3D OBJECT RECONSTRUCTION FROM AERIAL STEREO IMAGES

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ABSTRACT

Among the variety of problems in providing 3D information about topographic objects, efficient data collection and model construction are issues for research. The efforts are directed towards improving the tedious, time and man-power consuming process of data generation by applying automation. In this paper, we present a semi-automatic method for acquiring 3D topologically structured data from aerial stereo images. The process involves the manual digitising of a minimum number of points necessary for automatically reconstructing the objects of interest. Validation of each reconstructed object is done by superimposition of its wire frame graphics in the stereo model. The 3D topologically structured data are stored in a database and also used for visualisation of the objects.

KEYWORDS: object reconstruction, 3D modelling, data structuring, feature extraction, DTM, virtual reality

1. INTRODUCTION

3D modelling has become a topic of intensive investigations. Increased demand for 3D information in various applications, the availability of powerful hardware and computer graphics have contributed to focusing of attention on the third dimension. A variety of activities, ranging from architectural design to environmental analysis require construction of 3D models.

Although the objects of interest are dependent on the particular application, topographic objects of common interest are buildings and other man-made structures. Therefore most of the current research efforts are directed towards methods for reconstruction of man-made objects. Buildings exhibit an amazing variety of design. The regular shapes (*eg*, rectangular shapes, vertical walls) of some of the buildings often give a misleading impression that reconstruction of the building from its geometric primitives is an easy task. The lack of operational automatic methods for building reconstruction is an indication that the task is not as easy and simple as it seems. The problem is mainly related to appropriate methods of collecting information about "the third dimension" of buildings, *ie*, their heights, roofs, facades, windows, etc. In general two different approaches, *ie*, "top-down" and "extrusion", are utilised to reconstruct buildings. In the first approach, measured elements are upper parts of buildings, *eg*, roof outlines, while in the second, the reconstruction starts from the footprints. Which method is better depends upon a number of considerations such as desired resolution (complex roofs or rectangular boxes), available sources (2D GIS and/or aerial images), hardware and software, purpose of the model. House roofs show a wide variety of shapes, which make their classification challenging but necessary for establishment of a standard procedure. The top-down approach allows more details about the roofs to be collected but requires longer and complex processing of data [Brunn96] [Hendr97]. The extrusion method is applicable in the case of known footprints, *eg*, from cadastral maps, and heights derived from images without roof detail [Lammi97]. Although the resolution of the model is very low the algorithms for reconstruction are simple and allow fast implementation. Some vendors, *eg*, ESRI have already released extensions to available software utilising this approach [Pilou97].

In this paper we present a method based on [Tempf96] for 3D reconstruction of buildings, and surface, line and point objects such as streets, parking lots, power lines, lamp posts, manholes, etc. The procedure for buildings is based on manually digitising the corners of roof facets in a photogrammetric stereo model, thus creating a "skeletal point cloud". The reconstruction consists of automatically computing and assembling all the facets of the building from this point cloud. The model obtained in this way contains planar closed polygons (faces) which are oriented to meet the requirements of rendering engines, *ie*, the normal vector of the faces points towards the outside of the building. The reconstruction rules for other topographic objects are in most cases simpler than those for buildings. Each object of interest is processed individually and after reconstruction superimposed in the stereo model for validation.

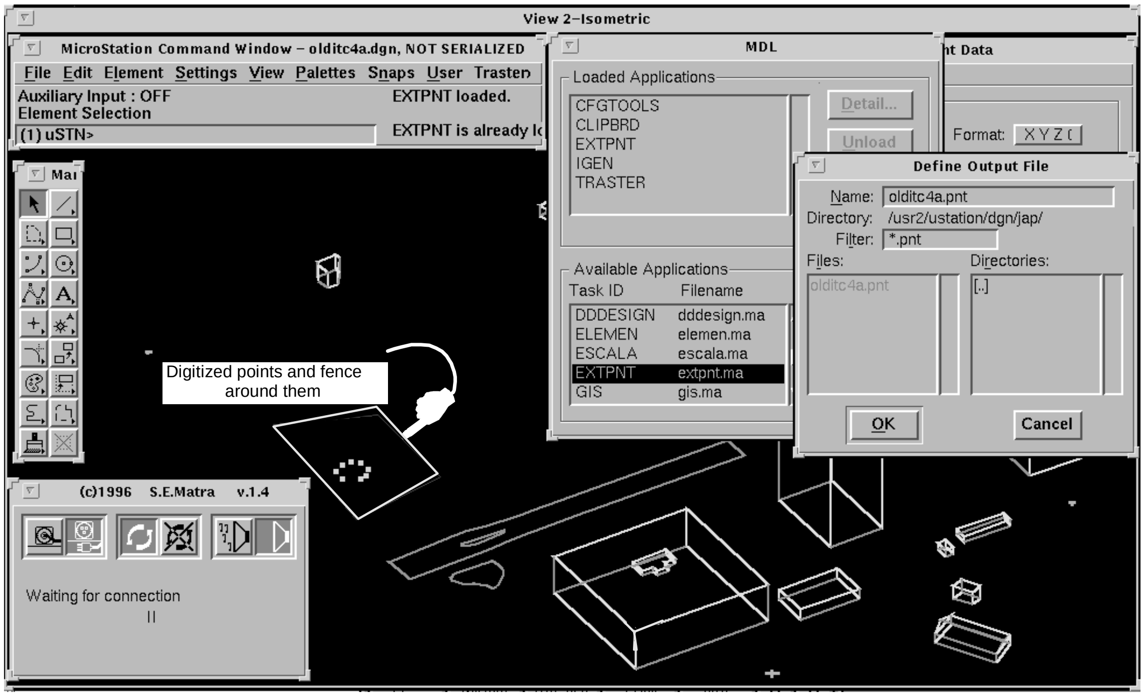


Figure 1: Digitising and co-ordinate extraction

Although advances have been reported in automatic building extraction, human intervention at some stage of the process is still indispensable. Current methods that aim at automating feature extraction require manual work for grouping and cleaning the data set [Hendr97], or for matching and fitting predefined shapes [Brunn96], [GrünA96]. The more complex the topography and the higher the required resolution of its model, the superior is human interpretation of the stereo model. It can be coupled then with simultaneous manual digitising. The operator has a better judgement on the composition of a building. Consequently, a sufficient number of optimally distributed points can be measured, which reduces the time and effort in editing. It also offers the possibility to process a greater variety of features than could not otherwise be done.

We reconstruct a building from a skeletal point cloud as a set of polygons without predefined shapes or volumetric primitives. A surface object such as a street can readily be assembled to a polyhedron, all vertices being digitised. Since our model is stored in a B-rep data structure, 3D topology is maintained and parametric description of features is not supported (unless shape parameters are admitted for arcs and faces).

Considerations that motivated our work on this approach can be summarised as follows:

- lack of fully automated reconstruction in the near future
- complexity of urban topographic objects and flexibility of the process of reconstruction
- 3D topologically structured data facilitating 3D spatial analysis
- proper orientation and triangulation of faces for purpose of visualisation of the model
- feasibility of implementation on commercially available systems
- storing original measurements.

2. DESCRIPTION OF THE METHOD

The procedure is based on the classical photogrammetric approach of acquiring data. The process followed in the experiment is represented in Appendix B. Appendix A gives an indication of the categorisation of objects in support of describing the data collection strategy.

The described process of reconstruction assumes that buildings have only vertical walls, without windows and doors, and non-over-hanging roof facets, *ie*, roof outlines are projected to the DTM to obtain their footprints. If specifications would ask for taking into account differences in projection between roof and building floor additional measurements and/or computations would be required. Lean-to roofs not being part of a solid object are digitised and stored as surfaces.

Testing of the procedure was done using a digital photogrammetric workstation (**Traster T10**), CAD package (**Microstation**), and the in-house developed software **Consob**. Digital aerial images 1:2200 of the central part of Enschede were used for the experimental work.

The main steps involved in the procedure are:

1. Data Acquisition
2. Data Processing
3. Superimposition
4. Database Updating
5. Visualisation

2.1 Data Acquisition

2.1.1 DTM generation

A key element in our building reconstruction approach is the Digital Terrain Model (DTM) of the area. The DTM has to be generated in advance. Various methods such as photogrammetry, surveying, etc. can be applied for this purpose. Even though the equipment we have is capable of producing DTM automatically, we measured terrain elevation values manually. Our experimental work showed that generating DTM automatically is not suitable for densely built-up urban areas. Editing of the automatically generated DTM usually was more time consuming. Secondly, often a lot of features coinciding with the ground surface (*eg*, streets) have to be digitised anyway. They should be digitised prior to measuring spot heights and than both data sets be used for DTM generation. For our model we digitised only those points necessary for describing surface objects. The number of measured points and their distributions were sufficient for creating Triangular Irregular Network (TIN), which was used in re-constructing the buildings.

2.1.2 Buildings

For digitising and superimposition we used Microstation on Traster T10. The process of data collection consists of measuring the points of interest from the stereo model in the Traster and extracting their co-ordinates into files using an extension of Microstation (MDL application) - see Figure 1. Digitising starts with the vertices of the eave line, which is used for projection onto the DTM and constructing footprints and vertical walls. A restriction on the sequence of digitising, *ie*, anti-clockwise, is imposed only for the eave points in order to facilitate orientation of all the other faces in the same anti-clockwise order.

All the other roof points can be digitised in arbitrary order. Extraction of the co-ordinates is done by bordering the points constituting a roof facet with a *fence* (a tool of Microstation) and recording them in a separate file. In this way all the facets of a particular roof are stored in a set of files. Each building is processed individually later, however digitising could be done for several buildings at a time.

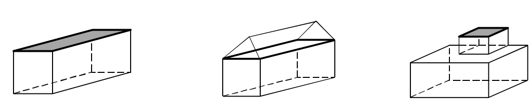
2.1.3 Other topographic objects

The digitising and co-ordinate extraction procedure is the same for the other categories of objects. Points bounding a surface, along a line or presenting point objects, are measured, grouped in the corresponding Microstation view, and extracted. The rule for anti-clock digitising has to be followed for surface features. Since the digitising is feature oriented, no restrictions on the shape of the polygon or number of the vertices are imposed. As a result concave and nested polygons can be obtained quite often (see Figure 3).

2.2 Data processing

Processing of data involves several steps, which finally leads to the construction of a topologically consistent 3D model. The procedure depends on the feature to be processed, *ie*, a building, surface, line or point. The prototype system also permits simple coding of semantic information such as type of the building or specification of the surface object, to be recorded when procedure starts.

The roof complexity is the leading consideration for the manner of building re-construction. The classification of the roof shapes shown in Appendix A allowed us to distinguish three main cases of roof constellations, *ie*, single-faced, multi faced and multi-level roofs.



a) **b)** **c)**

Figure 2: Three major types of roofs

- Single-faced roofs - isolated buildings (Figure 2a)

From the data acquisition process, a file with co-ordinates of the roof outline is obtained. The roof is projected onto the terrain, which in fact is interpolation of z co-ordinates for given x,y co-ordinates of its vertices from the DTM. The interpolation is done by solving the plane equation for a TIN triangle in which a point falls. Computed footprints and roof outlines are used for constituting the wall faces bounding the building. The developed algorithm takes care about 1)assigning an appropriate identifier per new face according to the information available already in the database, 2)anti-clockwise ordering of the nodes and 3)creating the 3D topology based on the chosen data structure (see section 2.4)

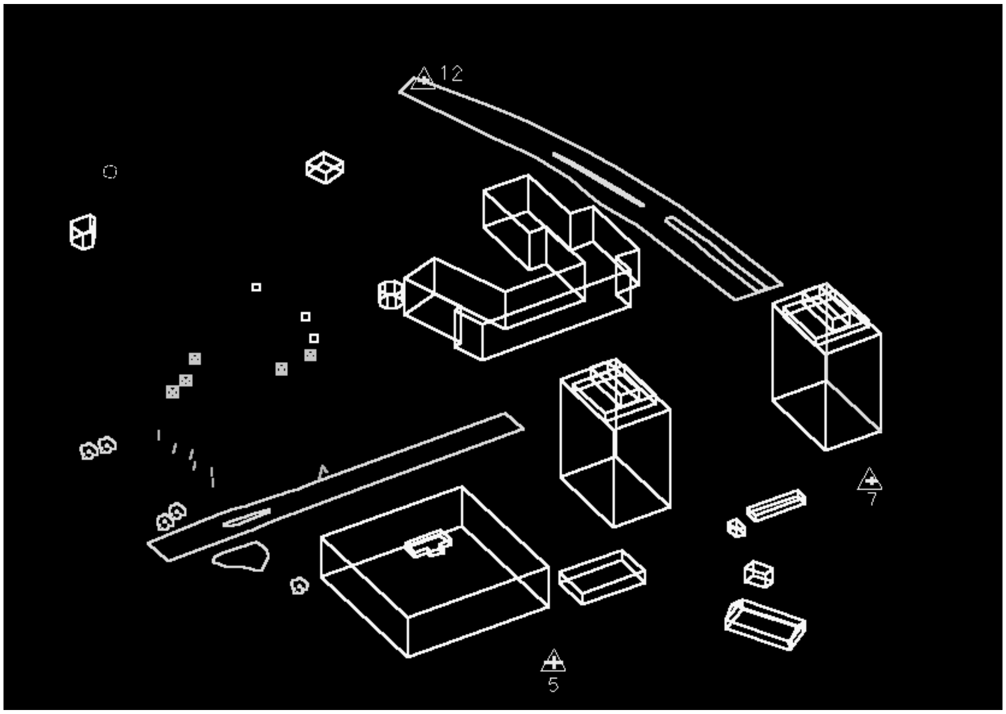


Figure 3: Reconstructed objects

- Multi-faced roofs , *eg*, gable roofs (see Figure 2b)

The approach to construct walls is the same as described above. We have a separate file with co-ordinates of the roof outline, which is processed to the stage composing the walls. In addition, however, the facets of the gable roof have to be created and assembled. We have extracted the co-ordinates of the points in separate files but they are not ordered in the required sequence yet. An algorithm based on the assumptions that 1)a roof edge is always a part of two roof facets and 2)the nodes of the edge appear in opposite order in the faces, completes the correct orientation of the building roof.

- Multi - level roofs (see Figure 2c)

The last case differs from the previous ones with respect to the surface for projection. The walls of the upper body do not reach the ground but another roof. In that case, the bottom roof has to be processed (triangulated) and used for projection of the upper roof. The further processing to obtain walls and the complete set of roof facets follows the steps described above.

The three different manners of construction are included in the prototype program **Consob** [Paint97]. The capabilities of the program are:

- removal of duplicated co-ordinates from the data extracted for each face
- orientation of faces such that the corresponding normal vector points towards the outside of the building
- generation of a building’s footprint
- construction of the roof and vertical walls of the building
- building of topology among the geometric primitives (nodes, arcs, edges, faces) of the building
- generation of an ASCII file in a format that facilitates the visualisation of the building in Microstation
- generation of a file in VRML format for visualisation of the reconstructed objects using Virtual Reality browsers.

The surface, line and point objects in general are not projected onto the DTM as roofs are in the case of buildings. Objects coinciding with the ground surface must be integrated in the TIN describing terrain relief. The program therefore builds the 3D topology and fills in the tables (see Figure 4) with measured faces, line or points as the case may be. An exception are some point objects like lamp posts, which can be projected to the ground if the top point is measured, but also can be extruded from a point on the terrain.

2.3 Superimposition

A file containing the co-ordinates of the constructed object is created for superimposition in the photogrammetric workstation. In practice, the wire frame of the reconstructed building can be viewed in the Microstation window and superimposed in the stereo model for verification. In the stereo model a wire-frame wraps the building and the operator can observe the results of the procedure. The completeness of the reconstruction and the accuracy of the measurements can thus be checked. The operator can trace the source of error and decide how to correct the model. In case of insufficient accuracy of measured points or missing points, the re-construction can be repeated with new measurements. In case of high discrepancy between observed and computed footprints, possibilities either to improve the accuracy of the DTM or to introduce new measurements or to utilise additional sources, can be analysed. The object is recorded in the data base only if the reconstruction is satisfactory otherwise the database is not updated.

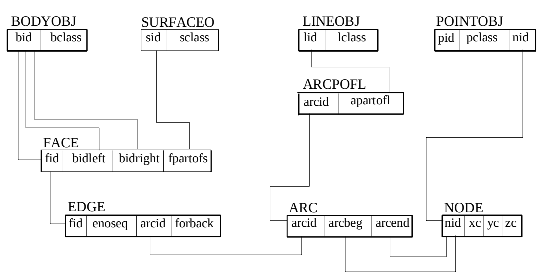


Figure 4: 3D FDS - implemented tables

2.4 Database Updating

The data created during topology building is written to a 3D Formal Data Structure (FDS) database. The data structure is a vector data structure with basic primitives *node*, *arc*, and *face*. Semantic information about *point*, *line*, *surface* and *body* objects can be stored in it. More information about the data structure and experimental results can be found in [Molen92] [Tempf94]. Not all the relationships are built after the procedure as it is implemented until now. However, we create the minimal set of relational tables as a result of the processing described above (see Figure 4).

2.5 Visualisation

Simultaneously a VRML 2.0 file of the model is created for visualisation and additional examination in a Virtual Reality (VR) browser. With our procedure we try to supply only correctly ordered faces presuming that the rendering engine will take care for the final display on the screen.

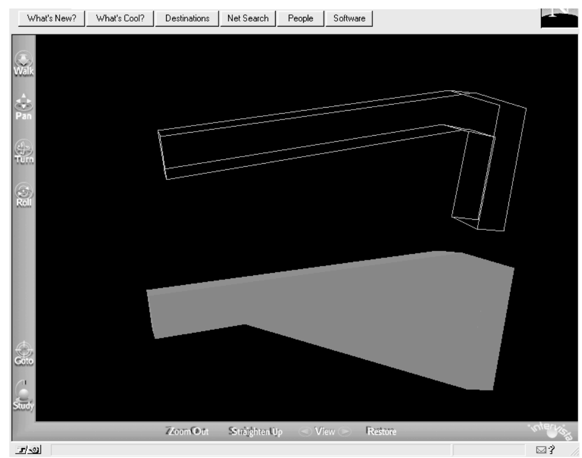


Figure 5: Pitfalls of rendering: wire frame and rendered mode of a building with a concave face

Unfortunately, the visualisation in various VR browsers exhibits new problems related to rendering concave faces and faces with holes. In general, faces with arbitrary number of nodes are allowed to be stored in both the data structure mentioned above and the VRML 2.0 file format. Therefore, using existing software for rendering, we relied on the triangulation provided by the VR browser. However the triangulation of some browsers, *eg*, World View is not precise enough. That is to say, the algorithm for partitioning the face does not ensure that triangles are created only inside the polygon. As a result undesirable effects as in Figure 5 can be observed. There are two alternatives either to wait for new improved releases of VR browsers or to execute algorithms for triangulation before building the scene with VRML. The second approach, however, will cause extra processing time for creating the VRML file, especially in the case of applying texture. The possibility to divide all the faces into triangles and store them in the data structure, has the disadvantage of considerable increase of data for storage and consequently for maintenance. A relatively small model with only 2000 rectangular faces immediately will grow up to 4000 triangles. The advantage of triangulation, however, is the unambiguous definition of surface geometry by planar faces.

3. CONCLUSIONS AND FUTURE WORK

The procedure presented here comprises the whole process from data acquisition, processing, storage and visualisation of 3D data. Human interpretation of aerial stereo images is coupled with manual digitising of surface, line and point features. Buildings with various composites of roof shapes can be reconstructed from skeletal point clouds. Topology building is automated.

Possibility to superimpose the assembled features into the stereo model together with the ability to examine the model in VR browser, offers a way for verification of the re-construction and facilitates the quality control. The method builds up a 3D topologically structured data and records semantic information as well. Another advantage of the procedure is the facility provided for visualisation (rendering and texturing) of the reconstructed objects.

Although encouraging results were obtained, a number of problems require more investigations. One area is extending the procedure and algorithm of reconstruction to cope with occlusions and geometric constrains, and optimising thematic encoding. Another problem area is reducing manual processing by structural analysis of skeletal point clouds.

Important issue is also optimisation of the data structure. The FACE table (see Figure 4) contains information about *left* (bidleft) and *right* (bidright) body. This information is quite useful for spatial analysis related to buildings but rather repetitive concerning ground surface features and DTM. The values in these columns are only 0 (for “air”) and -1 (for underground). A pertinent problem is the traversing of the data structure in order to extract the data needed to build the scene for visualisation. With the present structure, all the tables and records have to be scanned each time in order to collect the co-ordinates for the VRML node *IndexedFaceSet*. Last but not the least is the question of concave polygons and holes.

The future work is related mainly to improving the procedure for co-ordinate extraction and studying alternatives detailing the data structure to permit parametric description of features and curved surfaces and optimisation of the process of a 3D scene construction.

4. ACKNOWLEDGMENTS

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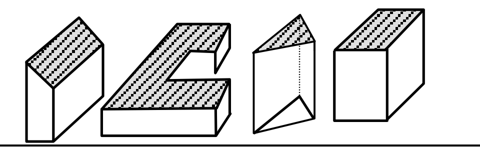
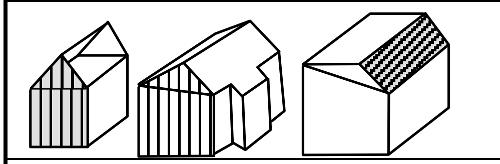
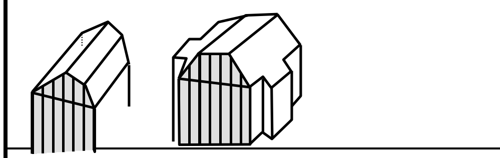
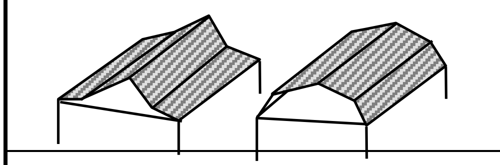
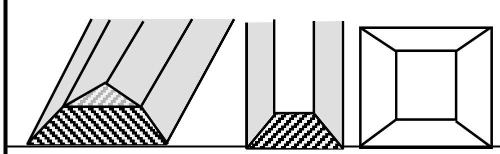
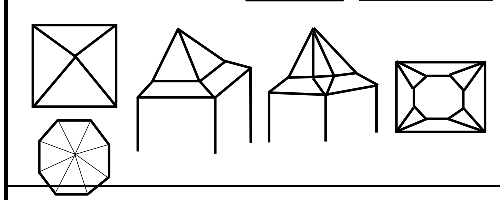
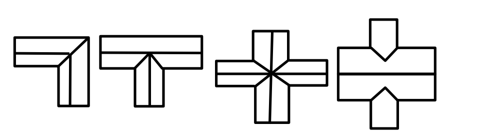
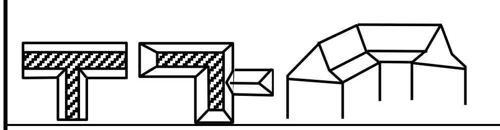
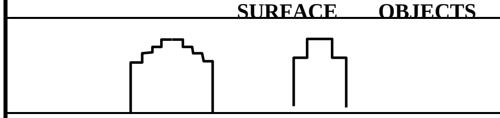
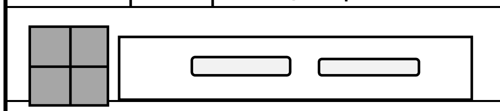
APPENDIX A: CLASSIFICATION OF ROOFS

BODY OBJECTS - CLASSES OF GRAPHICS	
	No longitudinal break (flat roof)
	One longitudinal breakline (two faces roof)
	Two longitudinal breaklines (three faces roof)
	Three longitudinal breaklines
	One, two or n front breaks
	Degenerated longitudinal break line (with and without lateral breaks)
	Roof Composites
	Roof Composites
SURFACE OBJECTS	
	Facades
	Parcels, roads etc.
LINE OBJECTS	
	Light poles, pipe lines, rail lines
POINT OBJECTS	
	Manholes, fire hydrants, etc.

APPENDIX B: THE PROCESS OF 3D TOPOLOGICAL STRUCTURED DATA ACQUISITION AND OBJECT RECONSTRUCTION