

COMBINED ADJUSTMENT OF LASER SCANNING DATA AND DIGITAL PHOTOGRAMMETRIC IMAGES

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KEY WORDS: Data fusion, Digital Terrain Model, Fast Vision, Laser Scanning, Modeling, Orthophoto, Photogrammetry, Surface reconstruction.

ABSTRACT

In this paper, a method is described, which introduces data from laser scanning devices into a process of automated photogrammetric surface reconstruction. The results of this process are the ortho image, the object surface that conforms with the ortho image and the areas, where laser data have been excluded from the reconstruction process. First, the concept of Facets Stereo Vision - a general method of automated photogrammetry - is explained and an efficient process of surface reconstruction is given. Then, laser scanning data is introduced as additional observations into the reconstruction process.

1 INTRODUCTION

Although the determination of object surface geometry has reached a high degree of automation using state-of-the-art methods of digital photogrammetry, in a very short time, laser scanning systems have already surpassed photogrammetry in some topographic as well as close-range applications. Considering the different fields of application of both techniques in geometric and semantic data collection, three important tasks can be outlined:

1. the production of true ortho images, which require a surface model including vegetation and man made objects like buildings and bridges (upper surface),
2. the collection of digital terrain models, usually in a regular spacing with additional information, e.g. breaklines, for various applications like contour interpolation, which require true ground information (lower surface) instead and
3. the discrimination of objects from their surrounding for mapping and monitoring purposes, which can be seen as the difference model between the two surfaces described above.

Both techniques are able to collect a large amount of geometric data in a very short time, but they also have in common, that a remarkable amount of user interaction is still necessary to verify, edit and refine that data, while the extraction of semantic information in either way to a large extent still is carried out by operators interactively. The reasons for user interaction even during or after geometric data collection due to failures or deficiencies of the methods are numerous: partially or totally occluded regions in forests or built up areas, insufficient reflectance of the surface leading to faint laser or image signals, multiple reflections due to surface roughness, moving or even flying objects and many more.

Numerous proposals have been made to overcome some of the deficiencies especially of laser scanning, e.g. the case of collecting the lower surface in forests. Some of the catchwords are: robust estimation, linear prediction or morphological filtering, cf. Pfeiffer et al. in: /Steinborn and Fritsch 1999/, /Lindenberger 1993/. Almost any of the proposed methods would benefit from the knowledge of the upper surface and also some information about areas, where a lower surface has to be expected. In this paper, a method is described, which introduces data from laser scanning devices into a process of automated photogrammetric surface reconstruction. The results of this process are the ortho image, the upper surface and the areas, where laser data have been excluded from the reconstruction process.

2 PHOTOGRAMMETRIC SURFACE RECONSTRUCTION WITH FACETS STEREO VISION

The concept of Facets Stereo Vision (FastVision) has been published first in /Wrobel 1987/. Instead of matching small patches of one image to corresponding patches of another image by applying geometric and radiometric transformations

in image space and, thus, yielding homologous image points, FastVision matches digital images directly to a radiometric model, i.e. an ortho image, of a surface in object space. The basic equation of FastVision is given with

$$G(X, Y) = T'[G'(x', y')] = T''[G''(x'', y'')] = \dots \quad (1)$$

An arbitrary number of two or more digital images G', G'', \dots is equally transformed by global or local, but usually linear transfer functions T', T'', \dots to the ortho image $G(X, Y)$. In case of central perspective imaging the geometric relation between images and object space is given by the collinearity equations, other sensor models can be considered as well. There are several ways to derive a feasible procedure for surface reconstruction and ortho image production from (1). In the following, a method according to /Weisensee 1992/ is used.

Expanding equation (1) into a Taylor series results in

$$G(X^0 + dX, Y^0 + dY) = G(X^0, Y^0) + \frac{\delta G(X^0, Y^0)}{\delta X} \cdot dX + \frac{\delta G(X^0, Y^0)}{\delta Y} \cdot dY \quad (2)$$

with the gradients of the radiometric model of a surface in object space $\frac{\delta G(X^0, Y^0)}{\delta X}$ and $\frac{\delta G(X^0, Y^0)}{\delta Y}$.

The collinearity equations account for a change dZ of the height of a point Z^0 in object space depending on a change dX, dY of its position X^0, Y^0 . Being X'_o, Y'_o, Z'_o the center of perspective of an image yields

$$dX = \frac{\delta X}{\delta Z} \cdot dZ = \frac{X^0 - X'_o}{Z^0 - Z'_o} \cdot dZ = X'_z \cdot dZ \quad (3)$$

$$dY = \frac{\delta Y}{\delta Z} \cdot dZ = \frac{Y^0 - Y'_o}{Z^0 - Z'_o} \cdot dZ = Y'_z \cdot dZ \quad (4)$$

Joining equations (1) - (4) for one image G' gives

$$T'[G'(x', y')] = G(X^0, Y^0) + \left(\frac{\delta G(X^0, Y^0)}{\delta X} \cdot X'_z + \frac{\delta G(X^0, Y^0)}{\delta Y} \cdot Y'_z \right) \cdot dZ \quad (5)$$

While the image function $G'(x', y')$ is given by discrete samples of a signal (intensity, optical density or gray value), the ortho image $G(X^0, Y^0)$ is represented by an interpolating function $G(X, Y)$ of order m, n as well as the height $Z(X, Y)$ of the surface in object space with coefficients α_{ij} and a_{ij} and function values G_{ij} and Z_{ij} in separate grids respectively.

$$G(X, Y) = \sum_{i=0}^m \sum_{j=0}^n \alpha_{ij}(X, Y) \cdot G_{ij} \quad (6)$$

$$Z(X, Y) = \sum_{i=0}^m \sum_{j=0}^n a_{ij}(X, Y) \cdot Z_{ij} \quad (7)$$

Using the function $G(X, Y)$ again should not be too confusing. Before $G(X, Y)$ denoted the ortho image in a continuous manner, in the following $G(X, Y)$ means an interpolating function from which also the gradients in equation (5) are to be computed.

Splitting up the ortho image and surface geometry in equations (6) and (7) into approximations $G(X^0, Y^0)$ and $Z(X^0, Y^0)$ and changes $dG(X^0, Y^0)$ and $dZ(X^0, Y^0)$ leads to

$$G(X^0, Y^0) = \sum_{i=0}^m \sum_{j=0}^n \alpha_{ij}(X^0, Y^0) \cdot G^0_{ij} \quad (8)$$

$$dG(X^0, Y^0) = \sum_{i=0}^m \sum_{j=0}^n \alpha_{ij}(X^0, Y^0) \cdot dG_{ij} \tag{9}$$

$$Z(X^0, Y^0) = \sum_{i=0}^m \sum_{j=0}^n a_{ij}(X^0, Y^0) \cdot Z^0_{ij} \tag{10}$$

$$dZ(X^0, Y^0) = \sum_{i=0}^m \sum_{j=0}^n a_{ij}(X^0, Y^0) \cdot dZ_{ij} \tag{11}$$

Inserting equations (8), (9) and (11) into (5) gives

$$T'[G'(x', y')] = \sum_{i=0}^m \sum_{j=0}^n \alpha_{ij}(X^0, Y^0) \cdot G_{ij}^0 + \sum_{i=0}^m \sum_{j=0}^n \alpha_{ij}(X^0, Y^0) \cdot dG_{ij} + \left(\frac{\delta G(X^0, Y^0)}{\delta X} \cdot X'_{,Z} + \frac{\delta G(X^0, Y^0)}{\delta Y} \cdot Y'_{,Z} \right) \cdot \sum_{i=0}^m \sum_{j=0}^n a_{ij}(X^0, Y^0) \cdot dZ_{ij} \tag{12}$$

Error equations of a parameter estimation in the Gauß-Markov model result from equation (12) by introducing e.g. the bilinear interpolation.

$$Z(X_p, Y_p) = \sum_{i=0}^1 \sum_{j=0}^1 a_{ij}(X_p, Y_p) \cdot Z_{ij} \tag{13}$$

with coefficients

$$\begin{aligned} a_{00} &= 1 - X_p - Y_p + X_p \cdot Y_p \\ a_{10} &= + X_p - X_p \cdot Y_p \\ a_{01} &= + Y_p - X_p \cdot Y_p \\ a_{11} &= + X_p \cdot Y_p \end{aligned}$$

Other interpolating functions have also been introduced for ortho images, e.g. wavelets in /Tsay 1996/, and object surfaces, e.g. Bezier splines in /Weisensee 1992/. A true 3D model for the geometry of objects has been derived by /Schlüter 1999/.

Some parts of a surface may have almost constant reflectance, leading to difficulties in solving surface reconstruction due to small gradients in equation (12), especially, when choosing a small grid spacing. One way to overcome this is to introduce some kind of regularization into surface reconstruction, cf. /Franek and Müller 1990/ and /Korten et al. 1988/, e.g. by adding conditions for the curvature of a surface model formed by a regular grid and an interpolating function.

$$\begin{aligned} C_{XX}(Z_{ij}) &= (Z_{ij-1} - 2Z_{ij} + Z_{ij+1}) + dZ_{ij-1} - 2dZ_{ij} + dZ_{ij+1} \\ C_{YY}(Z_{ij}) &= (Z_{i-1j} - 2Z_{ij} + Z_{i+1j}) + dZ_{i-1j} - 2dZ_{ij} + dZ_{i+1j} \\ C_{XY}(Z_{ij}) &= (Z_{ij} - Z_{ij+1} - Z_{i+1j} + Z_{i+1j+1}) + dZ_{ij} - dZ_{ij+1} - dZ_{i+1j} + dZ_{i+1j+1} \end{aligned} \tag{14}$$

In equations (14) the curvatures are the second derivatives of the discrete surface model. In a surface reconstruction procedure they can be treated as additional direct observations with value 0 and weights depending locally on the gradients of the image signal, /Schreyer 1998/.

Comparable to other tasks of geometric rectification, a pixel transfer can be carried out either directly, i.e. by projecting a pixel onto the object surface, or indirectly by projecting a regular grid from object space into the digital images and resampling the image signal. These values are then treated as pseudo measurements in the reconstruction process. The advantage of the regular grid becomes apparent from equation (12). The coefficients α_{ij} and a_{ij} are constant for all facets of the ortho image and the surface model and can be computed in advance for any given grid of pseudo measurements.

When choosing a grid spacing in object space equivalent to image resolution, the entire information content of the images is used.

In equation (12) three groups of unknown parameters can be distinguished and treated separately in an iterative parameter estimation, cf. /Weisensee 1992/:

1. the changes dG_{ij} of the grid values G_{ij}^0 of the ortho image $G(X,Y)$,
2. the parameters of the transfer functions T' , T'' , ... and
3. the changes dZ_{ij} of the grid values Z_{ij} of the surface $Z(X,Y)$.

Given the interior and exterior orientation of the images G' , G'' , ... and some approximations of Z_{ij} , the parameters $G_{ij} = G_{ij}^0 + dG_{ij}$ can be computed directly by the mean values of $G'(X,Y)$, $G''(X,Y)$, ... resulting from the image functions $G'(x',y')$, $G''(x'',y'')$, The parameters of the transfer functions T' , T'' , ... are then computable from the mean values and the variances of the histograms of $G'(X,Y)$, $G''(X,Y)$, The remaining group of unknown parameters dZ_{ij} has to be estimated by solving the normal equation system resulting from equation (12) which is a band matrix, that can effectively be processed.

The number of iterations needed to arrive at the final result primarily depends on the quality of the approximate values of the surface $Z(X,Y)$. Several strategies have been applied to decrease the demands on the approximations, e.g. using image pyramids and progressive refinement of the surface model, /Korten et al. 1988/. But, the availability of laser scanning data dramatically decreases the number of iterations, because in the ideal case of undisturbed reflection of the laser beam, the approximations are very close to the final solution.

3 LASER SCANNING

Although laser scanning systems are only available on a broad basis since less than a decade, already a large number of publications is at hand, which give insight in most of the concepts, technical details, algorithms and applications of this technique. In this paper, laser scanning data is considered as the raw coordinates $P(X,Y,Z)$ resulting also from different types of additional measurements (GPS, INS). For further information the reader is referred to the literature, e.g. special issues of journals /Baltsavias 1999/ and /Steinborn and Fritsch 1999/ or /Fritsch and Spiller 1999/.

The so called raw coordinates of laser scanning give those positions on an object surface, where a laser beam has been reflected first or last, depending on the registration mode of the system. Furthermore, some systems record the intensity of the reflected laser beam, which results in a digital image - usually in the near infrared channel - of the surface. Such images can be directly introduced in a surface reconstruction according to equation (12) when applying a suitable model for the image forming process. And, the information given by the images would be sufficient for the reconstruction of the surface, provided that an adequate overlap of flight strips is given. For most surfaces the difference between recording first and last reflection merely shows the roughness of the surface or the ability of the system to reproduce a result. Figures for the accuracy of such points are given by standard deviations between laser scanning and control areas from 5 cm to approximately 1 m, depending on a large number of parameters like height and speed of the platform. In forest areas the difference between first and last reflection gives the height of the trees - an extreme case of surface roughness. Depending on the type of wood, different percentages of points are reflected in the foliage or on the ground. Here, penetration rates between 30% and 70% have been reported. Points that are reflected in the foliage correspond to the surface that is reconstructed by photogrammetric methods, although in wooded areas photogrammetry lacks similar deficiencies as laser scanning.

4 COMBINED ADJUSTMENT

Introducing laser scanning data into FastVision can easily be accomplished when using the bilinear interpolation given in equation (7) and the separation of the grid Z_{ij} into approximations Z_{ij}^0 and their corrections dZ_{ij} given in equations (10) and (11). With equation (7) first approximations for the iterative parameter estimation of FastVision can be computed directly by utilizing the raw coordinates $P(X,Y,Z)$ as observations in

$$e = \sum_{i=0}^1 \sum_{j=0}^1 a_{ij}(X_p, Y_p) \cdot Z_{ij} - Z_p \quad (15)$$

Every laser point contributes an error equation of this type, leading to a parameter estimation which can be solved by standard methods. An iterative procedure which re-weights the observations depending on the resulting residuals \mathbf{e} has been given by Pfeiffer et al., /Steinborn and Fritsch 1999/. By this, upper and lower surfaces can be separated in a few iterations.

In order to combine laser scanning data with digital images in a common adjustment, in addition to equation (12) error equations have to be set up for the unknown parameters dZ_{ij}

$$e = \sum_{i=0}^1 \sum_{j=0}^1 a_{ij}(X_P, Y_P) \cdot dZ_{ij} - [Z_P - \sum_{i=0}^1 \sum_{j=0}^1 a_{ij}(X_P, Y_P) \cdot Z_{ij}^0] \quad (16)$$

For using equations (12) and (16) for parameter estimation, the weights of the observations have to be determined either beforehand or during the iterative procedure in a variance estimation. Estimates for the variances of digital gray values $G'(x',y')$, $G''(x'',y'')$, ... of an image or of the pseudo measurements that are used to accelerate the procedure can be derived from the ortho images $G'(X,Y)$, $G''(X,Y)$, ... resulting from the image functions and the mean values $G(X,Y)$. Similarly variances for laser scanning data can be computed.

While the filter strategies mentioned above only rely on laser scanning data, filtering by re-weighting in the combined adjustment is strongly supported by digital image data. When reducing the total number of laser scanning points by those which correspond to the upper surface with this method, even the elementary median filter, /Koch 2000/, may be applied for the elimination of the remaining erroneous points.

5 CONCLUSIONS

In combining laser scanning data with digital photogrammetric images in a common parameter estimation, a fast and reliable process of surface reconstruction and ortho image production is at hand. Separating the upper surface points from laser scanning data in addition gives advantages for filtering true ground points in wooded areas. Further research has to be done considering the weighting and re-weighting strategies of the process.

ACKNOWLEDGEMENTS

This research was supported by the Volkswagen Foundation. The author would also like to thank Dr. Peter Frieß and Dr. Joachim Lindenberger from TopScan for their support.

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