TRIANGULATION OF A SEQUENCE OF TERRESTRIAL DIGITAL IMAGES

João Fernando C. da SILVA, Adjunct Professor, Department of Cartography
Ronaldo A. de OLIVEIRA, Undergraduate Student, Cartographic Engineering

São Paulo State University - 19060-900 Presidente Prudente SP, Brazil
Phone 55-18-221-5388 - Fax 55-18-223-2227
Work Email: jfcsilva@prudente.unesp.br - Home Email: jfcsilva@stetnet.com.br

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ABSTRACT

A sequence of terrestrial images is a special sequence of consecutive frontal digital images taken from bases that are moved forward along the main axis of the site to be mapped. Tipically this situation arises when a pair of digital cameras is mounted on top of a vehicle of a mobile mapping system to take digital images of a street or road to be surveyed and mapped.

In general, sensor orientation is provided directly by means of integration of GPS and INS data. Particularly, in an urban environment, the reception of GPS signals is blocked mainly by buildings and others structures like tall trees and overpasses.

Although INS data can provide sensor orientation for a not long time interval, phototriangulation may also be used as a method of orienting (both sensors of) the stereocamera. In cases where navigational and real time data are not intended, bundle triangulation may be a reasonable method of connecting a sequence of stereopairs.

A computational simulation and an experimental street test were performed in order to check the potential of the method. The results reveal that bundle method provides average positional accuracy of less than 1,5m for the perspective centers.

1. Introduction

Mobile mapping systems (MMS) have drawn the attention of the international mapping community for the last decade and currently are heading to make possible a faster and reliable approach to acquire data for GIS and digital mapping applications. As long as mapping is concerned real and non-real time methods are in evidence. In both cases different sensors have to be integrated in order to deliver an accurate spatial position of the topographic details on or near the surveying surface. This means a complex and expensive hardware configuration where CCD cameras (photographic and video), GPS receivers, INS platforms, wheel sensors, gyroscopes, laser rangers and others are linked together to produce georeferenced images and spatial coordinates of attributes. This can be read in Bossler et al. (1994), Li et al. (1994), Maresch&Duracher (1996), Philips (1997) and Schwarz (1993).

In the software domain, data fusion and combination are essencial to derive position (local and global) and accuracy related to spatial attributes. The derived information can be put into digital databases accessed by or pertained to Geographic Information Systems (GIS) or even used as the end product in a particular application. These applications are reported by Bossler (1991), El-Sheimy (1996), He (1996), Li (1996), Novak (1995), Novak&Bossler (1995) and Toth (1996).

Consecutive digital images are taken in a sequence of stereopairs as in the figure 1. An object point or detail on the street, for example, may be clearly seen in two or three stereobases and then in four or six images. The spatial object coordinates can be computed by simple, double or even multiple photogrammetric intersection. Theoretically, the closest stereobase delivers the highest accuracy and the far base the lowest accuracy for an object point when the photogrammetric intersection is computed separately for each base. When the computation takes in account multiple intersections the final accuracy is diminished mostly by the far bases' data due to unfavourable geometry and minor quality observations. Edmundson&Novak (1992), Habib (1994) and Silva (1996) have treated sequences of digital images.

When preparing and working data out for the image sequence concatenation or phototriangulation object points are selected in images of two or three bases, which means four or six images, respectively. In other words, it is advisable to work with the two or three bases closest to the object point selected to function as a pass point in order to not to worsen the positional accuracy.

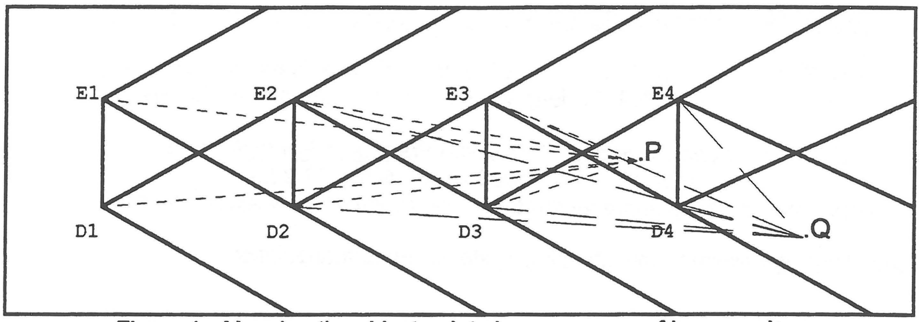

Figure 1 - Mapping the object points in a sequence of image pairs.

Photogrammetric intersection is computed when sensor orientation is complete and available. As already mentioned, in MMS this is possible with the integration of GPS and INS technologies. Unfortunately, in an urban environment, for instance, GPS data may be blocked for a significant time interval that INS data can no longer be effective to maintain a good quality sensor orientation. In this case phototriangulation may be a quite effective approach to compute exterior orientation parameters for those images without direct orientation by GPS-INS integrated technologies. Table 1, adapted from Novak (1992), shows different methods for spatial positioning from which a reasonable balance between price (except the vehicle) and accuracy can be seen in favour of photogrammetric intersection.

Table 1 - Accuracy and financial costs of different methods for positioning systems.

Method	System	Expected Accuracy (m)	Estimated Price (US$)
Inertial Positioning	Dead Reckoning	1,0 - 3,0	10,000-20,000
Inertial Positioning	Inertial (strap down)	0,1	100,000-150,000
External Positioning	Kinematic GPS (double frequency and P-code)	0,01 - 0,1	20,000-30,000
Photogrammetric Positioning	Simple Intersection	0,35 - 1,0	10,000-20,000

Before beginning the construction of the prototype (which is about to start!) a sequence of digital image pairs was taken in order to simulate an urban trip of a mobile mapping vehicle. It is intended to make intensive use of phototriangulation as the first version of the prototype will count only with a vehicle, a pair of digital videocameras and a non-linear editing workstation.

Prior to before going to the street a computational simulated study was done in order to know how the final accuracy figures would look like. Figure 2 shows a longitudinal view of a ficticious street that is expressed in terms of object point coordinates whose reference system's origin is arbitrarily set to the first base left camera's perspective center and the orientation X follows the base axis, Z is upward and Y is parallel to the street, making a right-handed reference system.

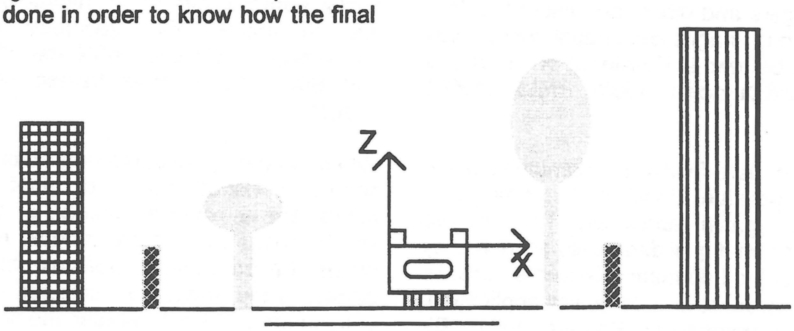

Figure 2 - Longitudinal view of a ficticious street.

2. Data acquisition and processing

In the computational study the ficticious photocoordinates were computed based on the well known collinearity equations and had random and empirical errors added. Random errors varied from -15 to +15μm. Empirical errors obeyed to an arbitrary rule that dictated an image point should receive additional random errors depending on its relative position in the image (e.g. 7, 10 and 20μm, for the ends, intermediary and center, respectively). The image coordinate system was made compatible to a 35mm CCD camera.

In a street in the vicinity of the campus of São Paulo State University in Presidente Prudente sixteen bases were marked on the ground equally separated by 25 m. Each base measured 1 m long and in both ends of it a tripod was setup to receive a GPS antenna and then a digital camera. There was no special device to force both antenna and camera centers coincide and the maximum "miscoincidence" was about a few centimeters.

GPS data was acquired by a pair of Trimble 4000 SL (carrier L1 and code C/A), one fixed in a reference station and the other moved to survey the positions of the perspective centers. The moving receiver stayed for 6 minutes in each point. The spatial coordinates supposed to represent the different positions of the camera perspective center in the 16 bases were determined in a post processing LS adjustment using software Trimble Trimvec Plus.

A Kodak DC40 digital camera was fixed on the tripod and shot 32 images covering almost 400 m along the street. The image coordinates (row, column) were extracted using PhotoFinish by visual comparison of the selected object point in four images (two bases). A camera calibration report (Tommaselli & Nóbrega, 1997) gave the interior orientation parameters and the image coordinates were transformed to x,y-photocoordinates by the following expressions:

$$x = (nc - nc_0) \cdot tpc + x_0$$
$$y = (nl - nl_0) \cdot tpl + y_0$$

where nc,nl are the numbers of the column and row, respectively (image size is 756 x 504 pixels); nc_0,nl_0 are the numbers of the central column and row, respectively (378, 252); tpc,tpl are the pixel size (45,6μm x 45,6μm), and x_0,y_0 are the principal point calibrated coordinates.

Three data files were structured: photocoordinates, exterior orientation and object point coordinates. The first arranged data related to the image and point identification and the corresponding photocoordinates. The second file arranged data related to the image identification and the corresponding situation code, the perspective center coordinates (determined and approximated), and the angular orientation (approximated); the image codes are: 'L' for an image with free six parameters, 'A' for "observed" angular parameters; 'C' for "observed" perspective centers and 'O' for all parameters "observed". In both computational and field experiments the codes used were 'L' and 'C'. The data file with the object point coordinates was created from the two files described above by the computer program *pre_tftc* which checks and prepares data for the bundle adjustment computer program *tftc* (see next section).

3. Phototriangulation of consecutive digital images

A bundle adjustment computer program named *fotrac* (*fototriangulação analítica com auto-calibração*, in portuguese) received little modification to become *tftc* (*triangulação de fotos terrestres por caminhamento fotogramétrico*). Now *tftc* computes the object point coordinates and exterior orientation parameters simultaneously based on this new approach.

There have been some difficulties to handle this kind of triangulation specially when it comes to point selection and measurement due to the particular geometry. Considering figure 3, an image can be partitioned into fours triangles: middle up, middle down, left and right. Upper triangle comprises mostly the sky while middle down triangle covers mainly the street pavement. Left and right triangles contain the sidewalks, trees, gates, drives, walls, poles and other street elements that can be selected to function as pass points in this phototriangulation procedure. These limited portions of the images associated with high contrast and extreme scale variation bring difficulties to this method.

Figure 3 - Two pairs of consecutive digital photographs.

Figure 4 shows the UTM coordinates of the triangulated digital images. Actually the bases from the fifth to the last were included in the phototriangulation project.

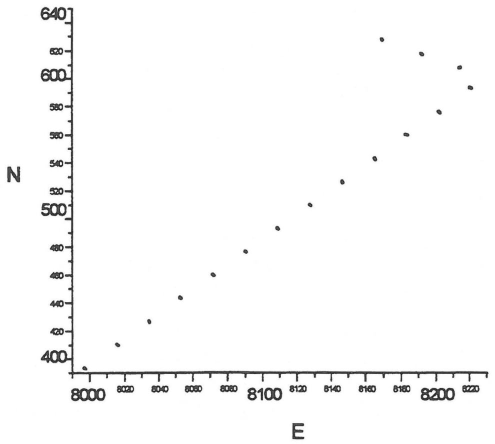

Figura 4 - UTM coordinates of the camera centers.

4. Results

Firstly the results of the simulated study are showed in table 2. Associating the root mean square error (rmse) for the Y coordinate to the cost (μ_Y) and the distance in the street covered by the sequence of images to the benefit (ΔY), the ratio $\mu_Y/\Delta Y$ was taken for comparison among the experiments. In the first column, for example, R151301 reads R for report, 15 is the bridging distance between two consecutives bases, 13 is the number of images in the bundle adjustment, 01 stands for σ = 1mm for the perspective center standard deviation and 02 for σ = 10cm. Second column reads total number of bases (NTB) and total number of free bases (NTBL). The worst accuracy is less than 1 m (3rd column).

Table 2 - Cost/benefit ratio.

Report	NTB/NT BL	Costs μ_Y (m)	Benefit ΔY (m)	$\mu_Y / \Delta Y$
R151301	13/11	0,575	195	0,00295
R151302	13/11	0,599	195	0,00307
R250901	9/7	0,946	225	0,00420
R250902	9/7	0,946	225	0,00420
R151101	11/9	0,698	165	0,00423
R151102	11/9	0,728	165	0,00441
R201002	10/8	0,969	200	0,00484
R201001	10/8	0,975	200	0,00488

The work in the field was also in this case considered a simulation because an actual mobile system has not been set up yet. However the field data and results were analyzed to make possible an understanding mainly concerned to the final accuracy of a "rough system" and to the problems related to this special kind of phototriangulation.

Table 3 shows the average standard deviation of the WGS84 coordinates of the 32 perspective centers. After bundle adjustment experiments most of them failed to the χ^2 statistical test. Two non-rejected experiments are shown in table 4. The X,Y resultant standard devitions are about the same: 1.4m and 1.2m for the cases 5/3 and 6/3, respectively. Not well understood are the bad results for coordinate h.

Table 3 - Average standard deviations of the WGS84 perspective center's coordinates.

	X (m)	Y (m)	Z (m)
average std dev	0,014	0,016	0,008
maximum std dev	0,076	0,196	0,132

Table 4 - Accuracy (μ) and precision (σ) of triangulated perspective center's coordinates estimated in the two non-rejected experiments.

exp	μ_E	μ_N	μ_h	σ_E	σ_N	σ_h
5/3	1,16	0,76	1,45	0,72	0,81	0,61
6/4	1,04	0,67	1,26	0,75	0,83	0,64

Photogrammetric intersection accuracy may lay between 0.3 to 0.5 m for object point-base distances up to 50m (Li et al., 1994). In conclusion the final accuracy for the object point coordinates lays in the interval 1.5 to 2.0m. Users who would accept this level of accuracy in their projects should be conscious of this new methodology to provide accurate spatial data for their applications.

5. Present and future projects

A prototype of a MMS is in its first steps in Brazil. As far as it is known it will be the first to be constructed in South America. The suggested short name is MovMap with letters taken from *Sistema Móvel de Mapeamento Digital*, the portuguese title for Mobile Digital Mapping System. Planned to be set up in two main phases, the first is concerned with the vehicle, two digital video cameras (Sony DCR VX-1000) and a non-linear editing workstation.

The vehicle is a very popular van made in Brazil by Volkswagen called Kombi. The video cameras are totally digital in the sense of the audio and video signals are recorded in a DVCAM format tape ready to be read by Adobe Première, for video edition, and Adobe Photoshop, for image manipulation. The non-linear editing workstation is a Pentium 233MHz, 32Mb RAM, 1HD 2.5Gb IDE for system software, 1HD 4.55Gb UW for video edition, HD controller board 2940UW, video controller board 4Mb, with Windows 95. This phase is planned to release the first results in 12 to 18 months starting April 1, 1998 (it is not a lie!). A local reference system is under consideration to overcome the absence of a global reference system. A database of georeferenced digital images is a target application.

The second stage in the construction process of the first Brazilian MMS is the integration of GPS and INS technology and possibly an additional sensor to enhance the vision system to be decided based on the evaluation of the video system used in the first phase.

6. Conclusion

The subject of this article delt with an emerging technology and methodology to collect spatial data for GIS and digital mapping purposes. All the published material dates no more than ten years which suggests that the matter is in its infancy. Based on the growing number of people interested in this theme a great future is envisioned for this complex although efficient technique for mapping applications.

It was proposed the concatenation of a sequence of digital image pairs by bundle adjustment to provide positioning of the perspective centers when GPS data can not be received by the antenna. The experiments were simulated in a computer and in the field. The results lead to conclusions that will help the construction of the prototype of a mobile digital image acquisition system. This system will comprise a vehicle, a pair of digital videocameras and a workstation.

Although the accuracies obtained in the simulated experiments can be improved they appear to be acceptable for many GIS applications. A digital image database for GIS support is envisioned as the first application of the planned prototype.

References

BOSSLER, J. et al., 1991. GPS and GIS map the nation's highway. *Geo Info Systems*, March, p.27-37.

BOSSLER, J. D. et al., 1994. Digital mapping on the ground and from the air. *Geo Info Systems*, January, p. 44-8.

EDMUNDSON, K. & NOVAK, K., 1192. On line triangulation for autonomous vehicle navigation. In: INTERNATIONAL CONGRESS OF ISPRS, 17., 1992, Washington-DC. *International Archives*..., ISPRS, v. 29, t. B5, p. 916-22.

EL-SHEIMY, N., 1996. A mobile multi-sensor system for

GIS applications in urban centers. In: INTERNATIONAL CONGRESS OF ISPRS, 18., 1996, Viena. *International Archives...*, ISPRS, v. 31, t. B2, p. 95-100.

HABIB, A. F., 1994. *Estimation of motion parameters for stereo-image sequences using data association of linear features.* Columbus-OH. 129p. Dissertation, Ph. D. Department of Geodetic Science and Surveying, The Ohio State University.

HE, G. Design of a mobile mapping system for GIS data collection. In: INTERNATIONAL CONGRESS OF ISPRS, 18., 1996, Viena. *International Archives...* ISPRS, 1996, v. 31, t. B2, p. 154-9.

HE, G. & NOVAK, K., 1992a. Automatic analysis of highway features from digital stereo images. In: INTERNATIONAL CONGRESS OF ISPRS, 17., 1992, Washington-DC. *International Archives...*, ISPRS. v.29, t.B3, p.119-24.

LI, R. et al., 1994. VISAT: a real time system for highway spatial information acquisition. In: ASPRS-ACSM ANNUAL CONVENTION AND EXPOSITION, 1994, Reno. *Proceedings...* Bethesda: ASPRS & ACSM, v.1, p.344-9.

___, 1996. Mobile mapping for 3D GIS data acquisition. In: INTERNATIONAL CONGRESS OF ISPRS, 18., 1996, Viena. *International Archives...* ISPRS, v. 31, t. B2, p. 232-7.

MARESCH, M. & DURACHER, P., 1996. The geometric design of a vehicle based 3 line CCD camera system for data acquisition of 3D city models. In: INTERNATIONAL CONGRESS OF ISPRS, 18., 1996, Viena. *International Archives...*, ISPRS, v. 31, t. B1, p. 121-7.

NOVAK, K., 1992. Real time mapping technology. In: INTERNATIONAL CONGRESS OF ISPRS, 17., Washington-DC. *International Archives...*, ISPRS, 1992, v. 29, t. B2, p.569-75.

___, 1995. Mobile mapping technology for GIS data collection. *Photogrammetric Engineering & Remote Sensing, 61*(5):493-501.

NOVAK, K. & BOSSLER, J. D., 1995. Development and application of the highway mapping system of Ohio State University. *Photogrammetric Record, 15*(85):123-34.

NOVAK, K., SILVA, J. F. C. & TOTH, C., 1994. Eletronic imaging systems developed at The Ohio State University. In: INTERNATIONAL SIMPOSIUM OF THE ISPRS COMMISSION I, Milão. *Proceedings...* p. 56-60.

PHILIPS, J., 1997. Impacto das novas tecnologias na Engenharia Cartográfica: a Geodésia brasileira no 3° milênio. In: IMPACTO DAS NOVAS TECNOLOGIAS NA ENGENHARIA CARTOGRÁFICA, SEMINÁRIO, 1997, Presidente Prudente. *Coletânea de Trabalhos*. Presidente Prudente: Departamento de Cartografia/FCT/UNESP. p.1-20.

SCHWARZ, K. P. et al., 1993. An integrated INS/GPS approach to the georeferencing of remotely sensed data. *Photogrammetric Engineering & Remote Sensing, 59*(11):1667-74.

SILVA, J. F. C., 1997. *Fototriangulação no caminhamento fotogramétrico.* Presidente Prudente. 85p. Livre Docência, Tese. Faculdade de Ciências e Tecnologia, Universidade Estadual Paulista.

___, 1995a. A new concept for panoramic close range photogrammetry. *Rev. Eng. e Ciênc. Aplic., 2*:55-67.

___, 1995b. Análise de parâmetros para a construção de uma estereocâmara de pequeno formato. In: CONGRESSO BRASILEIRO DE CARTOGRAFIA, 17., 1995, Salvador. *Anais (v. Fotogrametria)...* Rio de Janeiro: Soc. Bras. Geod., Cart., Fotogram. e Sens. Remoto, 8p.

___, 1996. Solução sequencial para o caminhamento fotogramétrico. *Coletânea Politécnica - Rev. Bras. Tecnol. Ciênc. 1*(1):92-6, 1996.

TOMMASELLI, A. M. G. & NÓBREGA, R. A. A., 1997. Qualidade geométrica de câmaras digitais: avaliação da câmara Kodak DC40. In: GIS BRASIL 97, Curitiba. *Anais...* Curitiba: Sagres Editora (CD-ROM).

TOTH, C., 1995. Mapping with a mobile image acquisition system. *Geo Info System, 12*:35-7.

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