USING FREE - FORMED SPATIAL CURVES FOR OBJECT RECONSTRUCTION FROM DIGITAL IMAGES

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Abstract

Recent developments in the field of digital image processing suggest to use line information for object reconstruction instead of or in addition to traditional methods based on distinct points. We have chosen a car as a real-world test object. Images were taken under natural illumination and scanned with a high precision scanner. Point measurement for image orientation was supported by image matching techniques. After orientation, edges were extracted from the digital images, and the object curves were reconstructed by bundle block adjustment. For that purpose, a new concept using free-formed curves was applied. The results show that high accuracy can be achieved by using the methods described in this paper.

1. Introduction

One of the main tasks in photogrammetry is the geometrical reconstruction of 3-D objects from 2-D images. Common reconstruction methods are based on distinct points of the object surface. However, it seems more appropriate to use edge features in cases where no or hardly any point information is available on the object. Edge features can be extracted automatically from digital images using some edge detection algorithm. If homologous edges can be found in two or more images, the curve can be reconstructed in object space by spatial intersection of homologous bundles of rays. Several methods for the reconstruction of "simple" curves such as straight lines or circles have been described in literature, e.g. [8]. In this work we want to demonstrate the possibility to reconstruct objects from digital images using free-formed spatial curves.

2. The Test Object

Figure 1: car image

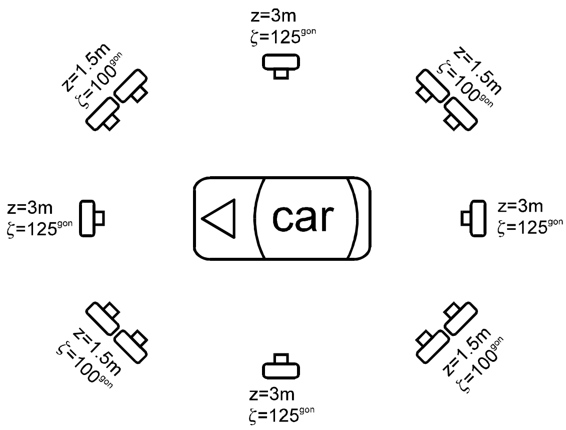


Figure 2: arrangement of photos

A car was chosen as a test object for digital object reconstruction. 12 images were taken from that car using a P31 terrestrial metric camera with a principal distance of 100 mm. The camera was focused to 4m, thus achieving an average image scale of 1:40. The image format was 12 cm by 9 cm. Figure 1 shows one of the images; the arrangement of the photographs can be seen in figure 2. It was mainly chosen according to considerations about the depth of field. For orientation purposes, 116 points were targetted on the car surface using black adhesive paper dots with a diameter of 8 mm. Some of these targets were observed geodetically to provide the scale of the photogrammetric block. In addition, check points on some of the object curves were measured, too.

In order to get digital images, the photographs were scanned with a resolution of 15 µm using a Zeiss PhotoScan PS1. Due to the large image format we obtained digital images with 50 MB each.

3. Image Orientation

For inner orientation, the fiducial marks were matched using an area based algorithm. A synthetical template is moved in the search image, and the cross correlation coefficient of the grey levels is calculated at each position. The position of the fiducial mark corresponds to the position of the maximum of the cross correlation function. Subpixel estimation is performed by a polynomial approximation of that function and by determination of the position of the maximum of the polynomial. Thus, the fiducial marks could be located with an accuracy of ±1/3 pixels [7].

The measurement of the targets was done using a "digital mono comparator". The targets are interactively identified on screen and their final position determined by calculating the weighted centres of gravity of the gray levels within a small window [4]. The accuracy of the position of the targets was estimated to be about ±1/2 pixels.

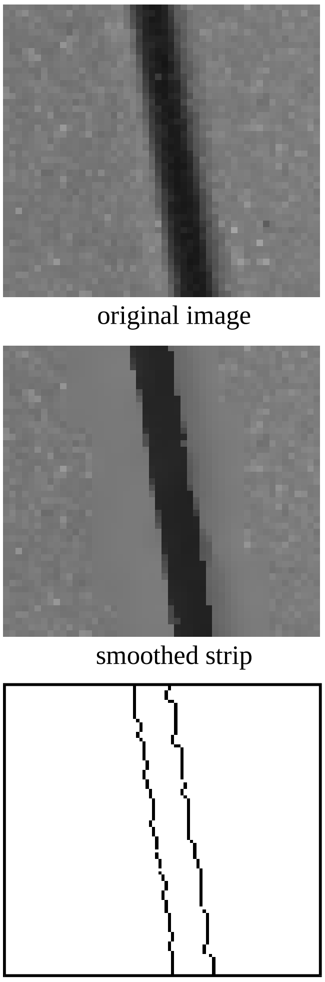
In addition to the targets, 10 non-targetted points distributed symmetrically on the car had to be identified interactively in the images, thus enabling the definition of an object coordinate system whose xz-plane is identical to the symmetry plane of the car body.

The geodetical observations together with the image coordinates of both the targetted and the non-targetted points provided the input for bundle block adjustment. Altogether 3491 observations were used to determine 1347 unknowns; 90 observations were eliminated as gross errors by a robust estimation technique. The r.m.s. errors a posteriori of the targets and the non-targetted points were estimated by ±6.5 µm and ±27 µm, respectively. This corresponds to an average 3-D r.m.s. error of 0.5 mm of the object points, the greatest error being 1.1 mm. The accuracy of the adjustment was mainly limited by the uncertainity of the symmetry assumptions. As a result of bundle block adjustment, the orientation parameters of the images were obtained.

4. Edge Detection

Obviously the test object can be well described by the curves which are visible on the car. These curves are border lines between different parts of the car body, e.g. a slit between two doors.

Depending on the viewing direction and the illumination these curves appear in the digital images as more or less sharp grey level edges which have to be extracted. In order to reduce the computational effort required for edge detection, irrelevant regions of the images are masked and only pixels in "interesting" regions are used. A detail with two edges is shown in figure 3. First the partly noisy images are prepared for edge extraction using an edge-preserving smoothing filter [1]. Then the smoothed images are convolved with a modified LoG-kernel of 5x5 pixels. Candidates for edge points are found at zero-crossings of the convolved images. The algorithm delivers a binary image of candidates with a resolution of 0.5 pixels. Now neighbouring candidates are connected to form segments which should be as long as possible. In this step, gaps which are smaller than 2 pixels are bridged. Finally, edge segments which are likely to belong to the same object line are joined together automatically [6]. The results of edge detection in one of the images can be seen in figure 4.



candidate pixels

Figure 3: door slit

As contrast was rather low in certain parts of the images, the edge detection and tracking algorithm delivered short edge segments in some cases. Thus, single parts of one object curve had to be joined together interactively. Tests have shown that longer segments could be derived from images of lower resolution, e.g. 30 µm. Combining the results derived from images along the image pyramid promises to get longer segments of high geometrical accuracy.

Figure 4: results of edge detection in one of the images. The regions outside the car body have been masked.

Interactive editing is also necessary for the identification of homologous edges in different images although automation of this step appears to be possible.

As a result we now obtain two or more homologous bundles of image rays for one object curve, and the curve can theoretically be found as the intersection of all these

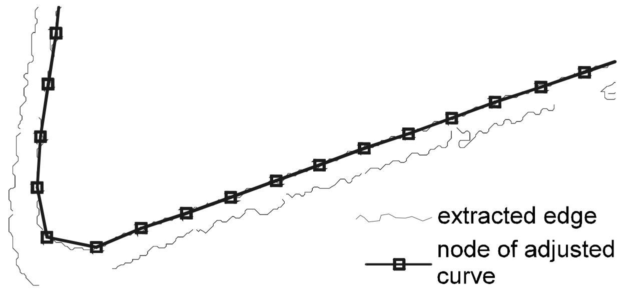


Figure 5: representation of the extracted edge by adjusted nodes (right back door)

bundles.

For reasons of data reduction and smoothing, the edges are first approximated in the images by splines with equidistant node points. These node points are used as observations for the reconstruction of the curve instead of the original edge points (figure 5).

5. Reconstruction of Object Curves

5.1 Basic Concept

Figure 5 shows the basic concept of object reconstruction using free formed curves. This concept was first published in [2]. We have recorded points (e.g. *P'*) from the images of the original curve Φ in the way described in section 4. Note that in general it is not possible to find homologous edge points in different images. The unknown three dimensional curve point *P* corresponding to the two dimensional image point *P'* is located on its image ray running from the projection centre through the image point. So, a "bundle" can be formed by all relevant rays of an image. Now, the curve *S* can be adjusted to the bundles of rays coming from two or more images.

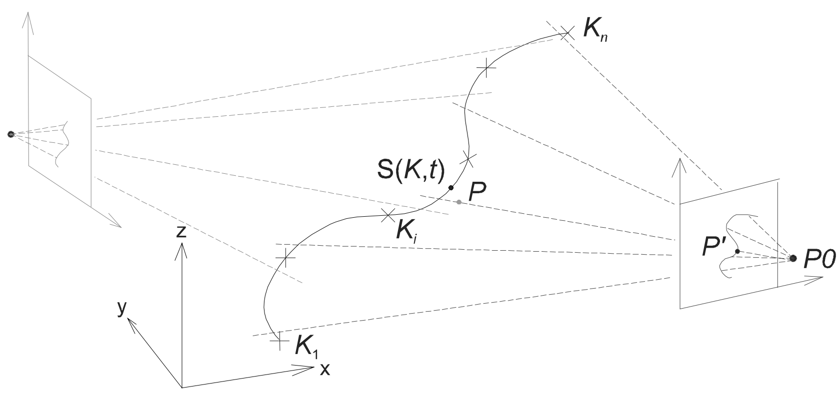


Figure 5: basic concept of curve reconstruction

The curve *S* which shall be the best possible reconstruction of Φ is described by a series of cubic polynomials, each representing one curve segment. These curve segments are joined together at node points with at least the first derivations of the polynomials being continuous. Well-known examples for such "joined cubic polynomial curves" are cubic splines or Akima curves.

All these considerations lead us to an adjustment problem which can be formulated as follows. We have observed image coordinates of a certain (huge) number of points *P'* in different images (i.e. the nodes of the smoothing splines, see section 4), and we have also observed that these points are located on the same curve Φ in object space. The well-known observation equations for an image point can formally be written as:

$$P' + v_{P'} = F(P0, R, P) \tag{1}$$

In equation (1), *P'* represents the observed image point, $v_{P'}$ the vector of residuals, *P* the unknown object point and *P0* and *R* represent the projection centre and the rotational parameters, respectively.

The sentence: "*P* is located on the curve *S*." in a mathematical sense means that the distance $\overline{S}$ between *P* and *S* is observed to be 0. Thus, the observation equation can be written as:

$$\overline{S} + v_{\overline{S}} = 0 + v_{\overline{S}} = F(S(K,t), P) = S(K,t) - P \tag{2}$$

Note that the shape of *S* is completely described by a set of node points *K*. Parameter *t* describes the position of point *P* on *S*.

As can be seen from equations (1) and (2), the unknowns of our adjustment are the coordinates of the node points (*K*), the positions of the points along the curve (*t*) and the object coordinates of the curve points (*P*). Theoretically, the orientation parameters of the images could also be considered to be unknowns. One effect of considering parameters *t* unknown enables optimization of the positions of the nodes both laterally and along the curve ([3], pp. 11-15). This might cause a collision of nodes in regions of maximum curvature. In order to prevent this, additional observations for the positions of the node points along the curve can be introduced. For a detailed description of the algorithm, see [3].

As the observation equations are not linear, approximate values for the unknowns are required for bundle block adjustment. The approximate position of each curve point is obtained from the intersection of its image ray with the polygonal pyramid formed by the rays of another image. As soon as approximations for all curve points are available, the nodes are distributed in regular intervals along the polygon of object points. All the algorithms described in this section were implemented into the universal bundle block adjustment system ORIENT [5].

5.2 Reconstruction of our Test Object

Using the observed image points (see section 4) and the orientation parameters (section 3), we can reconstruct the object curves iteratively by spatial intersection as described in the previous section. In our test, the orientation parameters were assumed to be constant. The iterative process of curve adjustment consists of two main steps alternately applied until the expected accuracy is achieved:

1. adjustment with a given number of nodes
2. insertion of additional nodes in the intervals containing points with the greatest mean residuals

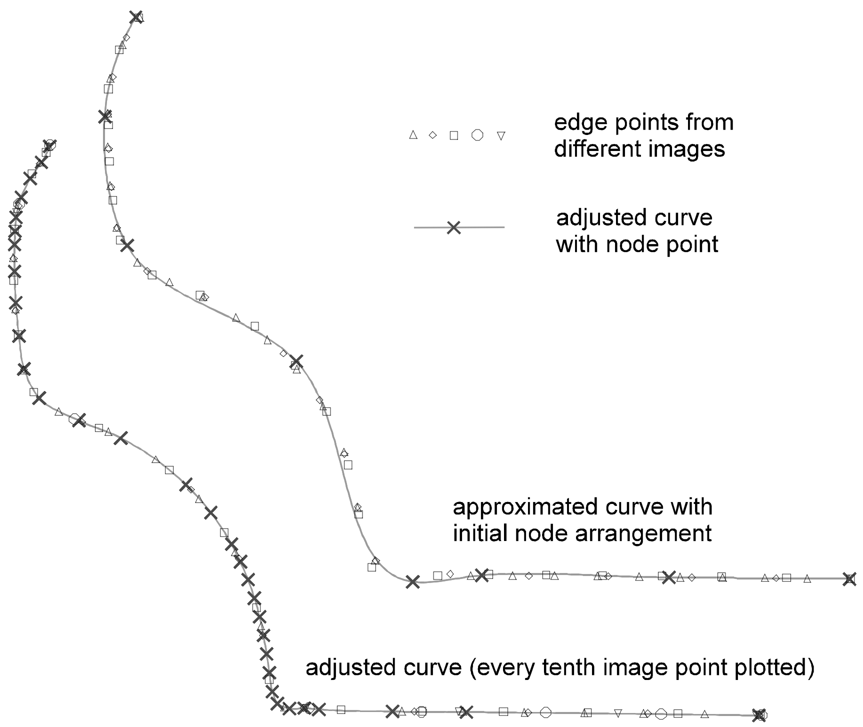


Figure 6: reconstructed curve (right back door): approximated and final version

Good approximate values for the node points are essential for a nice convergence behaviour of curve adjustment. Applying the algorithm described in the previous section results in rather good approxima-tions for the object points. Experi-ence shows that it is advisable to carry out the first iteration of curve adjustment using these approxi-mated object points as constants in order to get a better initial distribution of node points (figure 6).

Figure 6 shows the reconstructed curve adjusted to five bundles of rays. Note that in general there will always be images in which only parts of the curve are visible. Due this fact and due to geometrical reasons it is necessary to use more than two images to achieve reliable results. Dangerous configurations are described in [3] (pp. 101-106). An axonometric plot of the reconstructed car can be seen in figure 7.

No. images	No. edge points	r.m.s error in image	max. res. in image	No. curves	No. nodes	mean r.m.s on object	max. r.m.s. on object
12	15704	7 µm	60 µm	44	501	0.5 mm	2.5 mm

Table 1: results of curve adjustment
(r.m.s. errors refer to edge points in image and object coordinate systems, respectively)

The results of curve reconstruction can be seen in table 1. The r.m.s. errors are theoretical values resulting from inversion of the normal equation matrix. As mentioned in section 2, check points were also measured geodetically on some of the lines. The average distance of these check points from the adjusted curves was 1.1 mm, and the maximum distance was 1.7 mm. Another plausibility criterion is symmetry of the adjusted curves. Figure 8 is a plot of curves of the front of the car superimposed by mirrored curves of the opposite side. The greatest discrepancies appear at the side window rubber seal.

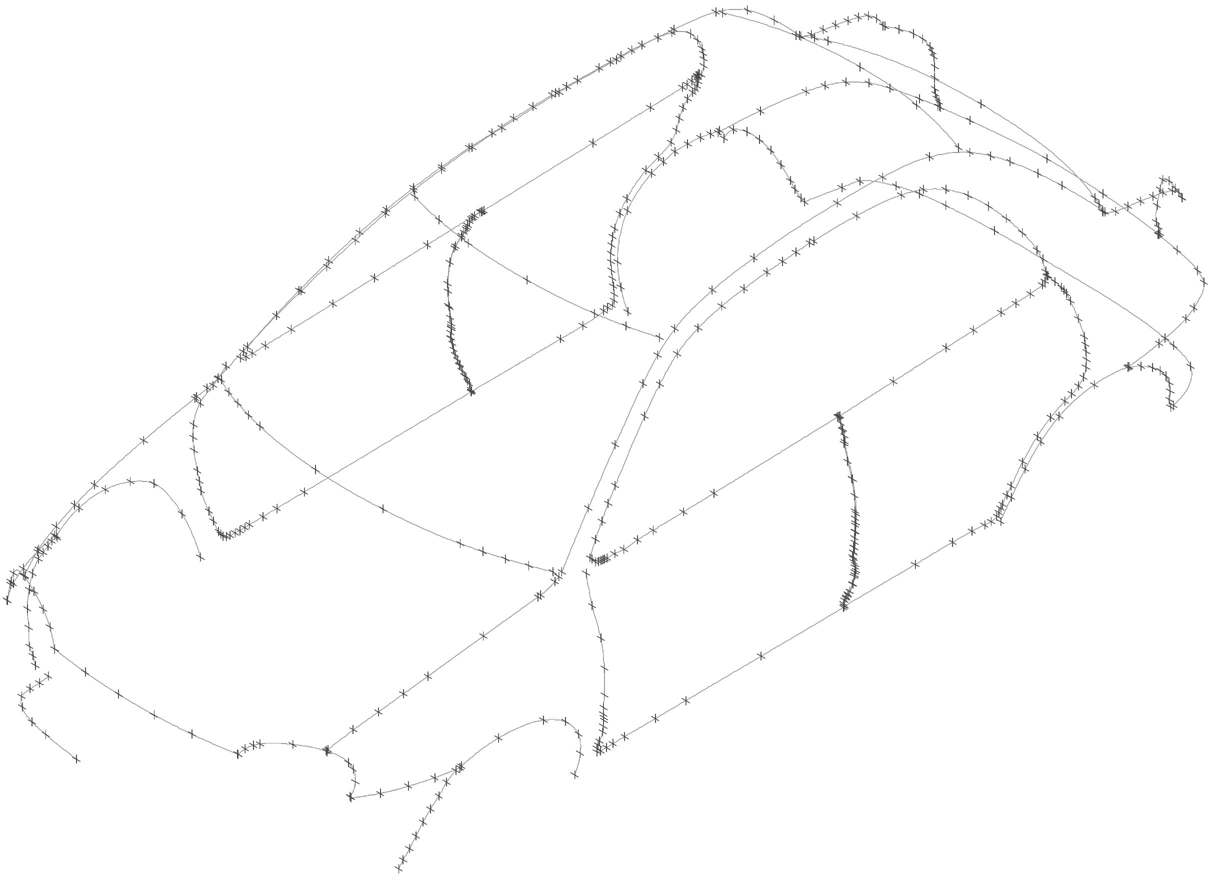


Figure 7: axonometric plot of the reconstructed car

Figure 8: superimposition of adjusted curves with symmetrical curves mirrored from the opposite side

6. Conclusion and Future Work

This test project demonstrates the feasibility of high precision digital object reconstruction using free-formed curves. The accuracy of the reconstructed lines corresponds to the uncertainty of definition of these lines on the car. Emphasis was laid on working with realistic conditions (natural illumination, real-world object, non-targetted lines). In the future further tests with lower image resolution are planned. Although a certain level of automation has already been achieved, some tiresome user interaction is still required. In order to reduce interactive work we think of using hierarchical methods for extracting longer edges. Also we will concentrate on finding optimum matching algorithms for edge features.

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