News from CyberCity-Modeler

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**ABSTRACT:** Semi-automated object extraction has become a viable concept for the generation of 3-D city models. CyberCity-Modeler (CCM) has been developed with the aim of creating not only buildings, but also other objects pertaining to a city model efficiently and with a high degree of flexibility concerning the level of detail. In its commercial implementation, CCM has been confronted with a number of user requirements which needed to be observed. This led to some extensions in functionality, which are addressed in this paper: Geometrical regularization of buildings, editing functions for topology adjustment, integration of façades and other vertical walls and modeling of roof overhangs. These extensions of the original concept make CyberCity-Modeler an even more powerful tool for 3-D city modeling.

1 INTRODUCTION

CyberCity-Modeler (CCM) represents a methodology for semi-automated object extraction and modeling of built-up environments from images of satellite, aerial and terrestrial platforms. It is generic in the sense that it allows to model not only buildings, but all objects of interest which can be represented as polyhedral model, which includes DTM, roads, waterways, parking lots, bridges, trees and so forth (even ships have been modeled). As such it produces 3-D city models efficiently, with a high degree of flexibility with respect to metric accuracy, modeling resolution (level of detail), type of objects and processing speed. The basic algorithm and related projects have been previously reported in Gruen & Wang (1998).

In a parallel effort and as a pilot project, a spatial information system (CC-SIS... CyberCity Spatial Information System) has been developed which, based on a relational database (ORACLE), includes both 3-D functionality and image raster data integration on database level and as such represents a fully hybrid system (Wang & Gruen 2000).

In the meantime, CCM became a commercial software product, marketed by the ETHZ spin-off company CyberCity AG (www.cybercity.ethz.ch). As a matter of fact, there is a steadily increasing interest for 3-D city models, with the current major customers being city planning and surveying offices, industrial facilities (chemical and car industry) and telecom companies. With the different types of customers comes a great variability in project specifications. Here it turned out to be of advantage that CCM was set up from the very beginning as a technique with high degree of flexibility. In spite of that, some additions to and extension of the original functionality had to be developed in order to fulfill specific requests.

This paper reports about these extensions. After a brief review of the original CCM concept we will address the issues of regularization of buildings, editing functions and the integration of building façades and automated modeling of roof overhangs.
2 CCM – THE ORIGINAL CONCEPT

CyberCity-Modeler, as the name suggests, was designed as a tool for data acquisition and structuring for 3-D city model generation. From the very beginning, CCM has been devised as a semi-automated procedure. This was done in view of the need to observe the following constraints:

- Extract not only buildings, but other objects as well, like traffic network, water, terrain, vegetation and the like
- Generate truly 3-D geometry and topology
- Integrate natural (real) image textures
- Allow for object attribution
- Keep level of detail flexible. Accept virtually any image scale
- Allow for a variety of accuracy levels (5 cm to 2 m)
- Produce structured data, compatible with major CAD and visualization software

In site recording and modeling, the tasks to be performed may be classified according to:

- Measurement
- Structuring of data
- Visualization, simulation, animation
- Analysis

In CCM, the image interpretation and even the measurement task is done by the operator. The software does the structuring. For visualization, simulation, animation and analysis we largely resort to other parties’, mostly commercial, software.

Figure 1 describes the work- and dataflow of CCM. The operator measures on an Analytical Plotter or on a Digital Station in the stereomodel individual points that fully describe the visible part of an object, i.e. the roof of a building. The measurement sequence of these points is only weakly structured.

![Diagram of CCM work- and dataflow](image)

Figure 1. Work- and dataflow of CCM.

CCM presents a new method for fitting planar faces to the resulting 3-D point cloud. This face fitting is defined as a consistent labeling problem, which is solved by a special version of probabilistic relaxation. In theory there are various labeling methods available, but only one solution is desired, which meets the inherent topological constraints of the object. From a geometrical point of view, the inherent topological constraints can be summarized as: (1) a 3-D object is a closed multiple-plane object; (2) planes are not supposed to pierce each other; (3)
every two adjacent boundary points are always part of a face. As an automatic topology generator, CCM is generic in the sense that any object, which is bounded by a polyhedral surface, can be structured. With this technique, hundreds of objects may be measured in a day. The computation of the structure is much faster than the measurements of the operator, such that the procedure can be implemented in on-line mode. If overlay capabilities are available on the stereo device the quality control and the editing by the operator becomes very intuitive and efficient.

The DTM, if not given a priori, can also be measured and integrated.

Texture from aerial images is mapped automatically on the terrain and on the roofs, since the geometrical relationship between object faces and image planes has been established. Façade texture is produced semi-automatically via projective transformation from terrestrial images, usually taken by camcorders or still video cameras.

The system produces its own internal 3-D data structure, including texture. Interfaces to major public data formats are available.

For a detailed description of CCM see Gruen & Wang (1998). The system and software are fully operational. In the order of 100,000 buildings at high resolution have been generated already with this approach. Figure 2 shows one of the models, the Congress Center RAI, Amsterdam, location of the XIXth ISPRS Congress 2000.

3 SOME RECENT EXTENSIONS

What looks like a complete approach and system from a scientific point of view may not necessarily fulfill some specific practical requirements efficiently. This is the case with the original approach of CCM. Whereas it does the job in most projects very well there are always some specs which require modifications and additions. One of those is geometric regularization. While CCM was built to model the objects as close to their existing size and shape as possible, there arises sometimes the need to regularize the geometry. Under these constraints do fall the requests to make straight lines parallel and perpendicular where they are actually not, or to have all points of a group (e.g. eaves or ridge points) at a unique height. Another problem grew from the fact that CCM was designed to handle individual buildings sequentially and independent of
each other. Building neighbourhood conditions were not considered. The geometrical inconsistencies originating from that fact, like small gaps or overlaps between adjacent buildings (in the cm/dm range), are not dramatic and tolerable in many applications, especially those which are purely related to visualization. However, the topological errors constitute a serious problem in projects where the 3-D model is subject to legal considerations or some other kind of analysis which requires topologically correct data.

Another significant extension refers to the precise modeling of building façades. Façades are usually not visible in aerial images, but available in cadastral maps. We combine this façade information with the roof landscape modeled with CCM in order to be able to represent the roof overhangs. We also show that we can model other vertical walls explicitly.

In the following, we will describe all these extensions in more detail. Figure 3 shows the flowchart of the processes mentioned above, which are executed after the face definition by probabilistic relaxation is done.

3.1 **Geometrical regularization and neighbourhood topology**

Geometrical regularization refers to the task of modifying the geometry in such a way that regular structures are obtained. Measurements from images are always erroneous, although the errors may be very small. In addition, in particular with older buildings, the geometry deviates from regular patterns sometimes significantly. Edges are not parallel, intersections not perpendicular, roof faces not planar. We therefore have developed two strategies for regularization: A fully automatic adjustment based on least squares and a semi-automated approach of CAD editing. Both approaches are integrated in the software package CC-Edit.

The requirements for geometrical regularization are as follows:
- Same height for groups of eaves points, ridge points and other structure points
- Roof patches containing more than 3 points should form planar faces
- Parallelity of straight edges
- Right angles of intersecting roof edges
- Collinearity of edge points

3.1.1 **Least squares adjustment**

We solve these requirements by formulating the constraints as stochastic constraints, i.e. as weighted observation equations in a least squares context. This results in the following system for each roof unit:
In a first step all points which form a group whose height should be a unique value are identified and an average height is computed as

\[
\bar{z}_j = \frac{1}{n_z} \sum_{i} z_{ij} ; \quad i = 1, \ldots, n_z ; \quad n_z = \text{no. of points per group} \quad j = \text{ID of point group}
\]

(1)

This height is introduced as approximate value in the following computations. There will be only one correction value \(dz\) for all points of this group. The group definition is subject to a tolerance value set by the user (e.g. ± 0.2 m).

Parameters of planar faces
The parameters of the planar faces are derived from the observation equations

\[
A_k x_{ik} + B_k y_{ik} + C_k z_{ik} + D_k = v_{ik} ; \quad w_{ik} \quad i = 1, \ldots, n_p ; \quad n_p = \text{no. of points per planar face} \quad k = \text{ID of faces} \quad v = \text{residuals} \quad w = \text{weights}
\]

(2)

Since the system is linear in \(A, B, C, D\), we get these parameters in just one least squares adjustment (LSA) step.

Parallel edges constraints
For each group of parallel straight edges, the parameters of a 2D straight line are derived from the observation equations

\[
a_k x_{im} + b_k y_{im} + c_{km} = v_{im} ; \quad w_{im} \quad i = 1, \ldots, n_p ; \quad n_p = \text{no. of points in mth line} \quad k = \text{kth line group} \quad m = \text{mth line}
\]

(3)

Since the system is linear in \(a, b, c\), we also get these parameters in just one LSA step.

Planar face constraints

\[
A_k dx_{ik} + B_k dy_{ik} + C_k dz_{ik} + \left( A_k x_0^0 + B_k y_0^0 + C_k z_0^0 + D_k \right) = v_{ik} ; \quad w_{ik} \quad i = 1, \ldots, n_p ; \quad n_p = \text{no. of points per planar face} \quad k = \text{ID of faces} \quad dz_{ik} \text{ will be set to just one parameter } dz_j \text{ per point group (j), if the constraint (1) must be applied. Otherwise, all } dz_{ik} \text{ are allowed as individual parameters.}
\]

(4)

Right angle constraints
For the perpendicular line pair \(L_1: (x_k, y_k), (x_i, y_i)\) and \(L_2: (x_i, y_i), (x_h, y_h)\) we get

\[
(x_i - x_k)(x_i - x_h) + (y_i - y_k)(y_i - y_h) = 0
\]

or

\[
c_1 x_i^2 + c_2 y_i^2 + c_3 x_i + c_4 y_i + c_5 = 0
\]

(5)
The observation equation is
\[a_i \cdot dx_i + a_2 \cdot dy_i + \left( c_1 x_i^0 + c_2 y_i^0 + c_3 x_i^0 + c_4 y_i^0 + c_5 \right) = v_i \cdot w_i\]

\[i = \text{intersection point}\]
\[k = \text{another point of line } L1\]
\[h = \text{another point of line } L2\]

(6) Collinearity constraints

\[a_k \cdot dx_i + b_k \cdot dy_i + \left( a_k x_i^0 + b_k y_i^0 + c_k \right) = v_i k \cdot w_i k\]

\[i = 1, ..., n_p; \quad n_p = \text{no. of points in } k\text{th line}\]
\[k = k\text{th line}\]

(7) Coordinate change range limit constraints

\[dx_i = 0; \quad dy_i = 0; \quad dz_i = 0; \quad w_i\]

\[i = 1, ..., n; \quad n = \text{no. of points involved in the adjustment}\]

Equations 1, 2 and 3 are processed first in that sequence. Equations 4, 5, 6 and 7 form the observation equations for a joint least squares adjustment. A proper weighting scheme is crucial to the success of the method. This scheme involves tolerances set by construction rules and user requests. The observation equations are set up for all planar faces involved in a particular roof and can also be extended to handle several neighbouring roofs simultaneously.

The normal equations are solved via Gauss factorization. Since most of the constraints are nonlinear the system has to be iterated. The iteration also includes Equations 2 and 3. Covariance matrices for internal quality control are readily available. Since we use stochastic constraints there will be some deviations from the strict values. It has to be decided whether these deviations are of an acceptable size or not.

This adjustment can be executed for a single roof unit or a group of units simultaneously. In the last case additional observation equations for point identities are added. The selection of the group has to be done manually. Figure 4 shows an example of automated geometry regularization for a whole group of roofs.
Figure 4. Correction of roof group by automated geometry regularization.

3.1.2 Regularization by CAD editing

This is a semi-automated supervised procedure which operates only in planimetry. Therefore, it requires that the equal height condition is already observed during the point measurement phase.

Then, a grid of parallel construction lines is generated and overlaid to the measured lines. The measured lines are automatically adjusted to the direction of the grid. The grid's direction itself is derived from the average direction of the measured lines concerned. The selection of the concerned lines can be done automatically or manually. The overlay display is used for checking and manual editing if something went wrong.

The right angle, collinearity and the planar face constraints are automatically observed by that procedure. Since we use hard constraints here, the results are strict. An example is shown in Figure 5.

Figure 5. Line rectification (dotted line: before, solid line: after).

3.1.3 Topology adjustment

Inconsistencies in topology between adjacent buildings may arise because of measurement errors and because of mutually overlapping roofs.

Figure 6 shows a typical topology problem, which may exist even after the previous geometry regularization. For its solution, we provide both an automated and a semi-automated procedure.
In the automated mode, the system selects a reference border line which is kept fixed and onto which the points of the other lines are projected perpendicularly. As reference line, we select the longest line (which is supposed to be the most stable). In the semi-automated mode, this reference line is selected manually.

The functioning of the automated and semi-automated procedures described above can be monitored by an operator within an editing window as shown in Figure 6. This has of course a certain similarity with a CAD interface. It actually contains many typical CAD functions, but also others which are unique to our system and application-related. An example of automatic topology correction is shown in Figure 7.

3.2 Building façade integration

Here, we aim at a higher level of detail in building modeling. Since façades are in general not accessible in aerial images we use digital cadastral maps, which show the outer walls of buildings as part of the legal definition of real estate property. By integrating this information into the rooflandscape we are able to model the roof overhangs. What sounds like a simple problem at first sight turns out to be a formidable task to automate. In terms of structural detail, the rooflandscape looks very different from the façade landscape. Sometimes the maps are outdated and the roofs do not match the map content at all. Maps may also be inaccurate to an extent that the façade appears shifted and rotated with respect to the roof by a substantial amount. Façades can show a lot of additional, peripheral detail, as for instance stairs and other add-ons (Fig. 8).
Figure 9 shows a result of automated façade integration. The problem is not yet solved in general terms and still needs some manual interference in complex situations. We will report about technical details of our approach in another publication.

Beyond façade integration, also other vertical wall sections, as they may appear on parts of a building and not be available from maps, need to be explicitly modeled as faces. This holds for all vertical building sections that do not constitute the legal building boundary. We also have developed a solution for this problem based on the intersection of gutter point projections onto other building parts like roofs, balconies and terraces.

4 CONCLUSIONS

We have presented some extensions to the standard approach of CyberCity-Modeler, which were dictated by the requirements of users. We have developed solutions for geometry regularization, topology adjustment and vertical wall integration. In all cases we have provided automatic and semi-automatic approaches, with process and result monitoring possibilities for the operator.

As the requirements for high-resolution, precise, reliable and complete city modeling are increasing continuously, these additional functions are becoming more and more important.

The original concept of CCM, to use a semi-automated approach, has proven a valuable and successful concept and has also been the underlying philosophy of these new developments.

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REFERENCES

