3D BUILDING RECONSTRUCTION USING COMPOSITES OF SURFACE PRIMITIVES: CONCEPT

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ABSTRACT

A *modus operandi* for semi-automatic building reconstruction from photogrammetric imagery is presented. The key component is a generic object modeling scheme based on composites of primitive surfaces. This scheme is well-suited to implementation in an operational context. A strategy for an implementation is developed.

KURZFASSUNG

Ein *modus operandi* für eine halbautomatische Gebäuderekonstruktion mit Hilfe photogrammetrische Bildaufnahme wird vorgestellt. Die Schlüsselkomponente ist ein generisches Objektmodellierungsschema, welches auf der Zusammenstellung primtiver Flächen basiert. Diese Schema ist für eine Anwendung in einem operationellen Zusammenhang gut geeignet. Ein Konzept für die Implementierung wurde bereits entwickelt.

1 INTRODUCTION

One of the important tasks in extracting information from aerial photographs is the precise, 3D reconstruction of buildings. Applications requiring this data abound, from town planning, architectural design and in-situ evaluation, real estate, virtual tourism, dispatching systems for police and fire departments, mobile phone communications, to environmental simulations. Photogrammetric techniques for building reconstruction are well-established but largely based on manual measurements. While offering high accuracy and reliability, they require expensive instruments, highly-trained operators and are very time-consuming. Since the early 1980's, research has aimed at automating image measurement and understanding. Despite considerable efforts, robust methods have failed to eventuate and formidable conceptual and technical problems remain. The key to improvements in operational performance lie, therefore, in the development of semi-automation concepts.

A fundamental issue in the design of semi-automatic procedures is facilitating optimal utilization of the human's skills and knowledge in an intuitive and economical manner. In building reconstruction the user's primary task is to communicate the presence and form (appearance) of the buildings in a given scene. This can be achieved by selecting the model(s) best describing the building *and* choosing a representation for that model both amenable to automated feature extraction procedures and natural to the user. We maintain that in attempting to reconstruct a scene, especially for complex and irregular structures, a user most naturally perceives a building as a composite of surfaces. Since a photogrammetric image is a projection of the 3D world into 2D, the visible surfaces are the most direct source of information for reconstruction available to the computer.

This paper presents, at a methodological level, a *modus operandi* for semi-automatic 3D building reconstruction from photogrammetric imagery. An object modeling scheme is developed which facilites a simple and intuitive user-interface, enabling low-skilled users to communicate interpretations of the shape of arbitrarily complex buildings. This scheme is generic, modeling buildings as composites of primitive surfaces (CPS). In Sec. 2 basic issues in building reconstruction from imagery are discussed. Sec. 3 reviews object models for reconstruction and details introduces CPS modeling. Sec. 4 describes an operational building reconstruction strategy based on CPS modeling. Finally, Sec. 5 outlines future work, in particular, prospects for increased automation.

This research was commenced by the author under the *AMOBE* project at ETH-Zürich and has been continued within *UrbanModeler*, a project being conducted at UCT to develop operational rapid mapping technologies for both formal and informal settlements relevant to the African context. Informal settlement mapping is of great relevance to developing countries with drastic and rapidly changing urban environments.

2 ISSUES IN BUILDING RECONSTRUCTION

2.1 Object Reconstruction Task

The terms object reconstruction, object recognition, and object extraction are often used in the image understanding context to denote the same or similar activities. We define *reconstruction* as the acquisition of a description of a specific object. This is achieved by *recognition*, the task of finding (object detection) and labelling parts of images(s) of a scene that correspond to objects in the scene (Suetens et al, 1992). Localization of the labelled parts is implied. In order to carry out the recognition task, general descriptions, or models, of each object to be recognized must be provided. Information *extracted* from the image(s) by segmentation is matched to these object models to enable labelling of the symbolic structures in the image(s). This information, which may include object shape, pose, material, texture, colour and other attributes, constitutes a reconstruction of the object in the scene. The object reconstruction process is illustrated in Fig. 1.

2.2 Data Sources

Currently, scanned, photogrammetric quality aerial photography is the most practical *source of imagery* for accurate and detailed building reconstruction. Image scale, film type

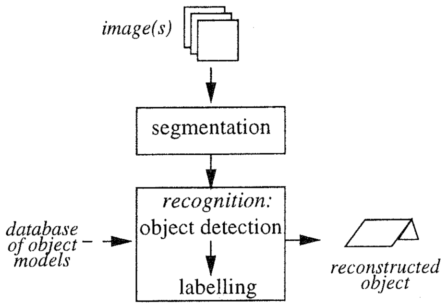

Figure 1: Object reconstruction in image understanding.

and imaging geometry can be selected to optimize the photography for a given application. Image scales in the order of 1: 4000 to 1: 10 000 are commonly used. Nadir photography with forward overlap of 60% is practical for most urban mapping applications. Multi-photo geometries are advantageous in providing redundant information and improving the accuracy of reconstruction. Colour photography is preferred over panchromatic photography not only because of the additional segmentation cue, but also because image interpretation is improved. Similarly, stereo imagery is preferred over monocular. False-colour infrared photography is useful in automating the separation of man-made object, vegetation and water bodies by image segmentation. As a rule of thumb, photography should be scanned to achieve a minimum spatial resolution of ca. 25cm. This is generally a good compromise between managable image size and detail for many applications.

The *measurable features* in near-nadir photography are primarily building roofs and the structures on them. Walls, while potentially visible when a building appears at other than the nadir point in a photograph, are commonly obscured by eaves or by the camera viewpoint, subject to shadows and imaged with poor geometry such that they cannot be reliably measured. If the building model should include accurate wall detail, terrestrial measurements, e.g. photogrammetric, become necessary. Alternatively, building walls may be inferred by projection of the reconstructed roof perimeter onto an underlying terrain model. Eaves may also be modeled in the reconstruction if their dimension is known (Mason and Streilein, 1996).

Other data sources for building reconstruction include digitized maps and plans (Nebiker and Carosio, 1995). Technological developments promise improved data sources in the near future, such as direct digital aerial imagery (Hofman et al, 1993) which avoid the need for scanning, and laser-scanners (Krabill, 1989) which provide direct 3D coordinates at higher accuracy (but currently lower spatial resolution) than stereo techniques

2.3 Fidelity of Reconstructed Models

Quantifying model fidelity is a prerequisite to judging the utility of reconstructed buildings for an intended application. It consists of two parts: the geometric accuracy of the reconstruction and model completeness. *Model completeness* must be judged against the level of generalisation required by the application. In order to quantify *geometric accuracy*, the accuracy of all components in the reconstruction process need to be accounted for and propagated as uncertainties in the reconstruction. This requires knowledge of camera calibration, the effects of photograph scanning, etc. Importantly, accurate camera models, exterior orientation information etc., can be exploited in feature extraction, e.g. in using the epipolar constraint and providing a statistical basis for generating hypothesis in matching and for fusing different information sources (see Förstner, 1993; McKeown and McGlone, 1994).

2.4 Semi-automation as Goal

Building reconstruction is difficult. Buildings themselves are complex, often irregular, structures, varying in appearance according to function, cultural, climatic and topological context, building codes, architectural and aesthetic tastes, construction materials, colour, state of repair, etc. Their extraction from imagery is difficult due to shadows, weak constrast, noisy imagery, interferences such as trees, loss of information due to perspective projection, occlusions and so on. Nevertheless, humans are generally very effective in coping by being able to "understand" the imagery using a vast skill/knowledge-base. The key to automating image understanding is, therefore, to give a computer the background of common-sense knowledge and skills that humans possess. Practical results in coding and using common-sense knowledge in AI have, however, not been achieved nor are forseeable (Dreyfus, 1994). This problem is fundamental; we do not yet understand how the human performs such task und thusfar have developed ad hoc methods (Förstner, 1993). Image understanding systems therefore require integration of the superior interpretative skills of the human operator to achieve operational performance. It is this fact which motivates the work described here.

In an operational context, semi-automated approaches to object reconstruction are justifiable when they are able to deliver results in less time and/or more reliably than a user with conventional (manual) tools with at least comparable accuracy. It is also desirable that the expertise requirements of the user be reduced. To this end, we expect that most gains can be made by relieving the user of the measurement task. Accurate image measurement using conventional technology demands expertise, is time-consuming, tiring and consequently, not without errors. Interpretation, whilst still requiring experience, comes more naturally to the untrained person.

3 OBJECT MODELING FOR BUILDING RECONSTRUCTION

The most important user input in a semi-automated object reconstruction system is selection of an object model. Object models may contain geometrical, physical, functional and other elements and must be view-invariant in order to be invariant to the observation process used to infer the presence, form, class, etc. of object instances. We focus here on the modeling of building geometry as the most common objective, although other properties such as radiometry (including colour), texture, etc. are often important (cf. Förstner, 1993). The representational criteria include: (i) 3D modeling capability, (ii) generic, i.e. capable of modeling most, if not all, buildings including those complex and irregular, and (iii) compatibility with a user's intuitive representation of buildings observed in imagery. Following a short review of object representations used in building reconstruction, a new modeling scheme was developed which fulfills these criteria.

A comprehensive overview of object shape modeling is given in Braun et al (1995). *Parametrized volumetric primitives* (i.e. fixed topology and variable geometry) have been used for reconstructing classes of simple buildings (Haala and Hahn, 1995; Lang and Schicker, 1993). While this representation provides for volumetric modeling, it is not suitable for irregular or complex buildings. Moreover, constructing a complete database of such models is unfeasible because the range of building shapes is practically infinite.

Lin et al (1994) assume buildings to consist of *union of rectangular blocks*. Herman and Kanade (1993) employ *prismatic models* representing buildings by their height and a set of closed polygons describing the ground plane. Buildings may also be modeled (indirectly) as *blob features* in digital surface models (DSMs) (Baltsavias et al, 1995). This coarse representation can be employed as an approximation to reconstructing buildings in the form of prismatic or parametric models (Weidner and Förstner, 1995). All these three representations generalise building shape to the extent that they are inappropriate for precise building modeling, e.g. capturing roof detail.

CAD systems employ representations such as the boundary representation (BRep) and constructive solid geometry (CSG) which are well-suited to and aimed at the construction of models of complex spatial objects. CAD models have been used to reconstruct specific, a priori known buildings, e.g. "control houses" (Schickler, 1992) but due to their fixed topology and geometry are inappropriate for unknown and complex buildings. *Generic building models*, on the other hand, are characterized by both variable topology and geometry. Fua and Hanson (1991) reconstruct flat-roofed buildings from aerial images using a generic model consisting of simple shapes (rectlinear enclosures of edges) and photometric (planar intensity within each building enclosure) components.

Mohan and Nevatia (1989) and this author in Baltsavias et al (1995) hypothesized that generality in man-made object reconstruction may be achieved by having a not too large set of common, regular geometrical shapes; any man-made shape in the scene can be modeled by one of the shapes in the set or a combination thereof. This suitability of this approach, which we term *composites of primitive surfaces* (CPS) modeling, for implementation in an operational building reconstruction system is established below. Note that a similar concept has been adopted by Braun et al (1995) in suggesting the reconstruction of buildings as combinations of CSG primitives using aspect representations.

3.1 Composites of Primitive Surfaces Modeling Scheme

CPS modeling is characterized by:

- A building is modeled by the reconstruction of its component surfaces visible in the imagery. These surfaces, when connected, produce a (partial) 3D description of the building.
- CPS modeling enables a high degree of genericity: a very large number of buildings can be modeled by combinations of a small set of geometrically-simple surface primitives. Limiting assumption, such as flat roofs, 90° angles, or simple rectangular shapes, typical of other approaches, are avoided in CPS modeling.
- The modeling set is extensible to surface composites which characterise typical geometries of building components.

Class 1a in Figure 2 illustrates (some of) the core elements of this set of surface primitives, i.e. primitive planar shapes. The dimensions and 3D orientation of each primitive are variable. For application in reconstruction, each primitive is represented in the computer as a set of criteria that extracted 3D surfaces fitting this model must fulfill. For example, the primitive *square* is interpreted in the extraction procedure (see Sec. 4.3) as a 4-sided polygon (4 lines, 4 corners) with 2 sets of parallel lines, all sides of equal length, 90 degree intersections. Parallelity, intersection angles, line lengths and planarity can be used as constraints in an adjustment of 3D lines hypothesized as a surface fitting the model (Sayed and Mikhail, 1990). Image measurement inaccuracies must be accommodated in formalizing these constraints. The planarity constraint must be relaxed for curved surfaces, e.g. domes.

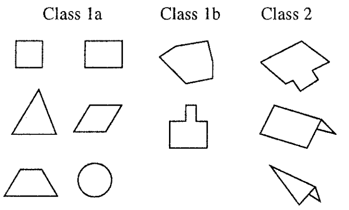

Figure 2: Non-exhaustive classification of primitive surfaces and composites for object modeling.

Class 1b contains closed planar surfaces with n-sides. Note that the first primitive in this class permits non-orthogonal intersections between the sides and is the generic representation of all other primitives in classes 1a and 1b. A differentiation is made, however, in order to take advantage of the added constraints and checks the user is able to convey to the system through the selection of more specific primitives, e.g. the *square* primitive conveys provides the system with a greater number of constraints than an *n-sided polyface*. The number of primitives remains small and manageable.

This database of surface primitives is extended to include commonly-occuring composities of the core (Class 1) primitive surfaces. Each composite in Class 2 in Fig. 2 is subject to additional constraints and represents a subclass of 3D shapes. Further extensions are conceivable, with more complex composites being formed to model increasingly more specific cases. The parametric models of complete buildings employed by Haala and Hahn (1995), Lang and Schickler (1993), etc. can be seen as special cases of CPS modeling.

An example of the representational power of CPS is seen in Fig. 3. The building can either be reconstructed using two Class 1 primitives or two Class 2 composites.

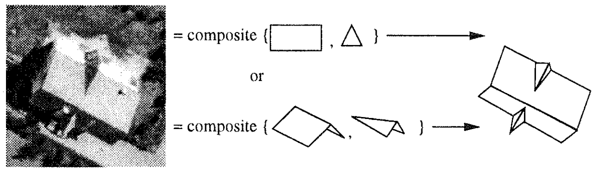

Figure 3: Representing objects as composites of primitive surfaces.

A number of features of CPS modeling may be seen as limitations: (a) surface models cannot, in general, be uniquely converted to solid representations, as may be required by some applications; (b) large number of surfaces may be need to be reconstruct complex buildings; and (c) surfaces which are not visible in - or reconstructable from - the imagery, e.g. occluded walls, need to be inferred to obtain a complete volumetric model. Note that these problems are partially resolved when modeling by combinations of CSG primitives (Braun et al, 1995). We believe, however, that the CPS modeling scheme is more general. Because buildings are modeled at a lower level, some potentially ambiguous situations can be avoided, as might occue when only one surface of a building component is visible. Moreover, eaves and similar structures are more easily modelled by surfaces. Of equal importance, we expect that surface primitives are more intuitive to the user and that their correct reconstruction is easier to validate than CSG primitives. In the following section an implementational scenario for CPS modeling in a semi-automatic building reconstruction system is described.

4 TOWARDS AN OPERATIONAL RECONSTRUCTION STRATEGY

4.1 Modes of Interaction

Two basic paradigms of user-system interfacing for semi-automatic object reconstruction can be identified: (1) *corrective*, in which fully automatic reconstruction is attempted (see Fig. 1) with any errors being corrected a posterior using manual methods; and (2) *instructive*, in which the computer is conveyed what to extract by user instruction of the appropriate object model and possibly identification of the object's image location. As with (1), errors by automatic methods must be corrected manually.

In the absence of models for reliable general scene understanding (see Sec. 2.4) the corrective paradigm, however desirable from an AI point of view, remains unoperational. Firstly, correcting large numbers of errors is generally more time consuming and difficult than manual methods. The user must intrepret the scene *and* also understand the interpretation reconstructed by the computer. Then, detected errors must be manually corrected. Secondly, the danger is greater that some errors will be missed than errors in the case of instructive reconstruction. Thirdly, the computational expense of the necessarily complex procedures for automatic reconstruction may well render them slower than manual or instructive methods.

Instructive reconstruction can take different forms (cf. (Lang and Schickler, 1993; Haala and Hahn, 1995). Our philosophy is to *interact minimally but early, assisting automated processes by supplying sufficient information to ensure a reliable result and in so doing limiting corrective action.* The degree of assistance will depend on the robustness of the automated processes and the extent to which their failure can be self-diagnosed and reported back to the user. The CPS modeling scheme is thus well-suited to implementation in an operational environment.

4.2 Interaction Model for Reconstruction based on CPS Modeling

An interaction model for building reconstruction based on modeling object using the CPS schema is depicted in Fig. 4. The basic interactive steps are described. Potential for automation of some of these steps is described in Sec. 5. The first interactive task entails identifying a buildings to be reconstructed. This is followed by a mental process of building decomposition, wherein the user decides on the appropriate combination of surface primitives from the database in Fig. 3 for modeling the building. Each of these primitives is conveyed to the computer with the approximate location of the surface to guide the extraction step (detailed below). The result(s) are presented to the user for verification, possibly in stereo-viewing mode. Once all component surfaces have been successfully reconstructed, a composition process connects these surfaces, exploiting neighbourhood relations and possibly user interaction, to construct the building model. Due to occlusions etc. this model may not be a complete 3D reconstruction. A final step is need to infer, e.g. walls and missing surfaces, to form a complete volumetric model. A strategy for the automated surface reconstruction step is explained in Sec. 4.3.

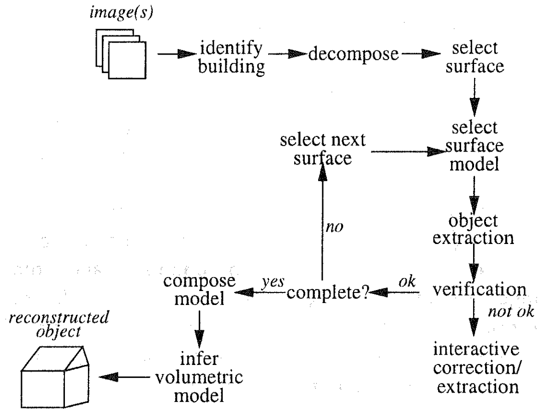

Figure 4: Reconstruction strategy based on CPS modeling.

Building model selection entails two basic interactions: (1) indicating the approximate location of the surface; and (2) selection of the relevant geometric model. Options for task (1) include pointing to the surface in an image in 2D or 3D, or marking a box encompassing the surface in an image. These are simple "mouse-clicks" and do not require fine-pointing. Geometric model selection (2) is made from the surface primitive database illustrated in Fig. 2, and should reflect what the user understands is extractable from the imagery. Difficult scenes will require Class 1 primitives; composite models can be used on simplier scenes. This database is small and thus well-suited to display as graphical icons for intuitive understanding and selection. The database could also be customized to suit a specific domain (see Sec. 4.4). We are currently exploring the potential and feasibility that additional information conveyed by the user, e.g. surface *type* (e.g., wall, roof, window), building *function* (e.g., house, factory, school) and the *context* (e.g., light industrial, medium urban, CBD), might have in semi-automatic building reconstruction.

4.3 Strategy for Surface Extraction

The main task of the computer in our model of semi-automatic building reconstruction is the precise and reliable extraction of 3D surfaces corresponding to the primitive surface model selected in a designated image window. The strategy illustrated in Fig. 5 is proposed. The key steps are outlined below. Note that the images and the object model are inputs to each step.

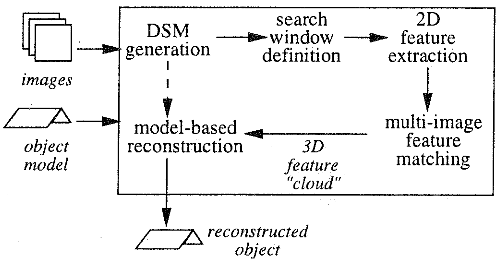

Figure 5: Process flow in surface extraction.

1. Acquisition of a digital surface model (DSM) of the scene. DSMs automatically generated from stereo imagery provide reasonable results if the sampling density of the DSM in object space is high (Baltsavias et al, 1995). Airborne laser scanning technology promises to be a viable alternative in the near future (see Sec. 2.2).
2. The 2D (or 3D, in the case of stereoviewing) pointing to the surface of interest in an image is used as the centre of a search window. This window is projected into all overlapping images using the DSM (see Fig. 6). The dimensions of the original window are critical insofar as the entire surface to be extracted should be contained within it and its associated projected windows. Minimizing the area encompassed has operational consequences: image segmentation will be faster (if performed on-line) and there will be fewer image features to consider during the feature matching and surface-forming steps.

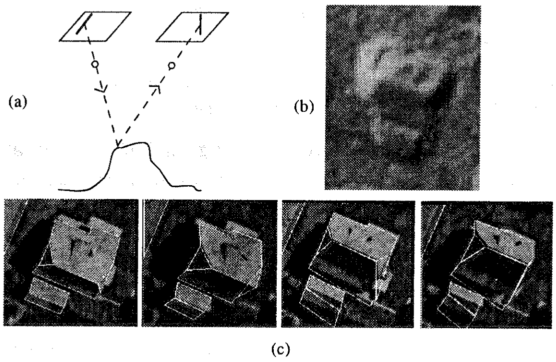

Figure 6: Exploiting DSMs in feature matching: (a) principle; (b) example DSM; (c) projection of manually measured lines in the upper left image into three overlapping images using the DSM.

3. Polymorphic feature extraction is conducted in a segmentation step to extract points (corners, junctions), straight line segments (edges) and homogeneous regions (texture, colour, intensity) in the search windows defined as above in the images. Image feature attributes and relations may also be extracted, e.g. in the form of an attributed graph (Henricsson, 1995) to assist in latter steps, although at the cost of significant demands on memory and processing time.
4. 3D object reconstruction can best proceed using 3D features, thus the next step is to derive 3D information, in particular 3D lines, by multi-image matching of the extracted 2D image features. The DSM is employed along with the epipolar constraint for the determination of search spaces.
5. The matching step produces a "cloud" of 3D linear and point features. Search is conducted for structures of 3D lines which satisfy the constraints of the selected surface primitive (e.g., parallelity, orthogonality).

4.4 Implementation Issues

A number of issues with respect to operational implementation motivate the proposed reconstruction strategy above.

- Where interaction is required, *real-time system response* is needed. Delays, even if short but frequent, will inevitably lead to its poor acceptance. This implies the development of computationally efficient tools and minimisation of search area.
- Demanding operations, such as DSM generation, image segmentation and attributed graph computation, should be carried out *off-line*. In addition, systems should support the *batch processing* of repeated sequences of processing steps, e.g., when a row of same-shaped buildings or surfaces is to be extracted.
- The system should support *customization*, e.g. in form of macros for sequences of processing steps that may have general application. This extends to the user being able to contribute composite surfaces to the surface primitive database specific to the user's domain (see also Sec. 5).
- It is important that tools for automated reconstruction include *self-diagnosis* to provide information useful to user in the verification of reconstruction. This information should include *quantitative accuracy measures* to relieve the user of laborious checking.
- Capabilities for storing and accessing large image databases, moving fluently between mono and stereo viewing, colour and intensity image display, and switching between multiple overlapping images are necessary.

5 SUMMARY AND OUTLOOK

The conceptual framework for a semi-automatic building reconstruction methodology from photogrammetric imagery was presented. This methodology is novel in its suggestion of an interaction model implementable in an operational context. The key component is a generic object modeling schema based on composites of primitive surfaces, i.e. CPS modeling. It was shown that CPS modeling is well suited to both: (a) interaction, users can convey a decomposition of the building structure in terms of the visible surfaces in the imagery in a natural way; and (b) for the automatic extraction of building shape.

Successful developments of automated procedures for the following tasks can be accommodated in this methodology and will further reduce interaction requirements:

- DSMs can be used in some circumstances for automatically detecting buildings, i.e. as blobs on the terrain (Baltsavias et al., 1995; Haala and Hahn, 1995).
- The analysis of the DSM blob detected for each building may be exploited to automatically select appropriate

surface models for its reconstruction (Baltsavias et al, 1995).

A number of extensions to the approach are also conceivable:

- A combination of surface and CSG primitives should be considered to provide a more powerful and flexible modeling scheme.
- The approach is equally applicable to close-range photogrammetric applications, e.g. for industrial and architectural object reconstruction. The surface model database can easily be extended, in particular, to accommodate composite surfaces in new domains.

Current research is focussed on implementing the surface extraction methodology using CPS object modeling. The full potential of CPS modeling is being explored, in particular, towards definition of an exhaustive database of primitive surfaces. Investigations into the inclusion of additional contextual information conveyed by the user are underway.

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