UDC 681.5.015:629.7.05
DOI: 10.15587/1729-4061.2017.118640

DEVELOPMENT OF A FUNCTIONALLY STABLE ORIENTATION SYSTEM FOR AN UNMANNED AERIAL VEHICLE

I. Zhezhera
Postgraduate student*
E-mail: ivanzhezhera92@gmail.com
B. Ouissam
Postgraduate student*
E-mail: boudiba.ouissem@yahoo.fr
S. Firsov
Doctor of Technical Sciences, Professor*
E-mail: sn.firsof@gmail.com
*Department of electrical engineering and mechatronics
National Aerospace University named after M. Zhukovsky Kharkiv Aviation Institute
Chkalova str., 17, Kharkiv, Ukraine, 61070

Представлений підхід до вирішення проблеми функціонально стійкого управління безпілотним літальним апаратом на підставі мінімальної системно апаратної надмірності вимірювальних органів. Описано впровадження алгоритмів комп'ютерного зору в завданні візуального орієнтування і відновлення параметрів просторового положення. Продемонстровані дихотомічні алгоритми діагностування системи на наявність відмов, апарат реконфігурації і відновлення в режимі реального часу

Ключові слова: функціональна стійкість, діагностика, компенсація, реконфігурація, орієнтація, відмовостійкість, оптична навігаційна система

Представлен подход к решению проблемы функционально устойчивого управления беспилотным летательным аппаратом на основании минимальной системно аппаратной избыточности измерительных органов. Описано внедрение алгоритмов компьютерного зрения в задаче визуального ориентирования и восстановления параметров пространственного положения. Продемонстрированы дихотомические алгоритмы диагностирования системы на наличие отказов, аппарат реконфигурации и восстановления в режиме реального времени

Ключевые слова: функциональная устойчивость, диагностика, компенсація, реконфигурация, ориентация, отказоустойчивость, оптическая навигационная система

1. Introduction

Under conditions of increasing requirements to the operation of small autonomous aerial vehicles (SAAV), it is necessary to fulfill a flight task with the assigned indicators of quality and enhanced probability of returning of an object.

To avoid or reduce the impact of failure of measuring instruments on the performance of a system, it is essential to set up continuous monitoring of their operation, as well as to control the entire system as a whole [1]. Sensors of motion and orientation parameters of SAAV are the elements of diagnosis with unknown inputs. Provision of functional stability requires existence of structural redundancy, which ensures structural diagnosis of a measuring unit and restoration of measurement parameters in the real-time mode. By the concept of structural redundancy, we imply a steady set of resources that can support accuracy properties in case of a failure due to reconfiguration of algorithmic support. A characteristic feature of the use of structural redundancy is a possibility not only to make compensation of failures, but also to enhance indicators of control quality, accuracy and reliability. Despite these advantages, application of structural redundancy leads to an increase in weight, dimensions, power consumption, complexity of data processing algorithms, etc. These circumstances determine the need to address the challenge of providing of functional stability of the elements of the control system of small-dimensional AAV with minimal structural redundancy [2].

In the first case, it is necessary to develop new highly-reliable equipment that can provide for its efficiency with a desired quality level in the case of the damage to the system's components. A considerable complication of technological processes leads to an insignificant change in reliability indicators, while the level of reliability of characteristics of the elements of control systems is saturated. These circumstances determine the relevance of application of another method of providing the elements of stability of the motion systems of SAAV with the lowest structural redundancy.

Development of the system is relevant and enjoys demand due to the possibility of enhancement of aerial vehicle protection and integration into currently existing control systems. The use of this system will provide for retaining of functional properties of an aerial vehicle while performing a task. Implementation of this system does not require hardware transformations.

2. Literature review and problem statement

Determining motion parameters of an aerial vehicle is an integral part of the task of the aerial vehicle's motion control. The classic navigation system of small unmanned aerial vehicles consists of the inertial navigation system (INS), which includes angular velocity sensor (AVS) and accelerometers, a receiver of the satellite navigation system (SNS), which measures parameters of a spatial position in a given coordinate system, and a magnetometer, able to measure the angle of magnetic course of an aerial vehicle. These sensors are the minimal set of devices for determining of the full set of navigation parameters [3]. However, this set is not sufficient to solve the diagnosis problem due to the absence of structural redundancy. In order to perform auto-diagnosis of correctness of the system's parameters in the real-time mode, it is necessary to have their reference values. In the absence of redundancy of measuring units (able to measure one parameter), it is impossible to perform diagnosis with the proper level of accuracy, moreover, while determining of the place and the type of a failure. Because of the absence of reservation, a failure of one of the sensors will lead to a failure of a correct feedback signal of the system, which will cause a failure of the entire system. The risk of failure of described above measuring devices is great due to the structural characteristics of micromechanical sensors, existence of vibration, existence of discrete integration errors, the drift of "zero" value of sensors, probability (temporary or long-term) of the loss of the satellite network, as well as occurrence of magnetic anomalies [4].

That is why the most common solution to this problem is hardware reservation of all measuring units. This solution leads to an increase in dimensions, cost, and complexity of computation load of an aerial vehicle, especially in the case of micro- unmanned aerial vehicle. In turn, program diagnosis of measuring devices (above) alone is not always able to provide the ability to identify the place of a failure. In this case, restoration of a lost signal becomes impossible as a result of the absence of redundancy of elements.

Modern SAAV have a purpose load, from the streaming video image of which, it is possible to provide information about dynamics of the angular and spatial position of an aerial vehicle. Photogrammetric approach offers the possibility to synthesize metric indicators using visual information. Due to this fact, the optical system can be used as a backup source of information for compensation of lost and deformed navigation parameters [5, 6]. This requires algorithmic support, which is able to match the location of the camera (in reality, the fix of an aerial vehicle), parameters of satellite and inertial navigation systems.

In engineering practice, complexes, based on a combination with local systems of TERCOM type, optical lidars, radars or devices based on Doppler effect are used [7]. However, such systems have a number of disadvantages, the most important of which is the problem of fulfilling the task at comparatively low altitudes due to low resolution of the scanner, instability of operations at obstacles (such as trees or poles). That is why the use of such systems does not provide for functional stability of operation of an aerial vehicle at low altitudes.

DSMAC system, which is widely used in winged rockets, attained the most successful results in this area [8, 9]. However, this system is limited to determining only of spatial parameters, without determining the values of angular space and solving the problem of fault tolerance.

It is necessary to use a system, not connected with a specific control object that has a standard set of measuring elements without any direct reservation of channels [10]. In this case, it is essential to organize both a diagnosis system and restoration of a signal in the real-time mode with providing functional stability of an aerial vehicle.

Analysis of the sources demonstrated different approaches to solving the problem of provision of functional stability of the orientation system. It is evident that the majority of the proposed systems are based on redundancy, obtained as multiple reservations of devices. However, a promising way is collaboration of the algorithms of inertial, satellite and optical orientation systems (sources of variable nature of measurement), capable of providing redundancy at a minimal set of measuring tools. In this case, such a set of equipment can provide the functional stability of a system as a whole to full extent. The problem of synthesizing the data of an object's motion dynamics, acquired from the stream, has not been fully resolved so far, which makes research in this area relevant, in particular in the framework of solving the problem of providing of functionally stable orientation system.

3. The aim and objectives of the study

The aim of present study is to develop a functionally stable orientation system, capable to maintain its properties in case of emergency situations, which include failures of measuring instruments. As the system implies existence of hardware or system redundancy, one of the tasks of the research is to explore and develop the method of using existing tools of average small autonomous aerial vehicles with artificial synthesizing of information or sources of obtaining geospatial information. This will make it possible to respond timely to unforeseen changes in operation of a system and ability to perform correction of a distorted signal due to a failure in the measuring unit.

To accomplish the set aim, the following tasks were set:

– to introduce an additional unit of structural redundancy, which will be able to provide the required quality indicators;

– to develop an algorithm of diagnosis of the system based on indications of existing instruments;

– to perform algorithmic reconfiguration of the measuring system in order to provide countermeasures for a short or long-term failure of sensors with an error of no more than 3 %.

4. Materials and methods of research into functionally stable system of control over small autonomous aerial vehicles

4. 1. Diagnosis

We considered the global diagnosis of all existing measuring systems of SAAV using the classic set of sensors [11], which directly affect the quality of diagnosis. For operation stability of the system, it is necessary to provide a high-quality component of measurement.

The main idea behind this method is the use of sensors of different nature of measurement at calculation of a single parameter. To implement failure identification in a measuring system, it is necessary to carry out a series of transformations. A general parameter is the angle of course , because it can be synthesized from all the aforementioned meters.

First, we performed global diagnosis of all systems for existence of a failure.

Coordinate system of SAAV in shown below (Fig. 1).

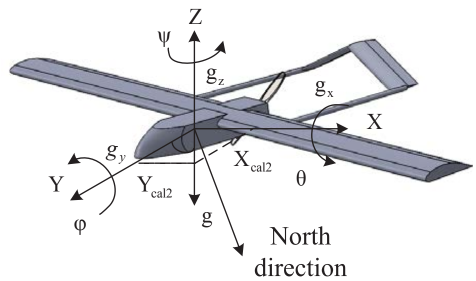


Fig. 1. Coordinate system of SAAV

Here g, g_x, g_y, g_z are the accelerations, θ is the pitch angle, φ is the roll angle, ψ is the course angle.

$$\begin{cases} g_x = -g\cdot\cos(\varphi)\cdot\sin(\theta); \\ g_y = g\cdot\sin(\varphi)\cdot\sin(\theta); \\ g_z = g\cdot\cos(\theta). \end{cases} \quad (1)$$

Hence, we can derive values of all angles

$$\varphi = \mathrm{arctg}\left[\frac{g_y}{(-g_x)}\right];$$

$$\theta = \mathrm{arctg}\left[\frac{\sqrt{{g_y}^2 + {g_x}^2}}{(-g_z)}\right]. \quad (2)$$

It should be noted that accelerometers are sensitive to presence of oscillations, that is why to solve this problem, angle velocity sensor (AVS) is used.

$$\dot{\theta} = \frac{d\theta_{AVS}}{dt};$$

$$\theta(t) = \int_0^t \dot{\theta}_{AVS}(t)\mathrm{d}t \approx \sum_0^t \dot{\theta}_{AVS}(t)Ts, \quad (3)$$

where Ts is the sample period. Then, according to complimentary law, we combine all values of angles, derived from:

$$\theta(t) = 0.73\cdot\int_0^t \dot{\theta}_{AVS}(t)dt + 0.27\cdot\theta_{ACCEL}(t). \quad (4)$$

Coefficients are chosen empirically. Value of roll angle φ is calculated similarly to (3), (4). Having values of roll and pitch angles, it became possible to carry out correction of magnetometer's readings.

$$X_{cal2} = X_{cal}\cos(\theta) + \\ + Y_{cal}\sin(\varphi)\sin(\theta) + Z_{cal}\cos(\varphi)\sin(\theta);$$

$$Y_{cal2} = Y_{cal}\cos(\varphi) + Z_{cal}\sin(\varphi);$$

$$\psi = \arctan 2\left(\frac{-Y_{cal2}}{X_{cal2}}\right). \quad (5)$$

The next step is to determine the value of the course angle with the help of an optical unit using the method of determining of descriptors in a sequence of images. The method involves determining of similarities between groups of descriptors with determining the angle of rotation relative to the original image, accepted as an initial value of zero [12, 13]. Implementation of the search for special points is shown below (Fig. 2). The left side of the figure shows a photograph, obtained from the optical unit, and its right side shows a fragment of a map. It is obvious that the program identified many specific points, which exist in both images. In addition, rotation of the image relative to the map was calculated (the outline of the image is marked by the white line).

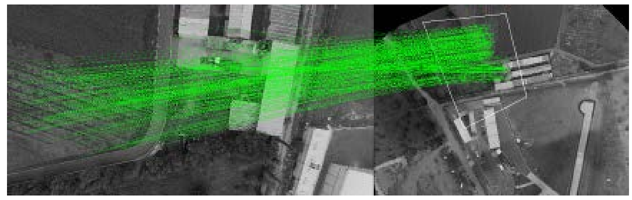


Fig. 2. Search for match between the map and the image

To determine the angle of the image rotation, it is sufficient to determine the angle between the corresponding pair of lines that pass through corresponding pairs of points in the image. The points are chosen based on maximal and minimal values on axis x.

The line that passes through 2 points can be represented as:

$$y = kx + b, \quad (6)$$

where k is the angle coefficient of the straight line, which equals to:

$$k = \frac{(y_2 - y_1)180}{(x_2 - x_1)\pi}. \quad (7)$$

Accordinly, the angle between the straight lines will be equal to:

$$\psi = \Delta k + \psi_0, \quad (8)$$

where ψ_0 is the original value of the course angle.

To determine the value of the course angle with the help of the satellite navigation system, a sufficient condition is required – existence of coordinates of 2 points of motion in this coordinate system, as well as the minimum number of satellites, not less than 6.

$$\psi = \arctan\left(\frac{\lambda_2 - \lambda_1}{\ln\left(\tan\left(\frac{\pi}{4} + \frac{\varphi_2}{2}\right)\left[\frac{1 - e\cdot\sin(\varphi_2)}{1 + e\cdot\sin(\varphi_2)}\right]^{\frac{e}{2}}\right) - \ln\left(\tan\left(\frac{\pi}{4} + \frac{\varphi_1}{2}\right)\right)\left[\frac{1 - e\cdot\sin(\varphi_1)}{1 + e\cdot\sin(\varphi_1)}\right]^{\frac{e}{2}}}\right), \quad (9)$$

where $\varphi_1\lambda_1$ is the latitude and longitude of the first point, $\varphi_2\lambda_2$ is the latitude and longitude of the second point,

$$e = \sqrt{1 - \frac{b^2}{a^2}}$$

is the eccentricity of the spheroid (a is the length of equatorial radius, b is the length of polar radius).

Let us assume that within a unit of time, there can be only one failure among three units (SNS, INS and optical system). In this case, two out of three sources should provide correct information, which is the control value of course angle. The values of measuring systems are compared to each other, and when there is a difference of values above the established norm, it can be argued that there is an error. Below (Fig. 3), we have a fragment of a dichotomous tree that describes the process of searching for a place of failure, where 1 is the positive result, 0 is the negative result, Z_i is the equation of predicates (equation of check).

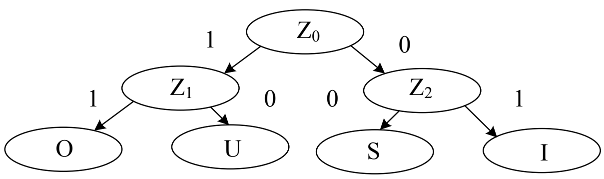


Fig. 3. Dichotomous fragment of a tree of failure search processes in inertial, SNS and optical devices: *O* — failure of optical system, *U* — unidentified failure, *S* — failure of SNS, *I* — diagnosis of INS

Analysis allows us to generate the following equations of predicates:

$$z_0=\{\psi_{INS}(t)==\psi_{SNS}(t)\}\text{ and}$$
$$\{\Delta\psi(t)>0\}=\begin{cases}1-\text{check of optical unit;}\\0-\text{check of SNS;}\end{cases}$$

$$z_1=\{\psi_{INS}(t)=!\psi_{OPTICAL}(t)\}\text{ and}$$
$$\{\Delta\psi(t)>0\}=\begin{cases}1-\text{failure in opticalunit;}\\0-\text{unidentified failure;}\end{cases}$$

$$z_2=\{\psi_{OPTICAL}(t)=!\psi_{SNS}(t)\}\text{ and }\{\Delta\psi(t)>0\}$$
$$=\begin{cases}1-\text{failure in SNS unit;}\\0-\text{check in INS unit.}\end{cases}\qquad(10)$$

Subsequently, diagnosis of signals the accelerometer and of the sensor of angular velocity is performed (Fig. 4).

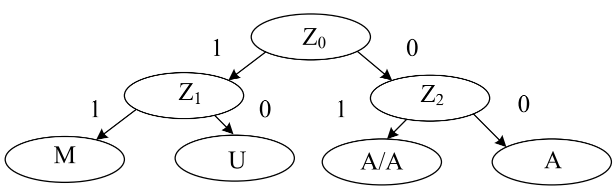


Fig. 4. Dichotomous fragment of a tree of failure search processes in magnetometer, accelerometer and AVS: M — failure of magnetometer, U — unidentified failure, A/A — failure of AVS or accelerometer, A — failure in accelerometer

Analysis enables us to generate the following equation of predicates.

At stage z0, values of three axes of accelerometer and one axis of AVS for failure detection are checked.

$$z_0=\left\{\int_t^0\dot{\theta}_{AVS}dt+\zeta_{noize}(t)==\operatorname{arctg}\left(\frac{\sqrt{g_x{}^2(t)+g_y{}^2(t)}}{g_z{}^2(t)}\right)\right\}\text{and}$$
$$\{\Delta\theta(t)+\zeta_{noize}(t)>0\}=$$
$$=\begin{cases}1-\text{ check of AVS and magnetometer (axis of roll angle);}\\0-\text{check of AVS and accelerometer.}\end{cases}\qquad(11)$$

When the equation is satisfied, it is possible to judge that:

$$\text{Failure}\supset\{\text{accelerometer[all axes]},\text{AVS[all axes]}\}.$$

Then the search for failure in the pair of accelerometer and AVS for values of roll angle is performed.

$$z_1=\left\{\int_t^0\dot{\varphi}_{AVS}\mathrm{d}t+\zeta_{noize}(t)==\operatorname{arctg}\left(\frac{g_y(t)}{-g_x(t)}\right)\right\}\text{ and}$$
$$\{\Delta\varphi(t)+\zeta_{noize}(t)>0\}=\begin{cases}1-\text{failure in magnetometer;}\\0-\text{failure in AVS.}\end{cases}\qquad(12)$$

Equation (12) explains that in the case of a positive result in axes of AVS, a failure will not occur. As mentioned earlier (11), in the accelerometer, failures were not detected, hence it follows that a failure can only be in the unit of the magnetometer. Otherwise, failure occurs in AVS unit, because according to equation Z_0, accelerometer gives control values.

In the case of a negative result of equation Z_0, we have:

$$\text{Failure}\supset\{\text{accelerometer[all axes]},\text{AVS[pitch axis]}\}.$$

This suggests that a failure exists in the set of values of the accelerometer and of AVS unit.

In this case,

$$z_2=\left\{\int_t^0\dot{\varphi}_{AVS}\mathrm{d}t+\zeta_{noize}(t)==\operatorname{arctg}\left(\frac{g_y(t)}{-g_x(t)}\right)\right\}\text{and}$$
$$\left\{\int_t^0\dot{\varphi}_{AVS}dt+\zeta_{noize}(t)>0\right\}=\begin{cases}1-\text{failure in AVS;}\\0-\text{failure in accelerometer.}\end{cases}\qquad(13)$$

Thus, if a failure exists in a set of values of the accelerometer and values of roll angle of AVS, value of roll angle from AVS should be correct.

Hence, at a positive result of equation Z_2, a failure will belong to the set of values of measurement of AVS or of accelerometer axis g_z, and at a negative result – in accelerometer (axes g_x or g_y). At a positive result of equation Z_2, we have uncertainty.

One of the variants of solutions to this problem can be the usage of the backup hardware part in the form of a camera (optical block), installed in the two-stage suspension. After setting the axis of camera perpendicularly to the horizontal plane, the image can be used as information for diagnosis and restoration.

We have the following dichotomous dependence (Fig. 5).

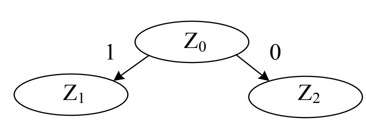


Fig. 5. Diagram of dichotomous tree of failure search process in accelerometer and uncertainty of AVS

$$z_0 = \{\theta_{INS}(t) == \theta_{SNS}(t)\} \text{ and } \{\Delta\theta(t) > 0\} = \\ = \begin{cases} 1 - \text{failure in AVS;} \\ 0 - \text{failure in accelerometer.} \end{cases} \qquad (14)$$

At this stage, the process of searching for time and place of failure finishes. Subsequently, reconfiguration of the system for measuring spatial position of the aerial vehicle is performed.

It is worth noting that the accelerometer, AVS or the magnetometer is considered inactive in case of a failure.

Below (Fig. 6), the algorithm block diagram of reconfiguration of the system is shown.

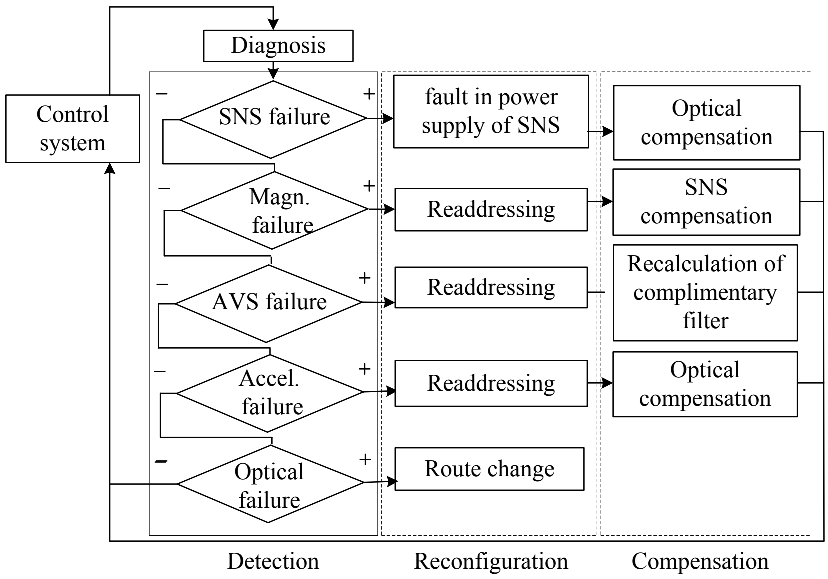


Fig. 6. Principle of operation of functionally stable system of orientation of unmanned aerial vehicle

As indicated in the block diagram of reconfiguration, in case of a failure in SNS unit, power of the device turns off, and the algorithm switches over to the use of the indicators of the optical unit. From this moment, the suspension of the camera works only in the horizontal mode (the camera is set constantly vertically relatively to the earth's surface).

Similar to the algorithm of search for angle of course with the use of a cloud of descriptors, the search for location is carried out. Corresponding pairs of descriptors are determined on the orthophoto plan and on the current digital image. Subsequently, coordinates of the centroid of a descriptors' cloud on the orthophoto plan in geodesic coordinate system are determined. The merits of this method include resistance to distortion caused by a slight deflection of the camera [14]. Such approach allows a reliable identification of the necessary place that was subject to large affine transformations, obtained during image taking. After that, it is possible to say that coordinates of the centroid are equal to the coordinate of an aerial vehicle (which implies equality of latitude and longitude).

In the event of a failure in the magnetometer, the system continues to operate in emergency mode. Value of angle of course is taken from the SNS, as an aerial vehicle has a plane scheme and has no modes of hovering (with possibility of rotation around the vertical axis). These values are calculated using equation (9). Probability of this type of failures is growing at using aerial vehicle in the area of iron ore mining, where the magnetic field level is high for a sensitive element of the meter.

In the event of AVS failure, its readings are excluded from the algorithm of the complimentary filter.

$$\theta(t) = \theta_{ACCEL}(t);$$

$$\varphi(t) = \varphi_{ACCEL}(t). \qquad (15)$$

Since AVS has a component of the inertial section, which suppresses high frequency noise, when excluding it from the system, the noise level of an output signal will increase. That is why adaptation of the filter (the Kalman filter is used in the system) to new noise parameters will be a compensation [15].

In case of a failure of the accelerometer, the configuration of sensor units does not provide sufficient hardware redundancy. One of the solutions is the use of the optical unit for determining of the horizontal line position. In this case, reconfiguration of the system consists of two parts: temporary and major.

Temporary reconfiguration operates within two seconds. It is activated when an accelerometer failure is detected. The principle of operation lies in turning off the accelerometer's indicators from computing of the complimentary filter. Its role lies in temporary compensation of data of the angular position of an aerial vehicle until the run of high-precision optical correction. To run the optical device, it is necessary to set the suspension of the camera to a position, where the main camera image axis is parallel to the longitudinal axis of the aerial vehicle, in this case, stabilization of the suspension is deactivated.

The principle of the system's operation is based on determining of relationship between the position of the horizon line relative to the horizontal centerline of the digital image taking into account the altitude of a flight and approximated models of surface in the flight visibility area. Altitude of an aerial vehicle flight is taken from the NMEA Protocol of SNS readings.

To determine the local curvature of relief, it is necessary to calculate the visible part of the earth's surface in the digital image, taking into account altitude of a flight (Fig. 7). To do this, it is necessary to calculate the distance to the line of visible horizon (16).

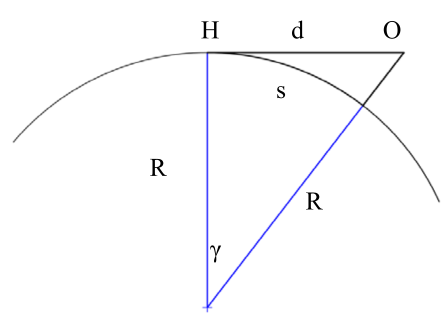


Fig. 7. Distance to visible horizon

In Fig. 7, O is the place of an aerial vehicle, h is the altitude, R is the radius of the Earth, d is the distance to visible horizon, s is the curve, equal to the distance from the position of an aerial vehicle to the point of visible horizon on the 2D map, γ is the angle between the vector to the surface of the Earth's tangent and the vector to the point of an aerial vehicle.

Location of visible horizon is determined as the boundary between the sky and Earth, then geometric range of visible range can be calculated as follows:

$$d=\sqrt{(R+h)^2-R^2}, \tag{16}$$

where d is the geometric range of visible horizon, R is the radius of the Earth, h is the height of the observation point relative to the Earth's surface.

We have the assumption that the Earth has the form of a circle (without taking into account refraction).

Taking the Earth's radius of up to 6371 km and dismissing value of $h2$ from the root, that has a small effect due to the small ratio of h to R, we obtain the equation:

$$d=113\sqrt{h}. \tag{17}$$

Since the aerial vehicle's flight altitude (of about 100 m) relative to the dimensions of the Earth is small, the curvature of the horizon can be neglected. The range to visible horizon d is 35.7 km for given altitude, that is why it is necessary to estimate the relief curvature in the sector with radius, equal to d, the camera's observation angle is equal to 60°. The section with the angle of 60 degrees is divided into 12 subsectors by 5 degrees each. Subsequently, we perform the search for the highest value of altitude in each small sector. Thus, we get the discrete horizon line (taking prospects into account). To determine the line of visible horizon in the image, it is necessary to carry out a strict sequence of transformations (Fig. 8).

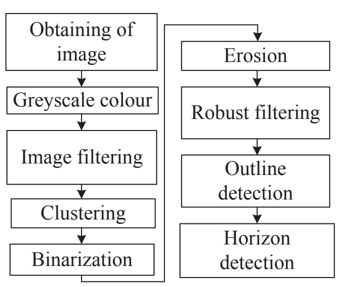


Fig. 8. Algorithm of visual identification of the horizon line

The camera provides a sequence of images, each of which is a two-dimensional matrix of dimensions of 800×600 pixels. The first step is transformation of the value of each pixel into the grayscale color and filtering of white noise.

Then, it is necessary to split the image into two groups of colors that correspond to the sky and the Earth's surface. This part is implemented by using the algorithm of cluster analysis [16]. The algorithm finds two the most common shades and transforms the others to the closest of the two existing ones. Because the sky usually has a uniform color, its color will be the first group, and the second group will join darker colors, existing on the surface. For greater simplification and optimization of the algorithm operation, it is necessary to get a double-digit image of the picture.

In the aforementioned algorithms, owing to a number of factors, in the regions of clusters, there appear noises, expressed as separately standing invariant pixels, the presence of whose may complicate subsequent processing. To prevent this, it is necessary to decrease their amount by using the algorithm of threshold erosion. For deeper noise cleaning, the algorithm of removal of closed small-area regions is used (the size of a region is determined experimentally). At this stage, filtering process finishes.

The next step is to find the separation line – the line of visible horizon. To do this, we use the Canny algorithm. At the output of this procedure, we have a double image, which shows the edge of transition from one region to another. To avoid errors in values of angles of angular position in the presence of distortion of the camera's optical system, it is necessary to approximate the horizon to a straight line. Then taking into account two horizon lines – true and false – we have value (7) of roll angle inclination.

The weight of a failure of the optical unit depends on the flight task purpose. In the case of search-and-rescue missions or reconnaissance, the flight loses sense. That is why, in the event of a failure, the return home mode is activated. Since the system is considered with only one optical sensor, compensation of visual image is impossible.

5. Results of implementation of the functionally stable system

Simulation of failures was made programmatically. This research examines such failures as a change of power supply loss and temporary loss of AGC signal, or weather conditions: variable cloud, variable wind.

The control system was built based of the controller ATmega 2560-16 AU, the inertial sensor MPU 521 (the angular velocity sensor and the accelerometer), magnetometer HMC5883l, the GPS receiver Ublox NEO m8n, the digital camera 5Mp and the Rapberry controller Pi 3, which is used for video information processing and flight data calculation. This system is shown below (Fig. 9).

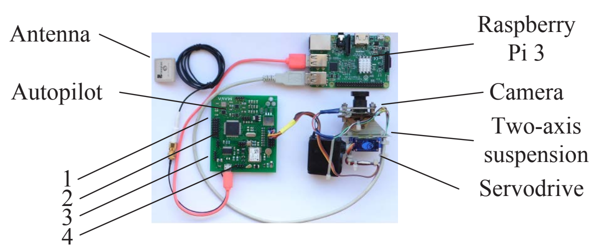
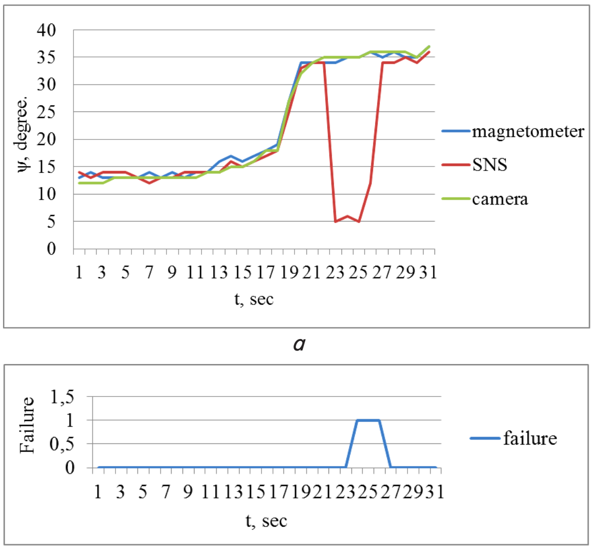


Fig. 9. Image of functionally stable system of control of small autonomous aerial vehicle: 1 – sensors; 2 – microcontroller AT mega 2560; 3 – converter ft232; 4 – GPS receiver Ublox NEO m8n

The image below (Fig. 10) shows three values of angle of course, obtained from SNS, optical system and inertial sensors. The image shows that mismatch of signals appears at the twenty-second second. The system made a search for the place and the time of a failure.

Result of reconfiguration and restoration of a SNS signal is shown below (Fig. 11).

Using the methods of restoration of damaged parameters, described above in the article, we performed the process of restoration of SNS values. Parameters to be restored are latitude and longitude.



a

b

Fig. 10. Image of failure in AVS: *a* — image of output sensor signals; *b* — finding time of failure

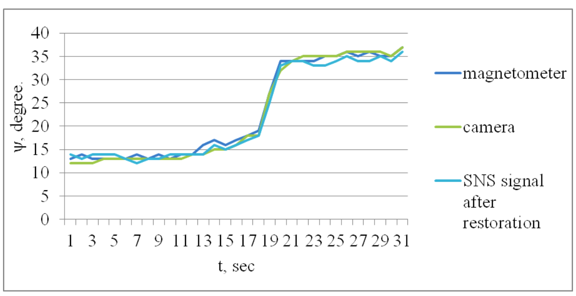
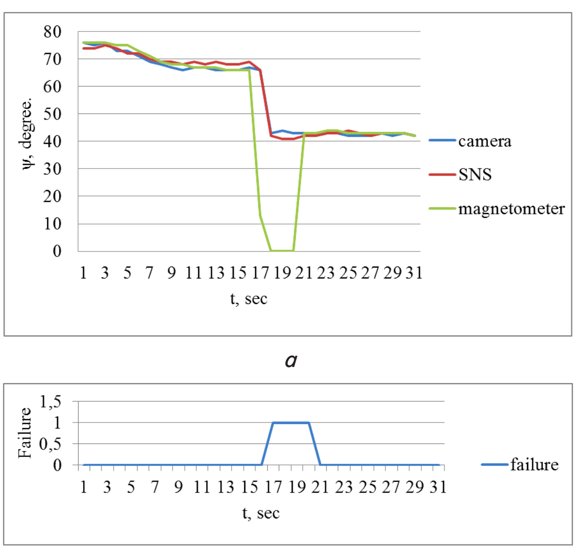


Fig. 11. SNS after restoration

The diagram showing the experiment with simulation of a magnetometer failure is shown below (Fig. 12).



a

b

Fig. 12. Image of magnetometer failure: *a* — image of output sensor signals; *b* — finding a failure

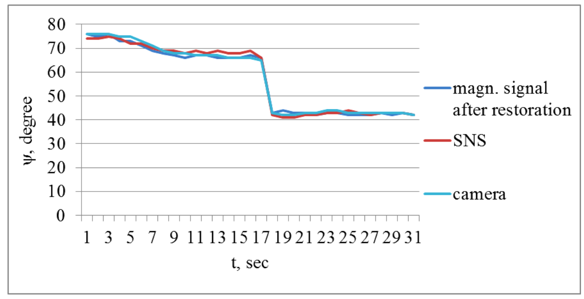


Fig. 13. Magnetometer signal after restoration

Experimental results show practical applicability of this system when applied with existing control systems.

As shown in the images above (Fig. 11, 13), over the entire period of a failure, the system was restoring the values of the damaged channel with permissible accuracy (of less than 3 %).

6. Discussion of provision of the system's functional stability

In our research, the algorithm, capable of providing functional stability of the orientation system of an autonomous aerial vehicle, was presented, in particular, the methods of diagnosis of devices by the majority feature in real time mode were proposed, the method for solving the problem of provision of measuring sources' redundancy at a minimal set of meters was offered.

Useful algorithms for control systems of small-dimension aerial vehicles that have a standard set of measuring instruments (a three-axis accelerometer and an angular velocity sensor, a three- or two-axis magnetometer, GPS) and the optical system (a camera with a suspension) were explored. Using the above dichotomous algorithm and bringing measurement parameters of all sensors, installed aboard, to a single indicator, it is possible to determine time and place of a failure in measuring systems with minimal loading on the computing resource and high precision. This makes it possible to compensate a failure, eliminate emergencies, and enhance measurement quality.

The advantage of this method is integrity (possibility to implement without hardware upgrades) in most existing autonomous aerial vehicles, high economic efficiency due to absence of costs for hardware upgrades, diagnosis operation rate (only one measurement interval), absence of a long-term adaptation process for calculation of the correct value of the damaged signal. Unlike existing functionally stable systems, for example, dji matrice 600, it uses by three times fewer measuring devices. In comparison with currently existing correlation–optical systems of unmanned aerial vehicles and cruise missiles, the orientation system, described in the work, makes it possible to provide functional stability by constant diagnosis of all meters and timely pairing of failures with the help of redundancy.

The shortcomings of the system include sensitivity to external factors (visibility, temperature), ability to work correctly only during one failure per unit of time, the use of mechanical elements (suspension).

Experimental study has shown efficiency of this approach to solving the problem of functionally stable orientation system.

Subsequent research will be improved for diagnosis of a type and a cause of a failure.

7. Conclusions

1. A backup source of geoinformation (visual information of the camera) was determined, due to which structural redundancy of the measurement system was provided.

2. Based of values of all installed measuring instruments, the method of stepwise dichotomous diagnosis of values of signals of measuring instruments in the real-time mode was developed. The principle of diagnosis provides for accuracy of readings with the depth to time and place of a failure. The results were achieved by measuring of a single parameter by using three independent sources. According to the rule of majority, (two true to one failed), place and time of a failure is detected.

3. The process of reconfiguration of instruments and restoration of a failed parameter at a short-term or long-term failure was described. Using existing redundancy of measuring instruments from the moment of failure identification, reconfiguration of the algorithm of navigation parameter calculation without using the damaged meter, while keeping functional software of an aerial vehicle as a whole, is performed.

According to the experimental research, the system is resistant to single failures (one parameter per unit of time), the error of the system reaches less than three per cent, which satisfies the requirements and make the system suitable for use.

References

1. Mutuel, H. Research on SINS/GPS/CNS fault-tolerant integrated navigation system with air data system assistance [Text] / H. Mutuel, L. S. Jason // Navigation. Journal of the institute of navigation. – 2017. – Issue 49. – P. 5–44.
2. Liu, Y. The Pedestrian Integrated Navigation System with micro IMU/GPS/magnetometer/barometric altimeter [Text] / Y. Liu, T. Cai, H.Yang, C. Liu, J. Song, M. Yu // Gyroscopy and Navigation. – 2016. – Vol. 7, Issue 1. – P. 29–38. doi: 10.1134/s2075108716010089
3. Kim, Y. Vision/INS Integrated Navigation System for Poor Vision Navigation Environments [Text] / Y. Kim, D.-H. Hwang // Sensors. – 2016. – Vol. 16, Issue 10. – P. 1672. doi: 10.3390/s16101672
4. Bukin, A. G. A computer vision system for navigation of ground vehicles: Hardware and software [Text] / A. G. Bukin, A. S. Lychagov, R. N. Sadekov, O. A. Slavin // Gyroscopy and Navigation. – 2016. – Vol. 7, Issue 1. – P. 66–71. doi: 10.1134/s207510871601003x
5. Yachong, Z. On fault-tolerant navigation technique and its application in INS/GPS/Doppler integrated navigation system [Text] / Z. Yachong // 2008 27th Chinese Control Conference. – 2008. doi: 10.1109/chicc.2008.4605457
6. Chen, M. Adaptive Fault-Tolerant Control of Uncertain Nonlinear Large-Scale Systems With Unknown Dead Zone [Text] / M. Chen, G. Tao // IEEE Transactions on Cybernetics. – 2016. – Vol. 46, Issue 8. – P. 1851–1862. doi: 10.1109/tcyb.2015.2456028
7. Geofrey, B. I. Image processing for tomahawk scene matching [Text] / B. I. Geofrey, P. C. Jамеі // Johns Hopkins APL Technical Digest. – 1994. – Vol. 15, Issue 3. – P. 250–264.
8. Huang, W. Design of a Fault Detection and Isolation System for Intelligent Vehicle Navigation System [Text] / W. Huang, X. Su // International Journal of Navigation and Observation. – 2015. – Vol. 2015. – P. 1–19. doi: 10.1155/2015/279086
9. Koren, I. Fault-Tolerant Networks [Text] / I. Koren, C. M. Krishna // Fault-Tolerant Systems. – 2007. – P. 109–146. doi: 10.1016/b978-012088525-1/50007-9
10. Sari, A. Fault Tolerance Mechanisms in Distributed Systems [Text] / A. Sari, M. Akkaya // International Journal of Communications, Network and System Sciences. – 2015. – Vol. 08, Issue 12. – P. 471–482. doi: 10.4236/ijcns.2015.812042
11. Morel, J.-M. ASIFT: A New Framework for Fully Affine Invariant Image Comparison [Text] / J.-M. Morel, G. Yu // SIAM Journal on Imaging Sciences. – 2009. – Vol. 2, Issue 2. – P. 438–469. doi: 10.1137/080732730
12. Al-Asaad, H. Fault tolerance for multiprocessor systems via time redundant task scheduling [Electronic resource] / H. Al-Asaad, A. Sarvi // Available at: http://citeseerx.ist.psu.edu/viewdoc/download?doi=10.1.1.132.5022&rep=rep1&type=pdf
13. Yu, G. A fully affine invariant image comparison method [Text] / G. Yu, J.-M. Morel // 2009 IEEE International Conference on Acoustics, Speech and Signal Processing. – 2009. doi: 10.1109/icassp.2009.4959904
14. Isermann, R. Trends in the application of model-based fault detection and diagnosis of technical processes [Text] / R. Isermann, P. Ballé // Control Engineering Practice. – 1997. – Vol. 5, Issue 5. – P. 709–719. doi: 10.1016/s0967-0661(97)00053-1
15. Pat. No. 102894 UA. Orientation system of of small-scale unmanned aerial vehicle. MPK G01C 23/00 [Text] / Firsov S. M., Zhezhera I. V., Budib V.; zaiavnyk i patentomavets Natsionalnyi aerokosmichnyi universytet im. M. E. Zhukovskyi "KhAI". – No. u201504880; declareted: 19.05.2015; published: 25.11.2015, Bul. No. 22. – 3 p.