RECONSTRUCTION FROM A SINGLE ARCHITECTURAL IMAGE FROM THE MEYDENBAUER ARCHIVES

Frank A. van den Heuvel

Delft University of Technology, Department of Geodesy
Thijsseweg 11, 2629JA Delft, The Netherlands
Email: **F.A.vandenHeuvel@geo.tudelft.nl**

KEYWORDS: single image, reconstruction, camera calibration, line photogrammetry, object constraints, adjustment, architecture

ABSTRACT

An approach for the reconstruction of a building from manual measurements in a single image and a priori object information is described. The image is taken with an uncalibrated camera. Parallelism and perpendicularity of facades and building edges are examples of the object information that makes reconstruction and camera calibration from a single image possible. The reconstruction results in a boundary representation of the vissible part of the building. Before the reconstruction, the interior orientation parameters of the single image are determined in a separate step. The adjustment involved is based on parallelism and perpendicularity constraints on automatically extracted image line observations. These constraints result from a vanishing point detection procedure. With successful vanishing point detection the determination of the parameters of the interior orientation does not require manual interaction.

The approach is applied for the reconstruction of a demolished building using a single image from the Meydenbauer archives. The interior orientation of the image was unknown. It is concluded that the approach is very suitable for this type of imagery and results in a partial reconstruction of which the precision is assessed.

1 INTRODUCTION

The research reported in this paper concentrates on object modelling in architectural photogrammetry. The main goal is to exploit the characteristics of this application in order to allow object modelling from a single image, and assess the quality of the resulting object model. The main characteristic of the application is the availability of object information that results from knowledge or assumptions on the construction of the building. The object information applied in the approach presented in this paper is split into three groups:

1. Object edges are straight. When lens distortion is absent, straight object edges result in straight line features in the image. Especially in architectural photogrammetry line features show advantages over point features for measurement (Streilein, 1998; van den Heuvel, 2000). Therefore, only line features are used as photogrammetric observations.
2. Object faces are planar. In fact, this type of object information relates to the previous type as the intersection of two planar faces leads to a straight edge. This object information implies that a polyhedral boundary representation or B-rep is a suitable type of representation for the object at hand.
3. Object shape constraints. The main constraints used are:
    - Parallelism of object edges and faces
    - Perpendicularity of object edges and faces
    - Coplanarity of object points and faces
    - Symmetry of object edges

Control points, i.e. object points with known co-ordinates, are not required, other than a minimum set for defining a co-ordinate system. It is possible to include known distances between two points or between two parallel planes.

Assumptions on the shape of the building are applied in the reconstruction in the form of weighted constraints. The need for object constraints also results from the use of a polyhedral B-rep for model representation. The so-called point-in-plane constraint (section 4.1) ensures planar faces. Other methods refrain from the use of shape constraints and therefore these methods require multiple images (Streilein, 1998) or an image sequence (Pollefeys et al., 2000). With the use of assumptions on the construction of a building, a single photograph contains valuable information for 3D documentation (Streilein & van den Heuvel, 1999), even when it is taken with an uncalibrated camera (Karras & Petsa, 1999).

CIPA established a task group named “Single Images in Conservation”. The website of this task group contains information on various approaches for reconstruction from a single image (CIPA-TG2, 2001). The main difference of the approach presented in this paper and other approaches is the application of a rigorous least-squares parameter estimation for the camera calibration as well as for the object reconstruction. This adjustment facilitates error propagation and simplifies the assessment of the quality of the results.

This paper is structured as follows. Section 2 gives an overview of the method. The camera calibration from a single image is presented in section 3, and the object reconstruction in section 4. The method is applied to a scanned reproduction from the Meydenbauer archives. Conclusions are drawn in section 5.

2 OVERVIEW OF THE METHOD

The developed method for object reconstruction from a single image with unknown interior orientation consists of two main steps (Figure 1). The first step is a highly automated procedure for camera calibration. Interior orientation parameters including lens distortion are estimated in a least-squares adjustment based on parallelism and perpendicularity object constraints on straight edges. The image edges are automatically extracted using a line-growing algorithm. The constraints result from a vanishing point detection procedure that usually does not require manual interaction.

In the second step manual measurements are required to extract edges in the image that correspond to object edges. Furthermore, object information - such as topology and shape constraints - is to be inferred from the image. After computation of approximate values, a bundle adjustment is used to adjust the line observations and estimate the parameters of the boundary representation, and the exterior orientation. Interior orientation parameters from the first step are not estimated in the latter adjustment. The type of object constraints used in the first step is also used in the second step, supplemented with other types of object constraints such as symmetry constraints. However, the image line observations are different in both steps.

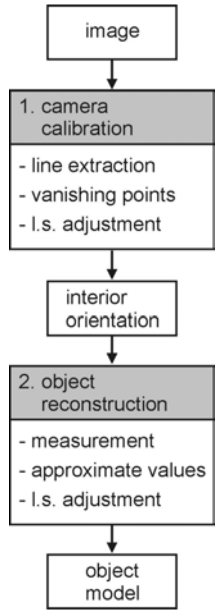

Figure 1. Overview of the procedure

3 CAMERA CALIBRATION

In the first step of the procedure the interior orientation parameters of the single image are determined from edges extracted using image processing. Section 3.1 explains how an image edge is used as an observation in the adjustment. In section 3.2 the vanishing point detection method is discussed. This can be regarded as a procedure for grouping edges that have the same orientation in space. This parallelism information supplemented with perpendicularity assumptions is used for the formulation of condition equations of the adjustment. The estimation of the interior orientation parameters using this model is discussed in section 3.3.

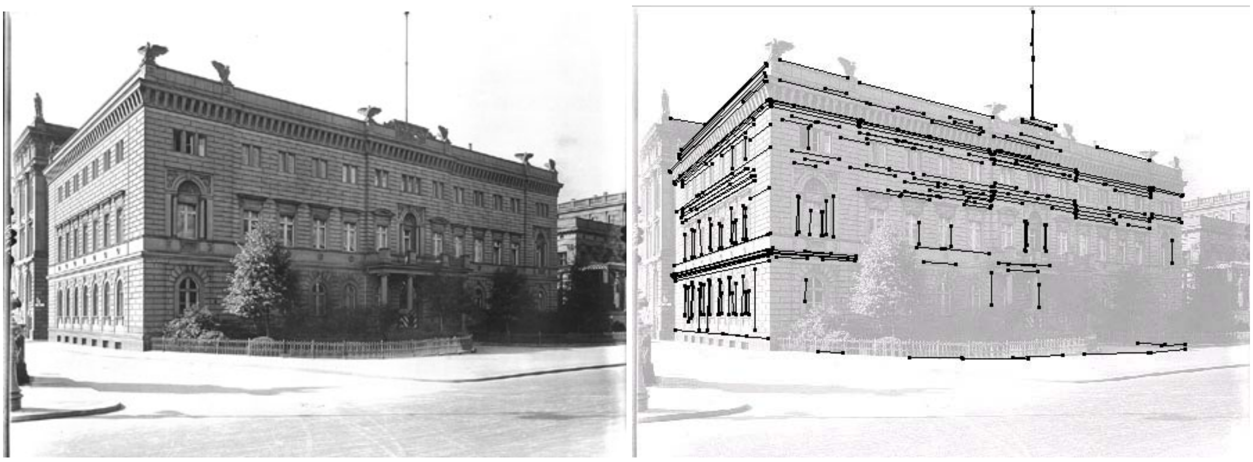

Figure 2. The Meydenbauer image (left) and the automatically extracted image lines (right).

3.1 From edge extraction to observations

Edges are automatically extracted by applying a line-growing algorithm. More details on this algorithm can be found in (van den Heuvel, 2001). The results are shown in Figure 2. The image that is used to illustrate the methods presented in this paper is a low resolution scan (1200 × 865 pixels) of a reproduction of a photograph by Albrecht Meydenbauer taken in the year 1911. It depicts a building in the historical centre of Berlin called “Kommandantur”. This building no longer exists like many other buildings in the historical centre. There is a need for reconstruction using the photographs from the Meydenbauer archives such as this one (Wiedeman et al., 2000). In Figure 2 (right) the automatically extracted lines are overlayed with the image. The extraction was limited to the part of the image that contains the building. 223 lines were extracted with the minimum line length set to 40 pixels.

How are the image lines represented in the adjustment? Like a point in the image is associated with a ray in space, a line in the image is associated with a plane in space. This plane is called the interpretation plane (Figure 3). The equations that build the adjustment model are all condition equations on the normal vectors of the interpretation planes. Each normal vector is constructed from two vectors of two points of the image line ($\mathbf{x_1}$ and $\mathbf{x_2}$ in Figure 3). Note that the points in the image do not have to correspond to corner points of the building; in principle they can have an arbitrary location on the line.

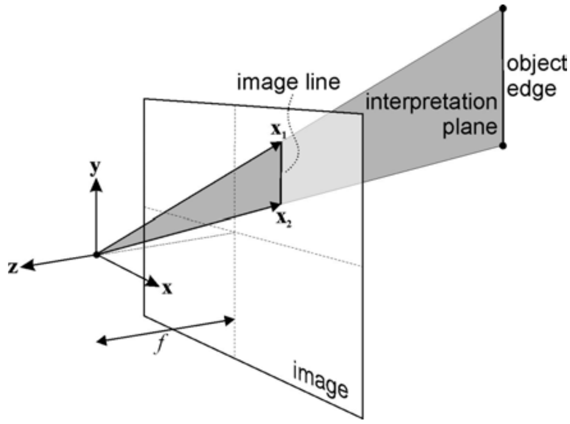

Figure 3. A line in the image and its associated interpretation plane

3.2 Vanishing point detection

When straight image lines have been extracted the parameters of interior orientation are determined by applying two types of object constraints. First, parallelism assumptions of object edges are applied. Second, perpendicularity is assumed for the three major object orientations defined by three groups of parallel edges. When lens distortion is absent, the projections of object edges that are parallel intersect in a point in the image called the vanishing point (Figure 4). With the detection of a vanishing point the parallelism of the related object edges is assumed.

The method for vanishing point detection was designed to make use of the assumption of perpendicularity between the three main object orientations (van den Heuvel, 1998a). However, when principal point and effective focal length are unknown only parallelism assumptions can be used in the vanishing point detection procedure. Projections of parallel object edges intersect in a vanishing point independent of the location of the principal point or the focal length. The perpendicularity assumption is introduced to allow the estimation of the interior orientation parameters (section 3.3).

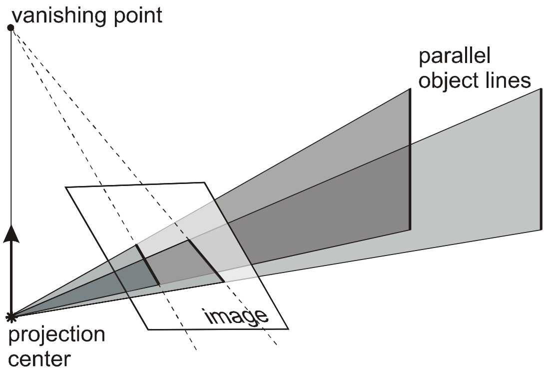

Figure 4. Vanishing point as the intersection of the projections of parallel lines in object space

The method for vanishing point detection is based on the statistical testing of the intersection hypotheses of combinations of three image lines, or rather the intersection of the three interpretation planes associated with these lines. Therefore, each intersection test involves three normal vectors defined by two image points each.

The procedure for the detection of the vanishing points is summarised as follows:

- The longest of all available image lines is chosen as the first line of the vanishing point.
- The test values of all combinations of this longest line and two other image lines are computed.
- Lines are clustered using the results of the testing. This usually results in several clusters.
- For the largest clusters an adjustment is set up, based on all (independent) constraints in the cluster and a line error hypothesis is tested for each line.
- Rejected lines are removed from the clusters and the adjustment is repeated until all remaining lines are accepted.
- The cluster with the largest number of lines is selected as the first vanishing point cluster.

The procedure is repeated with the remaining (non-clustered) lines to detect the other two vanishing points. More details on this procedure are found in (van den Heuvel, 1998a).

The result of the vanishing point detection procedure applied to the extracted lines of the Meydenbauer image is shown in Figure 5. The left most image corresponds to the first vanishing point and contains the longest line (264 pixels). A few lines of this vanishing point do not correspond to object edges with the same orientation, but were not removed. All extracted lines were assigned to one of the three vanishing points. The number of lines of the first, second, and third vanishing point is respectively 117, 42, and 64. Note that the third vanishing point (of the vertical lines) is at infinity in the image plane. In other words, the image is in a two-point perspective (Williamson & Brill, 1990).

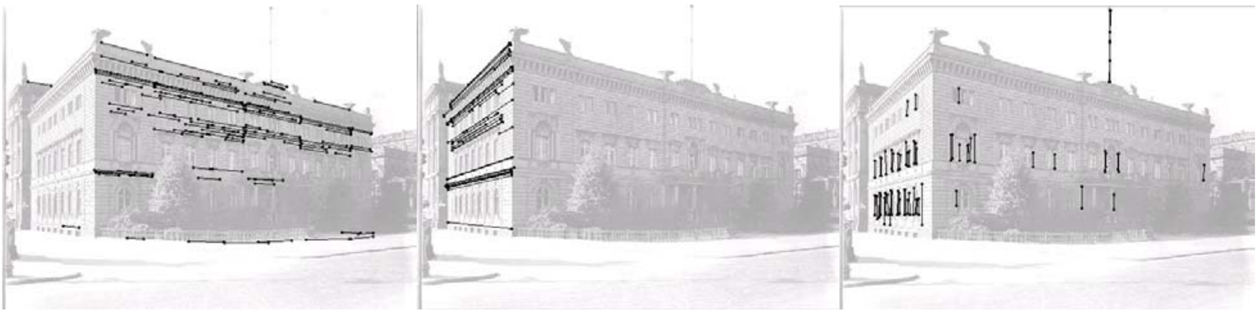

Figure 5. Result of detection of three vanishing points.

3.3 Interior orientation parameter estimation

To build the mathematical model for the least-squares parameter estimation two types of constraints are applied, i.e. parallelism and perpendicularity constraints. There are three independent perpendicularity constraints between three combinations of two object axes (*XY, YZ,* and *ZX*). The constraints are specified automatically using the vanishing point detection algorithm described in the previous section. Now the model of the vanishing point detection is extended with perpendicularity constraints and the interior orientation parameters, i.e. the position of the principle point, the effective focal length, and a parameter for the lens distortion. More details on the parameter estimation can be found in (van den Heuvel, 1999b).

The procedure for estimation of interior orientation parameters is applied to the Meydenbauer image. Trying to estimate the three interior orientation parameters using the adjusted observations from the vanishing point detection, a correlation of close to a 100% between the focal length and the principal point x co-ordinate appears. This is due to the two-point perspective. Fixing the principal point in the middle of the image in column direction, the estimation of the two remaining parameters converged in five iteration steps. Convergence is not sensitive to the approximate values. For both parameters starting values were more than 150 pixels different from the solution presented in Table 1. The formal standard deviations are based on the a priori standard deviation of 1 pixel for the endpoints of the image lines. Estimation of the radial lens distortion parameter results in a value only 2.5 times its standard deviation, and was not applied for the object reconstruction. All parameters are specified in pixels because the pixelsize was unknown and not required for the reconstruction.

Interior orientation (pixels)	Parameter	Standard deviation
Principal point y	601	12.8
Focal length	1152	9.4

Table 1. Estimated parameters from observations adjusted in the vanishing point procedure.

4 OBJECT RECONSTRUCTION

In this section, first a short overview of the line-photogrammetric bundle adjustment is presented (section 4.1). Approximate values for the parameters are required because of the non-linearity of the model. Especially in the case of single image processing, approximate value computation needs special attention (section 4.2). The application of the presented bundle adjustment procedure on the Meydenbauer image is discussed in section 4.3.

4.1 Overview of the line-photogrammetric bundle adjustment

In the line-photogrammetric bundle adjustment the image line observations (section 3.1) are related to the parameters of the object model. Although usually only the co-ordinates of the points represent the geometry of a boundary representation or B-rep, in this approach also the parameters of the object planes are incorporated in the model. The reason is the simplicity of the formulation of geometric object constraints. Two groups of parameters can be distinguished:

1 object model parameters (points and planes)

2 exterior orientation parameters

Interior orientation parameters are not estimated and have to be determined beforehand (section 3).

The basic relation of the line-photogrammetric bundle adjustment is the point-in-plane constraint. First, there is an *object point in interpretation plane* constraint (Figure 6). Second, the *object point in object plane* constraint is formulated that is very similar to the first one. More details on the mathematical model can be found in (van den Heuvel, 1999a).

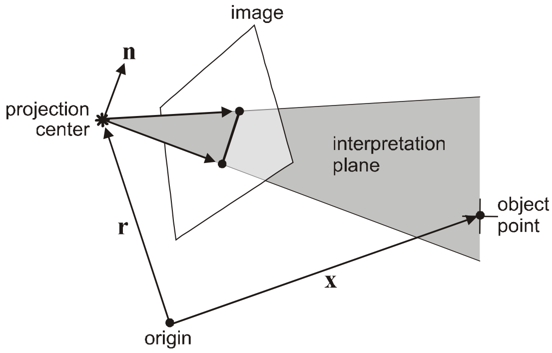

Figure 6. Object point in interpretation plane.

A number of object shape constraints have been implemented. The formulation of most of them is presented in (Hrabacek & van den Heuvel, 2000). They apply the line-photogrammetric bundle adjustment to the images of the Zürich city hall from the CIPA test dataset. The following shape constraints are available:

- Points: coplanarity, distance between two points, and co-ordinates of control points.
- Lines: parallelogram, symmetry constraint.
- Planes: angle, parallelism, and distance between two planes.

All constraints have been implemented as weighted observation equations. This has the advantage that realistic weights can be used for the shape constraints, and thus uncertainty in the constraints is taken into account.

4.2 Measurement and approximate value computation

Only a few of the automatically extracted lines are suitable for object modelling and correspond to the edges of the building façades. Many other edges show poor contrast in the image. Therefore, manual interaction is required. Not only for line measurement, but also for the specification of the topology of the B-rep, and object shape constraints.

Approximate values of all parameters have to be available to set up the linearised observation equations. With the image line measurements, object topology, and shape constraints available, the approximate values are computed in the following order:

1 Exterior orientation parameters

2 Object point parameters

3 Object plane parameters

The last two steps are then repeated until no new parameters are computed.

In the first step the direct solution that is presented in (van den Heuvel, 1997) is used to compute the exterior orientation parameters based on the measurement of 4 points (or lines) that correspond to a rectangle in object space. For the second step all available linear equations that contain the object co-ordinates are gathered. For the computation of the approximate plane parameters (step 3) the point co-ordinates from step 2 are treated as constants which results in linear relations for the computation of the plane parameters from the object point co-ordinates. Plane parameters can be computed when the co-ordinates of at least three points are available. Similarly, object point co-ordinates can be computed when three or more planes are available. These planes can be interpretation planes as well as object planes.

Another approach for reconstruction that can be used for approximate value computation is described in (van den Heuvel, 1998b). In that approach first the line observations are adjusted using redundant object constraints. Then object reconstruction is performed in a separate step using the adjusted observations and the a priori object information. The resulting reconstruction is not unique because an incomplete set of condition equations is applied. However, the co-ordinates that can be computed are good approximate values

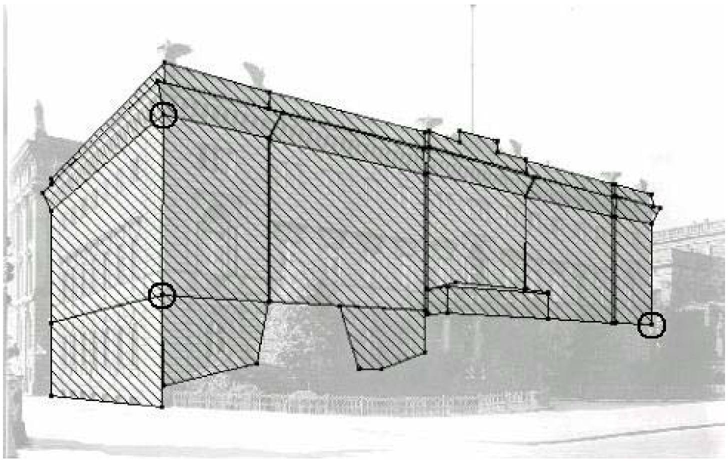

Figure 7. Manually measured points, lines, and faces.

4.3 Reconstruction using the Meydenbauer image

In Figure 7 the manual measurements are overlayed on the Meydenbauer image. Closed polygons are measured through their corner points of which the image co-ordinates are stored. Each corner point is an endpoint of at least two individual image lines and relates to one point in object space. Each closed polygon is associated with an object face and each image line with an interpretation plane (Figure 3). In this way the topology of the polyhedral B-rep is specified together with the relations between image measurements and object points. In this approach only object parts (parts of building faces) that are visible in the image are reconstructed.

	number	parameters	equations	precision (σ)
image lines	100	-	152	1 pixel
distance	1	-	1 (control)	0.1m
object points	76	228	6 (control)	0.001m
object planes	12	48	12	10^{-6}
image orientation	1	7	1	10^{-6}
point-in-plane	-	-	123	0.01m
plane angles	11	-	11	0.1deg
parallelogram	15	-	45	0.01m
symmetry	6	-	18	0.01m
totals		283	369	

Table 2. Parameters and equations in the adjustment.

In Table 2 the number of image and object features, and the related number of parameters and equations are listed. This table also contains an overview of the object constraints that were inferred from the image and the precision that was assigned to them. Although 29 faces were specified, for only 12 planes there are parameters in the model. In this way coplanarity of several faces is enforced. In Figure 7 three control points are indicated by circles. Six co-ordinates of these points have been fixed. The distance between the two points on the front of the building was derived from a cadastral map (41.39m), and processed as a distance constraint. In this way the co-ordinate system is fixed with minimum control. The formal standard deviations of the object co-ordinates (excluding control points) are summarised in Table 3. Note that the standard deviations depend on the control point choice, and the applied shape constraints and their weights. The largest residual to an endpoint co-ordinate is 2.0 pixel. Reliability parameters are not computed. However, it is noted that for some observations there is no redundancy and thus reliability is absent.

Standard deviation (m)	X	Y	Z
Average	0.080	0.095	0.055
Minimum	0.013	0.008	0.022
Maximum	0.135	0.384	0.127

Table 3. Precision of the object points (σ in meter).

The estimated exterior orientation parameters show that the photograph was taken at a distance of 34.5m (σ 0.17m) from the corner of the building at a height of 1.78m (σ 0.08m) above the lowest (ground) points of the object model.

The determined boundary representation is converted to VRML-format with textures derived from the image by a rectification for each face. Two views of the resulting object model are shown in Figure 8. The error ellipsoids are enlarged with a factor 10 relative to the model and visualise the covariance matrices of the object points. The model is available on the Internet (Meydenbauer, 2001).

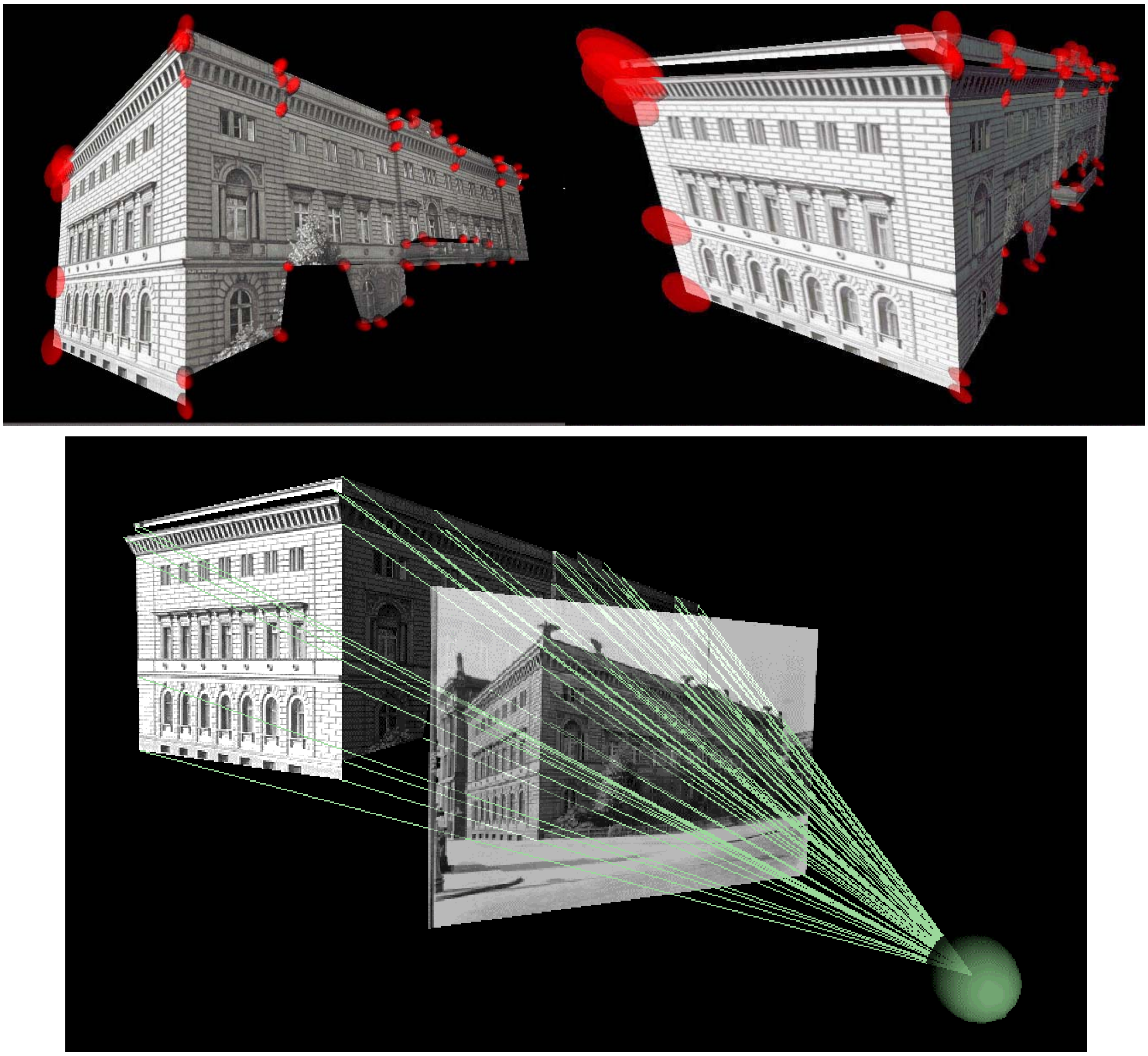

Figure 8. Top: two views of the texture mapped model, bottom: including the bundle of rays and the original image.

5 CONCLUSIONS

Methods are presented for camera calibration and object reconstruction from line measurements in a single image. No manual measurements are required for the procedure for camera calibration when vanishing point detection is successful. The parameters of interior orientation are estimated in a least-squares adjustment from image lines extracted by line-growing. A vanishing point detection algorithm infers the constraints for the adjustment. Applying the calibration procedure to a historical image of a building, the position of the principal point could not be estimated in column direction due to the two-point perspective. Estimation in row direction showed the principal point is more than 150 pixels below the centre of the image. The formal precision of the principal point is 12 pixels (1σ). The precision of the focal length is 11 pixels.

In the procedure for object reconstruction the point and plane parameters of a B-rep are estimated together with the parameters of exterior orientation using a line-photogrammetric bundle adjustment. The adjustment model is built from point-in-plane constraint equations that relate the image line measurements to the object co-ordinates, and the object co-ordinates to the plane parameters. Furthermore, the topology of the B-rep and several object shape constraints are incorporated in the least-squares adjustment through weighted observation equations. Adjustment of 100 image lines (standard deviation of endpoints set to 1 pixel) and 32 shape constraints resulted in the 3D co-ordinates of 76 points with an average precision between 5 and 10 cm.

The paper demonstrates the potential of a single image with unknown interior and exterior orientations for partial reconstruction of architectural objects. All parameters involved are estimated using a least-squares adjustment that facilitates the assessment of their precision. If available, more images with possibly different interior orientations can be included in the adjustment. A more complete reconstruction of higher quality will be the result.

REFERENCES

IAPRS - International Archives of Photogrammetry and Remote Sensing
CIPA-TG2, 2001: http://info.uibk.ac.at/sci-org/cipa/tg2_1.html, accessed May 14, 2001.

Heuvel, F.A. van den, 1997: Exterior Orientation using Coplanar Parallel Lines. 10th Scandinavian Conference on Image Analysis, Lappeenranta, 71-78.

Heuvel, F.A. van den, 1998a: Vanishing point detection for architectural photogrammetry. IAPRS, Hakodate, Vol. 32 part 5, 652-659.

Heuvel, F.A. van den, 1998b: 3D reconstruction from a single image using geometric constraints. ISPRS Journal of Photogrammetry and Remote Sensing, Vol.53, No.6, 354-368.

Heuvel, F.A. van den, 1999a: A Line-photogrammetric mathematical model for the reconstruction of polyhedral objects. Videometrics VI, 28-29 Jan. 99, San Jose, Proceedings of SPIE, Vol. 3641, 60-71.

Heuvel, F.A. van den, 1999b: Estimation of interior orientation parameters from constraints on line measurements in a single image. IAPRS, Thessaloniki, Vol. 32 (5W11), 81-88.

Heuvel, F.A. van den, 2000: Line-photogrammetry and its application for reconstruction from a single image. 19. Jahrestagung der DGPF, Essen, Publikationen der Deutschen Gesellschaft für Photogrammetrie und Fernerkundung, Vol. 8, 255-263.

Heuvel, F.A. van den, 2001: Object reconstruction from a single architectural image taken with an uncalibrated camera. Photogrammetrie Fernerkundung Geoinformation, Vol. 4, 247-260.

Hrabacek, J., F.A. van den Heuvel, 2000: Weighted geometric object constraints integrated in a line-photogrammetric bundle adjustment. IAPRS, Amsterdam, Vol. 33, Part B5, 380-387.

Karras, G.E., E. Petsa, 1999: Metric information from uncalibrated single images. Proceedings XVII CIPA Symposium October 99, Recife/Olinda, Brazil.

Meydenbauer, 2001: http://www.geo.tudelft.nl/frs/architec/Meydenbauer/, accessed May 14, 2001.

Pollefeys, M., R. Koch, M. Vergauwen, L. van Gool, 2000: Automated reconstruction of 3D scenes from sequences of images. ISPRS Journal of Photogrammetry & Remote Sensing, Elsevier, Vol. 55, 4, 251-267.

Streilein, A., 1998: Digitale Photogrammetrie und CAAD. Dissertation Nr. 12897, ETH Zuerich.

Streilein, A, F.A. van den Heuvel, 1999: Potential and limitation for the 3D documentation of cultural heritage from a single image. Proceedings XVII CIPA Symposium October 99, Recife/Olinda, Brazil.

Wiedemann, A., M. Hemmleb, J. Albertz, 2000: Reconstruction of historical buildings based on images from the Meydenbauer archives. IAPRS, Amsterdam, Vol. 33, part B5, 887-893.

Williamson, J. R., M.H. Brill, 1990: Dimensional analysis through perspective - a reference manual. ASPRS, ISBN 0-8403-5673.