

# Facade Reconstruction of Destroyed Buildings Using Historical Photographs

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## ABSTRACT

A methodology for the metric reconstruction of the planar surface of facades of destroyed buildings using historical single-view photographs has been presented in this work. The methodology is based on using a-priori object properties like linearity, parallelism, perpendicularity, symmetry etc. in addition to information extracted from the photographs. The methodology involves the determination of line segments and vanishing points and, if necessary, intrinsic camera calibration. The methodology may be a useful tool for tasks like documentation of historical architecture, surveying, and restoration. Reconstruction examples and results of facades of destroyed buildings are presented and error estimation results are given.

## 1 INTRODUCTION

Historical buildings often have been destroyed or damaged by natural phenomena and human activities. But in recent times people are interested in reconstruction of destroyed buildings in order to restore or rebuild the buildings or just for documentation. Unfortunately, the reconstruction of destroyed historical buildings poses a great problem owing to the lack of architectural records in most cases. Historical photographs are the only means available for this task. But usually such photographs do not have metric properties. In the case of historical photographs stereo views are not to be expected. So one may give up to determine the metric properties of the reconstructed model or, and this will be the purpose of this work, find a method for metric reconstruction using only image information.

Assuming that neither the camera information nor any reference points are available, projective 3D-2D-mapping is not reversible and hence metric reconstruction is theoretically impossible. However, certain image information may be extracted from a photograph by a human observer using common reception patterns together with usual construction rules. These construction rules, if not obviously violated, should complete our a-priori information about the imaged architectural object. Mainly, these are feature oriented properties like linearity, parallelism, perpendicularity, and symmetry.

Assuming that such properties hold, the observer has an imagination of the object shape, e.g. one supposes lines to be parallel or perpendicular and surfaces to be planar, orthogonal, etc. This information should be included in monocular reconstruction algorithms and denoted by a-priori knowledge or information.

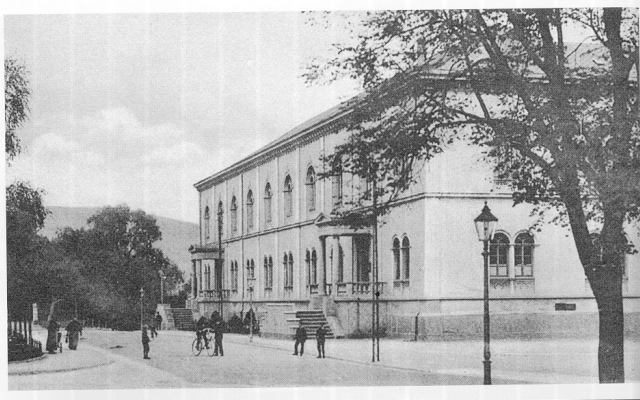


Fig. 1: Historical photograph of the university library in Jena (Germany), destroyed during world war two



Fig. 2: View of destroyed buildings in Jena

The idea of architectural object documentation using photographs is due to Meydenbauer (1834-1921). He was the founder of the "Kgl. Preußische Meßbildanstalt" in Berlin (Germany) in 1885. His aim was to collect architectural records together with photographs of national and international historic monuments in order to make possible a later reconstruction of the buildings in the case of destruction or damage by natural phenomena or wars. In order to do this he developed a methodology which allowed the metric object reconstruction from his photographs together with the stored camera parameters (Meydenbauer 1912). Unfortunately, many

documents and cameras of the Meydenbauer archive have been destroyed during world war two. So one of the reasons to develop algorithms for facade reconstruction was to get metric properties from the Meydenbauer images without camera information. More information about Meydenbauer can be found (Li 1997 and Hemmleb 2001).

Surely, in recent times methods for object reconstruction using single views have been developed and improved and numerous publications dealt with this problem. Liebowitz (1998 and 1999) proposed in his studies methods for the metric rectification of planes. His work involved the removal of projective and affine distortions. Van den Heuvel (1998a) gives a reconstruction method using and formulating geometric constraints. Becker and Bove (1995) suggested a method for 3D model extraction from uncalibrated views. Debevec (1996) presents a photogrammetric modeling technique. Suggestions concerning the metric rectification of a plane used by Hemmleb (1999) are similar to those of Liebowitz. He demonstrated this method on images of destroyed buildings. The methodology of Petsa (1993) and Karras (1999) was based on the estimation of intrinsic camera parameters and exterior orientation by analysing vanishing point co-ordinates and was also applied on images of destroyed buildings.

Although some methods have been proposed, a number of problems still persists depending on the individual mapping conditions. Especially the precise determination of principal point may be a difficulty which is essential for accurate image transformations. The main aim of this work is to improve and complete existing reconstruction methods and to add some new procedures.

## 2 IMAGE PREPROCESSING

### 2.1 Radial Lens Distortion Correction

Photographs of architectural objects are often taken using a wide-angle lens which usually suffer from radial lens distortion. Since the lens information is not at our disposal we have to determine if any radial distortion exists and then work for their removal. A methodology was developed to detect and correct these distortions using only single images. Assumptions on linearity of the imaged objects are explained elsewhere (Bräuer-Burchardt and Voss 2000a). The distortion function can be expressed as

$$r = \frac{r'}{1 + d_2 r'^2 + d_4 r'^4} \quad (1)$$

with  $r$  the undistorted and  $r'$  (measured in the image) the distorted distance of an image point to the symmetry centre  $P$  of distortion and coefficients  $d_2$  and  $d_4$ . Using this model an approach for sufficient exact calculation of the distortion coefficients  $d_2$  and  $d_4$  and the symmetry point co-ordinates of distortion under the assumption of well distributed extractable points throughout the image area was developed. When points on straight lines are not well distributed, the algorithm may fail.

Since the mentioned algorithm requires only linearity, vanishing points are not required at this stage. With this we are able to determine whether significant radial lens distortion exists. The iterative algorithm works as follows:

Input: single image with points on (3D-scene) straight lines extractable

Output: coefficients of the distortion function and co-ordinates of the symmetry point of the radial distortion

1. Extract points assigned to a number of  $n$  straight lines
2. Choose a starting value for the symmetry point (usually the image centre)
3. Calculate the distortion coefficients  $d_2$  and  $d_4$  within a least squares task
4. Improve the symmetry point co-ordinates using a quality measure
5. Test the finishing criterion, goto 3 or 6
6. End of the algorithm

Alternatively, depending on applicability, other methods (Becker and Bove 1995, Prescott and McLean 1997, van den Heuvel 1999) may be used.

### 2.2 Vanishing Points and Intrinsic Camera Parameters

In the pinhole-camera model, a bundle  $G$  of parallel straight lines intersects in one point of the image plane, the vanishing point  $Q$  of  $G$ . Several methods for the determination of vanishing points have been proposed, e.g. (van den Heuvel 1998b). The procedure we used is described elsewhere (Bräuer-Burchardt and Voss 2000b) and shall not be repeated here in detail.

Considering three orthogonal directions of the 3D-object and their vanishing points  $Q_1$ ,  $Q_2$ , and  $Q_3$  in the image plane, it can be shown (Caprile and Torre 1990) that the triangle  $Q_1Q_2Q_3$  together with the principal point  $P$  form an orthocentric system. The principal point is the intersection point of the heights of the triangle  $Q_1Q_2Q_3$ . Let  $P=(X, Y)$  be the principal point,  $f$  be the effective focal length, i.e. the distance of the projection centre from the image plane and the vanishing point co-ordinates be  $Q_1=(\xi_1, \eta_1)$ ,  $Q_2=(\xi_2, \eta_2)$  and  $Q_3=(\xi_3, \eta_3)$ . Then the three vectors

$$\begin{aligned}\mathbf{v}_1 &= (\xi_1 - X, \eta_1 - Y, -f)^T, \\ \mathbf{v}_2 &= (\xi_2 - X, \eta_2 - Y, -f)^T, \\ \mathbf{v}_3 &= (\xi_3 - X, \eta_3 - Y, -f)^T\end{aligned}$$

are equal to the unit vectors of the three considered orthogonal directions up to a normalising factor. As it holds

$$\langle \mathbf{v}_1, \mathbf{v}_2 \rangle = \langle \mathbf{v}_2, \mathbf{v}_3 \rangle = \langle \mathbf{v}_3, \mathbf{v}_1 \rangle = 0$$

the effective focal length  $f$  can be determined by the principal point  $P$  and two of the three vanishing points:

$$f = \sqrt{-\left[(X - x_i)(X - x_j) + (Y - y_i)(Y - y_j)\right]}. \quad i, j \in 1, 2, 3; i \neq j \quad (2)$$

Then the third vanishing point  $Q_k = (\xi_k, \eta_k)$  can be calculated by:

$$\xi_k = X + \frac{f^2}{q^2}(X - x_L) \quad \eta_k = Y + \frac{f^2}{q^2}(Y - y_L) \quad k \in 1, 2, 3 \quad (3)$$

where  $p_L = (x_L, y_L)$  is the intersection-point of the perpendicular line from  $P$  to the straight line through  $Q_i$  and  $Q_j$  and  $q$  is the distance between  $P$  and  $p_L$ .

### 2.3 Principal Point Transformation

Using the principal point transformation (PPT) proposed by Kanatani (Kanatani 1988) similarity mapping of any plane perpendicular to one of the three directions can be achieved.

This transformation is performed in such a way that a given image point  $p = (\xi, \eta)$  is mapped onto the principal point  $P$ . That means the ray  $t$  through  $p$  and the projection centre will be turned into the optical axis. All planes orthogonal to  $t$  are parallel to the image plane after the transformation. More precisely, they are mapped from their original 3D world co-ordinates by similarity transformation to the 2D-image plane thereby removing projective and affine distortions.

Now one of the three vanishing points, e.g.  $Q = (\xi_q, \eta_q)$  is transformed into  $P$ . This mapping is a special 2D-2D-transformation, characterised by five parameters  $\xi_q, \eta_q, X, Y$  and  $f$  only (Kanatani 1988, Bräuer-Burchardt and Voss 2001).

This method yields good results if all the three vanishing points are not very far from the principal point. Otherwise if one of the vanishing points is at infinity, the vanishing point calculation becomes erroneous and the calculation of the principal point and the focal length becomes numerically unstable. If the conditions are "good", rectification, i.e. similarity mapping of the main planes of the object can easily be obtained as demonstrated by Fig. 3.



Fig. 3: Original image with vanishing point triangle and principal point, rectified facades

Unfortunately, two main reasons hinder such a straightforward solution. First, there are often only two instead of three perpendicular directions represented in the image which means either the principal point or the focal length should be known which cannot be otherwise assumed. Second, a lot of historical photographs are taken with horizontal optical axis of the camera, i.e. the vertical vanishing point is at infinity which also prevents the calculation of the principal point by the aforesaid method.

### 3 PLANE RECTIFICATION TECHNIQUES

#### 3.1 Rectification with Two Vanishing Points

Having only two vanishing points, the principal point  $P$  should be known to use the PPT for image rectification. Then  $f$  and the third vanishing point can be calculated according to (2) and (3). If only  $f$  is known two solutions for  $P$  are obtained one of which holds good. The false solution can normally be recognised and removed. Unfortunately, the knowledge of the principal point or the focal length cannot be assumed using historical photographs. It is usually unknown, whether the photograph represents the whole negative film which would imply the principal point  $P$  to be situated near image centre  $C$ . Hence the identification of  $P=C$  may lead to considerable errors.

Supposing perpendicularity, rectification of the plane of interest can be achieved by transforming the finite vanishing points into infinity. Thus parallel lines of the object become parallel in the image and perpendicularity may be used to rectify the image. But the scaling factor between the vertical and horizontal image co-ordinate axis is still unknown. This factor can be determined if one of the following conditions (Liebowitz 1998) is satisfied

- a length ratio of two nonparallel directions is known
- two length ratios of nonparallel directions are equal
- an angle (not the right angle between x- and y-axis) is known
- two angles formed by nonparallel lines are equal
- a curve is known to represent a circle arc (Hemmler 1999)

Figures 4 and 5 show two examples for facade rectification. If no of the discussed conditions is satisfied the remaining scale factor cannot be determined.



Fig. 4: Original image and rectified plane using a circle arc



Fig. 5: Image rectified by one known window aspect ratio

#### 3.2 Rectification with Horizontal Camera

A typical situation is the horizontal adjustment of the optical axis of the camera parallel to the ground plane. All vertical lines of the object are also parallel in the image and the vertical vanishing point is near infinity; see the view in Fig.4 of the totally destroyed Municipal-theatre of Athens (Greece) which was already analysed for reconstruction (Karras 1999). Although a determination of the principal point and focal length from the vanishing point triangle cannot be robust, Karras tried to calculate the vertical vanishing point. But without using additional information it would be difficult to estimate the accuracy of the obtained reconstruction result.

Li (Li 1997) suggested in such cases the assumption of the x-co-ordinate of the principal point to be central. But this might have two drawbacks. First, it is usually unknown whether the photograph is only a section of a larger image thereby the difference between the image centre and the actual principal point could be considerable. Second, the camera construction might imply a principal point shift which is not unusual for historical photographs.

Supposing that the vanishing points of two perpendicular directions (normal vectors to the facade planes) are detectable, both planes can be rectified with the method described in the previous section if one of the conditions holds. If not, we may use symmetries in both facade planes.

Below we give a method to determine the principal point of such images. Assuming that the vertical vanishing point  $Q_1$  to be at infinity and the other two vanishing points  $Q_2$  and  $Q_3$  of the normal directions of the facade planes can be determined. For this method it is essential that the length ratio of two pairs of nonparallel edges, each pair on one of the two facade planes, be equal. Let the length ratio defined by the four (or three) coplanar 3D-points be  $P_1^*, P_2^*, P_3^*, P_4^*$  and  $P_5^*, P_6^*, P_7^*, P_8^*$ , respectively, having their image points  $P_1$  to  $P_8$  (see Fig. 6). It should hold

$$\frac{\overline{P_1^* P_2^*}}{\overline{P_3^* P_4^*}} = \frac{\overline{P_5^* P_6^*}}{\overline{P_7^* P_8^*}}.$$

From the model assumption it follows that  $P$  is located on the line  $Q_2Q_3$  between the two vanishing points. Applying the PPT we get the image points  $P_1', P_2', P_3'$  and  $P_4'$  and  $P_5', P_6', P_7'$  and  $P_8'$ , respectively, in a transformed image  $I'$ . If we use  $Q_2, Q_3$ , and the true value for  $P$  as parameters of the PPT, the planes  $E_2$  and  $E_3$  are correctly rectified implying

$$\frac{\overline{P_1^* P_2^*}}{\overline{P_3^* P_4^*}} = \frac{\overline{P_1' P_2'}}{\overline{P_3' P_4'}} \quad \text{and} \quad \frac{\overline{P_5^* P_6^*}}{\overline{P_7^* P_8^*}} = \frac{\overline{P_5' P_6'}}{\overline{P_7' P_8'}}. \quad \text{Thus} \quad \frac{\overline{P_1' P_2'}}{\overline{P_3' P_4'}} = \frac{\overline{P_5' P_6'}}{\overline{P_7' P_8'}} \quad \text{must hold.}$$

Consider now the function

$$h(x, y, P_1, P_2, P_3, P_4, P_5, P_6, P_7, P_8, Q_2, Q_3, f) = \frac{\overline{P_1' P_2'}}{\overline{P_3' P_4'}} - \frac{\overline{P_5' P_6'}}{\overline{P_7' P_8'}}$$

with free parameters  $x$  and  $y$  as principal point candidates from the range  $Q_2Q_3$  and points  $P_1$  to  $P_8$  extracted from the image. The function is zero just at the true principal point co-ordinates  $(X, Y)$ . Determination of  $(X, Y)$  is achieved by interval separation starting from  $Q_2$  and  $Q_3$ . The value for  $f$  we obtain according to formula (2).

Figures 6 and 7 show two examples of destroyed historical buildings which are desired to be reconstructed. Figures 6 shows the Municipal theatre in Athens (Greece) which was analysed for reconstruction (Karras 1999) as well as the Kommandantur in Berlin (Germany) in Fig. 7 (Hemmler 1999, van den Heuvel 2001).

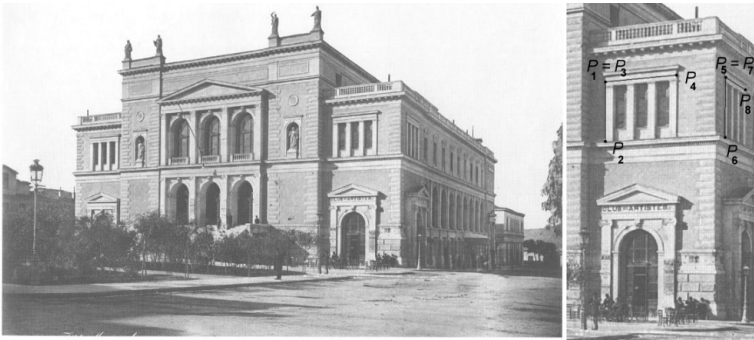


Fig. 6: Left: historical image of the totally destroyed Municipal theatre in Athens, right: points forming an equal length ratio on both facade planes



Fig. 7: View of the Kommandantur in Berlin (Germany) from the Meydenbauer archive

In both images the two visible facades of the buildings were rectified using the presented method. The resulting images are shown in Figs. 8 and 9.

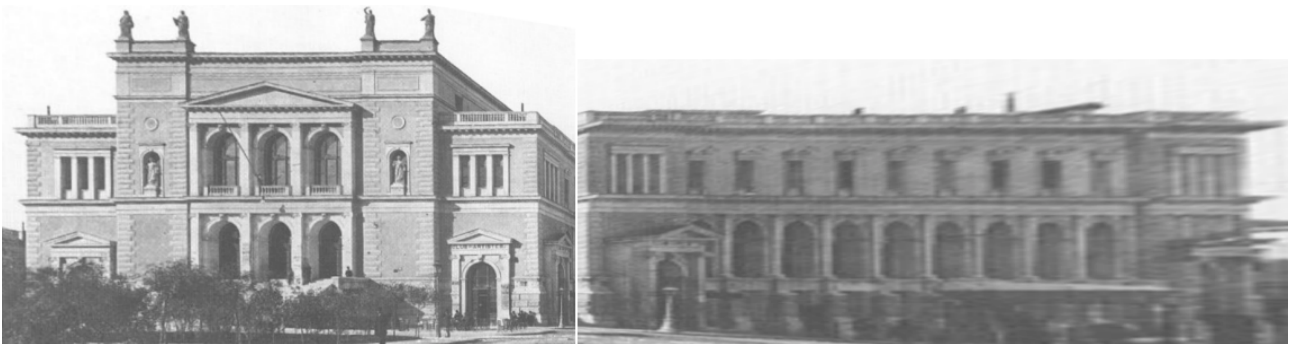


Fig. 8: Rectified facades of the Municipal theatre

#### 4 VISUAL IMAGE IMPROVEMENT

Concerning to the angle between the optical axis and the normal vector of the rectified facade the spatial resolution of the rectified images is not homogeneous. Hence the visual image quality (given) by the user is not acceptable in some parts of the image. Here symmetry properties may help to achieve an image improvement. The idea is to search for same or similar parts in the rectified image

with higher spatial resolution. This can be done interactively by the user with high effort or using algorithms for symmetry detection or object repetition. One method which can be used in such tasks is the Shift Detection by Restoration (SDR) technique.

The SDR method (Suesse 1999) is a robust technique to determine the translation between two images. It is based on detection of the shifted delta impulse using some well known restoration techniques. In principle, there is constructed a convolution image of the two entire images and the peak in this convolution image corresponds to the translation between the images. This technique can be used to find automatically the positions of repeated objects or symmetry axis in the rectified image.

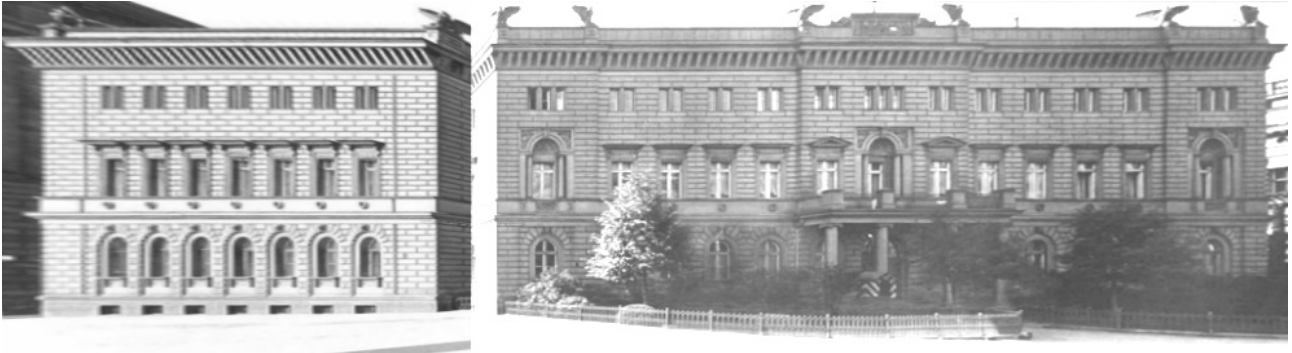


Fig. 9: Rectified facades of the Kommandantur

The occurrence of repeated objects which is typical for building facades may be considered as a special case of the symmetry property. Differences are expected concerning image quality in the case of rectified images, for the resolution is lower in the originally smaller mapped parts of the image. When some object parts are identical, the user may replace some of the image parts by those of higher quality. Especially windows may represent this typical situation as shown in Fig. 10.

As obviously to be seen in our example image there are a number of similar windows. According to the different spatial resolution depending on the angle of the optical axis in the original image the windows are less or more disturbed. The idea to improve the appearance of the image is to substitute disturbed or noisy parts of the object by those with low disturbances. The windows of best quality of our example are the rightmost in the 1<sup>st</sup> and one of those in the centre in the 2<sup>nd</sup> floor. This information should be given by the user to select the right window of the first and the 4<sup>th</sup> or 5<sup>th</sup> window (from right) of the second floor as reference objects.

The windows may be replaced interactively by the user or automatically by applying the SDR technique. Using SDR the reference object is shifted into the centre of a new image with same size and the candidates of the shift vector are the peaks of the deconvolution image. After substitution of the strongly disturbed windows by the reference windows there still remain errors of the front view of the facade caused by occlusions and other disturbances (shadows). In order to make further improvements of the resulting image one can determine vertical symmetry axis of the whole facade or parts of it, because house facades often have the property to be symmetric.

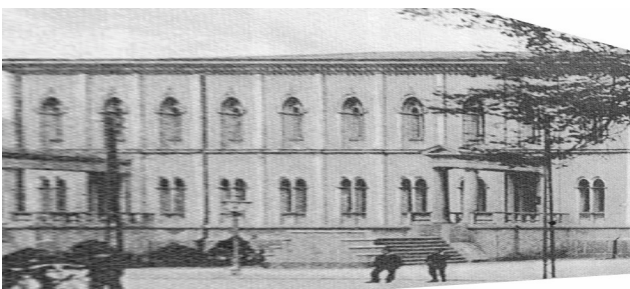


Figure 10. Rectified view of the library building

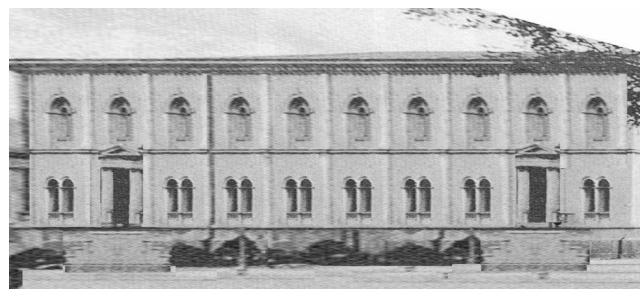


Figure 11. Rectified view with replaced image parts

The procedure of the replacement of parts of the imaged facade is certainly connected with some effects to the reconstruction result. The most important one is the improvement of the object information. Image disturbances or parts with low information are covered. Usually a better rendering of the texture is reached. On the other hand, some individual information is lost. For example small details like opened windows, balcony plants or similar things which do not repeat would be lost by replacement. However, for the purpose of a facade reconstruction these effects of information lost are positively desired.

Another effect of the replacement procedure which should be considered is surely not desired. There may occur systematic errors of the position of the replaced objects. For example in some facade images, the windows in some area of the image may be slightly shifted. This systematic error occurs when the window planes are a little bit behind the main facade plane and should be reduced by a-priori knowledge. For instance it could be assumed that the horizontal distance between neighboured windows in the same floor are always equal. Then the detected distance of the other part of the image or an average value could be used. Finally, advantages and

disadvantages of an actual replacement procedure should be evaluated by the fact, whether an improvement of the desired result is reached. The procedure of object replacement, of course, always needs some certain effort of interaction with the user. Similar to the object replacement procedure using repetitions is the symmetric completion. The SDR technique may be used again to find automatically the symmetry axis. In our example (see Fig. 11) this was used to produce the view of the stairs.

## 5 RESULTS

A number of images was analysed with the presented methods. The quality of the resulting rectified facade views was different and can often be evaluated only intuitively (see Fig. 12). In the case of destroyed buildings it is very difficult to estimate the error of measurements obtained by the rectified images if no camera information is available. Therefore several reproducibility experiments have been performed with existing objects and cameras. In the following the experiments are described and the main quantitative results are given. A more detailed documentation of the results has already been published (Bräuer-Burchardt and Voss 2001).

In the first experiment we tried to estimate the accuracy of the principal point determination using three vanishing points. We imaged a number of buildings with a SLR-camera and calculated the principal point co-ordinates according to the model described in section 2.2. The coefficients of variation for the principal point co-ordinates were about 5% and for the focal length 1.4%. The error of the metric measurement resulting from the erroneous intrinsic camera parameters depends on the error of vanishing point calculation and additionally on the angle between the optical axis of the camera and the normal vectors of the rectified planes. Thus this error is difficult to estimate. We reconstructed a building with known measures and determined the mean percentage error of the aspect ratio of all its facades. The coefficient of variation was found to be about 2%. Additionally, the error of the principal point co-ordinates using the method described in section 3.2 was determined by the following experiment. A number of photographs of buildings with the requested property of an equal aspect ratio on different facades was made by a horizontal adjusted camera without changing the camera parameters. We used pairs of points with short, medium, and long distances for the aspect ratio and considered different angles ( $15^\circ/75^\circ$  up to  $45^\circ/45^\circ$ ) between optical axis and facade normal vectors. Whereas longer distances between the points of the same length ratio improved the accuracy, no significant angle dependence could be found.

Figure 12 shows a possible negative effect in image rectification. Whereas the facade of the right building seems to be correctly rectified, the facade of the left house is not. This results from the deviation of the supported preconditions. In this case the facades are not in parallel planes which requires the separate analysis and more interactive effort.



Fig. 12: Rectified view of the image shown in Fig. 2.

## 6 SUMMARY, DISCUSSION, AND OUTLOOK

A methodology to produce similarity mappings of planar surfaces with the input material of only single view photographs was presented. The technique is deemed suitable to reconstruct destroyed historical buildings or parts of them since there is a lack of considerable information such as architectural records and camera information. We depicted the use of feature conditions such as linearity, parallelism, perpendicularity, and symmetry together with vanishing points for the metric reconstruction of plane facades of the imaged buildings.

Concerning the geometric constraints our methodology is similar to others (van den Heuvel 1998, Becker 1995), especially in relation to vanishing points and perpendicularity. But we did neither focus here on probabilistic representations for uncertain geometry nor the determination of absolute orientation. A comparative study with the methods of other authors concerning the uncertainty of reconstructed measures has not yet been performed but should be one of the aspects of our future work.

However, we presented some remarkable amendments and additions to existing methods. We also discussed about the additional properties affecting metric reconstruction and presented a new technique to achieve correct rectification. Although exact metric measurements cannot be achieved using single images only, images with sufficient reconstruction accuracy can be obtained using the discussed methodology as depicted by some of the included examples.

The most difficult issue in the reconstruction using single images is the estimation of errors and the determination of the measuring accuracy which attributes to the fact that image properties for historical photographs are different and also because of the dependency of the reconstruction methodology on the properties of the imaged object itself. Although experiments using measurable objects were performed a main aspect of the future work should be to search for methods which improve reproducibility.

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