# TRENDS IN CAD-BASED PHOTOGRAMMETRIC MEASUREMENT

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**ABSTRACT**

In the past few decades, Computer Aided Design (CAD) systems have evolved from 2D tools that assist in construction design to the basis of software systems for a variety of applications, such as (re)design, manufacturing, quality control, and facility management. The basic functions of a modern CAD system are storage and retrieval of 3D data, their construction, manipulation, and visualisation. All these functions are needed in a photogrammetric measurement system. Therefore, photogrammetry benefits from integration with CAD, and thereby from developments in this field. There are two main interpretations of the term CAD-based photogrammetry. The first interpretation is on a system level: there is a trend towards integration of photogrammetric tools in existing CAD systems. The second interpretation is on an algorithmic level: developments in the field of CAD regarding object modelling techniques are being implemented in photogrammetric systems. In practice, the two interpretations overlap to a varying extent. The integrated photogrammetric processing of geometry and topology is defined as a minimum requirement for CAD-based photogrammetry.

The paper discusses the relation between CAD and photogrammetry with an emphasis on close-range photogrammetry. Several approaches for the integration of CAD and photogrammetry are briefly reviewed, and trends in CAD-based photogrammetry are outlined. First of all, the trend towards CAD-based photogrammetry is observed. The integration of photogrammetry and CAD increases the efficiency of photogrammetric modelling. One of the reasons for this is the improvement of the user-interface, which allows better interaction with the data. A more fundamental improvement is the use of advanced object modelling techniques such as Constructive Solid Geometry, and the incorporation of geometric object constraints. Furthermore, research emphasis is on CAD-based matching techniques for automatic precise measurement of CAD-models. An overall conclusion remains: the integration of photogrammetry and CAD has great potential for widening the acceptance of photogrammetry, especially in industry. This is firstly because of the improvement in efficiency, and secondly because of the established and well-known concept of CAD.

## 1 INTRODUCTION

Before trying to describe trends in CAD-based photogrammetry, it is useful to first define the term. We are dealing with two concepts: CAD and photogrammetry. The reader is expected to be familiar with both terms and these will not be explained here. An introduction to CAD and solid modelling can be found in (LaCourse, 1995) and (Mortenson, 1997). Principles of state-of-the-art close-range photogrammetry are presented in (Atkinson, 1996) and (Luhmann, 1999).

In this paper several photogrammetric systems of commercial and research nature are briefly discussed. It is stressed that the aim is not to give a complete overview of existing approaches. The information on these systems is acquired from the literature. Although recent publications are used, the information could be outdated. The characteristics of the systems presented in this paper primarily serve the illustration of the different approaches in CAD-based photogrammetry.

### 1.1 History

Although CAD stands for Computer Aided Design, it is applied for a wide range of applications other than product design, such as manufacturing (CAD/CAM), facility management, planning, quality assurance, and selling (Peipe, 1999; Schürle, 1999). CAD has become a broad concept, but CAD is, in the first place, associated with software packages for storage, manipulation, and increasingly for visualisation of 3D data.

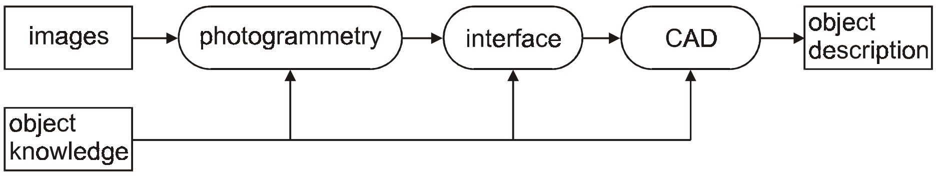


Figure 1: Photogrammetry interfaced with CAD

Traditionally, close-range photogrammetry concentrates on the accurate measurement of 3D co-ordinates. In many application fields, such as industrial photogrammetry, the co-ordinates were considered to be the end-product of the photogrammetric process (Fraser, 1988). Nowadays, 3D co-ordinate measurement with close-range photogrammetry can be done in (near) real-time and with astonishing precision in a variety of applications (Grün, 1994). This paper concentrates on object modelling rather than co-ordinate measurement alone. The need for computer models of existing objects increased as a result of the developments in the fields of CAD, computer graphics, and virtual reality. In particular the use of computer models for visualisation imposes the requirement of a valid boundary description of the object, i.e. a geometric and topologic description that is unambiguous. A CAD-system is a powerful tool for the construction of such a model. The creation of an interface between photogrammetric and CAD-system was the first step towards integration of photogrammetry and CAD (Figure 1). In the depicted approach, a set of 3D co-ordinates of points is the product of the photogrammetric process. The function of the interface can vary from a tool for reformatting the 3D co-ordinates into a CAD-readable format, to a tool for adding the topology that enables the transfer of a complete object model to the CAD-system. In the latter case object knowledge is required for the process, which is then undervalued by use of the term “interfacing”. A human operator can introduce object knowledge through interaction, for instance by image interpretation, or object knowledge can be stored in a knowledge-base and retrieved in a semi-automatic way.

First, interfacing between photogrammetry and CAD through 3D co-ordinates of points is discussed. In the next section, CAD-based photogrammetry is defined as a closer integration of photogrammetry and CAD.

Depending on the application, and thereby on the type of object, two interfacing approaches are possible:

1. Transfer of a structured point cloud, i.e. 3D co-ordinates of points that represent the geometry of a polyhedral object description. The topologic information is added using a CAD-system; design functionality of the system is used to construct edges and faces. This approach is suitable for polyhedral objects such as buildings. An example of this approach to architectural photogrammetry can be found in (Hanke & Ebrahim, 1996). An alternative to adding the topology information with the help of a CAD-system is to perform this step as a part of the interface. A highly automated (aerial photogrammetric) version of this approach for city modelling is called CyberCity Modeler (Grün & Wang, 1998). This tool can be regarded as an advanced interface between photogrammetry and CAD that requires object knowledge (Figure 1).
2. Transfer of an unstructured point cloud to the CAD-system or the interface is the second approach. In contrast to the previous approach the points are at arbitrary location on the object, or they cover the object in a regular pattern or grid. For automatic DEM extraction in aerial photogrammetry and in many 2½D close-range (stereo) applications this is a common approach. Here the topology can be automatically generated, for instance by the well-known Delauney-triangulation. Adding (more) knowledge on the shape of the object into this interfacing step allows simultaneous structuring of the point cloud and data reduction. A good example is presented in (Petran et al., 1996) where point clouds of car parts are converted in a semi-automatic way into a surface description using Bezier polygons. In (Luhmann, 1999) the computation of parameters, and the adjustment involved, of so-called geometric elements (e.g. a line, plane, or cylinder) from 3D co-ordinates is discussed. In both cases it is not the 3D co-ordinates that are transferred to the CAD-system, but the shape parameters derived from them.

The 3D point cloud acquisition methods are not the topic of this paper, but it has to be emphasised that, as well as photogrammetric techniques such as structured light approaches (Maas, 1997; Malz, 1996), laser scanning is often applied for automatic acquisition of unstructured point clouds. This is true for aerial (Maas & Vosselman, 1999) as well as close-range applications (El-Hakim et al., 1998; Sequeira et al., 1999). However, the way in which the point cloud is acquired does not affect the process depicted in Figure 1.

### 1.2 A definition of CAD-based photogrammetry

The term *CAD-based photogrammetry* is not often used and as a consequence the term is not well defined. The term was probably first used in (Li & Zhou, 1994) and later in (Luhmann, 1998). However, it was never widely accepted. In the computer vision community the term *CAD-based computer vision* is well known (Camps et al., 1998; Byne & Anderson, 1998). Although there is a great deal of overlap between the two fields, two main differences can be noted. First, the emphasis in computer vision research is on object recognition, rather than on object reconstruction or reverse engineering as it is called in the CAD-world. However, research in the area of object recognition is also reported in the photogrammetric literature (Huang & Trinder, 1999; Brenner et al., 1998; Zhou, 1997). In photogrammetric practice, where image content can be complex, an operator still performs the recognition (i.e. interpretation) step. The second difference between photogrammetry and CAD-based computer vision is that the latter approach uses range data more often than intensity images, see for instance (Werghi et al., 1999).

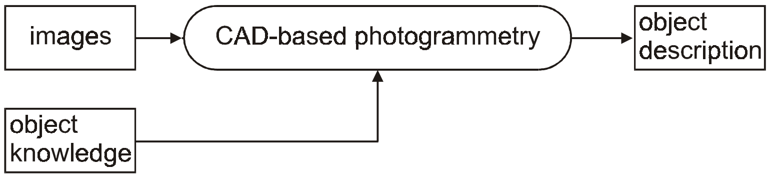


Figure 2: Integrated photogrammetry and CAD

CAD-based computer vision is loosely defined in (Byne & Anderson, 1998) as “using CAD models directly in vision programs”. Building on this definition, and accounting for the fact that photogrammetry is more reconstruction oriented than computer vision, CAD-based photogrammetry can be defined as photogrammetry in which the object description in the form of a CAD-model is integrated. In other words, in CAD-based photogrammetry the mathematical model contains the relations between the image measurements and the (parameters of the) CAD-model under construction. A CAD-based photogrammetric system does not necessarily have the full functionality of a CAD-system, but the photogrammetric process results in a complete CAD-model that contains geometry and topology (Figure 2).

This definition of CAD-based photogrammetry is quite a general one and leaves room for a variety of photogrammetric approaches and systems. In section 2 different types of CAD-based photogrammetry are distinguished, illustrated by existing approaches, of commercial as well as non-commercial nature. The trends in CAD-based photogrammetry are presented in section 3, conclusions in section 4.

| | Modelling by | Geometry | Topology | B-rep | CSG |
|---|---|---|---|---|---|
| 1 | **Points** | Point co-ordinates | | | |
| 2 | **Wireframes** | Line parameters (curved / straight) | Yes | | |
| 3 | **Surfaces** | Parametric surfaces (curved / planar) | Yes | Yes | |
| 4 | **Solids** | Parametric object model (curved / polyhedral) | Yes | Yes | Yes |

Table 1 : Modelling techniques and parametrisation of geometry

## 2 APPROACHES TO CAD-BASED PHOTOGRAMMETRY

The approaches to CAD-based photogrammetry are quite diverse. As a minimum requirement for the term CAD-based photogrammetry to be applicable, the result of the photogrammetric processing must be a complete CAD-model, containing geometry and topology. Although this description includes wireframe models, most systems render a surface or solid description. Table 1 supplies an overview of different levels of object modelling techniques and possible parametrisations. Note that in higher levels, the parametrisations of the lower levels can be applied. For instance, point co-ordinates and topologic relations often define a polyhedral surface description. A discussion on the choice of parameters for polyhedral objects can be found in (van den Heuvel & Vosselman, 1997). Topologic information is present in levels 2, 3, and 4. A boundary representation (section 2.3) can be applied for surfaces or for solids, while Constructive Solid Geometry (CSG) is only applicable to solids (section 2.4).

Many systems use a conventional photogrammetric approach (i.e. based on collinearity of image point, projection centre, and object point) to establish geometry. The topology is added within the system in a separate, often manual step (section 2.1). Some systems are developed as photogrammetric tools within an off-the-shelf CAD-system (section 2.2). Although the functionality and the geometric modelling techniques of the CAD-system are available to perform the reconstruction (and thereby specify the topology), the mathematical model is primarily conventional. The most common type of CAD-models in photogrammetry is the polyhedral boundary representation (section 2.3). Applying geometric object constraints within this geometric modelling technique results in object models that can have the same characteristics as parametric object models (section 2.4). However, parametric models have the ability to define a complex (possibly curved) shape with only a few parameters. Which modelling technique is favoured depends on the application at hand. Figure 3 depicts an example of a parametric model of a house. The parameters l, w, h, and r define the length, width, height, and roof height respectively, and thereby the shape of the building.

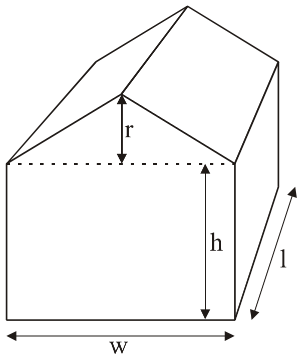


Figure 3: A parametric model of a house

Efficiency improvement is an incentive for CAD-based photogrammetry. However, automation in close-range photogrammetric modelling is still limited, and this is not expected to change in the short term. Research efforts in aerial photogrammetry are more concentrated and, thus, automation is at a somewhat higher level. An overview of the current status can be found in (Förstner, 1999). The most advanced CAD-based close-range systems aim at object recognition and feature an automatic fine measurement by fitting the back-projected CAD-model to the images (section 2.5).

### 2.1 Building topology

Photogrammetric systems that allow the specification of topology can be called CAD-based. However, in many systems topology is completely separated from geometry. Systems of this type have a conventional photogrammetric approach for the establishment of 3D co-ordinates of object points through the measurement of points in several images. Then, points (or edges) that border an object face are selected in the images, thereby building the topology of a polyhedral boundary representation. As long as only triangular faces are used, the topology has no geometric implications. However, a face that contains $n$ points implies $n - 3$ geometric constraints to enforce the coplanarity of these points. There are several commercial PC-based photogrammetric systems on the market that belong to this category. (PhotoModeler, 2000; ShapeCapture, 2000), where faces are restricted to triangles. PhotoModeler allows fitting of points to a plane in post-processing. ShapeCapture features tools for automatic point measurement and creation of a triangular mesh.

The combination of point measurement and the restriction to triangular faces allows the use of a conventional mathematical model based on collinearity equations, without the need for object constraints. These are the characteristics of some of the photogrammetric systems developed as an integral part of a CAD-system described in the next section. The main difference however, is the specification of topology within the CAD-environment.

### 2.2 Integration with a CAD-system

Although CAD-based photogrammetry is not defined as photogrammetry integrated with a CAD-system, the use of the geometric modelling functionality offered by a CAD-system definitely makes these systems CAD-based. We have to distinguish between of-the-shelf CAD-systems, like MicroStation and AutoCAD, to which a photogrammetric toolbox is added, and photogrammetric systems that make use of a CAD-toolbox in the form of a geometric modelling kernel. Examples of the first approach are the systems PHIDIAS (Benning, 1997) for an integration with MicroStation, and DIPAD (Streilein, 1996) for a photogrammetric system based on AutoCAD. Both systems allow photogrammetric modelling within the user-interface of the CAD-software and, thereby, the advanced modelling functionality of the CAD-system. This advantage holds for the second approach as well, although the CAD-functionality has to be made available to the photogrammetric system explicitly. An example of this approach is the system PIPER (Ermes & van den Heuvel, 1998) that is based on the geometric modelling kernel ACIS that applies Constructive Solid Geometry (CSG) (section 2.4).

The photogrammetric systems HAZMAP (Jones et al., 1996) and PHAUST (Hilgers et al., 1998) have functionality for the measurement of geometric elements, such as cylinders. The mathematical model is extended for image measurement of contours of cylinders and estimation of the parameters of the elements. This approach guarantees a smooth interface to the CAD-packages Plant Design & Management System (CadCentre Ltd) for HAZMAP, and MicroStation for PHAUST. The PC-based photogrammetric packages PhotoModeler and ShapeCapture (section 2.1) have similar functionality for measuring of, for instance, cylinders. Like the package 3D-Builder (section 2.3.2), they support several exchange formats, but do not interface to a particular CAD-package.

The integration of photogrammetric and CAD-software, and the adaptation of the photogrammetric mathematical model for the estimation of parameters of the CAD-model, other than co-ordinates of points, are the main characteristics of CAD-based photogrammetric systems. In the following sections the implications of the geometric modelling technique for the photogrammetric part of such a system are discussed.

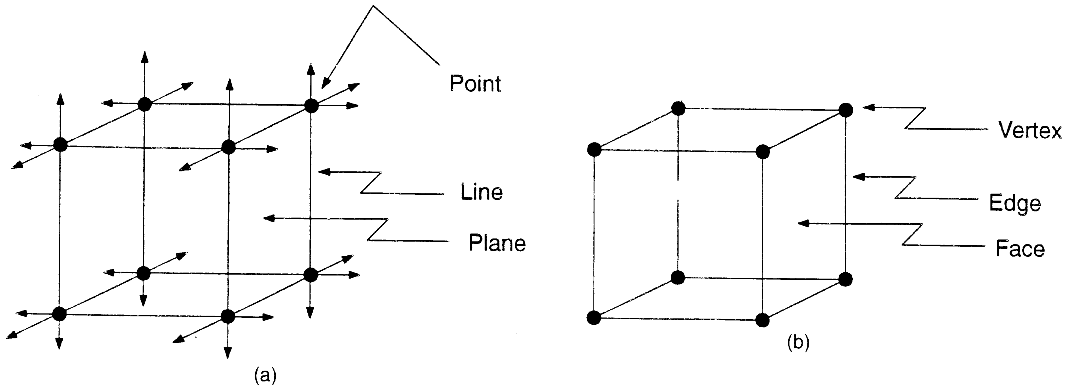


Figure 4: The geometric (a) and topologic (b) elements of a polyhedral boundary representation (LaCourse, 1995)

### 2.3 Modelling with a boundary representation

In CAD-based photogrammetry the mathematical model depends on the type of geometric modelling chosen. Two main types can be distinguished for use in CAD-based photogrammetry. First, the boundary representation or B-rep is the most common one. An approach using a boundary representation for curved surfaces is presented in (Petran et al., 1996) (see section 1.1). Currently, most CAD-based photogrammetric systems use a polyhedral boundary representation in which the geometry is represented by the 3D co-ordinates of the object points. Relations between the points define the topology (Figure 4). Such an object description is suitable for complex man-made structures with planar faces such as buildings. The advantage of a polyhedral B-rep for CAD-based photogrammetry is the availability of projections of object features (vertices and edges) in the images for measurement and, thus, the relation between object parameters and measurements is more direct than in the case of parametric object models.

Cad-based approaches for recognition and measurement of industrial parts that use a boundary description are described in (Huang & Trinder, 1999) and (Brenner et al., 1998). A system with the same characteristics that uses CSG-modelling is presented in (Zhou, 1998), see section 2.4. These systems aim at automated inspection of parts for which a CAD-model is available. For this application, the CAD-models are usually not restricted to polyhedral boundary representations.

The choice of a modelling technique can be regarded as the application of a form of a priori object information. Even more a priori information is added with the use of object constraints, such as parallelism or perpendicularity of object faces. In the next two sections the integration of object constraints distinguishes different approaches.

#### 2.3.1 Polyhedral B-rep without object constraints

Modelling with a polyhedral B-rep without object constraints allows the use of a conventional bundle adjustment based on collinearity equations, relating the points measured in the images to the 3D co-ordinates of the object points. In principle, this is only true when the B-rep consists of a triangular mesh (see section 2.1). Most of the systems that are mentioned in section 2.2 are examples of this approach. Some of these approaches aim at industrial applications and are extended for measurement of geometric elements, such as cylinders. Although parametric models (see section 2.4) describe these elements, there are no object constraints between parameters of different elements in the mathematical model. For instance, the connection of two differently oriented straight pipes and the creation of a curved element in between is usually a separate operation in the CAD-environment.

#### 2.3.2 Polyhedral B-rep with object constraints

In recent years research has been directed to the integration of object constraints in the photogrammetric mathematical model. An example is the inclusion of geometric constraints in the conventional bundle adjustment (McGlone, 1996). Quite an amount of research was devoted to so-called line-photogrammetry, i.e. mathematical models were developed in which (points on) image lines, being the projections of object edges, serve as observations. In these approaches a parametrisation for the 3D line, on which the object edge resides, is often chosen (Zielinski, 1993; Schwermann, 1995).

An approach in which geometric constraints enforce polyhedrality and allow the inclusion of a variety of object constraints such as coplanarity or parallelism of object faces, was developed by the author (van den Heuvel, 1999). In this line-photogrammetric approach, instead of parameters of object lines, parameters for object points and planes are used. This parametrisation facilitates the formulation of geometric constraints and their weighting (Hrabáček & van den Heuvel, 2000).

The PC-based software package 3D-Builder (3D-Builder, 2000) supports object constraints on a polyhedral B-rep. The use of object constraints reduces the number of images required for an accurate reconstruction. An extreme case is the (partial) object reconstruction from a single image. A considerable amount of research is devoted to this topic (CIPA-TG2, 2000)

### 2.4 Modelling with parametric object models

The choice of a geometric modelling technique depends on the application. For 3D city modelling from aerial images there is a trend towards the use of parametric object models (Brenner, 1999; Förstner, 1999; Vosselman, 1998), although research based on polyhedral B-reps continues (Baillard et al., 1999; Faugeras et al., 1998). Looking at recent research projects, the same trend can be noticed in close-range photogrammetry for industrial applications (Ermes & van den Heuvel, 1998) as well as for architectural applications (Debevec et al., 1996). In the latter field the choice of a polyhedral B-rep description is made in some approaches (Streilein, 1998; van den Heuvel, 1999). In industrial photogrammetry for the processing industry the trend towards the use of parametric CAD-models is emphasised by developments in systems used in practice, as discussed in section 2.3.1. These systems allow the estimation of parameters of objects such as cylinders. However, in this section only those approaches are discussed that allow geometric constraints between different parametric object models.

Constructive Solid Geometry (CSG) is a geometric modelling technique based on parametric object models of primitives such as boxes and cylinders. Boolean operations with primitives of which the shape, position, and orientation are known, are defined to build the final model. In Figure 5 Boolean operations are shown with a box and a cylinder. The box is a polyhedral primitive (parameters: width, length, and height), and the cylinder a non-polyhedral primitive (parameters: length and radius). Approaches that use polyhedral objects are the subject of the next section. Systems that allow the use of non-polyhedral parametric models are all based on CSG (section 2.4.2).

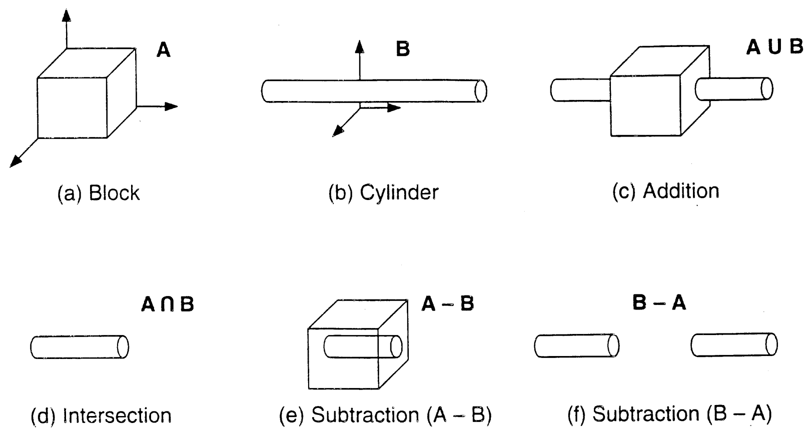


Figure 5: Boolean operations in Constructive Solid Geometry (c) – (f) (LaCourse, 1995).

#### 2.4.1 Polyhedral parametric models

A separate class of CAD-based photogrammetric systems uses polyhedral parametric models or primitives. The relative position and orientation (pose) of different models can be controlled with constraints. A commercial system called Canoma (Canoma, 2000), and the research system Façade (Debevec et al., 1996), are examples of close-range systems in this category.

The low-cost PC-based software package Canoma allows the selection of parametric object models from a predefined set of polyhedral shapes and approximately positions them in 3D space. It allows the manual measurement of points on the projection of object vertices and edges. The different shapes that constitute the complete model are aligned and "glued" together with the specification of constraints. It has to be noted that the system does not allow weighting of observations or constraints, and does not supply information on the quality of the resulting model. Details on the adopted mathematical model are not available. An attractive feature of Canoma is that there is virtually no camera information required. However, a distortion-free pinhole camera model with the principle point in the middle of the images is assumed. The initial focal length can be adapted interactively.

In (Debevec et al., 1996) the photogrammetric modelling system Façade, that aims at architectural applications, is described. From the user point of view, the approach for interactive modelling is similar to the one described above. Building primitives, such as a box, are selected and corresponding edges are measured in the images. In contrast to the procedure above, fine measurement can be performed with a gradient-based technique to align edges with sub-pixel accuracy. Constraints on the shape and pose parameters of primitives, and constraints between primitives are specified through a graphical 3D interface. The constraints are implemented in such a way that they reduce the number of parameters to be estimated (sometimes called "hard constraints" (Ermes, 2000)). The parameters are estimated through the minimisation of an objective function being the sum of error functions, one for each observed line. The error function is a non-linear relation containing both the parameters and the image co-ordinates of the end points of the observed edge segment. The objective function is minimised using a variant of the Newton-Raphson method. In this approach, observations and constraints are not weighted. The accuracy of the resulting model is visually assessed using the projection of the model in the original images. Façade features an advanced view-dependent texture mapping method that renders novel views from the scene from any desired location.

### 2.4.2 Constructive Solid Geometry

City modelling is an application of photogrammetry for which Constructive Solid Geometry is applied in several approaches (Förstner, 1999; Brenner, 1999). In the field of close-range photogrammetry not many systems are being developed on the basis of CSG. Two systems are briefly discussed here. The first one is a dedicated vision system designed for a robotics application in space called SIVE (Zhou, 1998). The second system, called PIPER, is designed for modelling industrial installations (Ermes et al., 1999).

The vision system SIVE uses six (three pairs of) high-speed cameras, each pair in stereo configuration, two pairs mounted on a robot arm. The system aims at recognition, aided by a structured light approach, and shape measurement of industrial objects. Object models are constructed from CSG-primitives with the CAD-system GEMS. Complete CSG-models are input to the vision system that features an interactive as well as an automatic mode for object recognition. Parametric equations are derived for each edge or contour of a primitive. Using the collinearity equations, the image measurement of a point on an edge is related to the parameters of the related primitive. All parametric primitives are specified in the same object co-ordinate system. Parameters for relative position and orientation of two primitives are introduced in the model when required. Therefore, no constraints on the pose of primitives are needed. Parameters of the CSG-primitives are estimated from the image observations by a least-squares adjustment.

PIPER is a photogrammetric modelling system based on CSG that is primarily designed for efficient modelling of industrial plants. Modelling with this system can be summarised as follows. The operator selects a primitive or CSG-model (i.e. a predefined CSG-set of primitives) from the database, changes its shape parameters, and positions it in space by manipulating its projection superimposed on the images. Manipulation is done by selecting an edge or contour and dragging it - or rather a point on it - to the desired location in the image. In order to obtain approximate values of exterior orientation parameters, they can be manipulated to obtain a good object-to-image match while object parameters are kept fixed. In contrast to the system described above, PIPER introduces six pose parameters and the shape parameters of each primitive into the adjustment. Furthermore, it allows the introduction of so-called soft-constraints (weighted constraints) on these parameters and on the relative pose of two primitives (Ermes, 2000). For instance, in the measurement of connected (curved) piping elements, these constraints play a major role. This is a general and flexible approach, with the number of parameters to be estimated as a minor disadvantage. Furthermore, the system supports Boolean operations with primitives (Figure 5). The edges that result from these operations (in fact, a conversion from CSG to B-rep is performed) are available for measurement. The same holds for the object contours that result from the so-called hidden-line projection performed for each image in the project. For all these operations with CSG-primitives the geometric modelling kernel ACIS is integrated in the system. Manually the object models need only be approximately aligned to the image content, because an automatic matching procedure is part of the system (Tangelder et al., 1999). This procedure applies a smoothed step-edge model that allows error propagation. All information is gathered in a weighted least-squares bundle adjustment in which, next to the solution of the parameters, their standard deviations are computed. Furthermore, statistical testing (so-called data snooping) of the observations is performed in order to detect errors in the measurements or constraints specified. Currently, variance component estimation is implemented in order to improve the weighting of the different types of observations.

## 2.5 Matching object models to image data

The major benefit of CAD-based photogrammetry is an improvement in modelling efficiency due to the use of advanced modelling techniques and CAD-functionality for model construction. Automation of the measurement task through matching techniques further improves the efficiency. Two approaches can be distinguished. The first approach starts with image feature extraction, followed by a matching step in which image features are related to features of the CAD-model, and finally object parameters are estimated. This approach is encountered in systems that aim at object recognition as well as pose measurement and fine measurement of shape (Huang & Trinder, 1999; Brenner et al., 1998; El-Hakim & Westmore, 1992).

In the second approach the operator performs the image interpretation and CAD-model recognition. The operator selects a primitive or model from a database, and modifies the shape and pose parameters to obtain an approximate fit of the projected model and the image content. This fit is then refined using an automatic matching procedure. This approach is found in the systems DIPAD (Streilein, 1998), HAZMAP (Jones et al., 1996), and PIPER (Ermes et al., 1999). In DIPAD the operator selects and positions the model with the 3D user-interface of the CAD-system, while in HAZMAP and PIPER the images supply the views on the 3D model world and the interface for model construction.

In DIPAD a straight-line extraction procedure is guided by the projection of the CAD-model in the images. The lines in the images are intersected, based on the topology of the polyhedral object model. Co-ordinates of object points are computed with a bundle adjustment and the improved model is projected in the images again. This procedure is applied iteratively.

A similar approach for cylindrical objects is encountered in HAZMAP. Edge detection is guided by the projection of the cylinder, and extracted edge points are fitted to image lines that define the tangent planes of the cylinder. Finally, the parameters of the cylinder are determined from the tangent planes using a primitive-fitting program.

In PIPER two matching methods are combined. In the first one the pose and shape of the CSG-model is improved by fitting the projections of its edges and contours to maximum grey value gradients in the neighbourhood of the initial projection. This method is applied first, and supplies an improved initial match for the second method. The second method applies a model for the grey value changes on a profile perpendicular to the edge (a smoothed step edge model). This model is fitted to the image data using a template matching technique. Both approaches are integrated in the bundle adjustment that can contain constraints on the shape and (relative) pose of the CSG-models. In contrast to the first method, the second one allows the error propagation from grey values to object parameters. The two methods are presented in (Tangelder et al., 2000).

## 3 TRENDS IN CAD-BASED PHOTOGRAMMETRY

In recent years the integration of photogrammetry and CAD has continued. More CAD-based photogrammetric systems are being developed and, thus, there is a clear trend towards CAD-based photogrammetry. However, there is some diversity in the direction of these developments. Three directions can be distinguished:

1. Systems integrating photogrammetric tools in a CAD-environment. These systems are build upon existing CAD-systems, such as MicroStation and AutoCAD, the data structures of which are applied.
2. Photogrammetric systems extended with CAD-functionality. These systems add topologic information to the geometric data and can often produce parametric descriptions of geometric primitives, such as cylinders.
3. Systems that apply advanced geometric modelling techniques (CSG or B-rep, both with geometric constraints) that integrate the information gathered during model construction in the photogrammetric mathematical model.

With the use of CAD-models and geometric constraints we, in fact, see a trend towards the use of domain specific a priori object information and, thereby, a trend towards data fusion. A similar trend is observed in aerial photogrammetry with the use of a priori knowledge in the form of house models and available digital maps (Brenner, 1999).

CAD-based photogrammetry shows a trend towards image line measurement and, thus, towards line-photogrammetry. Lines can be extracted automatically from the images or points on lines can be measured manually. As a result, not only the projections of object edges are available for measurement, but also its possibly curved contours. Furthermore, the use of lines facilitates automatic fine measurement. Systems that feature such as model-to-image matching procedure allow more efficient modelling because the operator only is required to align the projection of the object model and the image data approximately.

Although the choice of a geometric modelling technique depends on the application, CSG is gaining in popularity. Particularly for industrial modelling applications the use of parametric primitives is advantageous, simply because they are often used for the design of industrial parts and plants. The same holds for CSG as a solid modelling technique for the construction of models from parametric primitives. It is expected that parametric models and CSG will have a more prominent role in the future. Furthermore, it is quite likely that, as photogrammetry benefits from the integration with CAD, geodetic and photogrammetric expertise in the field of adjustment theory can be beneficial to CAD.

The integration of photogrammetry and CAD is an ongoing development that will continue to the point where efficiency improvement as a result of better integration becomes insignificant. Therefore, the final level of integration will depend on the task at hand and the demand for it. Seamless integration of CAD and photogrammetry can be expected for applications in which the objects are designed with the help of a 3D CAD-system and only when there is a substantial need for reverse engineering. In close-range photogrammetry as-built modelling of industrial plants is one such application. Benefits of photogrammetry over alternative acquisition techniques, such as tacheometry, are numerous. This is especially true for hazardous environments (Chapman et al., 1992). In architectural photogrammetry the need for models for monument preservation and cultural heritage in general is apparent (Streilein, 1998). However, funding for this type of project is often limited. Therefore, the development of CAD-based photogrammetric systems, or CAAD-based systems (Computer Aided Architectural Design), for this application is expected to be less rapid. Furthermore, parametric object modelling is not expected to become a dominant modelling technique in this field. Although city models also contain models of buildings, parametric models play an important role because of the considerably smaller scale of the aerial images (allowing buildings to be imaged in full) and the need for a high level of generalisation of the house models. Furthermore, development of CAD-based photogrammetric approaches is rapid due to a large demand for city models and, consequently, the considerable research efforts (Förstner, 1999).

The acquisition and storage of non-geometric or semantic information, partly integrated with the modelling task, is another reason for integrating photogrammetry and CAD. This information can be quite diverse, such as information on the materials used, contents or purpose of vessels and pipes, or information on the construction of a building. All types of information can be gathered in a Computer Aided Facility Management (CAFM) system; a management tool of growing importance (Schürle, 1999).

In recent years we have seen low-cost PC-based photogrammetric modelling tools coming onto the market. They are designed to be used by a broad public, putting specialised photogrammetric knowledge in a “black box”. This development allows photogrammetric modelling by non-photogrammetrists. However, modelling large constructions or installations according to pre-set quality requirements still necessitates photogrammetric knowledge. A cost-effective approach, in which a large image set is triangulated by photogrammetric experts and delivered to the client for modelling, is proposed in (Chapman & Deacon, 1998). This approach limits (labour-intensive) modelling to the parts of the construction for which geometric information is needed, at the time it is needed (“just in time”). Furthermore, in contrast to the photogrammetrist, the operator is likely to have the domain-specific knowledge required for efficient modelling. The use of panoramic image mosaics from a collection of images acquired at the same location can be regarded as a related trend (Haggrén et al., 1999). An approach that uses a “panoramic” fish-eye camera can be found in (FrankData, 2000).

For many applications, especially when complex (curved) shapes are involved or texture is lacking, laser scanning can be an efficient, direct way to obtain 3D information. For these applications, it is expected that range images will be used more frequently in the future although, for obvious reasons, photogrammetrists tend to restrict themselves to the use of intensity images. A combination of intensity and range data is presented in (El-Hakim et al., 1998; Sequira et al., 1999). Research in CAD-based computer vision is mainly based on the use of point clouds acquired by laser scanning (section 1.2).

Research is driven by the need for efficiency improvement and is thus directed towards automation. Many CAD-based systems feature a matching technique for automatic fine measurement (section 2.5). Successful approaches for recognition of objects of which CAD-models with fixed shape, but arbitrary pose, are reported (section 1.2). Future research will be directed towards automatic recognition of CAD-models or primitives, of which shape and pose parameters are to be determined, and on recognition of constraints on shape and pose. For a boundary representation approach, this means recognition of points and lines that relate to vertices and edges of the object and automatic establishment of topologic relations between them. Aerial photogrammetric research on the latter approach is reported in (Baillard et al., 1999).

## 4 CONCLUSIONS

Photogrammetric approaches that result in a CAD-model are defined to be CAD-based. The model is a valid surface or solid description of the object that contains geometry and topology. More advanced CAD-based approaches integrate domain specific knowledge, in the form of CAD-models or primitives and their geometric constraints, in the measurement process and in the photogrammetric mathematical model. Furthermore, model-to-image matching or fitting is applied.

The paper gives an overview of different approaches in CAD-based photogrammetry and their state-of-the-art, illustrated by existing systems of commercial and research nature. The emphasis is on the geometric modelling techniques applied and their consequences for the photogrammetric measurement.

Trends in CAD-based photogrammetry are reviewed. Research continues in the direction of further integration with CAD and automation through recognition of CAD-models and constraints. Seamless integration is envisaged for applications of photogrammetry where efficiency improvement, and thereby cost-reduction, will boost the demand. Furthermore, the integration of photogrammetry and CAD is expected to ease acceptance of photogrammetry in all fields where CAD was accepted many years ago.

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