EXTERIOR ORIENTATION OF SINGLE SCAN-LINE IMAGES BY DIRECT SENSOR ORIENTATION AND CONTROL POINTS

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ABSTRACT:

Single scan-line images, obtained from aircrafts, can be used for environmental monitoring, control of oil pipelines and also can have some other similar applications. The requirements to the accuracy of georeferencing are not as strict as in case of photogrammetric mapping. However, direct sensor orientation may have insufficient accuracy, because of desirability to use low cost decisions. Thus, the information about control points should be used to receive the necessary accuracy. Nevertheless, it is possible to achieve the necessary accuracy only when the elements of exterior orientation are measured with error, the doubled dispersion of high-frequency component of which does not cause the error, which exceeds the allowable. The data to estimate the elements of exterior orientation for every line are as follows: the measurements of some of the elements of exterior orientation by sensors for every line and control points in some of the lines. To perform that two kinds of approaches exist: determined and stochastic. In case of the determined approach, the elements of exterior orientation are represented by a linear or polynomial model. The parameters of these models can be calculated from the observation equations for control points. In this case, a sufficient quantity of control points should be located in every interpolation interval. When the quantity of control points is not sufficient the intervals would be too long to ensure the adequate representation of the aircraft dynamics. The possible variant of stochastic approach is presented here. For the lines, which contain control points, the estimation of the elements of exterior orientation, optimal in the sense of the maximum likelihood, is calculated. Information about the coordinates of control points is used as a training. To calculate the elements of exterior orientation for the lines without control points optimum linear nonstationary filter-interpolator is constructed.

1. INTRODUCTION

Linear scanners are widely used for acquisition of images at different ground resolution for photogrammetric mapping and remote sensing. The image is formed by side-to-side scanning movement while a platform travels along the path. Single scan-line images, obtained from aircrafts, can be used for environmental monitoring, control of oil pipelines and also have some other similar applications. In this case, an operator analyses the obtained image, locates and recognizes the objects of interest. The ground coordinates of these objects have to be calculated. The requirements to the accuracy of the ground coordinates of these objects are not as strict as in case of photogrammetric mapping. However, the accuracy of direct sensor orientation may be insufficient because of desirability to use low cost decisions. Thus, control points are used to receive the necessary accuracy.

2. CONDITIONS OF ACHIEVEMENT OF THE NECESSARY ACCURACY

The transformation of an image point P with coordinates $\boldsymbol{x} = (\mathrm{x,j})$ into an object coordinate system XYZ in accordance with the geometric model is represented (1).

$$\mathbf{X} = \mathrm{F}(\boldsymbol{\alpha}(\mathrm{j}), \boldsymbol{x}), \tag{1}$$

where

j = number of the line,
$\boldsymbol{\alpha}(\mathrm{j})$ = corresponded elements of exterior orientation.

Generally, $\mathrm{F}(\boldsymbol{\alpha}(\mathrm{j}), \boldsymbol{x})$ is the project transformation.
The measured elements of exterior orientation are determined with the error $\eta_{\alpha m}(\mathrm{j})$ (2).

$$\boldsymbol{\alpha}_{\mathrm{m}}(\mathrm{j}) = \boldsymbol{\alpha}_0(\mathrm{j}) + \boldsymbol{\eta}_{\alpha\mathrm{m}}(\mathrm{j}), \tag{2}$$

where

$\boldsymbol{\alpha}_0(\mathrm{j})$ = true elements of exterior orientation,
$\boldsymbol{\eta}_{\alpha\mathrm{m}}(\mathrm{j})$ = stationary random process with the zero average and the dispersion $(\boldsymbol{\sigma}_\alpha)^2$.

The object coordinates X, Y will be determined with the error $\boldsymbol{\eta}_{\mathbf{X}}$ (3).

$$\mathbf{X}_0 + \boldsymbol{\eta}_{\mathbf{X}} = \mathrm{F}(\boldsymbol{\alpha}_0 + \boldsymbol{\eta}_{\alpha\mathrm{m}}, \boldsymbol{x} + \boldsymbol{\eta}_{\mathrm{x}}) + \boldsymbol{\eta}_{\mathrm{F}}, \tag{3}$$

where

$\mathbf{X}_0$ = true object coordinates of the given point,
$\boldsymbol{\eta}_{\mathrm{F}}$ = error of the geometric model F(),
$\boldsymbol{\eta}_{\alpha\mathrm{m}}$ = error of the measurements of exterior orientation,
$\boldsymbol{\eta}_{\mathbf{X}}$ = error of the object coordinates;
$\boldsymbol{\eta}_{\mathrm{x}}$ = error of the image coordinates.

Every control point in the line supposedly allows to estimate the elements of exterior orientation for this line more precisely. The number of control points to the number of lines, taken for the period of time, can be considered as a random number, distributed according to the law of Poisson $\mathrm{P}\{\nu_0 = \mathrm{x}\} = \frac{\lambda^{\mathrm{x}}}{\mathrm{x}!}\mathrm{e}^{-\lambda}, \mathrm{x} = 0,1,2,\ldots$, where λ is interpreted as the average number of the event per the interval of time. In this case

λ can be considered as the frequency ω_{CP} of the appearance of control points on the image.
The error of the measurements of exterior orientation may be decomposed into two components: with the frequency higher than frequency ω_{CP} - $\boldsymbol{\eta}_{\alpha m}^{hf}$, and with the frequency lower than frequency ω_{CP} - $\boldsymbol{\eta}_{\alpha m}^{lf}$. The high-frequency component cannot be corrected by using the information about control points. Its component, which corresponds to the high-frequency mutual shift of lines, can be compensated by using the information, contained in the image itself. Low-frequency component can be corrected. For every line, in which a control point is located, the corrective value can be obtained (4).

$$\begin{aligned}&\boldsymbol{\alpha}_{cor}(j_{CP}) = \boldsymbol{\alpha}_m(j_{CP}) - \boldsymbol{\alpha}_{m+CP}(j_{CP}) = \\ &= \boldsymbol{\alpha}_0(j_{CP}) - \boldsymbol{\alpha}_{m+CP}(j_{CP}) + \boldsymbol{\eta}_{\alpha m}^{hf} + \boldsymbol{\eta}_{\alpha m}^{lf} = . \\ &= \boldsymbol{\eta}_{\alpha cor} + \boldsymbol{\eta}_{\alpha m}^{hf} + \boldsymbol{\eta}_{\alpha m}^{lf}\end{aligned} \quad (4)$$

It corrects the error of exterior orientation $\boldsymbol{\eta}_{\alpha m}^{hf} + \boldsymbol{\eta}_{\alpha m}^{lf}$ with the own error $\boldsymbol{\eta}_{\alpha cor}$. This value $\alpha_{cor}(j_{CP})$ can be used as the estimation of low-frequency component $\boldsymbol{\eta}_{\alpha m}^{lf}$ for the correction of the elements of exterior orientation for any line by interpolation (5).

$$\hat{\boldsymbol{\alpha}}(j) = \boldsymbol{\alpha}_m(j) - \boldsymbol{\alpha}_{cor}(j_{CP}) . \quad (5)$$

The estimation of exterior orientation $\hat{\boldsymbol{\alpha}}(j)$ for line j has the error of correction $\boldsymbol{\eta}_{\alpha cor}$, the error of interpolation $\boldsymbol{\eta}_{\alpha\, int}$ and two high-frequency components of measurements error $\boldsymbol{\eta}_{\alpha m}^{hf}$ (6).

$$\begin{aligned}&\hat{\boldsymbol{\alpha}}(j) = \boldsymbol{\alpha}_m(j) - \boldsymbol{\alpha}_{cor}(j) = \boldsymbol{\alpha}_0(j) + \boldsymbol{\eta}_{\alpha m}^{lf}(j) + \boldsymbol{\eta}_{\alpha m}^{hf}(j) - \\ &- \boldsymbol{\alpha}_{cor}(j) = \boldsymbol{\alpha}_0(j) + \boldsymbol{\eta}_{\alpha m}^{lf}(j) + \boldsymbol{\eta}_{\alpha m}^{hf}(j) - \\ &- \boldsymbol{\eta}_{\alpha m}^{lf}(j_{CP}) - \boldsymbol{\eta}_{\alpha m}^{hf}(j_{CP}) - \boldsymbol{\eta}_{\alpha cor} + \boldsymbol{\eta}_{\alpha\, int}(j) = \\ &= \boldsymbol{\alpha}_0(j) + \boldsymbol{\eta}_{\alpha m}^{hf}(j) - \boldsymbol{\eta}_{\alpha m}^{hf}(j_{CP}) - \boldsymbol{\eta}_{\alpha cor}(j_{CP}) + \boldsymbol{\eta}_{\alpha\, int}(j)\end{aligned} . \quad (6)$$

Thus, it is possible to achieve the necessary accuracy only when the elements of exterior orientation are measured with the error, the doubled dispersion of high-frequency component of which $2 * \left(\boldsymbol{\sigma}_{\eta_{\alpha m}}^{hf}\right)^2$ does not cause the error, which exceeds the allowable.

3. ALGORITHM

The data to estimate the elements of exterior orientation for every line are as follows: the measurements of some of the elements of exterior orientation by sensors for every line and control points in some of the lines. The accuracy of the measurements of exterior orientation by sensors is insufficient, and there is not sufficient quantity of control points. So the algorithm should use both types of data: the measurements of the elements of exterior orientation and the coordinates of control points.
To calculate the elements of exterior orientation two kinds of approaches exist: determined and stochastic. In the case of the determined approach, the elements of exterior orientation are represented by a linear or polynomial model. The parameters of these models can be calculated from observation equations for control points. In this case, a sufficient quantity of control points should be located in every interpolation interval. When the quantity of the points is not sufficient, the intervals would be too long to ensure the adequate representation of the dynamics of the aircraft. The possible variant of stochastic approach is presented here.

3.1. Estimation of the exterior orientation for the lines with control points

For the lines, which contain control points, the estimation of the elements of exterior orientation, optimal in the sense of the maximum likelihood, can be calculated. Let us examine the line j, which contains one or more control points. For calculating the ground coordinates X, Y of every image point is used the following information: the image coordinates of the point $\boldsymbol{x} = (x, y)$; the elements of exterior orientation, measured by sensors $\boldsymbol{\alpha}_m$; the apriori known elements of exterior orientation $\boldsymbol{\alpha}_a$; ground and image coordinates of control points $CP = \left(\mathbf{X}_{CP_1}, \boldsymbol{x}_{CP_1}, ..., \mathbf{X}_{CP_N}, \boldsymbol{x}_{CP_N}\right)$.

The estimation of the ground coordinates $\hat{\mathbf{X}}$, which is optimal in the sense of the maximum likelihood, is represented by the following expression (7).

$$P\left(\boldsymbol{x}, \boldsymbol{\alpha}_m, CP \middle| \hat{\mathbf{X}}\right) = \max_{\tilde{\mathbf{X}}} P\left(\boldsymbol{x}, \boldsymbol{\alpha}_m, CP \middle| \tilde{\mathbf{X}}\right). \quad (7)$$

The information about the coordinates of control points is used as a training. It is possible to reduce the estimation of the object coordinates of every image point to the estimation of the elements of orientation, because the object coordinates of the image points are connected by the unique determined dependence with the elements of exterior orientation (8).

$$\begin{aligned}&P\left(\boldsymbol{x}, \boldsymbol{\alpha}_m, \mathbf{CP} \middle| F(\boldsymbol{x}, \hat{\boldsymbol{\alpha}})\right) = \\ &= \max_{\tilde{\boldsymbol{\alpha}}}\left[P\left(\boldsymbol{\alpha}_m \middle| \tilde{F}(\boldsymbol{x}, \tilde{\boldsymbol{\alpha}})\right) \prod_{i=1}^{N} \left(P\left(\mathbf{X}_{CP_i} \middle| \boldsymbol{x}_{CP_i}, \tilde{\boldsymbol{\alpha}}\right) P(\tilde{\boldsymbol{\alpha}})\right)\right]\end{aligned} . \quad (8)$$

Under the assumption, that the distributions of all parameters are normal, the expression (8) can be written as follows (9).

$$\begin{aligned}&P\left(\boldsymbol{x}, \boldsymbol{\alpha}_m, \mathbf{CP} \middle| F(\boldsymbol{x}, \hat{\boldsymbol{\alpha}})\right) = \min_{\tilde{\boldsymbol{\alpha}}}\Big[(\boldsymbol{\alpha}_m - \tilde{\boldsymbol{\alpha}})\mathbf{V}_m^{-1}(\boldsymbol{\alpha}_m - \tilde{\boldsymbol{\alpha}})^T + \\ &+ \sum_{i=1}^{N}\Big(\left(\mathbf{X}_{CP_i} - F\left(\boldsymbol{x}_{CP_i}, \tilde{\boldsymbol{\alpha}}\right)\right) * \\ &\mathbf{V}_{\Sigma X_{CP}}^{-1} * \left(\mathbf{X}_{CP_i} - F\left(\boldsymbol{x}_{CP_i}, \tilde{\boldsymbol{\alpha}}\right)\right)^T + (\tilde{\boldsymbol{\alpha}} - \boldsymbol{\alpha}_a)\mathbf{V}_a^{-1}(\tilde{\boldsymbol{\alpha}} - \boldsymbol{\alpha}_a)^T\Big)\Big]\end{aligned} , \quad (9)$$

where

$F(\boldsymbol{x}, \boldsymbol{\alpha})$ = transformation of an image point P with the coordinates $\boldsymbol{x} = (x, j)$ into an object coordinate system XY with the known elements of exterior orientation $\boldsymbol{\alpha}$,

$\mathbf{V}_m$ = diagonal dispersion matrix of the measurements of the external orientation elements,

$\mathbf{V}_a$ = diagonal dispersion matrix of apriori information about the external orientation elements,

$\mathbf{V}_{\Sigma X_{CP}}$ = diagonal dispersion matrix of the error of control points object coordinates.

In the case, when the apriori values of the elements of exterior orientation have substantially greater error than the error of the measurements, the apriori information $\boldsymbol{\alpha}_a$ can be disregarded (10).

$$\mathrm{P}(\boldsymbol{x},\boldsymbol{\alpha}_m,\mathbf{CP}|\mathrm{F}(\boldsymbol{x},\hat{\boldsymbol{\alpha}}))=\min_{\tilde{\boldsymbol{\alpha}}}\Big[(\boldsymbol{\alpha}_m-\tilde{\boldsymbol{\alpha}})\mathbf{V}_m^{-1}(\boldsymbol{\alpha}_m-\tilde{\boldsymbol{\alpha}})^{T}+ \\ +\sum_{i=1}^{N}\Big((\mathbf{X}_{CP_i}-\mathrm{F}(\boldsymbol{x}_{CP_i},\tilde{\boldsymbol{\alpha}}))*\mathbf{V}_{\Sigma X_{CP}}^{-1}*(\mathbf{X}_{CP_i}-\mathrm{F}(\boldsymbol{x}_{CP_i},\tilde{\boldsymbol{\alpha}}))^{T}\Big)\Big]. \quad (10)$$

The selection of the numerical method of the search for the minimum is determined by the form of the function F(), which describes transformation of coordinates and entering into the minimized function. Function F() depends on angular orientation nonlinearly, and on the coordinates of carrier linearly. Moreover, namely the coordinates might cause the greatest deviation of the initial values from the true.

Newton's method is used to search for the minimum of three angles, and at each step the system of the equations "first-order derivatives are equal to zero" should be solved for other three. First-order derivatives are calculated analytically, the second-order via finite-difference approximation. As the initial approximation of the numerical method are used the values of the exterior orientation elements, measured by sensors.

3.2. Estimation of the orientation for the lines without control points

To calculate the elements of exterior orientation for the lines without control points optimum linear nonstationary filter-interpolator is constructed. During the first stage of the work of the filter-interpolator, i.e., filtration in the direction of time axis, this filter works in two different modes. For the lines without control points the classical scheme of the Kalman-Busey filtration is used. If one or more control points contains in the line, the obtained estimation should be defined more precisely according to the information about control points, employing the described before procedure.

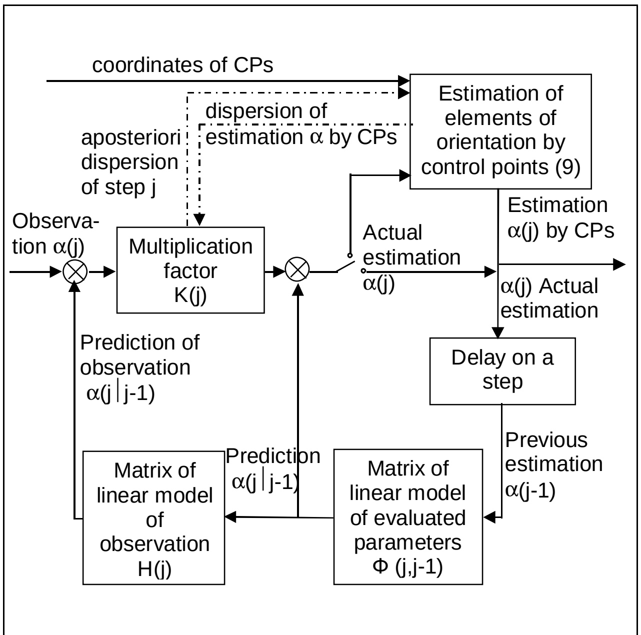
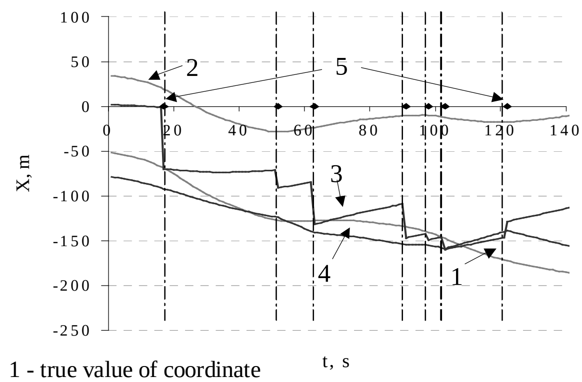


Figure 1. Block diagram of discrete nonstationary filter for estimating the elements of exterior orientation.

The block diagram of discrete nonstationary filter for estimating the elements of exterior orientation is represented in Figure 1. It is possible to see the intermittent decrease of the estimation error for the lines, which contain control points (Figure 2).

These jumps are smoothed out in the second stage of the work of the filter-interpolator - smoothing in the direction against the time axis. The classical form of the algorithm of smoothing with the fixed interval is used.



1 - true value of coordinate
2 - value, measured by GPS without differential regime (with noice);
3 - estimation by filter in the direction of time axis;
4 - estimation by the algorithm of smoothing in the direction against time axis;
5 - control points.

Figure 2. Example of the estimation of coordinate X.

The following assumptions are used for the generation of the algorithms of filtration: each element of exterior orientation $\alpha_i(j)$ (i=1..6, j - the number of line) is represented as the sum of the determined $\alpha_{\det i}(j)$ and random $\alpha_{randi}(j)$ components (11).

$$\alpha_i(j)=\alpha_{\det i}(j)+\alpha_{randi}(j). \quad (11)$$

The determined components $\alpha_{\det i}(j)$ are described by linear function and are calculated according to navigational information. The random components $\alpha_{randi}(j)$, evaluated by the developed nonstationary filter-interpolator, are described as the mutually uncorrelated stationary random processes with the zero average by the model (12).

$$\alpha_{randi}(j+1)=A_{\Delta\alpha i}\alpha_{ci}(j)+B_{\Delta\alpha i}\varepsilon_{\alpha i}(j), \quad (12)$$

where
$A_{\Delta\alpha i}$, $B_{\Delta\alpha i}$ = parameters of the forming filter for the random components of the exterior orientation elements,
$\varepsilon_{\alpha i}(j)$ = uncorrelated noise.

Errors of the sensors are described by the same model (13).

$$\eta_i(j+1)=A_{\Delta\eta i}\eta_i(j)+B_{\Delta\eta i}\varepsilon_{\eta i}(j), \quad (13)$$

where
$A_{\Delta\eta i}$, $B_{\Delta\eta i}$ = parameters of the forming filter for the measurements errors,

$\varepsilon_{\eta i}(j)$ = uncorrelated noise.

The possibility to use the selected model is confirmed by the testing, which shows that the required accuracy of georeferencing is achieved.

The parameters of the forming filter for the random components of exterior orientation elements and measurements errors $A_{\Delta\alpha i}$, $B_{\Delta\alpha i}$, $A_{\Delta\eta i}$, $B_{\Delta\eta i}$ may be evaluated by processing the data of imitation or nature experiments via the analysis of digital Fourier transformation of their realizations.

The algorithms of the estimation of the exterior orientation elements are developed for the case, when there are no sensors for some of the elements of exterior orientation. For the elements of orientation, which are not measured by sensors, the matrix of the linear model of observation dwindles, and filtration occurs in the regime of "memory". In the case, when the parameters of orientation are measured by the sensors, the error of each sensor is included into the vector of the evaluated parameters, because it is not the white noise.

4. CONCLUSION

The developed method makes it possible to calculate the estimation of the elements of exterior orientation by combined using of direct sensor orientation and control points with the sufficient for the complexes of environmental monitoring accuracy. The use of algorithms of optimal estimation and optimal filtration makes it possible to work in the conditions, when it would be problematic to use determined methods. From the other side, the additional information is necessary for the developed algorithm, namely: the statistical characteristics of the measurements errors and the information about the dynamics of aircraft.

REFERENCES

Ajvasjan S., Enjukov I., Meshalkin L., 1983, *Applied statistics: Bases of simulation and primary data processing*, Moskow - Finansy and statistics.

Engelhardt F.R., Nichols J.D., 1997, Remote Sensing for Pipeline Surveys and Monitoring: Analysis of Requirements and Capabilities. In: *Proceedings of Third International Airborne Remote Sensing Conference and Exhibition*, Denmark, v.1, pp.59-66.

Gill P., Murray W., Wright M., 1981, *Practical optimization*, London ; New York : Academic Press, 1981.

Gryslova T., Sukhareva I., Sharov V., 2000. The module of images georeferncing for the complexes of remote sensing. *Software & Systems*, 2000 (3), – pp. 23-27.

Poli D., 2004 Orientation of satellite and airborne imagery from multi-line pushbroom sensors with a rigorous sensor model. In: *Proceedings of XX ISPRS Congress, Commission I*, 12-23 July, Istanbul, Turkey, pp. 130-135.

Sage, A., Melsa J., 1971, *Estimation theory with applications to communications and control,* McGraw- Hilll Book Co.

Teuchert W.D., 1997, New achievements in an old art: Overview account on optical and infrared cameras and sensor. In: *Proceedings of Third International Airborne Remote Sensing Conference and Exhibition*, Denmark, v.1, pp.150-157.