Semi-automatic CAD based reconstruction of industrial installations

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Abstract
3D site models of industrial installations are required for tasks like maintenance management, revamping, and path planning. The traditional way of site modelling by photogrammetry relies on the measurement of numerous points and is quite time consuming. Attempts to fully automate 3D reconstruction by CAD based vision fail due to the complexity of the scenes and the lack of modelled knowledge. This paper presents an efficient reconstruction approach for 3D reconstruction which combines the strengths of the human image interpretation and the computer’s image processing speed and exploits the advantages of using CAD models in an interactive manner.

1. Introduction
A few decades after the invention of photography, Albert Meydenbauer, in 1858, was one of the first to use measurements in photographs for the purpose of 3D reconstruction. Since then many developments took place in the area of photogrammetry, one of them being the transition from photographs on film to digital images. One aspect, however, did not change: object reconstruction by photogrammetry is still based on the reconstruction of 3D points. 3D models of polyhedral objects are derived by reconstructing the corner points by the so-called forward intersection (figure 1) and by specifying the topology of the object’s edges and faces. Even objects with curved surfaces are measured this way. If no suitable points are available on these surfaces, they are simply created by pasting stickers or projecting a texture [Luhmann and Wendt, 2000]. This contribution deals with a new approach for object reconstruction based on the interactive alignment of CAD models to images that has been developed in the last few years. The advantages of such a CAD based approach will be demonstrated by the example of 3D reconstruction of industrial installations.

Figure 1: Forward intersection: a point is measured in two images. The 3D position of a point is reconstructed by intersecting the lines through the image points and lens positions. The position and view direction of both images as well as the position of the lens relative to the image need to be known.

The alignment of CAD models to digital images is an active research area in computer vision. CAD based computer vision aims at fully automated recognition and location of objects in imagery making use of CAD modelling techniques [Byne and Anderson, 1998, Jain and Flynn, 1993]. Features are derived from the rigid or articulated CAD models and matched to features derived from images. Often use is made of aspect graphs [Dickinson et al., 1992]. Although the success rates of the object recognition systems as published in the literature are sometimes quite high, it is yet not possible to fully automate the 3D reconstruction of complex industrial installations such as shown in figures 3 and 4. Object recognition systems usually require a fairly good segmentation. When segmenting images of (often dirty) industrial scenes, showing many irrelevant details, and taken under bad illumination conditions, the extracted features show only little correspondence to the ideal aspect graphs of CAD models. The high rate of occlusions in such scenes and the large number of objects complicates the automated recognition even further. Under these circumstances automated CAD based reconstruction seems not feasible.
However, this does not imply that all measurements required for reconstruction need to be done by hand. The largest problems encountered in automated reconstruction are the interpretation of the scene (image understanding), the selection of the appropriate CAD models, and the selection of the corresponding image features. The accurate alignment of the CAD models to image features is something computer algorithms can do much faster and much more accurate. The CAD based 3D reconstruction methods developed in the last few years therefore use a semi-automatic approach. In this approach difficult image interpretation tasks are done by a human image analyst, whereas the precise measurement is done by computer.

In the next section the principle and advantages of the developed CAD based reconstruction method are described. Section three then deals with the algorithmic aspects of the alignment of a single CAD model to one or more images. Industrial objects usually can be modelled as a combination of a large number of simple CAD models. In section four it is shown that geometric constraints between these primitive CAD models improve the efficiency of the 3D reconstruction. The 3D reconstruction requires a known position and rotation of the images. In section five it is described how the estimation of these image orientations can be integrated into the 3D reconstruction procedure. Some results obtained in pilot projects are presented in section six. The paper concludes with an outlook to possibilities for further automation of 3D reconstruction tasks.

2. CAD based reconstruction

CAD models of industrial installations can be built up from CAD models of simple parts like straight pipes, elbows, T-joints, and rectangular boxes. The developed CAD based reconstruction method makes use of a library of such simple CAD models. The model of the industrial installation is reconstructed by repeating the following steps for each simple model in the scene [Lang and Förstner, 1996].

- First, the image analyst interprets the images and selects an appropriate model from the library. This model, with some default shape, is placed somewhere in the 3D object space. When the orientation of an image is known, the object model can be projected into this image. In the image the visible object edges are displayed as a wire frame model (figure 2a).
- Next, the image analyst roughly aligns the object model to the image of the object by dragging the nodes and edges of the wire frame to the correct positions. By doing so, the image analyst implicitly modifies the position, rotation and shape of the object model (figure 2b).
- Although the image analyst could precisely align the object model, both the accuracy and the speed of the reconstruction improve if the previous step is followed by an automatic fitting of the wire frame to the object's edges in the images (figure 2c).

![Figure 2: Interactive alignment of a CAD model to an image. (a) Wire frame of an elbow model projected into an image with arbitrary orientation. (b) Model after approximate alignment by the image analyst. (c) Model after fitting to image gradients in multiple images.](image)

The usage of CAD models in the measurement process allows the reconstruction of objects like cylinders without the need for homologous points that have to be measured in multiple images. It also allows the reconstruction of polyhedral objects in case one or more corners of this object are not visible in the
images. Another advantage of the CAD based approach is a better communication between the image analyst and the construction engineers in industry, since the latter are used to think of an installation in terms of CAD models rather than in terms of points with topology.

3. Measurement with a single CAD model
The CAD models used in the reconstruction procedure are described by constructive solid geometry (CSG) [Mortenson, 1997]. The usage of CSG results in very compact descriptions in which a CAD model is composed by boolean set operations on shape primitives like boxes, cylinders, spheres, and wedges. A T-joint, for instance, is described by a union of two cylinders. Each shape primitive is represented by parameters describing its position, rotation, and shape. In the alignment process, these parameters need to be estimated such that the edges of the wire frame are properly aligned to the image of the object (in multiple images). The alignment is achieved by dragging the wire frame to the approximately correct position and fitting its edges to the image edges.

3.1 Dragging
Lang and Förstner [1996] developed a method for dragging wire frames of polyhedral objects. In their approach each node of the wire frame is associated with one or two parameters of the CSG model. When dragging a node of the wire frame with the mouse cursor, these parameters are modified such that the resulting modified position of the node in the image follows the cursor movement. The required modifications of the object parameters ($\Delta p_i$ and $\Delta p_j$) due to a movement of node $n$ ($\Delta x_n$, $\Delta y_n$) are derived from

$$
\begin{pmatrix}
\Delta p_i \\
\Delta p_j 
\end{pmatrix} =
\begin{pmatrix}
\frac{\partial x_n}{\partial p_i} & \frac{\partial y_n}{\partial p_i} \\
\frac{\partial x_n}{\partial p_j} & \frac{\partial y_n}{\partial p_j}
\end{pmatrix}^{-1}
\begin{pmatrix}
\Delta x_n \\
\Delta y_n
\end{pmatrix}
$$

(1)

in which the partial derivatives express the change of a coordinate of node $n$ in the image due to a change in a parameter of the CSG model.

Vosselman and Veldhuis [1999] introduced a method which allows dragging of edges of the wire frame, besides dragging of nodes. This feature makes it possible to also use object models with curved surfaces such as spheres and cylinders. In this approach the parameters are updated in such a way that the distances between points measured with the mouse cursor and the nearest edges of the wire frame are minimised. When measuring a point somewhat away from an edge, all $N$ parameters are updated such that the edge of the wire frame of the updated CSG model will again go through the new mouse position. These parameter updates $\Delta p$, are determined by solving the equations

$$
\Delta u_k = \sum_{i=1}^{i=N} \frac{\partial u_k}{\partial p_i} \Delta p_i, \quad k = 1 \ldots K
$$

(2)

that relate the distance $\Delta u_k$ for each of the $K$ measured points to the parameter changes. The partial derivatives in this equation express how the distance between the mouse position and the nearest edge would change due to a change in the value of one of the parameters of the CSG model. These derivatives can be derived analytically for both contour edges and edges at the intersections of faces [Ermes et al., 1999]. Clearly, equation system (2) can not be solved if $K < N$. Therefore, the minimum norm solution is calculated. This solution satisfies (2) while minimising the changes in the parameters of the CSG model. In case $K > N$ the least squares solution is computed.

3.2 Fitting
After dragging the wire frame to the approximately correct position in the images, a fitting algorithm can be applied to automatically align the object model more precisely. Lowe [1991] already designed an algorithm for fitting parameterised object models to grey value edges in images. Edge pixels are selected by thresholding a gradient image. For each edge pixel equation (2) is set up. By solving the equation system the edges of the wire frame are aligned to the edge pixels. The selection of a threshold can be avoided if
the absolute value of the grey value gradient of a pixel is used as a weight to the equation for that pixel [Vosselman and Tangelder, 2000].

Fitting methods assume that the pixels with the highest gradients indeed correspond to the location of the object's edges. In complex scenes an object is often surrounded by many other objects. Grey value gradients belonging to those objects may lead to biases in the fitting results if they are near the edges of the object to be measured. Edges of a shadow or non-homogeneous illumination of curved surfaces may also lead to fitting errors. Supervision of the fitting results is therefore a necessity. If required, fitting results need to be corrected manually by dragging the mismatched edges to their correct location.

4. Constrained measurement with multiple CAD models
When modelling a scene with CAD models of simple objects, these objects often show many geometric relationships. E.g. an industrial installation is not just a set of randomly placed pipes and elbows. Instead, these elements are connected to each other. This implies that the parameters of the corresponding CSG models are dependent. These dependencies can be modelled by geometric constraints.

Constraints greatly facilitate the efficient reconstruction of scenes, since they reduce the number of freedom while modifying a CAD model. Consequently, less measurements need to be performed in order to achieve the desired alignment. Several types of constraints can be discerned [Ermes, 2000]:

- **Constraints between simple objects.** A straight pipe and a connected elbow sharing their circular ends result into six constraints: three constraints on the position of the ends, two constraints on the normal direction of the coinciding faces, and one constraint for a common radius. A straight pipe is described by seven independent parameters. If the location of the elbow is already known, the constraints only leave one degree of freedom for the straight pipe. This, of course, corresponds to the length of the pipe. Thus, only one measurement in one image is required for the 3D reconstruction. In practice, often discrepancies can be found in the connections of pipes. E.g., the normal direction vectors of the ends will not be perfectly aligned. To allow these small deviations, these kind of constraints need to be implemented as so-called soft constraints. Soft constraints are treated as measurements and their validity can be tested statistically.

- **Constraints within a simple object.** Some simple parts in the library, like a T-joint, consist of multiple CSG primitives. If such an object is one physical piece, constraints like the perpendicular axes of the cylinders in the T-joint are known precisely. In that case they can be considered as so-called hard constraints, for which no discrepancies are allowed.

- **Parameter constraints.** In industry many objects have standardised sizes. Knowledge of these standards can be incorporated into the 3D reconstruction by constraining the parameter of the CSG model to a certain standard value.

5. Site modelling
So far, it has been assumed that the position and rotations of the recorded images were known. In the traditional way, the reconstruction of these image orientations involves a large number of point measurements and computations. Using the CAD models, the determination of the image orientations can be done in a similar way as the object reconstruction. In the case of object reconstruction, alignment is achieved by modifying the parameters of the CSG model, while the parameters of the image orientation are kept fixed. Knowing the position and rotation of an object in the image, one can also achieve alignment by modifying the image orientation parameters and the shape parameters of the CSG model. This leads to the following procedure for site modelling in which the reconstruction of the image orientations is integrated.

First, one needs to establish a site coordinate system. This coordinate system can be defined by taking a corner of a rectangular object as the origin and taking the edges of the object to be parallel to the coordinate axes. To determine the scale of the object space, one distance needs to be known. E.g., a length of the object can be measured with a tape when taking the images of the site.

1 On [http://www.geo.tudelft.nl/hrs/piping/overview.html#constraints](http://www.geo.tudelft.nl/hrs/piping/overview.html#constraints) a short movie shows how, with the help of constraints, a flanged T-joint modelled by five cylinders (35 parameters) can be reconstructed by measuring only eight points.
Now that the reference system is established, all orientations of all images in which the rectangular object is visible can be determined by alignment of the rectangular box to the images, while modifying the image orientation parameters and the width and height of the box. In fact, one can estimate the image orientations and the position, rotation and all shape parameters of the box simultaneously, when parameter constraints are used for the position, rotation and length of the box.

For a subset of images the orientations are now known. The part of the site that is visible in these images can now be reconstructed. The site model reconstructed so far (only one box) can be extended with several other simple CAD models from the library. Furthermore, constraints between these models will be specified. Some parts of the extended site model will be visible in some of the images for which the orientation is yet unknown. By alignment of the site model to these images, their orientations can be determined. In this way one can proceed by determining image orientations and extending the site model until all images have been processed and the site model has been completed.

By incrementally adding CAD models and images to the site model, the small errors that are made in each measurement add up and may lead to large discrepancies in the site model. This can be corrected by a simultaneous estimation of the parameters of all images and all CSG models.

6. Examples
Two examples of site models produced by this CAD based reconstruction are presented in figures 3 and 4. The figures show a machine room of a ship and a gas drying installation. Characteristic for these industrial sites is the high density of objects. Consequently, the images show a high amount of partially occluded objects. In particular the ship's machine room also shows a large number of details that are irrelevant for the reconstruction.

Although the usage of CAD models, constraints, and the fitting algorithm speeds up the production of site models, the 3D reconstruction is still time consuming. The site model of (a part of) the gas drying installation was produced in two weeks. This included the recording of the images, all measurements, and the extension of the CAD library with a few simple objects that had not been used before. The scene was reconstructed using 33 images. The 277 CSG primitives of the site model were described by 2268 parameters. 1548 measurements together with 1588 constraints were used to estimate those parameters and the 198 image orientation parameters. Because of the large number of parameters, special attention needs to be paid to the numerical stability of the equation systems to be solved.

Figure 3: Reconstruction of a ship's machine room. Left: wire frames of the CAD models aligned with an image. Right: reconstructed machine room model.
7. Further automation

In the presented semi-automatic CAD based approach for object reconstruction, the image analyst still has a large number of tasks. Despite the advances made, modelling the sites of industrial installations is still time consuming, and consequently, costly. Further automation of 3D reconstruction is therefore desired.

Knowledge based image interpretation in combination with the constraints between CAD models could contribute to further automation. Domain specific knowledge can be used to reason about the likeliness of the next CAD model to be added to an already reconstructed part of an installation. Although many models may fit geometrically, only a few may make sense when considering the function of an installation. The geometric constraints given by the connections between CAD models furthermore reduce the complexity of the image interpretation. As mentioned above, a straight pipe connected to an already measured part only has one degree of freedom left. This results in a very small search space in the images.

Another increase in the amount of automation is expected from the integration of image analysis with data acquired by laser ranging devices. Range images can be used to automatically detect shapes like cylinders and planar faces [Boyer et al., 1994]. Segmented range images can generate hypotheses for the appropriate CAD models. These hypotheses can be verified and refined by fitting the models to the images and range data simultaneously. An important aspect in the further automation will be the self-diagnosis of the fitting algorithms. If this can be done reliably, the tasks of the image analyst can be reduced to the control and correction of those parts of the 3D reconstruction where the automation may have failed. This could then lead to another reduction in the production costs of 3D site models.

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Literature


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