulation of "shape observations" as described in (Rottensteiner, 2001) has to be found, and model fitting is repeated.

6. MANAGING BUILDING DATA IN A TIS

In addition to investigating the work flow for object reconstruction, considerable efforts have been spent to find an object-relational technique for the management of large sets of building data in a TIS. This method is based on the principles which have been demonstrated to handle digital elevation data of whole states (Hochstöger, 1996). The program TopDM, a development of our institute, is used as a TIS. It is based on a relational data base with additional topologic and geometric elements (Hochstöger, 1996). An object-relational principle (Kraus, 2000) is used for the management of building data in order to use the existing relational data base and to offer an object oriented view at the data base for application programs.

TopDM offers an area called "derived products market" (DPM), where DTMs are managed in a table of the relational data base. Each line of that table corresponds to a DTM. However, only the meta data of the DTM are actually contained in that table, whereas the actual DTM is stored on the disk. The meta data comprise attributes such as object type, data format, file name and extension in object space, the latter one being used for queries according to geometric criteria. The principle of managing the meta data in a relational data base while treating

the actual data as BLOBs stored separately on disk was shown to be well-suited for managing digital elevation data of whole states in (Hochstöger, 1996). That principle could also be applied to building data by introducing new possible values for the attributes "object type" and "data format". The B-reps of the buildings are stored on disk in a specific binary data format.
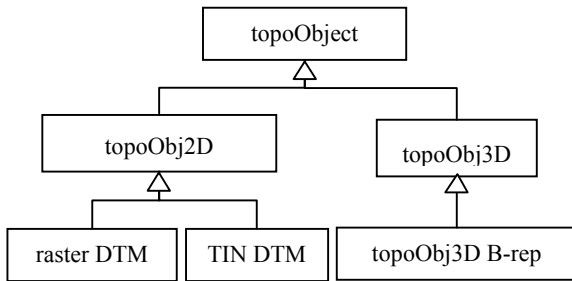

Figure 8. Inheritance tree for topographic objects.

An object oriented interface for the DPM was realized by creating an inheritance tree for topographic objects (Figure 8). The base class *topoObject* corresponds to a topographic object containing the meta data described above. The actual method of geometric modeling is not yet implemented in that class. In a first level, two classes corresponding to objects being modeled by 2.5D and 3D modeling techniques, respectively, are derived from class *topoObject*, but these classes do not yet correspond to real objects. The classes derived from them, however, correspond to actual data modeled by means of specific (2.5D or 3D) modeling techniques: DTMs in 2.5D grid-based representation or as TIN, and 3D objects in B-rep. In order to realize the object oriented view at the topographic data, an interface sending queries to the DPM had to be implemented. This interface has to interpret the attribute "object type" in the results of the query, instantiate an object of the class corresponding to the actual value of that attribute and use the class specific methods for reconstructing the object in memory from the data found on the file corresponding to the value of the attribute "file name". The results of the query are presented to an application as a list of instances of class *topoObject*, and the application can use the methods of that class, e.g., for visualizations such as the one presented in Figure 7.

7. CONCLUDING REMARKS

In this paper, we have presented a method for automatic extraction of buildings from multiple data sources. Parts of that method are still work in progress, but we were also able to present preliminary results achieved by the modules already implemented in a test project in the City of Vienna. These preliminary results show the high potential of the method.

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