A CONCEPT AND ALGORITHM FOR 3D CITY SURFACE MODELING

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ABSTRACT:

To realize a better representation of *complete* three-dimensional (3D) city models in Taiwan, this paper proposes an *alternative* concept and algorithm for 3D geometrical city surface modelling based on wavelets and least squares adjustment. The reasons why wavelets are adopted as an alternative *module* are stated. Firstly in this algorithm, a wavelets-based module for surface modelling makes it convenient to depict different types of city surfaces, where it enables an operator to choose a proper father wavelet in an interactive manner. It also can describe a fractal surface if fractal wavelets are adopted. Secondly, observations are acquired manually or (semi-)automatically. Simultaneously, any observation is recorded with a predefined code that defines a specific topology relationship with others. Then, the well-known least-squares adjustment is utilized to let the adopted wavelet surface function fit all observations, where the surface parameters, namely wavelet coefficients, in a local small stereo model (image window) are directly estimated and observation errors are filtered out. The surface function and observation equations are linear so that both estimation of initial values for unknown parameters and Gauss-Newton iteration are *not* needed. Current personal computer (PC) makes it possible to complete all computations in a short duration of time. It also provides quality figures, namely a covariance matrix, and enables a (near) real-time visual check on a DPW (Digital Photogrammetry Workstation). The afore-mentioned processes are done in each small window. Finally, a 3D city surface in a large area can be reconstructed by collecting the results in all windows, where neighbouring windows have a proper overlap. Some preliminary test results are also shown.

1. INTRODUCTION

1.1 Revolutionary New Generation of 'Maps'

A revolutionary new era for *user-friendly* (*easy-to-use* and *easy-to-know*) *maps* is coming. Instead of conventional analog cartographic maps displayed in 2D format on papers, 3D cyber cities become a popular new type of 'maps' nowadays.

1.2 Demands on 3D City Modelling

Today we see in photogrammetry, remote sensing, and computer vision many applications with varying requirements, e.g. from monument preservation with very high requirements in terms of resolution and accuracy to telecommunications with less stringent ones (Gruen, 2000). The demand for 3D city models increases among cartographers, city planners, architects, civil engineers, environmental analysts and, especially recently, among mobile telecommunication companies etc (Ruzgiene, 2001). Apparently, one of the current tasks of digital photogrammetry is to produce user-friendly digital 3D city models from imagery.

1.3 Brief Overview on Techniques for 3D City Modelling

There are currently three major techniques for city model generation: ①digitization of maps, ② extraction from aerial laser scans, and ③ photogrammetric modeling. Maps are often outdated and don't provide for detailed modeling of the roof landscape. Current aerial laser scans cannot easily provide sufficient edges, by which most objects in city models are best described. Also, their data resolution is still insufficient for detailed models. In photogrammetric modeling, aerial and terrestrial images are a very appropriate data source for generating city models (Gruen, 2001). For practical use, all problems still must be somehow solved.

For example, ETH developed the AMOBE system (Automation of digital terrain Model and man-made Object Extraction from aerial images) which includes a semi-automatic system TOBAGO (Topology Builder for the Automated Generation of Objects from 3-D *point clouds*) (Gruen and Dan, 1997) and an automatic system ARUBA (Automatic Reconstruction of Building from Aerial images) (Henricsson, 1996; Henricsson et al., 1996; Gruen, 1997). The commercial system, "CyberCity Modeler", of the CyberCity AG as a spin-off company of ETH (Gruen and Wang, 1999) fits planar surfaces to measured and weakly structured point clouds, thus generating CAD-compatible objects like buildings, trees, roads, etc. Although it generates a polyhedral world, also objects with non-planar surfaces can be modeled in sufficient resolution. Texture from aerial images and façade texture from terrestrial images can be mapped onto the terrain, the roofs, and the façade, respectively, since geometrical relationship between object faces and image patches has been established (Gruen, 2001).

The "IMAGIS 2.0 CyberCity" of the Supresoft Inc., Wuhan, integrates IMAGIS with CyberCity, a city modeling and visualization module, which provides functions of 3D city modeling, automatic texture extraction, creation of *real* 3D city animation, 3D roaming with stereo glasses, real-time attribute data query in 3D landscape roaming etc.

"InJECT" is a semi-automatic feature extraction system of the INPHO GmbH, Stuttgart, for measurement of 3D building models (3D wire frames) from *oriented* aerial and terrestrial digital images. It bases on the fitting of elementary, volumetric building models or, in case of complex buildings, building component models to image data (Gruen, 2001). The task is to *reconstruct* 3D complex buildings from images and to *model* buildings within *limited* numbers of types with different roof shapes as shown in Figure 1. InJECT provides automated tools for supporting a human operator in solving the building interpretation tasks and acquiring data by the Graphical User

Interface (GUI). A typical use of the GUI is a Constructive Solid Geometry (CSG) tree, where a building is reconstructed e.g. by union or *gluing* operations of building parts. Semi-automatic extraction of buildings is performed through parametric models, namely *CSG primitives*. Each parametric model is specified by a set of parameters: e.g. building point coordinates, length, width, height and roof height. A building is extracted by combining primitives needed for matching and gluing of edges. Finally, completeness of models and extracted feature for derivation of a photo-realistic view are checked by visualization of the results (Ruzgiene, 2001).

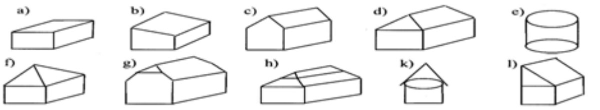


Figure 1. Different types of simple roof shapes: a) flat, b) pent (lean-to), c) saddleback (gable), d) hip, e) cylinder, f) broach (pavilion), g) hipped-gable, h) mansard (gambrel), k) cone, l) half-chock (Ruzgiene, 2001)

Also, (Haala and Hahn, 1996) utilizes the data fusion techniques for detecting and reconstructing buildings. (Fisher et al, 1997) used a generic hierarchical model to integrate 2D and 3D reasoning for building reconstruction. (Wu, 1998) used 2D CAD (Computer Aided Design) information, e.g. shown in Figure 9, to aid the roof reconstruction from digital aerial images. (Chio, 2001) developed a practical strategy for roof patch extraction from urban stereo aerial images. (Tseng and Wang, 2000) applies the least-squares model-image fitting algorithm to the semi-automatic building extraction, where some specific roof models are predefined in the CSG method. (Rau, 2002) presents the geometrical building modeling techniques for practical use, where all *visible, and often incomplete*, edge feature lines of roof surfaces in an aerial stereo model are measured and utilized for constructing a city surface.

1.4 Motivation and the Concept

The reasons why wavelets are here adopted as an alternative module are stated as follows. City surface models in Taiwan possess some special characteristics. For example, complex roof and facade shapes of temples and traditional Chinese buildings as shown in Figures 2 and 3 often contain a high degree of details. Buildings in a very small local area can be very different to each other in terms of building's size, height, shape, pattern, and orientation. Simple parametric models as shown in Figure 1 cannot describe the roof shapes accurately. Very high density of buildings in a city often causes occlusion areas in aerial images. Therefore, automatic and accurate modeling of complete 3D cyber cities in Taiwan is really not so easy.

Moreover, current 3D city modeling techniques still focus mainly only on accurate reconstruction of simple buildings, which are often constructed by simple rectangular/triangular prisms, circular columns, or simple non-planar surfaces. But, as shown in Figure 4, *complete 3D city models for practical use* contain not only simple buildings, but also much more complex buildings, vegetation objects, DTM, utility systems etc (Gruen, 2001). It motivates this wavelets-based algorithm, since wavelets are a good tool for fractal description and multi-resolution representation of a real 3D city scene. For example, Daubechies wavelet functions display a fractal geometry, even though they are continuous for order $N > 1$ (Kaiser, 1994). Fractal Geometry is apparently a "*correct mathematics*" to describe a real world landscape (Jaehne, 1991). For instance, Figure 5 shows a fractal synthesis of mountains with vegetation and clouds (Colonna, 1989).

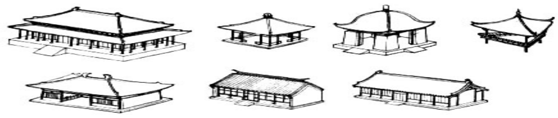


Figure 2. Complex types of roof and facade shapes of traditional Chinese buildings (edited from http://www.geocities.com/black_homework, accessed July 31, 2002)

Figure 3. Complex roof and façade shapes of temples in Taiwan contain a high degree of details; modeling canopies of trees and other vegetation objects makes *virtual* reality of a 3D city model much more "*real*"

Figure 4. *Complete* 3D city models contain not only buildings, but also DTM, vegetation objects, bridges, etc.

Figure 5. Fractal synthesis of mountains with vegetation and clouds (Colonna, 1989)

Besides, my concept also aims for the following main requirements: ① data-fitting model (the surface function is defined by all 3D points, features, and their topology relationships), ② filtering out observation errors, ③ multi-scale analysis for a city surface, if needed.

2. A WAVELETS-BASED MODULE FOR SURFACE MODELLING

2.1 General Description

For simplification, the 3D city surface function adopted here is still a conventional *single-valued real function* as follows:

$$Z(X,Y) = f(\phi; \alpha_{mn}, \forall m,n; X,Y; \Delta X, \Delta Y) \qquad (1)$$

where $Z(X,Y)$ = surface height at the position (X,Y)
it is a function of the following parameters
ϕ = a father wavelet function adopted
X,Y = horizontal coordinates of the point computed
$\alpha_{mn}, \forall m,n$ = unknown wavelet coefficients which are relevant to the Z(X,Y)
ΔX, ΔY=adopted resolution figures in both directions

2.2 A Practical Solution of the Gibbs Problem

If one wants to represent a (near-) discontinuous wall surface function Z(X,Y) by using its low-pass filtered approximation, the so-called Gibbs phenomenon (Michelson, 1898; Gibbs, 1899; Carslaw, 1925) will appear. The Gibbs oscillations appear when the highest frequencies of a discontinuous surface signal are filtered out. Such oscillation effect causes that exact surface representation near break-lines/points is theoretically impossible! Figure 6 shows four examples of the oscillation generated by different low-pass filter. Apparently, the error caused by using ideal low-pass filter is the worst. The Haar wavelets can completely solve the oscillation effect since they are typical step functions. Daubechies wavelets are the moderate ones. For details please see (Tsay, 2000).

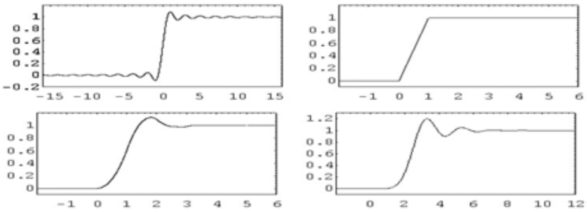


Figure 6. Four examples of the error function generated by different low-pass filter which is the ideal low-pass filter (upper left), Haar scaling function (upper right), Asymmetric Daubechies scaling function of order N=3 (lower left), and N=10 (lower right), respectively (Tsay, 2000)

In practice, a wavelet-based method given by (Tsay, 1999) can be used to solve the Gibbs effect. The method is derived from the fact that all measured data have observation errors and almost all natural or man-made break-lines/points in practice are not exactly theoretical ones. For instance, a wall surface of a building is often not exactly perpendicular to the ground surface. The observation errors and a very small discrepancy of the perpendicular condition could make the Gibbs effect become very insignificant, if the wavelet-based approximation method is utilized.

3. ACQUISITION OF OBSERVATIONS

3D point observations are measured manually or extracted (semi-) automatically each time in a local small stereo model, called an *observation window*. All available topological conditions are e.g. collinearity of edge points, parallelity of straight lines/curves, right angles of intersecting edges, planarity of faces, same height for groups of eaves points, ridge points and other structure points, etc.

4. LSA FOR SURFACE DETERMINATION

Then, the well-known least-squares adjustment (LSA) is used to fit the adopted wavelet surface function in with all 3D points and their geometrical conditions. Each 3D point gives a following linear observation equation, where for further simplification the point position coordinates (X,Y) in equation (1) are supposed to be constants:

$$Z + \boldsymbol{v}_{\mathbf{Z}} = \sum_{\mathbf{m,n}\in\mathbf{S}} \alpha_{mn} \cdot \boldsymbol{c}(\boldsymbol{m},\boldsymbol{n},\boldsymbol{\phi},\mathbf{X},\mathbf{Y}) \qquad (2)$$

where Z = height observation

$\boldsymbol{v}_{\mathbf{Z}}$ = observation error of Z

α_{mn} , $m,n\in S$ = unknown wavelet coefficients

c = a constant dependent on wavelet translates m,n, the father wavelet ϕ, and (X,Y) of the point computed

For detailed formulas please see the so-called *wavelets series*, e.g. (Daubechies, 1994). If necessary, each geometrical topological condition gives a relevant *bridging function*. All are used to solve the normal equations and the possible ill-posed and ill-conditioned problem as well.

5. ALGORITHM

The afore-mentioned operations are performed in each small observation window. If necessary, the surface data can be edited, re-measured, or re-extracted immediately in an interactive manner until the surface determined is acceptable. Neighbour-ing windows have a proper overlap. For details about the proper overlap please refer to (Tsay, 1996). Figure 7 illustrates this algorithm summarily.

For an entire large area:
- For each window:
  1. Acquiring 3D points and their topology data
  2. Select a father wavelet from the module
  3. Surface determination
  4. Visual check on DPW
  5. If needed, editing 3D points / topology data => 2.
  6. Output surface data and quality figures

Combine surface data in all windows to output an entire city surface and the relevant quality figures (covariance matrix)

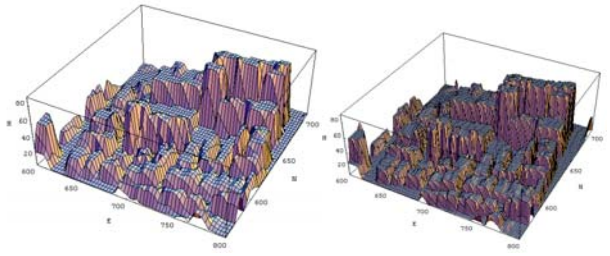
Figure 7. Algorithm for 3D city surface modeling

Figure 8. An aerial image in the test area in Taipei, Taiwan

Figure 9. Topographic map of the scale 1/1000 in test area

6. PRELIMINARY TEST RESULTS

Some tests are done, where 3D point clouds are measured using aerial stereo image pairs on analytical plotters. Figure 8 shows an aerial image in the test area of 200 x 150 $\boldsymbol{m}^2$, where the image scale is about 1/5800 and the pixel size is 12.5μm x 12.5μm. There are altogether 2032 3D points to be measured and their height values vary from 11.58m to 82.19m. The topographic map shown in Figure 9 provides data of 23 height points on ground surface in this area. Their height values vary from 9.34m to 10.74m. Figure 10 shows the results determined using the Haar-wavelets with the resolution figures ΔX = ΔY = 3.2m and 1.6m, respectively. The finer the resolution adopted, the more details the city surface can show, if the relevant 3D points are measured or extracted in a level of details required.



$\Delta X = \Delta Y = 3.2m$ (left), 1.6m (right)
Figure 10. Haar-wavelets derived geometrical city surface

7. CONCLUSIONS

It is just only the beginning of a long and relevant development for a better representation of complete 3D city models in Taiwan. For efficient practical use, all techniques must be further improved and integrated, and they are not yet ready for modeling 3D cyber cities in high resolution (Gruen, 2001).

Preliminary test results show that the algorithm is able to depict a 3D city surface correctly, if accurate observations and suitable bridging functions are adopted. Nevertheless, operational applicability and efficiency needs more further studies and tests. Besides, current computer vision techniques and CAD as well often use TINs (Irregular Triangular Networks) in a 3D space to describe and represent *a truly 3D* object surface that is a typical *multi-valued function*. Such techniques for modeling a truly 3D surface but in an analytical form or better are to be further developed, e.g. by the *spherical wavelets* (Pastor & Rodriguez, 1999; Schroeder & Sweldens, 1995) or *wavelets on triangulated surfaces* (Timoner, 2002) for 3D representation. The techniques for modeling truly 3D geometry and, if a GIS platform is being utilized, topology as well must be further developed.

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