D. Fritsch, M. Englich & M. Sester, eds, 'IAPRS', Vol. 32/4, ISPRS Commission IV Symposium on GIS - Between Visions and Applications, Stuttgart, Germany.

CC-MODELER: A TOPOLOGY GENERATOR FOR 3-D CITY MODELS

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KEY WORDS: 3-D City models, topology generator, building reconstruction, visualization

ABSTRACT

In this paper, we introduce a semi-automated topology generator for 3-D objects, CC-Modeler (CyberCity Modeler). Given the data as point clouds measured on Analytical Plotters or Digital Stations, we present a new method for fitting planar structures to the measured sets of point clouds. While this topology generator has been originally designed to model buildings, it can also be used for other objects, which may be approximated by polyhedron surfaces. We have used it so far for roads, rivers, parking lots, ships, etc. CC-Modeler is a generic topology generator. The problem of fitting planar faces to point clouds is treated as a Consistent Labeling problem, which is solved by probabilistic relaxation. Once the faces are defined and the related points are determined we apply a simultaneous least squares adjustment in order to fit the faces jointly to the given measurements in an optimal way. We first present the processing flow of the CC-Modeler. Then the algorithm of structuring the 3-D point data is outlined. Finally, we show the results of several data sets which have been produced with CC-Modeler.

1. INTRODUCTION

The generation of 3-D city models is a relevant and challenging task, both from practical and scientific point of views. Photogrammetry is an appropriate tool to provide information about man-made objects, vegetation cover and the like. Recently, many approaches for automated and semi-automated extraction of buildings and roads from aerial images have been proposed (Gruen et al., 1997). Due to the complexity of the natural scene and the lack of performance of image understanding algorithms the fully automated methods cannot guarantee results stable and reliable enough for practical use. Therefore we are investigating also into semi-automated approaches which would give the human operator strong computational support in order to generate 3-D city models from aerial images efficiently. We have developed a method which fits generic building models to measured, unstructured 3-D point clouds, which have been generated by a human operator on an Analytical Plotter or a Digital Station (Dan, 1997, Gruen, 1998). This system TOBAGO, although well proven in many pilot projects, is restricted to the modeling of buildings. With CC-Modeler (CyberCity Modeler) we present a new method for fitting planar structures to measured sets of point clouds. While this topology generator has been originally designed to model buildings, it can also be used for other objects, which may be approximated by polyhedron surfaces. We have used it so far for roads, rivers, parking lots, ships, etc. CC-Modeler is a generic topology generator and, from a practical point of view, it can be considered a generalization of our previous modeler TOBAGO. However, it follows a totally different algorithmic principle.

In the following section we will introduce the overall data flow scheme of CC-Modeler. In section 3 the key reconstruction algorithm is explained and finally some data sets which have been generated with CC-Modeler are presented.

2. GENERAL DATA FLOW

To generate 3-D descriptions of man-made objects from aerial photographs involves two major components: photogrammetric measurements and automated structuring. In CC-Modeler, the feature identification and measurement is implemented in manual mode, on an Analytical Plotter or a Digital Station. During the data acquisition 3-D points belonging to a single object should be coded into two different types according to their functionality and structure: boundary points and interior points (see Figure 4). Although the human operator tends to measure the points in a particular order, CC-Modeler can work with arbitrary sequences of measured interior points. Since the human operator is responsible for the interpretation and measurement, it is possible to acquire any level of object detail for buildings, roads, waterways, and other objects. With this technique, hundreds of objects can be measured in one day.

CC-Modeler is an automatic topology generator for 3-D objects. The main components of the system are shown in Figure 1. The first obligatory step is preprocessing, which includes the control of measurement order of the boundary points (BP), detection of redundant points, and determination of the possible groups of faces, based on adjacent (BP) point pair sets (compare section 3). The next

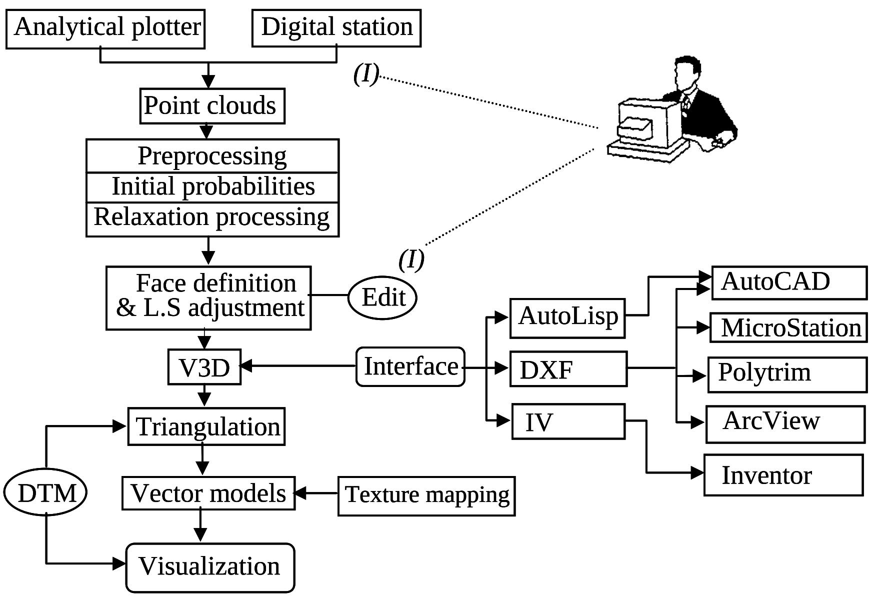

Figure 1: The data flow of CC-Modeler
(I) --- Interactive functions

Step is to build the face model of the 3-D object, i.e. to determine how many faces the 3-D object has, which points define an exact face and what spatial relations the faces take on. This is implemented through a Consistent Labeling algorithm by probability relaxation operations, in which two procedures are involved, the initial probability determination and the relaxation processing. The detailed algorithm will be presented in the following section. As the results of Consistent Labeling, CC-Modeler delivers the face definition for every face. Then, least squares adjustment is performed for all faces simultaneously, fitting the individual faces in an optimal way to the measured points and considering the fact that individual points may be member of more than one face. This adjustment is amended by observation equations that model orthogonality constraints of pairs of straight lines. Finally, a vector description of 3-D objects is obtained, which is represented in a self-developed data structure (V3D). For the purpose of visualization, the CC-Modeler can also triangulate the faces to get its TIN structure. Although the procedure is automated, human intervention and interaction with the automatic procedures is also available, as outlined in Figure 1.

V3D is a self-developed vector data structure, which builds the facet model of objects (Figure 2). The basic geometric element in this diagram is the point. Points are used to express faces or line segments. The object consists of faces, and the polyline consists of line segments. Once some attributes are attached, an object or polyline becomes an entity class. In addition, CC-Modeler has the ability to map images onto a 3-D object or DTM in order to create a more natural scene. The texture, taken from the original images, is attached to an exact face as a special attribute. The DTM is considered a particular entity class in V3D. With the help of interfaces, one can conveniently translate the V3D data structure into different data files, such as DXF, IV, and AutoLisp, which are readable by AutoCAD, MicroStation, Polytrim, ArcView and Inventor.

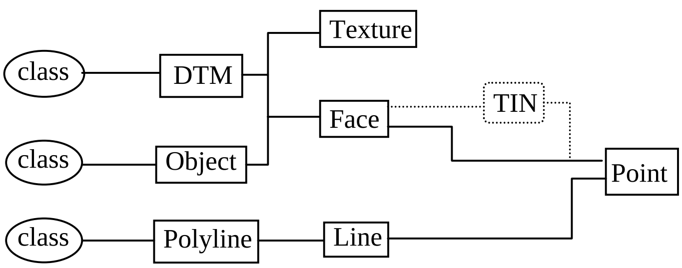

Figure 2: The data structure of V3D

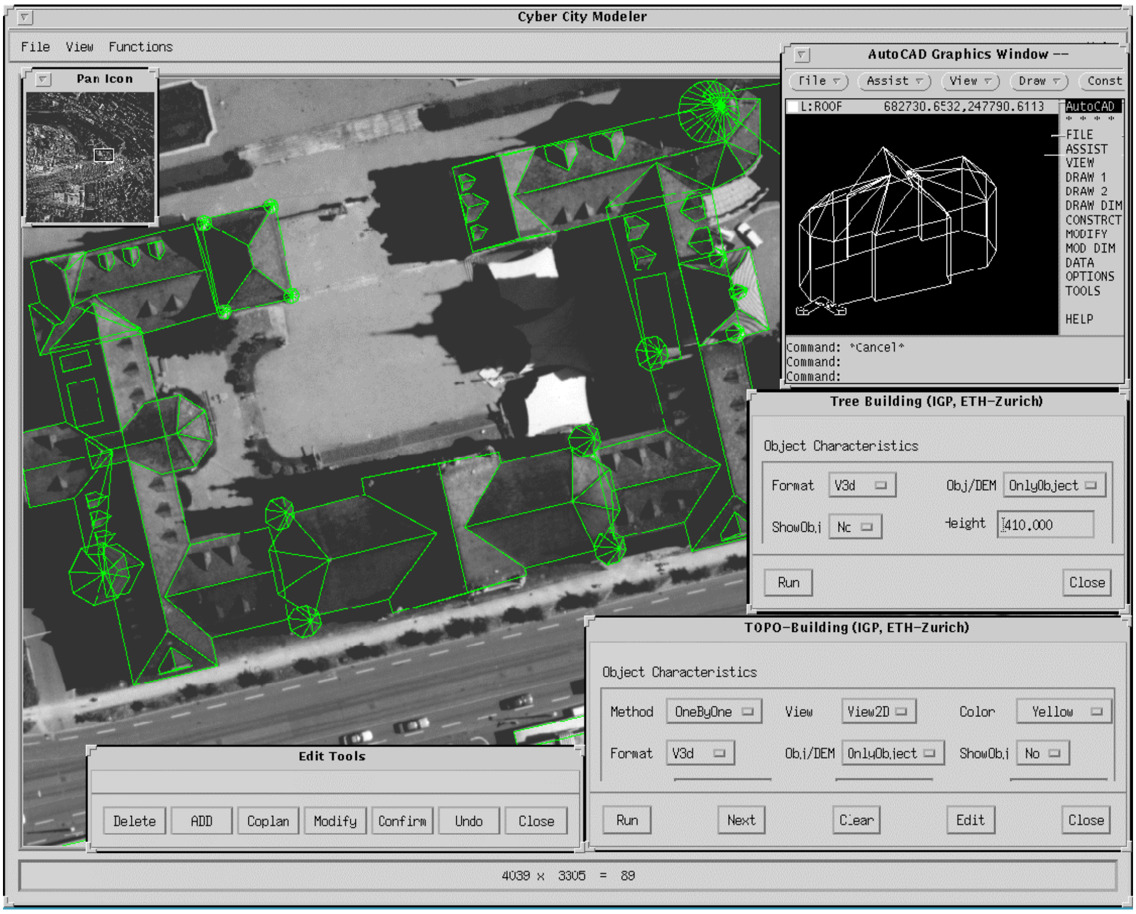

Figure 3: An overview of the CC-Modeler userinterface

CC-Modeler has been successfully implemented on workstations (Sun SPARC) under X-Windows and OSF/Motif. Figure 3 is an overview of the CC-Modeler userinterface. One can optionally set CC-Modeler to work in the automatic or the interactive mode. When working in the interactive mode, one can edit or modify 3-D objects with the help of 2-D or 3-D views, if any mistakes occur due to inadequate point measurements. With the 2-D view, CC-Modeler will project the vector data of 3-D objects onto the original image (see Figure 3) to help check the results. In the 3-D mode, a 3-D vector model of the object will be shown to monitor the procedure.
CC-Modeler is a general topology generator. It works not only with buildings, but also with other objects like trees, waterways, bridges, roads, etc. Moreover, CC-Modeler can combine a face model of a DTM with 3-D objects.

3. STRUCTURING THE 3-D POINT DATA

Assuming that a 3-D point cloud for each object of interest has been generated, e.g. by photogrammetric stereo model measurement. The sequence of the points should be partly in a semi-ordered fashion such that the boundary points of an object (P_1, ..., P_{10} in Figure 4) are to be measured either clockwise or counter-clockwise and labeled (BP). All other points (called "interior points", and there could be many more than shown in Figure 4) can be measured in an arbitrary sequence and are labeled (IP).
The points of an object are expressed as the nodes of a graph, and each line is expressed as an edge with two nodes. The topology structure of this object is shown in Figure 4 together with the related graph. Obviously, every sub-circuit in the related graph is a basic face of the object, and every two neighbor points (BP) can be always considered as a basic edge of a sub-circuit. Thus, our problem is to investigate how to construct every sub-circuit based on two adjacent points (BP) as its basic edge.
From a geometric point of view, every two adjacent points (BP) together with an interior point construct a possible face (such as P_1 P_2 with P_{13} in Figure 4). Then, to combine the adjacent points (BP) with different interior points will bring about different faces. Vice versa, every interior point (IP) may belong to more than one face.
In theory, the labeling methods are various, but only one solution is desired, which meets the inherent topological constraint of the object. Therefore, our problem is to determine for instance which interior points (P_{13}, P_{12} in Figure 4) lie on the face group determined by an adjacent point pair (P_1 P_2), and what link order those points take to construct a face ($P_1 \to P_2 \to P_{13} \to P_{12}$).

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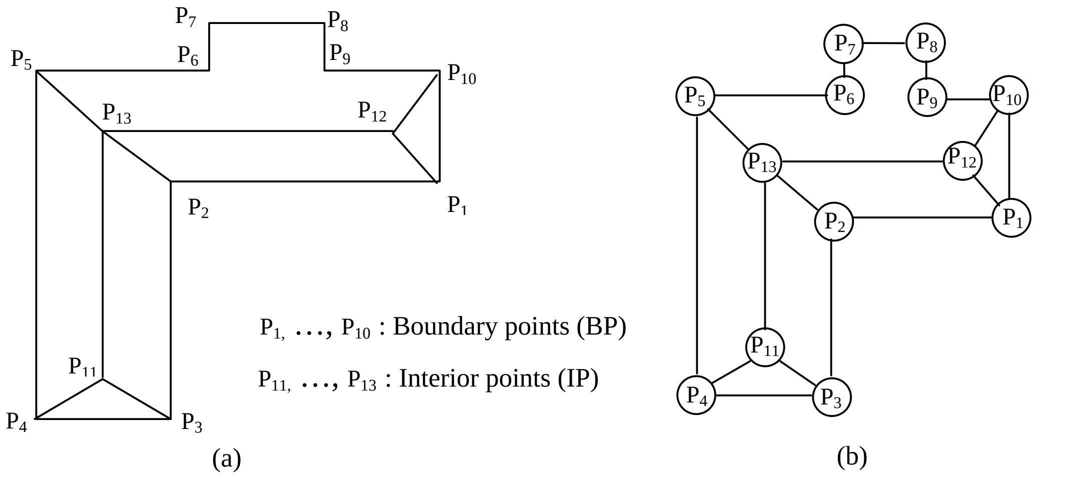

Figure 4: (a) Point definition in CC-Modeler
(b) Related graph

The whole of the 3-D points, expressed as a set *G*, can be decomposed into two subsets, i.e. the adjacent point (BP) pair set *C* and the interior points (IP) set *A*. According to graph theory, if a set of nodes of a graph *G* can be divided into two non-empty subsets *A* and *C*, such that an edge of *G* connects with a node of *A* and a node of *C*, this graph is called a *Bipartite Graph*. Our problem of generating the topology of a 3-D object is equivalent to the determination of the spatial relation between the elements in the set *G*, particularly that between the set *A* and the set *C*. Therefore, we define our problem as a *Bipartite Graph Matching* (Wilson, 1979) or a one-multiple *Consistent Labeling* problem (Haralick, Shapiro, 1979). Figure 5 shows the principle of *Consistent Labeling*.

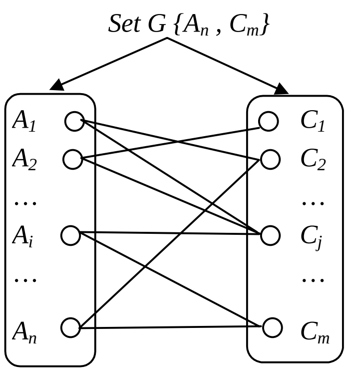

Figure 5: The principle of *Consistent Labeling*

For the solution of *Consistent Labeling* many methods have been proposed (Rosenfeld et al., 1976, Li, Wang, 1996). With CC-Modeler, we use a labeling algorithm based on *probabilistic relaxation*. The labeling probability, i.e. the probability of labeling each interior point as belonging to an exact face group, is modified according to the observations and the geometric constraints.

We have an objective set $A\ \{A_1, A_2, \ldots, A_n\}$ which will be labeled into *m* classes, and the class set is expressed as $C\ \{C_1, C_2, \ldots, C_m\}$. The labeling procedure is interrelated. For example, labeling $A_i \in C_j$ will affect the result of labeling $A_h \in C_k$. The interrelation is defined as a cooperative coefficient $\lambda(i,\ j;\ (h,\ k))$. Assuming that p_{ij} is the probability of $A_i \in C_j$, and G_i is the adjacent area of A_i, then the standard relaxation approach is expressed as:

$$p_{ij}^{n+1} = p_{ij}^{n} \frac{(1+q_{ij}^{n})}{norm_i^{n+1}} \tag{1a}$$

$$norm_i^{n+1} = \sum_{j=1}^{m} p_{ij}^{n}(1+q_{ij}^{n}) \tag{1b}$$

$$q_{ij}^{n} = \sum_{h\in G_i} \sum_{k=1}^{m} \lambda(i,j;(h,k))p_{hk}^{n} \tag{1c}$$

The traditional relaxation algorithm must be modified to work in our case, because our labeling procedure is not a one-one correspondence, but that of multiple matching. This means that an element in the objective set *A* may be labeled into more than one class sets.

The formula (1) is a recursive equation. p_{ij}^{n} is the probability of labeling *i* to *j* in the *n*th recursion, and $0 \le p_{ij}^{n} \le 1$ is always valid. The variable q_{ij}^{n} can be considered as the added magnitude of the probability labeling *i* to *j* in the next recursion step, and $q_{ij}^{n} \ge 0$. In fact, two types of possibilities always exist, i.e. labeling $A_i \in C_j$ and $A_i \notin C_j$. Assume that p_{ij} is the probability of labeling $A_i \notin C_j$, and the q_{ij} is the added magnitude of p_{ij}, such that:

$$\bar{p}_{ij}^{n} = 1 - p_{ij}^{n} \tag{2a}$$

$$\bar{q}_{ij}^{n} = \sum_{h \in G_i} \sum_{k=1}^{m} \lambda\big(i,\ j;(h,k)\big)\bar{p}_{hk}^{n} \tag{2b}$$

Thus the modified relaxation algorithm is expressed as:

$$p_{ij}^{n+1} = p_{ij}^{n} \frac{(1+q_{ij}^{n})}{norm_i^{n+1}} \tag{2c}$$

$$norm_i^{n+1} = \sum_{j=1}^{m} \left[p_{ij}^{n}(1+q_{ij}^{n}) + \bar{p}_{ij}^{n}(1+\bar{q}_{ij}^{n}) \right] \tag{2d}$$

Where p_{ij}^n expresses the probability that event $A_i \in C_j$ is 1, i.e. the probability that the objective element A_i belongs to the class C_j. $\lambda(i, j; (h, k))$ is the cooperative coefficient. If the event of $A_i \in C_j$ and $A_h \in C_k$ being fully cooperative, $\lambda(i, j; (h, k)) = 1$, on the contrary, -1. If the event $A_i \in C_j$ is not related with the event $A_h \in C_k$, $\lambda(i, j; (h, k)) = 0$. For our problem, the following formula is employed to compute $\lambda(i, j; (h, k))$

$$\lambda\big(i,\ j;(h,k)\big) = \begin{bmatrix} \cos\alpha & for(j=k) \\ 0 & for(j \neq k) \end{bmatrix} \tag{3}$$

Where α is the internal angle between the normal vectors constructed by the faces $A_i \in C_j$ and $A_h \in C_k$. Notice that to compute $\lambda(i, j; (h, k))$ one should follow a basic criterion, i.e. the result of labeling A_i (or A_h) to C_j (or C_k) should lead to a graph in which no intersection between every two circuits exists.
It should be noticed that the determination of the initial probability for p_{ij} is very important. Good initial proabilities cannot only accelerate the iterative procedure, but also improve the reliability of labeling results. The initial probability of $A_i \in C_j$ can be determined according to the spatial distance from A_i to C_j. The following formula is employed:

$$p_{ij}^{0} = \beta_1 + \beta_2 \frac{Max(d) - d(i \Rightarrow j)}{Max(d) - Min(d)} \tag{4}$$

Max(d) is the longest distance between element C_j and every point in the adjacent area of A_i and *Min(d)* is the shortest one. $d(i \Rightarrow j)$ is the distance from A_i to C_j. $\beta_1 = 0.1$ and $\beta_1 = 0.8$ are constants which are determined empirically.
The procedure of formula (1) and (2) is iterative. Finally, the labeling results of every objective point A_i is deter mined according to the probability p_{ij} . Thus every element C_j in the class set C together with all labeled elements (IP) constitute its maximum element group. To construct the final face, this element group is ordered by a spatial search procedure. Figure 6 shows the procedure, in which P_1P_2 is the basic link, P_i (i = 3, 4, ..., 7) are the interior points. The first step is to calculate the centre of the point group, P_c. If P_cP_2 is considered as the base, all internal angles that the vector P_cP_i (i = 3, 4, ..., 7) generates in relation to the base P_cP_2 can be obtained (see Figure 6(b)). Obviously, ordering the point group is equivalent to ordering these internal angles, which is a simple procedure. Thus the final ordering is shown in Figure 6 (c). We have obtained the face definition with a (BP) pair as its basic edge. In some particular situations, a roof unit may have some faces that are constructed by (IP) points. Therefore, CC-Modeler links all face groups to generate a whole loop, and then checks it. If any sub-loop exists, a new face is defined.
In the follow-up step all planar faces are simultaneously fit to their related 3-D point observations by a joint least squares adjustment. These observation equations are amended by observation equations which model the orthogonality constraints of pairs of straight lines to ensure that measurement errors do not lead to a violation of building construction rules. The complete adjustment is performed iteratively in the following manner:

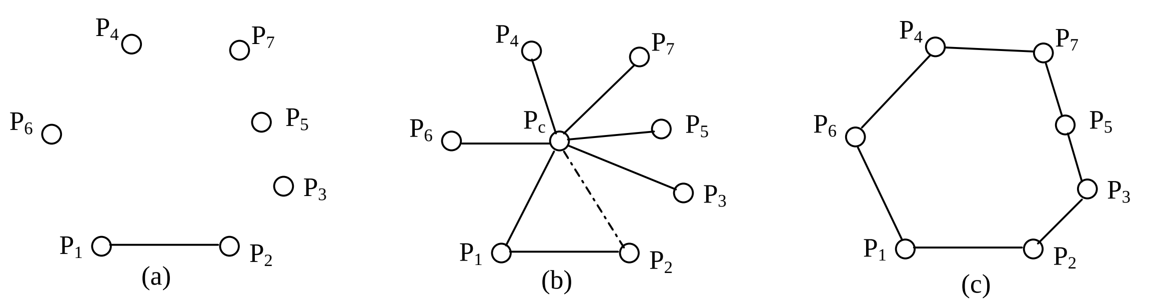

Figure 6: Principle of ordering an element group

(a) Original points (b) Centering of points (c) Ordering result

(1) Individual plane adjustment
Assuming that the face F_j is composed of k points (including interior points and boundary points), the adjusted observations of these points should fit an exact planar face function. Each point i gives an observation equation of the form:

$$v_i = A_j x_i + B_j y_i + C_j z_i + D_j \quad ; p_i \qquad (5)$$

p_i ...... weight for plane condition
A_j, B_j, C_j, D_j ...... estimated parameters.

(2) Projection of measured points onto all planes under consideration of orthogonality constraints
In a second step we formulate for all faces F_j and all points (i) the following observation equations:

$$\begin{aligned} v_i &= A_j dx_i + B_j dy_i + C_j dz_i \\ &+ (A_j x_i + B_j y_i + C_j z_i + D_j) \end{aligned} \quad ; p_i \quad i \in k \quad (6)$$

The unknown parameters dx_i ,dy_i ,dz_i represent changes to the original point locations such that the adjusted point location is optimal with respect to the fitted planes.
For m faces, these observation equations are set up simultaneously.
The geometric orthogonality constraint of straight lines is involved as an additional observation equation. A tolerance parameter (usually ±6°) for the deviations from orthogonality is selected. This procedure is performed in 2-D in the x-y plane.
Assuming that the angle between the straight lines l_1 $((x_{i-1}, y_{i-1}), (x_i, y_i))$ and l_2 $((x_i, y_i), (x_{i+1}, y_{i+1}))$, is less or more than the tolerance allows (see Figure 7), the following equation is formulated:

$$\begin{aligned} v &= (\Delta x_{i+1,i} - \Delta x_{i,i-1}) dx_i \\ &+ (\Delta y_{i+1,i} - \Delta y_{i,i-1}) dy_i \\ &+ \Delta y_{i+1,i} \Delta y_{i,i-1} + \Delta x_{i+1,i} \Delta x_{i,i-1} \end{aligned} \qquad (7)$$

Equations (6) and (7) are solved simultaneously. Step (1) and (2) are performed in an iterative manner. After the solution of (6), (7) the system (5) is solved again with improved point coordinates and a new solution of (6), (7) is computed.
In a follow-up step, every face can be triangulated for the purpose of visualization. Here an algorithm similar to Delauney triangulation is employed.
The photogrammetric measurement principle allows for a free choice of the object resolution, accuracy and fidelity. The CC-Modeler generates a planar world, in which curved surfaces can be approximated by a set of planar patches. Special objects can be generated and inserted. We have demonstrated this with trees (compare Figure 8), waterways and some houses with curved-shape. CC-Modeler has been successfully applied to several data sets. The results are overall positive.

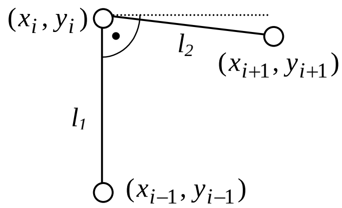

Figure 7: Geometric orthogonality

4. RESULTS OF SEVERAL PROJECTS AND VISUALIZATION

CC-Modeler has been tested in several projects (Zurich, Dietikon, Regensdorf), the statistics of which are presented in Table 1. "Structured automatically" refers to the number of roof units that CC-Modeler builds successfully with full automatic processing, and "structured interactively" refers to the number of roof units that needed to be manually modified in some faces. Obviously, the success rate of CC-Modeler's automatic processing is up to 95%, and almost all roof units can be constructed by using the convenient editing tools. The main factor determining the performance is the degree of familiarity of the human operator with the concept of automated reconstruction. With a person well familiar with CC-Modeler, 400 or more roof units can be generated per day.

Table 1: CC-Modeler statistics of three projects

Project	Total No. of roof units	Structured Automatically	Structured interactively	Failures
Zurich Hauptbahnhof	1733	1656	76	1
Dietikon	298	290	8	0
Regensdorf	925	894	30	1
Total	2956	2840	114	2

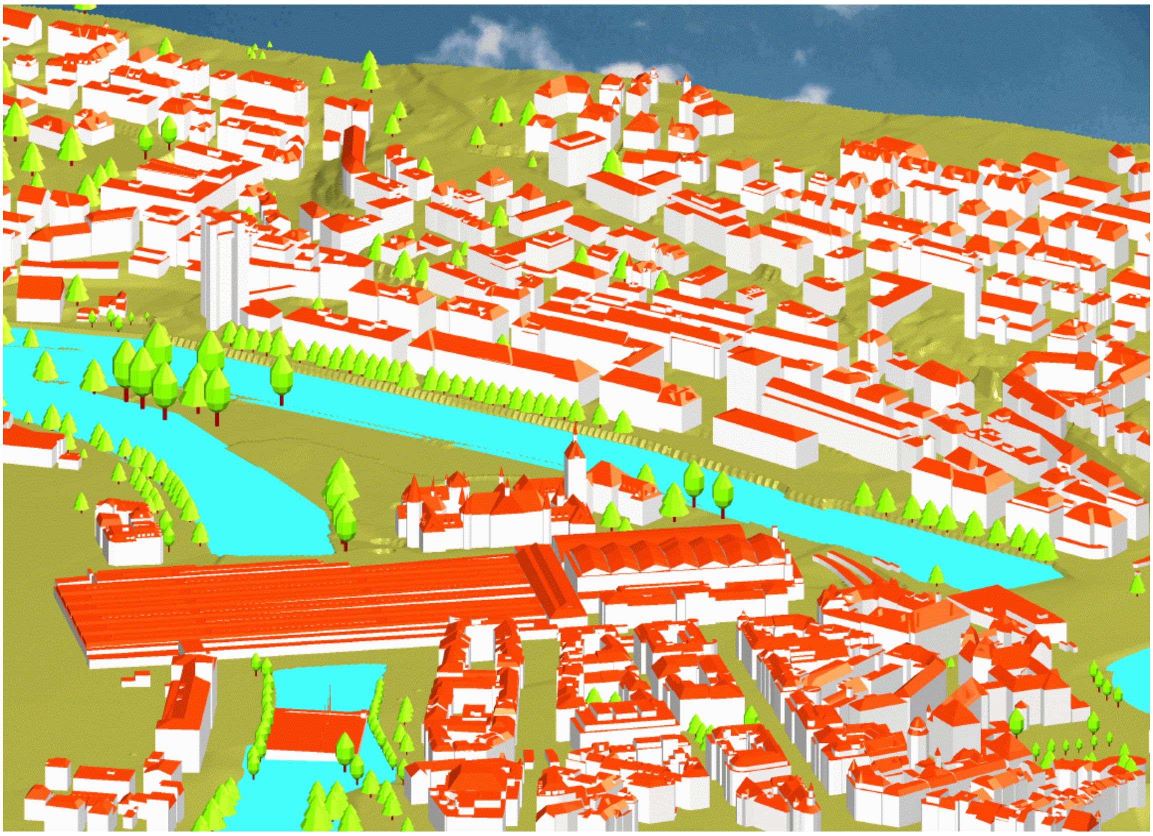

Figure 8: City model “Zurich Hauptbahnhof” generated with CC-Modeler

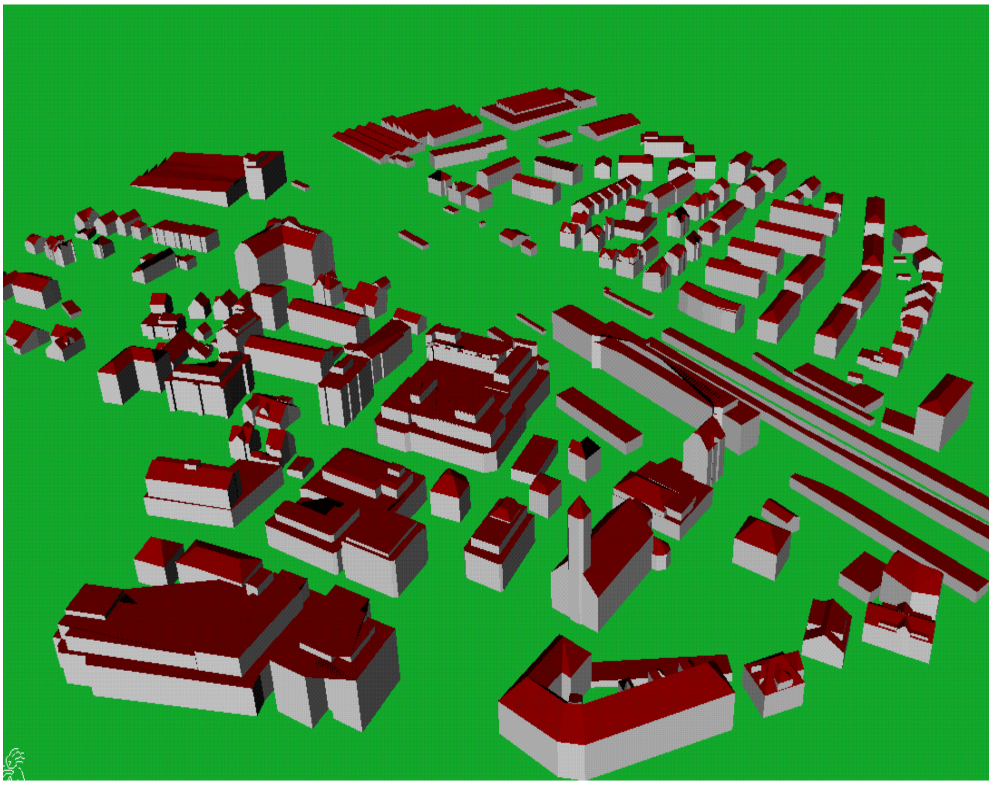

Figure 9: Data set of Dietikon project

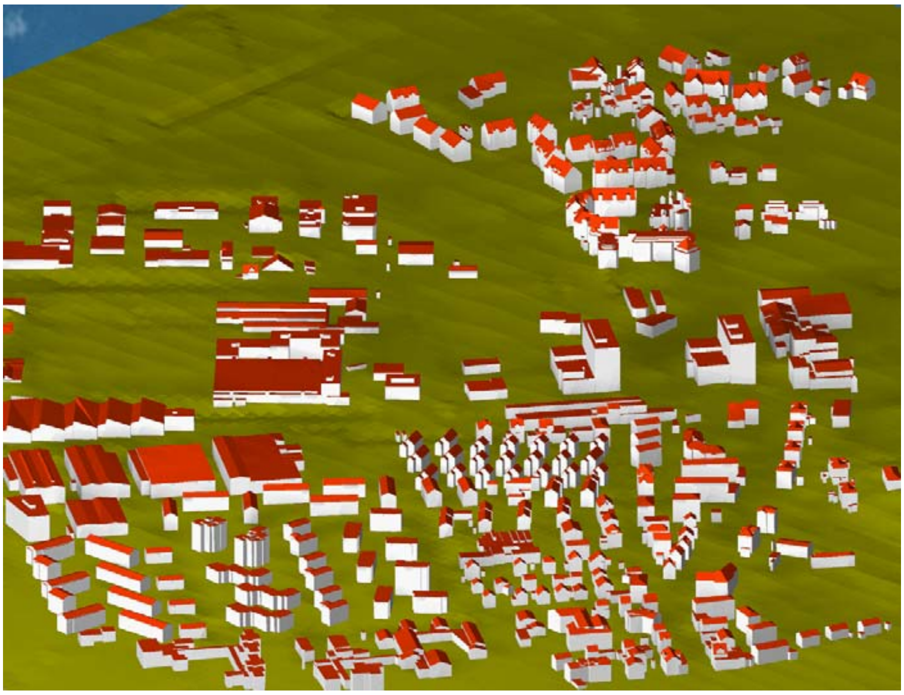

Figure 10: Data set of Regensdorf project

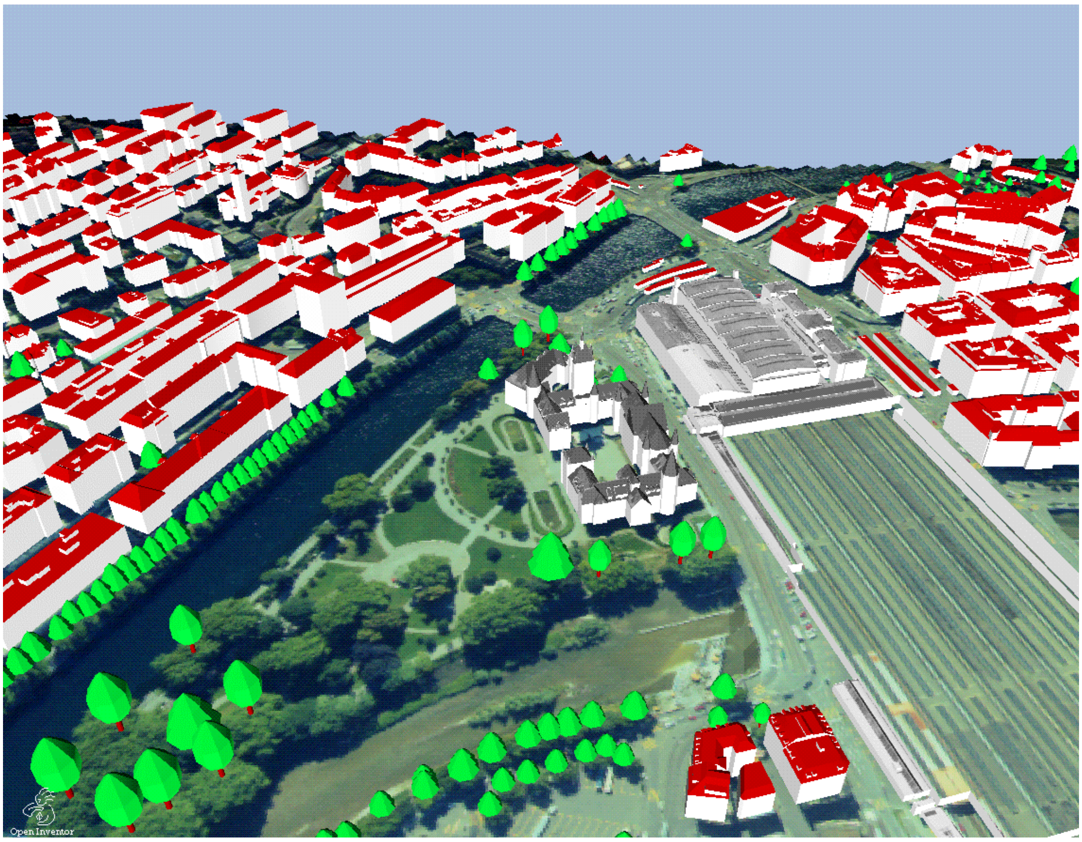

Figure 11 : “Zurich Hauptbahnhof” with mapped texture

For the visualization and animation of the data sets we use various software: AutoCAD, MicroStation, Inventor, and Polytrim. Figure 8 shows a view of the city model "Zurich Hauptbahnhof", including buildings, rivers, trees and DTM. Figure 9 and Figure 10 show "Dietikon" and "Regensdorf". For photorealistic rendering we combine the vector data of the buildings and the DTM with image raster data. The raster images are taken from aerial images. Figure 11 shows the result of mapping image data onto the DTM and some roofs.
CC-Modeler can also map digital images taken with still video cameras onto 3-D faces such as the walls of buildings.

5. CONCLUSION

CC-Modeler is a powerful data acquisition tool for the generation of 3-D city models. Our experiments show that it is flexible, reliable and accurate. In three pilot projects we have achieved a success rate of 95% percent in fully automated structuring mode. Remaining problems are indicated and can be solved interactively. We have developed our own data structure V3D with interfaces to a variety of CAD and visualization packages. CC-Modeler cannot only reconstruct multiple kinds of 3-D objects such as buildings, waterways, roads, trees, DTM, etc., but also map images onto 3-D objects. This can be combined with data from general land use, communication systems, pipeline, property and administrative boundaries, etc. to generate a complete 3-D city model. If required, the data generated with CC-Modeler may be operated by a data base management system to form a Spatial Information System (SIS). This in turn can be integrated into a multimedia environment for the purpose of better user interaction. This is also one of our further research goal.

Acknowledgments: The data sets "Regensdorf" and "Dietikon" have been generated with assistance of Swissphoto+Vermessung AG, Regensdorf. The data set "Zurich Hauptbahnhof" was produced for the City of Zurich Surveying Office and includes a DTM provided by this office. We appreciate very much the cooperation of both partners.
CC-Modeler is available as commercial software package from Born&Partner, Bellikon, CH, Fax: +41 56 4701862.

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