3-D MODELLING OF BUILDINGS FROM DIGITAL AERIAL IMAGERY

Jussi Lammi
ESPA Systems Ltd.
Tekniikantie 12, FIN-02150 Espoo
Finland

ISPRS Intercommission Working Group II/III

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ABSTRACT

Three-dimensional modelling of buildings from large-scale digital aerial images is studied. The main focus is on the integration of photogrammetric feature extraction and solid modelling. This combination is considered necessary to make the data collection for realistic three-dimensional models more efficient. The paper concentrates on solid modelling by boundary models. The principles of boundary models are described, and their applicability to building extraction is discussed. The extraction of primitives for the boundary models is done in a semi-automatic way: the user points to the feature of interest from one image using a mouse, and the matching procedure then finds the corresponding feature from other images. This paper presents a search-based method for least-squares matching of a line segment. Here the matching itself is done in object space. The procedure can make direct use of multiple images in matching. The use of search-based methods in the matching of planar faces is discussed.

1. INTRODUCTION

Automatic extraction of buildings from digital imagery has been the subject of many studies in photogrammetry (see e.g. Gülch, 1992; McKeown and McGlone, 1993; Braun, 1994). Methods have been developed to solve low-, mid- and high-level vision processes in building extraction. Initially, the research was focused on low-level processes like point and edge detection. This was followed by the use of high-level processes to identify and label the objects found with low-level operators. Currently scientists are looking increasingly at mid-level processes like grouping and spatial reasoning (see e.g. Förstner, 1995). It is obvious that a functional system combines processes from all levels.

Direct comparison of the different methods for building extraction is seldom very meaningful, because the approach chosen is strongly application dependent. In some applications the detection of buildings is of primary interest, while in others the reconstruction of buildings is also required. For many purposes it is sufficient to fit a building model determined by few parameters into a set of measurements (Haala and Hahn, 1995; Weidner and Förstner, 1995). Some visualizations made using automatically measured models of buildings are already quite highly evolved (Polis et al., 1995). However, the construction of detailed visualizations (Meister and Dan, 1994; Gruber et al., 1995) requires that at least some part of the extraction work is done manually, or semi-automatically under human guidance (see also Streilein, 1994).

This paper examines building extraction from large-scale aerial images. The objective of the study is to find methods to integrate the reconstruction and the solid modelling of a building into a single process. The main focus is on the construction of detailed solid models of buildings. The principles of solid modelling by boundary models are presented and the use of semi-automatic tools for image matching is demonstrated. Finally, the advantages and disadvantages of the approach are discussed.

2. SOLID MODELLING USING BOUNDARY MODELS

Geometric modelling techniques can be divided into three categories: graphical models, surface models and solid models. The main categories are further divided, e.g. according to how the mathematical modelling space is defined, what the representation space is and what kind of representation scheme exists between the modelling space and the representation space. Generally, we cannot use only one modelling technique. In this case, the geometric model of the object is called a hybrid model, or a multiple representation of the object.

Solid modelling techniques emphasize the general applicability of geometric models. Mäntylä (1988) defines the goal of these systems to be the capability to answer arbitrary geometric questions automatically, i.e. without human intervention. Solid models are typically divided into three classes: decomposition models, constructive models and boundary models. In decomposition models, the solid is described in terms of volume elements. The most common decomposition models are spatial enumeration and octrees. Primitive instancing, which is a simple parametric model, is also a kind of decomposition model of an object. In constructive models, the solid is thought of as a bounded set of points in three-dimensional space. The most important group of constructive models are the constructive solid geometry (CSG) models. Here the solid model is built from a composed set of parametrized primitives. Boundary models are a generalization of graphical models into solid models. They are constructed from vertices, edges and faces that imitate the common way of thinking of solid objects.

This chapter gives an overview of solid modelling using boundary models. The boundary model is chosen because its basic primitives are the same as the features of building extraction. It appears that powerful tools can be built to update the complex data structure behind the boundary model. A more profound presentation of solid modelling techniques and especially boundary models can be found in Mäntylä (1988). The papers by Li (1993) and Rikkers et al. (1994) are also interesting in this context.

2.1 Basics of Boundary Models

Boundary models describe 3-D objects using a hierarchy of vertices, edges and faces. The object's surface is a collection of faces that intersect each other only at the common edge. Each face is made of edges and vertices that bound the surface patch itself. The representation of the solid object is formed when the set of faces is closed.

The edge of the face does not have to be a straight line, nor does the face of the object have to be a planar surface. Instead of lines and planes it is possible to use parametric curves and surfaces to describe the shapes of the elements. The positions and shapes of these geometric elements are usually referred to as the geometry of the boundary model. On the other hand, the connections and relationships between the elements are referred to as the topology of the boundary model.

Many different data structures have been proposed for representing boundary models. These include polygon-based, vertex-based, edge-based and face-based boundary models. An example of a polygon-based model is the polyhedral model, which contains only a set of planar face elements but no topological information about them. On the other hand, the vertex-, edge- and face-based models inherently enable the representation of topological information. They differ from each other on the basis of how the topological information is maintained inside the data structure. The most common data structures are called the winged-edge data structure and the half-edge data structure.

A valid boundary model defines solid objects that fulfil the following validity criteria (Mäntylä, 1988):

1. The set of faces is closed.
2. Faces intersect each other only at common edges and vertices.
3. Edges of the faces do not intersect themselves.

The first two criteria exclude self-intersecting objects, and the third criterion rules out objects that are open. The first criterion ensures the topological integrity of a boundary model. This condition is fulfilled when each edge belongs to exactly two faces. In other words, the surface forms a 2-manifold, i.e. a surface where every point has a two-dimensional neighbourhood with all other points of the surface (Mäntylä, 1988). The second and third validity conditions ensure the geometric integrity of a boundary model. Note that the geometric integrity cannot be enforced directly with the help of the chosen data structure. Instead it has to be guaranteed through comparisons between each element of the model, or alternatively by limiting the scope for creating or editing a boundary model.

2.2 Construction of a Boundary Model

Boundary models are often formed by a sequence of local incremental operations that guarantee the topological integrity of the model within each modification step. Here the model is updated with the help of special tools called Euler-operators. These construction tools are based on the Euler-Poincaré formula (Mäntylä, 1988). This formula states that the numbers of vertices (v), edges (e), faces (f), shells (s), rings (r) and holes(h) in a valid boundary model are balanced through the following equation

$$v-e+f=2(s-h)+r \ . \tag{1}$$

In the model construction phase the use of Euler-operators guarantees that the above formula is valid in every step. A boundary model that is constructed with Euler-operators is always topologically valid.

Euler-operators work in much the same way as humans draw graphical objects. A common set of Euler-operators contains 10 different tools for building a boundary model. These 10 operators are called mvfs, mev, mef, mekr, mfkrh, kev, kef, kvfs, kemr and kfmrh. Here the letter "m" means "Make" and the letter "k" means "Kill". The other letters are as in the Euler-Poincaré formula. For instance the operator "mev" is read as "Make Edge and Vertex".

Euler-operators as such are too primitive for users of graphical systems. Normally, Euler-operators are hidden inside high-level tools containing several operators organized into a meaningful sequence. These high-level tools include operations like formation of a face from a sequence of vertices or sweeping of a set of face elements through space to form a solid.

2.3 Example of Euler-operators

Figure 1 illustrates the incremental creation of a boundary model of a simple building. The upper set describes the sequence of construction steps used to create the geometric model. The lower set in the figure shows the Euler-operators that correspond to the editing steps shown in the upper set. The lower set also shows two-dimensional plane models that describe the topological properties of three-dimensional objects (Mäntylä, 1988). Note that in practice many operators can be grouped together, and some of the operations are done automatically after an editing step. It is obvious that the boundary model in the figure can also be constructed using a different combination of Euler-operators. It is also easy to imagine a situation where the topological properties of the object are valid but the resulting model no longer describes a solid object.

3. IMPLEMENTATION OF TOOLS FOR BUILDING EXTRACTION

The semi-automatic feature extraction is a tractable approach to building extraction, especially when the goal is to create detailed geometric models of buildings. Semi-automatic tools are used to make the extraction work more fluent and more efficient. An important part in the implementation of these tools is image matching. With efficient matching tools the work-load of the user can be reduced significantly. The basic geometric primitives in this extraction work are points, lines and planes. In the following, we concentrate on the image matching of lines. A method for the constrained multiphoto matching of a line is described in detail. The matching method is a variant of the well-known least squares matching (Förstner, 1982). In the present paper, least squares matching is done by search techniques, instead of least squares adjustment. The search is done in object space in a way similar to works by Wrobel (1987), Helava (1988), Gruen and Baltsavias (1988). The theoretical principles of least squares matching by search are described in Sarjakoski and Lammi (1996).

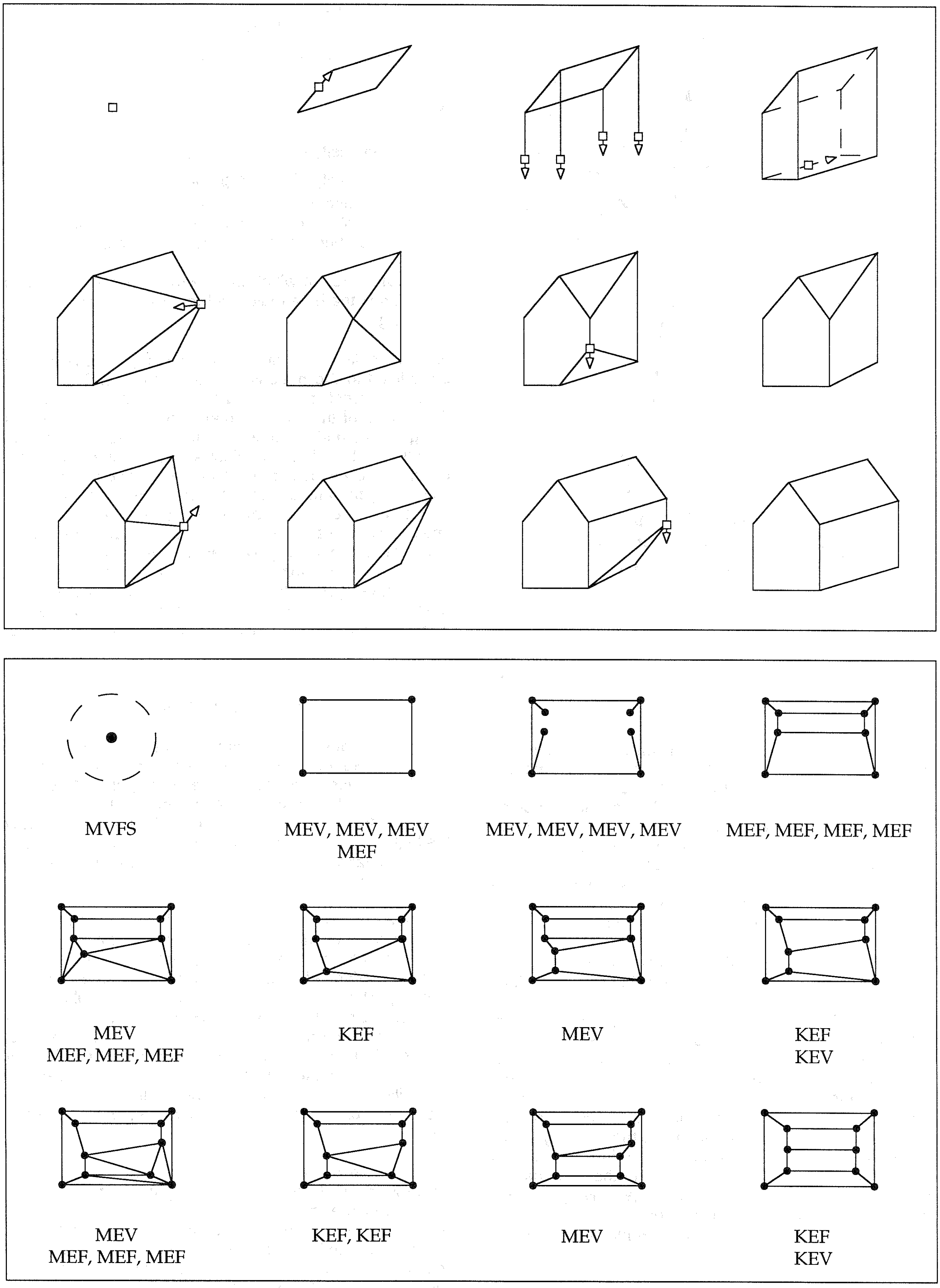

Figure 1. Construction of a boundary representation model. Upper set: sequence of editing steps used to create a geometric model. Lower set: Euler-operators that correspond to the editing steps shown in the upper set; plane model graphs illustrate the topology of the model.

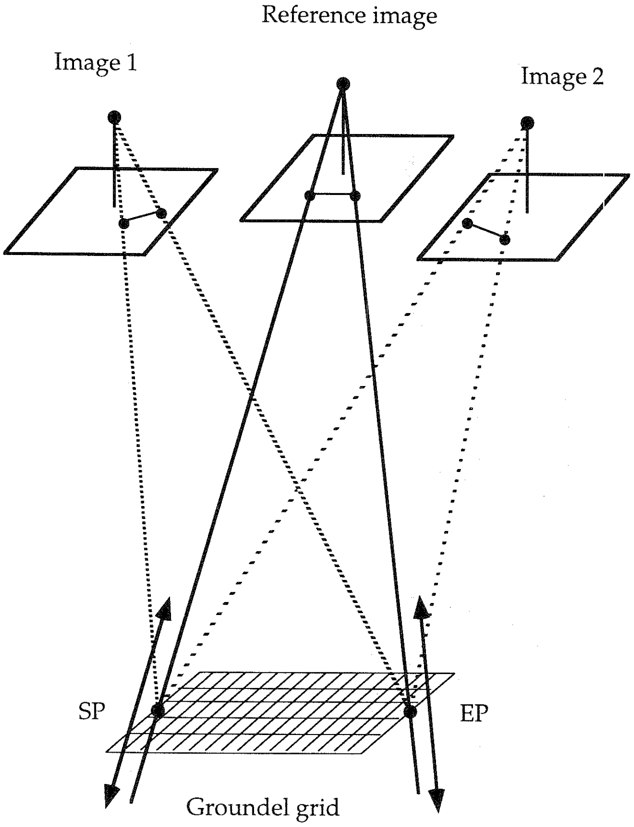

Figure 2. Geometrically constrained line matching by search.

The initial position of the line is determined by extracting the line segment from the reference image. With the help of known orientation parameters and an approximate Z-coordinate value the 3-D coordinates for the end-points are computed. As the position of the line is fixed on the reference image, the position of the line in object space has only two degrees of freedom. End-points are constrained to move along the collinear rays joining the projection centre of the reference image with the corresponding image point in the reference image.

Next the end-points of the 3-D line are incrementally changed at chosen intervals and within the given limit. After each step, a groundel grid is formed into the object space, see Figure 2. This rectangular grid is formed so that the current 3-D line belongs to it. Elements in the groundel grid are given intensity values, which are computed from images by a geometric transformation. The geometric transformation contains a spatial transformation similar to orthoprojection and a common gray-level interpolation. At this point, the intensity values in the groundel grid can be normalized into the required mean and variance. The first version of the groundel grid is computed from the reference image. This grid serves as a reference grid with which other grids are compared. The groundel grids from other images are computed similarly.

In each step, the difference between the reference grid and the search grids is computed. The difference is expressed by a mean-square error (σ_0^2) computed from the formula

$$\sigma_0^2 = \frac{\sum_{k=1}^{l}\sum_{i=0}^{m-1}\sum_{j=0}^{n-1}\left(g_k(i,j)-g_o(i,j)\right)^2}{lmn-1} \qquad (2)$$

where

$g_o(i,j)$	intensity of reference groundel grid
$g_k(i,j)$	intensity of search groundel grid
l	number of search images
m	number of column elements in the groundel grids
n	number of line elements in the groundel grids.

The search step in which the mean-square error is at its minimum is the best match in the terms of least squares matching.

Geometrically constrained line matching by search can be utilized in the matching of planar faces. The planar face of interest is extracted from the reference image. Two edges of the face are matched to the other images using the method described. From these two matches the equation of the plane in object space is computed. After this the final vertices of the planar face are determined by computing the intersections between the plane in object space and the set of rays coming from the reference image. Plane matching can also be implemented using least squares matching by search. In this case, it will still be reasonable to limit the search space by first matching one of the edges of the planar face by line matching. For example, a roof face would have only one degree of freedom if the correct position of the top of the roof is first searched.

4. DISCUSSION

Boundary models are generally applied in CAD/CAM software. Modelling tools in these packages are not usable as such in photogrammetric mapping. However, the kernel software defining and handling the geometric data structure can be the same in both applications. Only the high-level tools handling the geometric model have to be specialized e.g. by writing an application-dependent layer of tools above the kernel.

The use of boundary models in building extraction does not require that the geometric model of the building is always created from nothing. In practice, it is reasonable to have predefined models for the most common types of building. The use of predefined models is similar to the use of parametric models. However, there is one significant difference between these two approaches: parametric models can be modified only through their parameters, while boundary models offer general editability. Parametrization of a new building class at the moment of extraction could be extremely useful in many cases.

The accomplishment of many geometric tasks can be embedded inside the tools editing the data structure. These include generation of eaves by moving wall elements inwards, automatic completion of a model after a minimum number of features have been extracted and the preservation of the geometric integrity of the solid model. Some of these tasks cannot be implemented in a general way relevant to all different object types. However, the use of a common basis upon which this functionality can be built is beneficial.

Behind the proposed method for planar face matching is the idea that it is sufficient to find the minimum number of good matches to reconstruct the target. This does not mean that only one sufficient set of matches is necessarily favoured. With the help of simple heuristics we can choose several sets to define the plane equation. Ultimately the algorithm might propose just one solution to the user, or it might suggest a set of solutions from which the user accepts the most correct one.

5. CONCLUSIONS

This paper studies the integration of solid modelling techniques into photogrammetric mapping. The focus was on the geometric modelling of buildings by boundary models. The principles of boundary models have been presented and the interactive creation of the model has been discussed. The functionality of primitive modelling tools has been illustrated. In the case of man-made objects, close integration of modelling and mapping is seen as a necessity in detailed mapping. The integration eliminates the need for a separate step in which the solid model of an object is parsed from a set of independent geometric primitives. Solid modelling methods offer a general data structure into which the data can be collected. They form a good basis for mapping tools that utilize geometric constraints and geometric reasoning.

A geometrically constrained image matching procedure for matching lines in object space was described. The method fulfils the common least squares matching criterion, but was here formulated as a search task. The proposed line matching procedure by search is capable of making direct use of information from all images containing the line. It was also shown how line matching can be used in the geometrically constrained matching of planar faces. Later the matching of planar faces will also be implemented using least squares matching by search.

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