Scientific Journal of Silesian University of Technology. Series Transport
Zeszyty Naukowe Politechniki Śląskiej. Seria Transport

Volume 108 **2020**

p-ISSN: 0209-3324

e-ISSN: 2450-1549

DOI: https://doi.org/10.20858/sjsutst.2020.108.17

Journal homepage: http://sjsutst.polsl.pl

Article citation information:
Sabziev, E. Algorithm of aircraft flight data processing in real-time. *Scientific Journal of Silesian University of Technology. Series Transport*. 2020, **108**, 213-221. ISSN: 0209-3324. DOI: https://doi.org/10.20858/sjsutst.2020.108.17.

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ALGORITHM OF AIRCRAFT FLIGHT DATA PROCESSING IN REAL-TIME

Summary. In this paper, the problem of data bundling from different channels to determine the current location of a military aircraft belonging to the platform navigation system was investigated. The calculation of the data bundling coefficients by the least-squares method is proposed based on the data related to loads, orientation angles and speed recorded in the black box during the flight. Data from different channels (speed channel, load channel and GPS channel) are converted to like quantities (expressed as speed). The bundling coefficients (weight coefficients) of the speed and load channels data are calculated based on the GPS data of the flight start time (approximately 30-60 seconds of flight). Using these weight coefficients, the speed and load channels data are bundled, and the trajectory of the aircraft over the entire duration of the flight is plotted. This approach allows obtaining a satisfactory flight path in real-time for the subsequent flight period.

Keywords: navigation system, loads, flight speed, data bundling method, flight path

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1. INTRODUCTION

The use of the black box has traditionally been aimed at solving the problems of preventing future possible adverse situations by analysing the causes of various flight incidents and assessing the technical condition of various aviation equipment. To solve these problems, mathematical models based on the physical principles of devices and numerous software systems used in various fields of the aviation industry was developed. The general principles of black box data processing, models and algorithms related to the specifications of various design devices are reflected in numerous studies, including monographs on aircraft dynamics (for example, [1-8]).

Recently, the issue of determining the current location and orientation of the aircraft has added to the problems of the application of the black box. This is because, on the one hand, there is no direct access to aircraft devices and equipment for receiving information, while on the other hand, GPS signals come in intermittently, the coordinates are determined with errors. In addition, most importantly, GPS signals in areas of planned military operations cannot be received by appropriate devices as a result of noise pollution. Military aircraft indicators recorded by navigation instruments contain various errors and distortions, thus, numerous problems arise during their processing. Nevertheless, there is very little information in open sources about studies related to the elimination of these problems [6, 9, 10].

The problems of processing flight data are associated with the design features of measuring instruments. The object of study in this paper is an IKV-1 (inertial attitude and heading reference system) type navigation system (for example [4, 5]). The initial version of the IKV-1 navigation system was created for the Yak-3BM aircraft. Subsequently, the system is being used on Yak-38, MIG-23B, MIG-27, SU-17 and others. The main difference between the IKV-1 and other navigation systems is that its accelerometers are mounted on a gyroscopic platform that adjusts its orientation in space.

The flight path can be determined based on two data channels. One of them is carried out by one-time integration of the measured speed of the aircraft, and the second, by double integration of accelerations determined based on the loads. However, neither of these channels (which we will refer to as ordinary speed and load channels) can accurately determine the flight path during direct data processing. This is because the recorded parameters contain distortions and errors. Considering this, the flight parameters are smoothed and cleaned from the noise using various filters. Filtering somewhat improves the plotting of the flight path, but the problem remains without a satisfactory solution.

The aforementioned channels carry out measurements by means of devices that operate on different principles, and their errors do not have a strong correlation. Therefore, by fusing data from various channels, the flight path can be calculated with greater accuracy.

The application of this approach to similar technical systems led to the creation of the Kalman filter [11]. The use of this filter gives good results and the statistical characteristics of the errors of the measured values become known. In the case under investigation, there is no such information about the measuring devices of the data channels, and the Kalman filter cannot be applied.

In view of the above, the idea was put forward that, assuming the GPS data has the smallest error, we calculate the bundling coefficients (weight coefficients) of the speed and load channel data related to the flight start time and use these coefficients to calculate the flight path for the subsequent flight period.

A mathematical model of the bundling problem is developed in this paper, and an algorithm for calculating the bundling coefficients is given.

2. MATHEMATICAL FORMALISATION OF THE PROBLEM

An IKV-1 (ИКВ-1) navigation system operates in the right-handed Cartesian coordinate system $OXYZ$ [4, p. 31]: The axıs OZ is directed upward in the geodesic vertical direction and the axes OX and OY are located perpendicular to each other in the horizontal direction. The flight path of the aircraft is considered in the earth-fixed coordinate system $O_g X_g Y_g Z_g$. It is assumed that its coordinate axes $O_g X_g$, $O_g Y_g$ and $O_g Z_g$ are parallel to the axes OX, OY, OZ in accordance with the coordinate system $OXYZ$, and the origin of the coordinates O_g coincides with the starting point of the flight path.

It should be noted that measurements through different channels are carried out with a certain time increment Δt. Given below are the loads, angles and other quantities related to the moment $t_i = i\Delta t$, $i = 0,1,2,...$ with the addition of i to the index.

2.1. Mathematical model of the load channel

Three gyroscopes and three pendulum accelerometers are installed on a stabilised platform of a three-layer gyro stabiliser of the navigation system [6, P. 32]. According to the accelerometers' equations, the relationship between acceleration, linear and angular velocity of the aircraft is expressed by the following system of equations [4, P. 25]:

$$\begin{cases} V'_{x,i} = -\omega_{y,i} V_{z,i} + \omega_{z,i} V_{y,i} + n_{x,i} g \,, \\ V'_{y,i} = \omega_{x,i} V_{z,i} - \omega_{z,i} V_{x,i} + n_{y,i} g \,, \\ V'_{z,i} = -\omega_{x,i} V_{y,i} + \omega_{y,i} V_{x,i} + (n_{z,i} - 1) g \,. \end{cases} \tag{1}$$

Here $n_{x,i}$, $n_{y,i}$, $n_{z,i}$ are the loads, $\omega_{x,i}$, $\omega_{y,i}$, $\omega_{z,i}$ are the components of the angular velocity of the platform rotation, $V_{x,i}$, $V_{y,i}$, $V_{z,i}$ are the components of the aircraft velocity vector, g is the gravitational acceleration. The load is a ratio of the sum of all aerodynamic forces acting on the aircraft, except gravity, and engine thrust to gravity [1, P. 47]. The above quantities are given in the coordinate system $OXYZ$, the beginning of which can be assumed to be located in the centre of gravity of the aircraft.

The components of the angular velocity can be expressed by the orientation angles measured by the gyroscope – ψ (yaw angle), ϑ (pitch angle) and γ (roll angle) [12, P. 188]:

$$\begin{cases} \omega_{x,i} = -\psi'(-\vartheta\cos\psi + \gamma\sin\psi\cos\vartheta) - \vartheta'(-\sin\psi + \gamma\cos\psi\sin\vartheta) + \gamma'\cos\psi\cos\vartheta, \\ \omega_{y,i} = \psi'(\vartheta\sin\psi + \gamma\cos\psi\cos\vartheta) - \vartheta'(-\cos\psi - \gamma\sin\psi\sin\vartheta) + \gamma'\sin\psi\cos\vartheta \,, \\ \omega_{z,i} = \psi' + \vartheta'\gamma\cos\vartheta + \gamma'\sin\vartheta \,. \end{cases} \tag{2}$$

For simplicity, the quantities ψ, ϑ, γ in Equations 2 are written without indices.

Based on the known coordinates of the plane (can be taken as $\mathbf{S}_0 = (0, 0, 0)$) and the velocity $\mathbf{V}_i = (V_{x,i}, V_{y,i}, V_{z,i})$ at the starting moment $t = 0$, we can solve system (1)-(2) and plot the trajectory $\mathbf{S}_i = (S_{x,i}, S_{y,i}, S_{z,i})$.

2.2. Mathematical model of the speed channel

As a rule, measurements of a barometric height measuring instrument and a traditional Pitot tube are processed using experimentally confirmed standard transforms taking into account air temperature and pressure. To differentiate from the speed calculated based on the loads, the actual speed U_i calculated for the flight moment t_i here is denoted by the height h_i, U_i being a scalar quantity, $\mathbf{U}_i = (U_{x,i}, U_{y,i}, U_{z,i})$ represents the modulus of the velocity vector. The components of $\mathbf{U}_i$ in the coordinate system $O_g X_g Y_g Z_g$ can be calculated as follows:

$$\begin{cases} U_{x,i} = \sqrt{U_i^2 - h_{t.i}^2} \cos\psi_i , \\ U_{y,i} = \sqrt{U_i^2 - h_{t.i}^2} \sin\psi_i , \\ U_{z,i} = h_{t,i} , \end{cases} \tag{3}$$

where $h_{t,i} \cong \dfrac{h_i - h_{i-1}}{\Delta t}$.

2.3. Specific features of GPS data

Unlike the above data, GPS data usually does not come from sensors systematically. The interval between the data is $3\Delta t \div 7\Delta t$, and sometimes greater. The time of registration of this data can be synchronised with the time of other data. Another distinctive feature of GPS data is that the coordinates of the current path point – geographic longitude and latitude – are given in height metres. Suppose that, using conversion formulas, GPS data is also expressed in metric units.

It should be noted that integration of systems (1) or (3) does not allow calculating the flight path of the aircraft with satisfactory accuracy. The task is to bundle the data of the speed and load channels. According to the ideology of the Kalman filter, it is assumed that:

- there exist stable matrices $\mathbf{E}_v$ and $\mathbf{E}_u$ such that a linear combination of the "data" of the speed and load channels according to the coefficients of these matrices reflect the actual flight path with adequate accuracy;
- the estimates of the matrices $\mathbf{E}_v$ and $\mathbf{E}_u$ can be found from the condition of proximity of the calculated combination to the GPS data.

2.4. Solving of the bundling problem

Thus, suppose that there are such stable matrices $\mathbf{E}_v$ and $\mathbf{E}_u$

$$\sum_{i=1}^{N}(\mathbf{E}_v\mathbf{V}_i + \mathbf{E}_u\mathbf{U}_i)\Delta t\,, \tag{4}$$

that they give the aircraft flight path from the start to the moment $t_N = N\Delta t$ with sufficient accuracy. Suppose that the starting point corresponding to the moment of the path $t = 0$ (to the case $i = 0$) is in the origin of the coordinates, and at the starting moment, the velocity $\mathbf{V}_0$ coincides with $\mathbf{U}_0$:

$$\begin{cases} V_{x,0} = U_{x,0}\,, \\ V_{y,0} = U_{y,0}\,, \\ V_{z,0} = U_{z,0}\,. \end{cases} \tag{5}$$

Since the values ψ_i, ϑ_i, γ_i $(i = 0,1,2,\ldots)$ are known, for each $i = 1,2,\ldots$ the quantities $\omega_{x,i}$, $\omega_{y,i}$, $\omega_{z,i}$ from system (2) can be calculated:

$$\begin{cases} \omega_{x,i} = -(\psi_i - \psi_{i-1})(-\vartheta_i \cos\psi_i + \gamma_i \sin\psi_i \cos\vartheta_i) \\ -(\vartheta_i - \vartheta_{i-1})(-\sin\psi_i + \gamma_i \cos\psi_i \sin\vartheta_i) + (\gamma_i - \gamma_{i-1})\cos\psi_i \cos\vartheta_i\,, \\ \omega_{y,i} = (\psi_i - \psi_{i-1})(\vartheta_i \sin\psi_i + \gamma_i \cos\psi_i \cos\vartheta_i) \\ -(\vartheta_i - \vartheta_{i-1})(-\cos\psi_i - \gamma_i \sin\psi_i \sin\vartheta_i) + (\gamma_i - \gamma_{i-1})\sin\psi_i \cos\vartheta_i\,, \\ \omega_{z,i} = (\psi_i - \psi_{i-1}) + (\vartheta_i - \vartheta_{i-1})\gamma_i \cos\vartheta_i + (\gamma_i - \gamma_{i-1})\sin\vartheta_i\,. \end{cases} \tag{6}$$

Based on Equation 1, we can write an indefinite report scheme for the quantities $V_{x,i}$, $V_{y,i}$, $V_{z,i}$ $(i = 0,1,2,\ldots)$:

$$\begin{cases} V_{x,i+1} = V_{x,i} - \omega_{y,i+1}V_{z,i+1}\Delta t + \omega_{z,i+1}V_{y,i+1}\Delta t + n_{x,i+1}g\Delta t\,, \\ V_{y,i+1} = V_{y,i} + \omega_{x,i+1}V_{z,i+1}\Delta t - \omega_{z,i+1}V_{x,i+1}\Delta t + n_{y,i+1}g\Delta t\,, \\ V_{z,i+1} = V_{z,i} - \omega_{x,i+1}V_{y,i+1}\Delta t + \omega_{y,i+1}V_{x,i+1}\Delta t + (n_{z,i+1} - 1)g\Delta t\,. \end{cases} \tag{7}$$

The main determinant of system (7) being $\Delta_{\omega,i} \equiv 1 + (\omega_{x,i}^2 + \omega_{y,i}^2 + \omega_{z,i}^2)\Delta t^2 \geq 1$ allows calculating the values $V_{x,i}$, $V_{y,i}$, $V_{z,i}$ for each subsequent i.

For simplicity, let us index the sought-for fusion coefficients in the matrices $\mathbf{E}_v$ and $\mathbf{E}_u$ as follows:

$$\mathbf{E}_v = \begin{pmatrix} e_{11} & e_{12} & e_{13} \\ e_{21} & e_{22} & e_{23} \\ e_{31} & e_{32} & e_{33} \end{pmatrix}, \qquad \mathbf{E}_u = \begin{pmatrix} e_{14} & e_{15} & e_{16} \\ e_{24} & e_{25} & e_{26} \\ e_{34} & e_{35} & e_{36} \end{pmatrix} \tag{8}$$

As stated above, GPS data does not come from sensors systematically. Let us denote the moments of recording GPS data by i_k, $k = 1,2,..., N$. Since the number of unknown fusion coefficients for each channel is 6, for the least squares method to be informative, it is appropriate to take it as $N \ge 10$. The condition of the smallest possible difference of the flight path of the aircraft determined from formula (4) at the moments $t_{i_k} = i_k \Delta t$ from the corresponding GPS coordinates can be written as follows:

$$\sum_{k=1}^{N} \left[\sum_{i=1}^{i_k} (\mathbf{E}_v \mathbf{V}_i + \mathbf{E}_u \mathbf{U}_i) \Delta t - \mathbf{R}_{i_k} \right]^2 \to \min, \tag{9}$$

where $\mathbf{R}_{i_k}$ is the vector representing the coordinates of the aircraft obtained from GPS sensors at the moment t_{i_k}.

It is easy to see that the components of the minimised vector are independent of each other in terms of the sought-for coefficients. Therefore, they can be studied independently. First, let us consider the component $\mathbf{R}_x$, then the explicit form of the row to be minimised is as follows:

$$\Im_x(e_{11},...,e_{16}) \equiv \sum_{k=1}^{N} \left[\sum_{i=1}^{i_k} (e_{11}V_{x,i} + e_{12}V_{y,i} + e_{13}V_{z,i} + e_{14}U_{x,i} + e_{15}U_{y,i} + e_{16}U_{z,i}) \Delta t - \mathbf{R}_{x,i_k} \right]^2, \tag{10}$$

The coefficients $e_{11},...,e_{16}$, which give the minimum of the functional $\Im_x(e_{11},...,e_{16})$, can be found using the least squares method: it is obtained from the equality of the partial derivatives $\frac{\partial \Im_x}{\partial e_{1j}}$, $(j = 1,2,..., 6)$ to zero:

$$\begin{cases} e_{11} \sum_{k=1}^{N} a_{11}^{i_k} + e_{12} \sum_{k=1}^{N} a_{12}^{i_k} + \cdots + e_{16} \sum_{k=1}^{N} a_{16}^{i_k} = \sum_{k=1}^{N} \left(\frac{R_{x,i_k}}{\Delta t} \sum_{i=1}^{i_k} V_{x,i} \right), \\ e_{11} \sum_{k=1}^{N} a_{21}^{i_k} + e_{12} \sum_{k=1}^{N} a_{22}^{i_k} + \cdots + e_{16} \sum_{k=1}^{N} a_{26}^{i_k} = \sum_{k=1}^{N} \left(\frac{R_{x,i_k}}{\Delta t} \sum_{i=1}^{i_k} V_{y,i} \right), \\ \cdots \\ e_{11} \sum_{k=1}^{N} a_{61}^{i_k} + e_{12} \sum_{k=1}^{N} a_{62}^{i_k} + \cdots + e_{16} \sum_{k=1}^{N} a_{66}^{i_k} = \sum_{k=1}^{N} \left(\frac{R_{x,i_k}}{\Delta t} \sum_{i=1}^{i_k} U_{z,i} \right). \end{cases} \tag{11}$$

Having solved linear system of linear algebraic Equation 11, we can find the fusion coefficients $e_{11},...,e_{16}$.

To calculate other elements of the matrices $\mathbf{E}_v$ and $\mathbf{E}_u$, we need to write the corresponding analogs of system (11). Their simultaneous solution allows calculating all coefficients $e_{11},..., e_{66}$.

3. BUNDLING PROCEDURE

Numerical experiments show that for the procedure of data bundling for a flight with a total duration of 1÷1.5 hours to yield a satisfactory result, it is enough to process GPS data for the first 30÷90 seconds of flight. As a rule, during this flight start period, GPS sensors work more or less normally, so we can calculate the bundling coefficients. To calculate the flight path in the subsequent flight period, the formula (4) based on the known coefficients $e_{11},..., e_{66}$ can use. Its discrete analogue written with respect to coordinates is as follows:

$$\begin{cases} S_{x,i} = S_{x,i-1} + e_{11}V_{x,i} + e_{12}V_{y,i} + e_{13}V_{z,i} + e_{14}U_{x,i} + e_{15}U_{y,i} + e_{16}U_{z,i} \ , \\ S_{y,i} = S_{y,i-1} + e_{21}V_{x,i} + e_{22}V_{y,i} + e_{23}V_{z,i} + e_{24}U_{x,i} + e_{25}U_{y,i} + e_{26}U_{z,i} \ , \\ S_{z,i} = S_{z,i-1} + e_{31}V_{x,i} + e_{32}V_{y,i} + e_{33}V_{z,i} + e_{34}U_{x,i} + e_{35}U_{y,i} + e_{36}U_{z,i} \ . \end{cases} \tag{12}$$

Fig. 1 below shows versions of the flight path based on the coefficients determined from the processing of the initial flight data: based on the load channel (A), speed channel (B) and the fusion of data of these two channels (C). To assess the degree of proximity of the trajectory obtained as a result of data fusion to the actual flight path, the trajectory (D) is also plotted here based on the GPS data of the same flight. Comparison of the trajectories in Fig. 1 shows that the proposed approach allows calculating a more satisfactory version of the flight path.

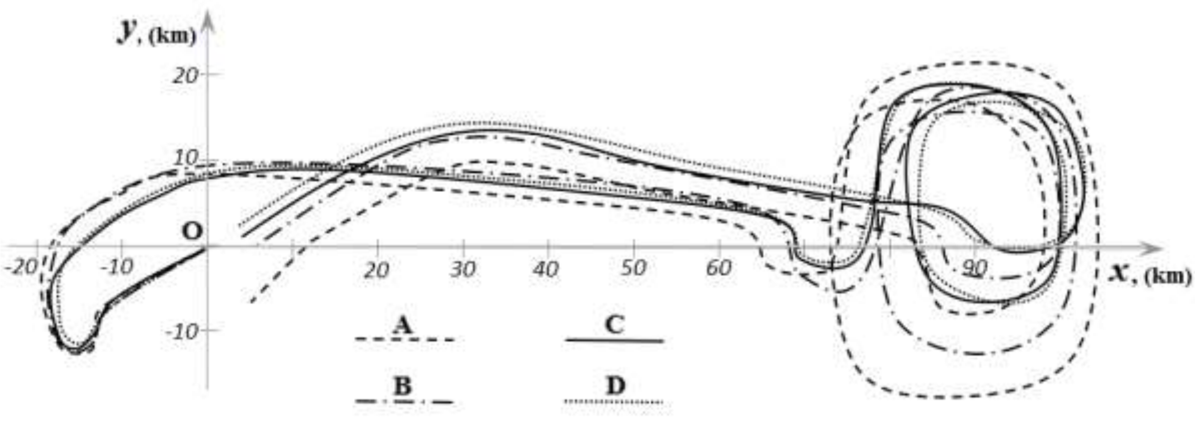

Fig. 1. Comparison of the flight path with the trajectories plotted based on various data: (A) – based on the loads; (B) – based on the speed data; (C) – based on the results of data fusion; (D) – the trajectory based on the GPS data of the real flight

Obviously, after determining the bundling coefficients, using system (12), we can determine the current location of the aircraft based on each new data frame. Thus, the proposed approach allows determining the location of a military aircraft in real flight conditions and plot a flight path.

3. CONCLUSION

This paper proposes a fusion method for plotting the flight path based on the data of the load and speed channels for the first period of flight of a military aircraft, also providing an algorithm for calculating the bundling coefficients. The calculated coefficients make it possible to obtain a satisfactory flight path in real-time for the subsequent flight period using the bundling algorithm. The results of the numerical experiments suggest that this algorithm can be successfully applied.

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Received 20.03.2020; accepted in revised form 21.06.2020