

METHOD OF VEHICLE NAVIGATION SYSTEM CORRECTION BASED ON PROCESSING OF DISTANCE IMAGES OBTAINED BY LASER LOCATOR.

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ABSTRACT:

The method of aircraft navigation system correction using position of buildings on a surface is considered. It is supposed that the aircraft flies at low altitude and the surface region is probed by an onboard laser locator under flat angles.

The analysis of the selected flat vertical surfaces directions on plane image of considered region and its etalon is the base of this method. To do this distance image is transformed from a central projection to the Cartesian coordinate system and then it is reduced to a fixed point. Then the reduced distance image is segmented to select flat vertical surfaces. After selection the plane image of scene with projections of vertical surfaces is created on the basis of the segmented image. The similar plane image is created using digital model of scene. Generally there is no one-to-one correspondence between these two images.

To solve this problem Hough transform is made for both plane images. Comparison of straight line images by increments of an inclination angle of their normals relative to an axis x is made. Some measure of distinction is introduced. Finding the minimum value of measure of distinction means finding the best correspondence of straight lines on images. Determining of correspondence between straight lines allows to determine an angle of turn of one coordinate system concerning another.

At last the displacement vector of coordinate systems is determined. For this purpose appropriate pairs of straight lines are selected. The displacement vector can be determined by the difference of coordinates of cross points of corresponding lines.

1. INTRODUCTION

The method of aircraft navigation system correction using position of buildings on a surface is considered. It is supposed, that the scene is probed by an onboard laser locator which measure distances inside some raster with rather high frequency of impulse repetition and thus forms distance image of the scene. It is supposed, that the aircraft flies at low altitude therefore probing of scene is made under flat angles. For correction of navigation system it is necessary to carry out some comparison between formed distance image and the reference (etalon) image. Here the digital model of scene obtained by processing space photo is used as the reference (etalon) scene. Some reference points with known geographical coordinates are included in this digital model.

At automatic navigation of aircraft in conditions of absence or nonoperability of satellite navigation systems the following sections of flight can be selected:

- a section of independent flight above some area with no reference points; on this section correction of inertial navigation system is carried out by radio engineering measuring instruments of navigation parameters of flight;
- sections when correction is carried out by a land relief;
- sections of high-accuracy correction of navigation system using information about objects making an industrial scenes located along a route.

Enroute navigation systems based on correction using a relief of land are capable to provide the accuracy of horizontal coordinates calculating no less than 80–100 m (Beloglazov, 1985). The accuracy decreases to 150–200 m when the aircraft moves away from the point of last correction on 25–30 km. In this case high-accuracy navigation system correction based on

objects that form the scenes, located along a route, will allow to increase accuracy of navigation systems tenfold and to reduce the error of horizontal coordinates determination to about 8–10 m.

2. GENERAL PROVISIONS

The comparison of the flat vertical surfaces directions on plane image of considered scene and its etalon is the base of this method.

The considered task is solved in some stages:

- distance image is reduced to a fixed observation point at the moment t_0 (when the distance image forming begins). This stage is necessary because the speed of forming of images by laser locator is relatively low, and for this time aircraft could fly by significant distance. At that it is supposed, that aircraft own speed and its angle of drift are known.
- distance image is transformed from the central projection to the Cartesian coordinate system.
- distance image is segmented to select flat vertical surfaces, such as walls of buildings.
- the plane image of scene with projections of vertical surfaces is created on the basis of the segmented image;
- similar plane image is created for the reference (etalon) scene;
- searching for conformity between object images on observed and reference (etalon) plane images of scenes;
- matrix of transformation from the coordinate system connected with the aircraft into the reference (etalon) one is determined;
- aircraft own position relative to an observed scene at the moment t_0 is determined.

To perform the first two stages the following equations are used:

$$D_i^* = D_{imesas} \cdot \cos \alpha \cdot \cos \varphi + \Delta t_i \cdot V \cdot \cos \beta$$

$$x_i^* = \frac{1}{\Delta \varphi_x} \cdot \arctg \frac{\sin \left[\Delta \varphi_x \left(x - \frac{1}{2} x_{\max} \right) \right] \cdot D_{imes} - \Delta t_i \cdot V \cdot \sin \beta}{D_i^*}$$

$$\Delta x_i = \text{int} \left[x_i^* - x_i + 0.5 \right]$$

where D_{imesas} is the measured distance to the i th pixel;

D_i^* is distance to the i th pixel, reduced to a motionless point;

α is an angel of a deviation of a line of sighting from an central point in a plane of scanning;

φ is an angle of elevation of a plane of scanning;

β is an aircraft angle of drift;

Δt_i is a time interval from the first pixel up to the i th pixel;

V is the aircraft own speed (it is considered a constant);

x_i^* is the reduced x coordinate of the i th pixel;

$\Delta \varphi_x$ is the angular resolution of system along x axis (an angel on which line of sighting turns between two pixels);

x_{\max} – number of pixels in one line of the image;

Δx_i is shift of the i th pixel on the reduced image;

$\text{int}[*]$ means integer part of number.

Here pixels with smaller distance can replace pixels with the greater distance. If some pixel on the image is empty (the value for this pixel is unknown) it takes on a value of an adjacent pixel with the greater distance.

Segmentation of distance images for selecting of flat vertical surfaces, such as walls of buildings, can be executed on the basis of the algorithms described in (Lisitsyn, 1995). After the segmentation the plane image of a scene with projections of the segmented flat surfaces can be created.

Let's introduce the coordinate system $O_2X_2Y_2$ connected with the aircraft. As origin of coordinates we accept the point where the aircraft is located at the moment t_0 . X_2 axis is directed forward along the aircraft axis and goes through the center of scanner at the moment t_0 . Y_2 axis is directed to the left and is parallel to the horizontal plane.

The similar plane image can be obtained using digital model of scene (etalon). Here the coordinate system of etalon image $O_1X_1Y_1$ looks like: origin of coordinates of the reference (etalon) scene coincides with the point were the aircraft should be positioned at the moment t_0 if navigation errors are absent during the previous stage of flight. Axis X_1 is directed along the predicted axis of the aircraft at the moment t_0 and axis Y_1 is directed to the left and is parallel to the horizontal plane. As the origin of coordinates of reference coordinate system is on some distance from an observed scene, and navigation errors are rather insignificant, only those surfaces on the reference (etalon) scene should be selected which could be observed by the laser system in case of possible variations of aircraft real position at the moment t_0 .

Generally the coordinate system in which the plane image of an observed scene is created, has some shift and turn relative to coordinate system in which the reference (etalon) image is created. Thus, we may say, that a task of algorithm is to determine matrix of transformation from one coordinate system into another.

To determine this matrix it is necessary to find conformity between images of objects on the plane image of observed scene and the plane image of reference (etalon) scene. This task becomes complicated because generally there is no one-to-one correspondence between these two images. It happens because:

- some objects, both natural, and an artificial origin, are not included in digital model of scene;
- the description of objects is not enough adequate to a real scene;
- the digital model of scene has some errors as for heights of buildings and a relief of land;
- after distance image segmentation some objects that are present on the etalon image are not selected, or some objects are selected which have been not included in the etalon image;
- distances measured by laser locator have some errors;
- reliability of an estimation of object images parameters obtained at segmentation has stochastic nature.

3. METHOD DESCRIPTION

To solve considered task Hough transformation (Hough P.V.C., 1962) is made for plane images of observed and etalon scenes. As a result the straight lines in the Cartesian coordinate system will be transformed to points with coordinates (ρ, ϑ) in polar coordinate system. Here ρ is the distance from the origin of coordinates along a normal to a straight line, and ϑ is an inclination of this normal relative to axis x . Thus all straight lines on plane images are ranged on increase of angle ϑ . To determine conformity of images their comparison on increments of angle ϑ by way of enumeration is made. At the same time some measure of distinction is introduced which allows to bring each specific situation to conformity with some positive real number. Minimal value of the measure of distinction means the best conformity of straight lines on images.

The algorithm could be presented in the following simplified form. At the first stage an angle of turn ϑ of coordinate system of the observed image relative to reference (etalon) image is determined. For this purpose the following procedure is carried out.

1. One of object images that are present on the reference (etalon) image is selected as a base object image. Differences are calculated between inclination of base object image and inclinations of all other object images: $\Delta_1 \vartheta_i = \vartheta_i - \vartheta_1, 2 \leq i \leq m$. Here m is number of object images on the plane image of reference (etalon) scene. All differences are reduced to 0–360° range.

2. An arbitrary object image of the plane image of observed scene is accepted as conforming to the base object image on the plane image of reference (etalon) scene.

3. Differences between inclinations of other object images of the observed scene and inclination of object image which conforms to the base object image are calculated:

$\Delta_2 \hat{\vartheta}_j = \hat{\vartheta}_j - \hat{\vartheta}_1, 2 \leq j \leq n$. Here n is number of object images on the plane image of the observed scene. All differences are reduced to 0–360° range.

4. For every i th from $n-1$ object images of the observed scene a nearest object image of the reference scene is determined. The nearest object image is understood as such object image, for which $r_i = \min_{k=2, \dots, m} (\Delta_1 \vartheta_k - \Delta_2 \hat{\vartheta}_i)^2$. To simplify algorithm the

situation is permitted when various object images on the observed scene are put in conformity to the same object image

of the reference scene. It is supposed, that if $r_i \geq Q$, where Q is some threshold, then for i th object image no conformity is found.

If number of object images d for which conformity is not established is more than some threshold P , then the next object image on the observed scene is selected as the one corresponding to the base object image on the reference (etalon) scene. The loop repeats from items 3.

5. For object images for which conformity is found, sum $S_1 = \sum_{i=1}^{n-d} r_{1i}$ is calculated. This sum is an analogue of distance between sets of object images.

6. After that the next object image on the observed scene is selected as the one conforming to the base object image on the reference (etalon) scene. The loop repeats from items 3.

7. After enumeration of all object images on the observed scene the next object image on the reference (etalon) scene is selected as the base one. The loop repeats from item 2.

8. Upon termination of the loop-in-loop (items 2–7) the minimum of S_{mm} is selected. If $\min S_{mm} < R$, where R is some threshold, it is supposed, that conformity is established. Further only object images for which conformity is established are used. At that parallel object images are considered as the same object image.

Threshold values Q, P, R are selected based on the algorithm simulation.

Determination of conformity between straight lines allows to find a turning angel of one coordinate system relatively another one.

Since the coordinate system $O_2X_2Y_2$ of the observed image relative to the coordinate system $O_1X_1Y_1$ of the reference (etalon) image is turned on angel ϑ , the matrix of transformation from coordinate system $O_1X_1Y_1$ to coordinate system $O_2X_2Y_2$ has the form $\begin{pmatrix} \cos \vartheta & \sin \vartheta \\ -\sin \vartheta & \cos \vartheta \end{pmatrix}$.

Some object image on the reference (etalon) image, having inclination angle ϑ_1 in coordinate system $O_1X_1Y_1$, can be characterized by directing vector $\begin{pmatrix} \cos \vartheta_1 \\ \sin \vartheta_1 \end{pmatrix}$. Directing vector of

a corresponding object image in coordinate system $O_2X_2Y_2$ by virtue of the specified transformation has the form

$$\begin{pmatrix} \cos \vartheta & \sin \vartheta \\ -\sin \vartheta & \cos \vartheta \end{pmatrix} \begin{pmatrix} \cos \vartheta_1 \\ \sin \vartheta_1 \end{pmatrix} = \begin{pmatrix} \cos(\vartheta_1 - \vartheta) \\ \sin(\vartheta_1 - \vartheta) \end{pmatrix}$$

However, taking into consideration real error of measurements the inclination of conforming object image in coordinate system $O_2X_2Y_2$ could be described as $\vartheta_2 = \vartheta_1 - \vartheta + \xi$, where ξ is some error of measurement. At that, the error of measurement is distributed under the normal law with characteristics (M_ξ, σ_ξ) . Here $M_\xi = 0$, σ_ξ is the value depending on the object image characteristics and algorithm of segmentation settings.

It follows that turning angle ϑ could be determined as $\vartheta = \vartheta_1 - \vartheta_2 + \xi$, where ξ is a random error with mean square deviation

σ_ξ . To increase an accuracy of turning angle ϑ determination it is advisable to use all object images for which conformity is established. By summing and averaging considered expressions it is possible to get the following form for turning angle ϑ :

$$\vartheta = \frac{1}{n} \sum_{i=1}^n (\vartheta_{1i} - \vartheta_{2i}) + \frac{1}{n} \sum_{i=1}^n (\xi_i)$$

In view of independence and identical distribution of errors ξ_i in expression for a turning angle ϑ mean square deviation can be estimated as

$$\sigma \left(\frac{1}{n} \sum_{i=1}^n (\xi_i) \right) = \frac{\sqrt{n\sigma_\xi^2}}{n} = \frac{\sigma_\xi}{\sqrt{n}}$$

Identification of Parallel Object Images

The considered above part of algorithm does not allow to distinguish parallel object images.

For parallel object images identification the distances ρ_1, ρ_2 from the origin of coordinates to strait lines on which object images are located on the reference (etalon) or observed scene correspondingly are used. For each group of parallel object images of the observed scene the following operations are carried out.

The specified object images of reference (etalon) and observed scenes are arranged in accordance with distances increase: $\rho_{11} < \rho_{12} < \dots < \rho_{1k_1}, \rho_{21} < \rho_{22} < \dots < \rho_{2k_2}$.

Loops (similarly to stage I) are formed to search for equal increments of distance ρ . Sequences of increments look like $\Delta_1\rho_{i1}, \dots, \Delta_1\rho_{ik_1}, \Delta_2\rho_{j2}, \dots, \Delta_2\rho_{jk_2}$, where $\Delta_1\rho_{il} = \rho_{li} - \rho_{l1}, 1 \leq i, l \leq k_1, \Delta_2\rho_{js} = \rho_{2j} - \rho_{2s}, 1 \leq s, j \leq k_2$.

Conformity is determined by the following expression:

$$r_l = \min_{\substack{1 \leq i \leq k_1 \\ 1 \leq s, j \leq k_2}} (\Delta_1\rho_{il} - \Delta_2\rho_{js})^2$$

Value $r_{m,n} = \sum_{l=1}^{k_1} r_l$ for each loop is determined. Here m and n are number of object image that was accepted for base on reference (etalon) scene and number of object image that is conforming to it on the observed scene. The same as on the Stage I $\min(r_{m,n})$ is selected and conformity of object images is established by this value.

Displacement Vector Determination

At the last stage the displacement vector (X, Y) of coordinate systems is determined.

Let's take an i th object image for which conformity was established between object images on the reference (etalon) and

observed scenes. It is possible to establish a coordinate system $O_i X_i Y_i$ with X axis directed along this object image. ϑ_i is the angle on which new coordinate system is turned relative to the coordinate system $O_1 X_1 Y_1$. Transformation matrix that allow to transform coordinate system $O_1 X_1 Y_1$ into coordinate system $O_i X_i Y_i$ has the form $\begin{pmatrix} \cos \vartheta_i & \sin \vartheta_i \\ -\sin \vartheta_i & \cos \vartheta_i \end{pmatrix}$.

It is possible to use the following expression in vector form: $\overline{O_1 O_1} + \overline{O_1 O_2} = \overline{O_i O_2}$. Projecting this vector equality onto the $O_i Y_i$ axis and taking into consideration that y_i -coordinate of $\overline{O_1 O_2}$ could be determined from the bottom line of transformation matrix, the following expression could be determined: $\rho_1^{(i)} - X \sin \vartheta_i + Y \cos \vartheta_i = \rho_2^{(i)}$. Having designated $\Delta \rho_i$ as $\Delta \rho_i = \rho_2^{(i)} - \rho_1^{(i)}$, we get $\Delta \rho_i = -X \sin \vartheta_i + Y \cos \vartheta_i$. To determine coordinates X, Y it is necessary to get the similar expression for another (j)th object image: $\Delta \rho_j = -X \sin \vartheta_j + Y \cos \vartheta_j$. Determinant of this system has the form: $\Delta = \sin(\vartheta_j - \vartheta_i)$ and system solving has the form

$$X = (\Delta \rho_j \cos \vartheta_j - \Delta \rho_i \cos \vartheta_i) / \sin(\vartheta_j - \vartheta_i)$$

$$Y = (-\Delta \rho_j \sin \vartheta_i + \Delta \rho_i \sin \vartheta_j) / \sin(\vartheta_j - \vartheta_i)$$

It follows, that the system has no unambiguous solution when object images are parallel to each other, and the determinant module reaches the greatest value when the object images are perpendicular to each other. Besides as it was specified, the object image angle of inclination on the plane image of observed scene is determined with some error. It results in inaccuracy of measurement of distance to this object image and in errors of calculation of values X, Y .

To reduce an error of X, Y coordinates determination it is necessary to average out coordinates of all object images for which conformity on reference (etalon) and observed scenes is established and which are not parallel to each other. If there are n of such object images then number of pairs is $N = n(n-1)/2$. It is advisable to use module of determinant $|\Delta| = |\sin(\vartheta_j - \vartheta_i)|$ as a weighting coefficient for averaging. For the convenience we denote coordinates X, Y that were determined using i th and j th object images as x_{ij}, y_{ij} , $1 \leq i \leq (n-1)$, $(i+1) \leq j \leq n$. Then the expression for averaged out coordinates \bar{X}, \bar{Y} has the form:

$$\bar{X} = \frac{\sum_{i=1}^{n-1} \sum_{j=i+1}^n x_{ij} |\sin(\vartheta_i - \vartheta_j)|}{\sum_{i=1}^{n-1} \sum_{j=i+1}^n |\sin(\vartheta_i - \vartheta_j)|} \quad \bar{Y} = \frac{\sum_{i=1}^{n-1} \sum_{j=i+1}^n y_{ij} |\sin(\vartheta_i - \vartheta_j)|}{\sum_{i=1}^{n-1} \sum_{j=i+1}^n |\sin(\vartheta_i - \vartheta_j)|} \quad (1)$$

RESULTS

For algorithm simulation some synthesized plane images of a reference and observed scene with 7–15 object images were used. Here on each scene there were object images which have no corresponding object image on the other scene. As varied parameter the error of determination of inclination of object

images on the observed image was used (σ). It corresponds to worsening of weather conditions or reduction of capacity of a laser locator. As estimated parameters of work of algorithm the calculated values of an angle of turn and value of a displacement vector of system of coordinates of the observed scene relative to reference scene was used. Here the displacement vector was calculated by usual averaging by all possible pairs (Table 1, part I) and by weighting summation according to the Equation 1 (Table 1, part II).

In Table 1 values of estimated parameters are presented for different values of error of determination of object images inclination.

In this realization the angle of turn was 30° , and value of a displacement vector was (50, 80) m. As follows from the Table 1 determination of the displacement vector by weighting summation is more accurate than by averaging. The algorithm steadily worked for $\sigma < 1.5^\circ$. For $\sigma \geq 1.5^\circ$ the wrong conformity between object images of the observed and reference scenes was observed. It has resulted in wrong determination of the displacement vector though an error of angles of turn determination was insignificant. As a whole the carried out simulation has shown reliability of work of the offered method for scenes with rather big amount of objects.

The offered approach will provide stability of work of algorithms in conditions of noise, probable shading of parts of objects and uncertainty about height of objects and a land relief. At that the algorithm permits various modification on the basis of heuristic use of a *priory* information about an observed scene.

Table 1. Results of the algorithm simulation

σ	m_x	σ_x	m_y	σ_y	$m_\vartheta, ^\circ$	$\sigma_\vartheta, ^\circ$
I						
0	50	0	80	0	-30	0
0.25	49.18	2.39	79.79	0.46	-30.046	0.238
0.50	50.21	2.41	80.93	2.94	-29.825	0.359
0.75	50.51	5.42	77.07	8.51	-29.813	0.829
1.00	51.50	1.70	76.02	12.08	-30.019	0.615
1.50	124.23	668.01	124.05	45.07	-30.973	0.453
II						
0	50	0	80	0	-30	0
0.25	49.91	0.77	79.99	0.24	-30.046	0.238
0.50	49.98	0.93	80.12	1.15	-29.825	0.359
0.75	51.19	2.07	79.69	3.33	-29.813	0.829
1.00	51.25	1.76	79.53	4.73	-30.019	0.615
1.50	49.24	209.08	113.40	44.94	-30.973	0.453
m_x, m_y, m_ϑ - average of distribution of displacement vector (X, Y) and angle of turn ϑ ; $\sigma_x, \sigma_y, \sigma_\vartheta$ - mean square deviation of displacement vector (X, Y) and angle of turn ϑ .						

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