OPTIMAL ACQUISITION OF 3D OBJECT COORDINATES FROM STEREOSCOPIC IMAGE SEQUENCES

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ABSTRACT:

3D object space coordinates of an object can be uniquely intersected by two geo-referenced digital images that overlap the object. The selection of the best combination of the two images from an image sequence so that the coordinates calculation has the optimization properties both in precision and reliability is very important for feature extraction, image matching, object reconstruction and recognition. Based on Kalman filter theory, great efforts have been made to research the optimization of 3-D coordinate calculation from the VISAT images. Considerations are given to a) establishing optimal criteria with precision and reliability, and b) choosing two optimal images from an image sequence for an intersection. An algorithm has been developed that meets the above requirements.

To verify the algorithm, it was used to extract objects from digital images taken by the VISAT mobile mapping system. The results show that the optimization algorithm is efficient for calculating 3D coordinates and providing geometric information for generation of large scale GIS databases.

1. INTRODUCTION

Digital images acquired by the VISAT system, a mobile mapping system using GPS, INS and CCD cameras, are georeferenced (Li et.al 1996). Coordinates of any object appearing in a stereo pair of the images can be calculated by measuring corresponding image coordinates and by an intersection in the object space. In order to obtain an accurate 3D object description, to reduce computational time, and to enhance the measurability of the system, an efficient algorithm for calculating optimal 3D object space coordinates with precision and reliability is necessary. Without the optimization using these criteria, some photogrammetric operations may not be applicable or practical considering the large amount of data involved and computational time required. The optimization algorithm presented in this paper demonstrates the advance of optimal processing of the images georeferenced in real-time and acquired by a mobile mapping system.

2. THE SEQUENTIAL IMAGE MODEL

A statistical model of the evolution of sequential images containing an object to be measured can be expressed as

$$P_k \sim N(P, D_{kk}), \qquad (2.1)$$

where P_k is the 3D object coordinate state of a normal distribution estimated by k images in which the object appears; P is it's statistical expectation $E[P_k]$ and D_{kk} is the corresponding covariance matrix.

The updated new collinearity equations using the (k+1)th image are

$$x_{k+1}=-f_{k+1}*u_{k+1}/q_{k+1}$$
$$y_{k+1}=-f_{k+1}*v_{k+1}/q_{k+1} \qquad (2.2)$$

where

$$u_{k+1}=m_{11}(X_{k+1}-X^0)+m_{12}(Y_{k+1}-Y^0)+m_{13}(Z_{k+1}-Z^0)$$
$$v_{k+1}=m_{21}(X_{k+1}-X^0)+m_{22}(Y_{k+1}-Y^0)+m_{23}(Z_{k+1}-Z^0)$$
$$q_{k+1}=m_{31}(X_{k+1}-X^0)+m_{32}(Y_{k+1}-Y^0)+m_{33}(Z_{k+1}-Z^0)$$

and X_{k+1}, Y_{k+1} and Z_{k+1} are the coordinates of the target point from the (k+1)th image; X^0, Y^0 and Z^0 are the coordinates of the (k+1)th exposure station; x_{k+1} and y_{k+1} are image point coordinates in (k+1)th image; f_{k+1} is the focal length of the (k+1)th image; and $M_{3\times 3}(m_{ij})$ is the rotation matrix of the (k+1)th image.

If only the measurement errors of the image coordinates are taken into consideration, Equation (2.2) can be expressed in a linearized form:

$Vx_{k+1} = a_{k+1,1}\, dX_{k+1} + b_{k+1,1}\, dY_{k+1} + c_{k+1,1}\, dZ_{k+1} - J_{k+1,1}$
$Vy_{k+1} = a_{k+1,2}\, dX_{k+1} + b_{k+1,2}\, dY_{k+1} + c_{k+1,2}\, dZ_{k+1} - J_{k+1,2}$ (2.3)

Where

$a_{k+1,1} = -(x_{k+1} * m_{31} + f_{k+1} * m_{11})/q_{k+1}$
$b_{k+1,1} = -(x_{k+1} * m_{32} + f_{k+1} * m_{12})/q_{k+1}$
$c_{k+1,1} = -(x_{k+1} * m_{33} + f_{k+1} * m_{13})/q_{k+1}$
$a_{k+1,2} = -(y_{k+1} * m_{31} + f_{k+1} * m_{21})/q_{k+1}$
$b_{k+1,2} = -(y_{k+1} * m_{32} + f_{k+1} * m_{22})/q_{k+1}$
$c_{k+1,2} = -(y_{k+1} * m_{33} + f_{k+1} * m_{23})/q_{k+1}$
$J_{k+1,1} = x_{k+1} + f_{k+1} * u_{k+1} / q_{k+1}$
$J_{k+1,2} = y_{k+1} + f_{k+1} * v_{k+1} / q_{k+1}$

In Equation (2.3), the a, b, c coefficients and J are evaluated at the approximations. In matrix form, Equation(2.3) is given as

$$V_{k+1} = A_{k+1} dP_k - J_{k+1} \quad (2.4)$$

Where

$V_{k+1} = (Vx_{k+1}, Vy_{k+1})^t$,
$dP_k = (dX_{k+1}, dY_{k+1}, dZ_{k+1})^t$,
$J_{k+1} = (J_{k+1,1}, J_{k+1,2})^t$

and

$$A_{k+1} = \begin{pmatrix} a_{k+1,1} & b_{k+1,1} & c_{k+1,1} \\ a_{k+1,2} & b_{k+1,2} & c_{k+1,2} \end{pmatrix}$$

With the statistical model given by Equation (2.1), we obtain the least squares estimation by using the Kalman filter(Kalman, R.E. 1960)

$$P_{k+1} = P_k + dP_k = P_k - D_{kk} A^t_{k+1} (D_{LL} + A_{k+1} D_{kk} A^t_{k+1})^{-1} (A_{k+1} P_k - L_{k+1})$$
$$D_{k+1k+1} = D_{kk} - D_{kk} A^t_{k+1} (D_{LL} + A_{k+1} D_{kk} A^t_{k+1})^{-1} A_{k+1} D_{kk} \quad (2.5)$$

Where $L_{k+1} = (x_{k+1}, y_{k+1})^t$, D_{LL} is the covariance matrix of observation x_{k+1} and y_{k+1}; D_{k+1k+1} is the covariance matrix of 3D object coordinates estimated by all k+1 images; $(A_{k+1} P_k - L_{k+1})$ is the difference between the observations (image coordinates) of the (k+1)th image and the projected image coordinates from the 3D coordinates P_k to the (k+1)th image plane.

By Equation (2.5), the updated 3D coordinates and their covariance matrix are calculated based on the new observation in the (k+1)th image and the previous 3D coordinates.

3. THE OPTIMIZATION CRITERION FOR PRECISION AND RELIABILITY

3.1 Precision Criterion

According to Equation (2.5), it is obvious that

$$\Delta D_{kk} = D_{kk} - D_{k+1k+1} = D_{kk} A^t_{k+1} (D_{LL} + A_{k+1} D_{kk} A^t_{k+1})^{-1} A_{k+1} D_{kk} \quad (3.1)$$

is a positive definite matrix only if the matrices D_{kk} and D_{xx} are positive definite. This ensures that every observation Equation (2.3) will improve the precision of 3D coordinate estimates. The efficiency dependents mainly on both the D_{LL} and 3D object coordinate covariance D_{kk} projected on (k+1)th image plane ($A_{k+1} D_{kk} A^t_{k+1}$).

Generally, we consider the relative gain matrix

$$D^{-1/2}_{kk} \Delta D_{kk} D^{-1/2}_{kk} = D^{1/2}_{kk} A^t_{k+1} (D_{LL} + A_{k+1} D_{kk} A^t_{k+1})^{-1} A_{k+1} D^{1/2}_{kk} \quad (3.2)$$

and define

$$Tr(D^{-1/2}_{kk} \Delta D_{kk} D^{-1/2}_{kk}) = Tr[\, I - D_{LL} (D_{LL} + A_{k+1} D_{kk} A^t_{k+1})^{-1}] = \text{maximum} \quad (3.3)$$

as the precision criterion of optimization for (k+1)th image.

The total precision criterion is

$$Tr\,(D_{k+1k+1}) = \text{minimum} \quad (3.4)$$

Let u_i be eigenvector of the matrix D_{kk} with its eigenvalues given as λ_i (i = 1, 2, 3)
and suppose

$$\lambda_1 \geq \lambda_2 \geq \lambda_3 \geq 0.$$

If we select $A^t_{k+1} = (u_1, u_2)$ in Equation (3.3), the precision gain becomes greatest. That means when the direction of the image observation is perpendicular to the 2D error ellipse plane defined by the eigenvectors u_1 and u_2, this particular image observation makes the greatest contribution to the enhancement of the accuracy of the 3D object coordinates.

In the special case, when there are only two images intersecting the 3D object point, we have

$D_{22}=(A^t_1A_1+A^t_2A_2)^{-1}$

$$= \left(\sum_{k=1}^{2} \begin{pmatrix} a_{i,k}*a_{i,k} & a_{i,k}*b_{i,k} & a_{i,k}*c_{i,k} \\ a_{i,k}*b_{i,k} & b_{i,k}*b_{i,k} & b_{i,k}*c_{i,k} \\ a_{i,k}*c_{i,k} & b_{i,k}*c_{i,k} & c_{i,k}*c_{i,k} \end{pmatrix} \right)^{-1}$$

In general, if there are four square matrices A, B, C and D, and $D = B^t$, the following holds

$$\mathrm{Tr}\begin{pmatrix} A & B \\ D & C \end{pmatrix}^{-1} =$$

$$\mathrm{Tr}(A^{-1} + A^{-1}B\,(C - B^tA^{-1}B)^{-1}B^tA^{-1} + (C - B^tA^{-1}B)^1)$$

Similarly, the precision criterion will be :

$$\mathrm{Tr}(D_{22})=(S^2_i+ S^2_j)/\sin^2 c_{ij} +H^2_{ij} /(\sin^2\alpha_i +\sin^2\alpha_j) = \text{minimum} \qquad (3.5)$$

where

i and j are IDs of two intersecting images;
S_i is the distance between i-th camera and the target P;
S_j is the distance between j-th camera and the target P;
c_{ij} is the space intersection angle between two observations;
H_{ij} is the distance between the target P and baseline vector ij;
α_i is the space intersection angle between i-th observation and baseline vector ij;
α_j is the space intersection angle between j-th observation and baseline vector ji.

3.2 Reliability Criterion

A statistical hypothesis test can be used to detect model errors by examining the difference in the observation Equation (2.5)

$$dL_{k+1}=(A_{k+1}P_k-L_{k+1}) \sim N(\Delta L_{k+1}, D_{LL}+A_{k+1}D_{kk}A^t_{k+1}), \qquad (3.6)$$

and a further χ^2 test can also be applied

$$dL^t_{k+1}(D_{LL} + A_{k+1}D_{kk}A^t_{k+1})^{-1}dL_{k+1}\sim \chi^2(2, \delta^2). \qquad (3.7)$$

A boundary value $|\Delta L_{k+1}|$ may remain undetected by

$$\Delta L^t_{k+1}(D_{LL} + A_{k+1}D_{kk}A^t_{k+1})^{-1}\Delta L_{k+1}= \delta_o^2 \qquad (3.8)$$

where δ_o^2 is a non-centrality parameter. It can be determined by α, the significance level, and β, the power of the statistical hypothesis test. The value of the undetected model error ΔL_{k+1} dependents mainly on matrix $(D_{LL} + A_{k+1}D_{kk}A^t_{k+1})$. Therefore, we define $(D_{LL} + A_{k+1}D_{kk}A^t_{k+1})$ as the reliability criterion matrix.

The reliability criterion is then set as

$$\mathrm{Tr}(D_{LL} + A_{k+1}D_{kk}A^t_{k+1}) = \text{minimun}. \qquad (3.9)$$

4. EXAMPLE

So far the precision criterion has been implemented. The results with the combined precision and reliability are to be reported. The above precision optimization criterion was applied to select two out of six images acquired by the VISAT mobile mapping system for intersecting the object (Figure 4.1). The camera positions are numbered as 2.0, 2.1, 3.0, 3.1, 4.0 and 4.1. The following table gives the optimization results of two tests initiated with different image pairs.

To some extent, the efficiency of the automatic optimal image selection procedure depends also on the reliability of point matching techniques. In this system, the distance between the target and camera exposure stations is limited to 65m. Further more, potential images for selection are limited to 3 neighboring image pairs. Thus, the mismatching rate can be greatly reduced and the efficiency of the optimization can be improved.

Test		Camera 1	Camera 2	X(m)	Y(m)	Z(m)
1	Initial pair	3.0	3.1	474617.209	5183959.219	69.935
	Optimal pair	4.0	2.1	474617.640	5183959.397	69.884
2	Initial pair	4.0	4.1	474617.042	5183959.663	69.804
	Optimal pair	4.0	2.1	474617.623	5183959.411	69.849

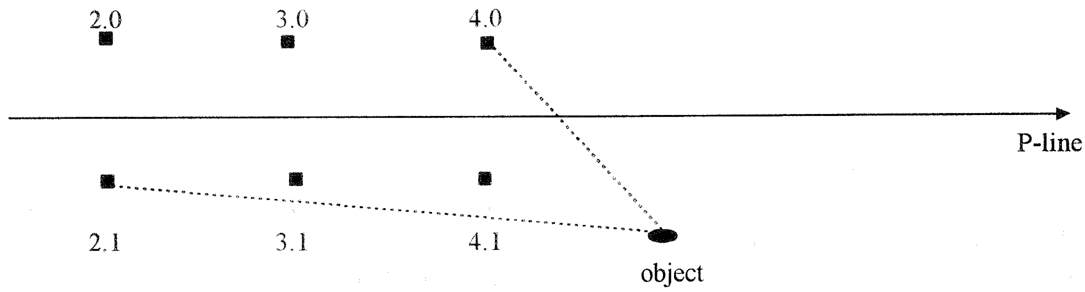

Figure 4.1 Geometric configuration of the experiment.

5. ACKNOWLEDGMENTS

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