УПРАВЛІННЯ У ТЕХНІЧНИХ СИСТЕМАХ

УПРАВЛЕНИЕ В ТЕХНИЧЕСКИХ СИСТЕМАХ

CONTROL IN TECHNICAL SYSTEMS

UDC 004.852

METHOD OF THE INTELLIGENT SYSTEM CONSTRUCTION OF AUTOMATIC CONTROL OF UNMANNED AIRCRAFT APPARATUS

Bieliakov R. O. – PhD, Lecturer of the Department of Technical and Metrological Support of the Information Technologies Faculty, Military Institute of Telecommunications and Informatization named after Heroes of Krut, Kiev, Ukraine.

Radzivilov H. D. – PhD, Associate Professor, Head of the Department of Technical and Metrological Support of the Information Technologies Faculty, Military Institute of Telecommunications and Informatization named after Heroes of Krut, Kiev, Ukraine.

Fesenko O. D. – Post-graduate student of the Department of Technical and Metrological Support of the Information Technologies Faculty, Military Institute of Telecommunications and Informatization named after Heroes of Krut, Kiev, Ukraine.

Vasylchenko V. V. – Head of the Laboratory Complex of the Department of Technical and Metrological Support of the Information Technologies Faculty, Military Institute of Telecommunications and Informatization named after Heroes of Krut, Kiev, Ukraine.

Tsaturian O. G. – Senior Researcher, Scientific Communication and Informatization Center, Military institute of telecommunications and informatization named after Heroes of Krut, Kiev, Ukraine.

Shyshatskyi A. V. – PhD, Research Associate at the Central Research Institute of Armament and Military Equipment of the Armed Forces of Ukraine, Kyiv, Ukraine.

Romanenko V. P. – PhD, Head of the Department of the Institute of Special Communications and Information Protection, National technical university of Ukraine "Igor Sikorsky Kiev Polytechnic Institute", Kyiv, Ukraine.

ABSTRACT

Context. Military conflicts of the late XX – early XXI centuries are characterized by the using of a large number of new weapons, which allowed the warring parties to distance themselves as far as possible from the direct collision with each other. Unmanned aircraft apparatus (UAA) have become one of the latest weapons on the battlefield, which during military conflicts were proven to be more effective than manned planes, in conducting air reconnaissance and other combat tasks, as well as strike at the enemy. One of the ways to increase the efficiency of UAA is to increase the level of technical excellence of their control systems.

Creating new approaches for designing navigation systems for unmanned aerial vehicles particular, based on a free-form inertial navigation system, is an urgent task, as it will allow automatic control of the UAA flight route in the absence of corrective signals from the global satellite navigation system.

Objective. The purpose of this work is to develop a methodology for managing an unmanned aerial apparatus using an intelligent automatic control system. This technique will minimize the error of a free inertial navigation system due to the using of a fuzzy neural network system. The algorithm of the proposed method of constructing the intellectual system of automatic control of UAA navigation system using the fuzzy neural network apparatus in the MatLab 7 software environment was developed. A neural network training was conducted in the Python 3.6 software environment (Jupyter-notebook), as well as testing the UAA model in the robot operational system (ROS) simulator environment for comparison with existing methods.

Method. To achieve this goal, the following methods were used: intelligent systems, the theory of automatic control, pseudo-spectral method; methods based on the genetic algorithm and apparatus of the fuzzy neural network.

Results. The method of constructing the intelligent system of automatic control of an unmanned aerial apparatus for minimizing the error of a free-form inertial navigation system due to the application of the neural network has been developed. The work of the intellectual system of automatic control of the UAA navigational system using the neural network in the MatLab software environment based on the proposed implementation algorithm were tested. The possibility of practical application of the obtained results and comparison with traditional methods were investigated.

DOI 10.15588/1607-3274-2019-1-20

Conclusions. The technique of the intelligent automatic control of UAA shows an advantage in comparison with the known methods without correcting signals from the global navigation satellite system.

KEYWORDS: automatic control intellectual system, navigation system, unmanned aircraft apparatus.

ABBREVIATIONS

NN is a neural network;
NS is a navigation system;
RM is a reference model;
CS is a closed system;
GSNS is a global satellite navigation system;
UAA is an unmanned aircraft apparatus;
INS is an inertial navigation system;
ROS is a robot operational system;
CM is a center mass of the controlling object.

NOMENCLATURE

$V(e)$ is a function of Liapunov;

I_Z is a moment of inertia UAA relative to the OZ axis;

$v\theta'$ is an acceleration in the vertical plane;

v' is an angular velocity;

ξ is the damping coefficient;

T_v is a constant aerodynamic time of the UAA;

Y is a vector of the state of executive mechanism;

$F()$ is an equation of forces;

$K(p)$ is a transfer function of the control channel of the UAA;

$W_0(p,c)$ is a transfer function of the controlling object;

$W_1\left(p,\hat{b}_1\right)$, $W_2\left(p,\hat{b}_2\right)$ are a transfer functions of the regulator of the navigation system;

$W_{RM}\left(p,b^*,c^*\right)$ is a transfer function of the reference model;

t_a is a training interval;

$u(t)$ is a function of the control of the UAA ailerons;

th is an activation function: hyperbolic tangent;

m, l, k, j are an indices of the elements of the sample of possible values of the states of the object;

$\varepsilon(t)$ is an error function (deg);

$\dot{\varepsilon}(t)$ is a speed error function (deg/s);

$\ddot{\varepsilon}(t)$ is an acceleration error function (deg/s^2).

INTRODUCTION

One of the most important subject areas is the management system of moving objects.

Special feature of which is that each new generation satisfies new requirements to the conditions, modes and quality of functioning, as well as extends the range of solvable tasks [1].

The variety of moving objects in the environment of their functioning and the importance of effective implementation lead to a large range of scientific problems arising in the development of traffic control systems.

Nowadays, the base of navigation systems for unmanned aerial apparatus is made up of receivers of global satellite navigation systems, integrated with a block of inertial sensors of spatial orientation. Such a system provides a very accurate determination of the UAA location and its parameters (up to 15 m) in the presence of receiving signals GSNS. If it is integrated with satellite navigation, cheap low-precision inertial systems equipped with micromechanical motion sensors (accelerometers and gyroscopes) are possible.

The cost of such a system is from 5 to 15 thousand dollars, depending on the accuracy of the sensors. It should be noted, that the inertial system of such a price range is not able to carry out an autonomous calculation of the traversed path due to the high speed of drift gyroscopic sensors. Some samples are capable of maintaining the accuracy within a few minutes (not more than 10) of the absence of a GSNS signal at a level of 100–150 m. In this case, generally, the mode of rectilinear motion is used without acceleration.

Thus, the presence of GSNS signals is currently a prerequisite for the implementation of unmanned aerial vehicles set tasks. The absence or deliberate suppression of navigation signals leads to the inability to determine their own coordinates accurately and, as a result, to perform flight on a given route. In the same case using of inertial systems of ultralow precision (especially on short-range UAA) in the UAA, the lack of corrective signals from the GSNS can lead to the complete cessation of the inertial system functioning and the UAA accident. Therefore, the suppression of the GSNS is considered as the main method of fighting the UAA with the newest type of inertial systems.

Using of high-precision inertial navigation systems also completely does not solve the problem for the following reasons:

1) such systems are expensive (30–50 thousand dollars);

2) the mass of the inertial system of “medium accuracy” on laser or fiber-optic gyroscopes is from 8 kg, which makes it problematic for their using in small and medium-range UAA;

3) the limitation of the INS is increasing in the error of coordinates determination with the time of autonomous operation. The accuracy of an autonomous number of coordinates for modern INS is about 2 kilometers per hour of flight (for systems of high accuracy), which does not allow to provide high-precision determination of the coordinates of goals.

The growing interest of scientists in intelligent control systems, based on artificial neural networks gives grounds to assert about the qualitative influence of the latter on the performance indicators of the UAA complex. At the same time, their using can significantly reduce the cost of such systems. Therefore, the intellectualization of control sys-

DOI 10.15588/1607-3274-2019-1-20

tems in the present conditions is one of the main scientific and practical directions of their improvement.

Thus, **the object of study** is the system of automatic control of UAA movement.

The **subject of the study** is the UAA motion control process based on intelligent control systems based on artificial neural networks, without the use of GSNS signals.

The **purpose of the study** is to develop a method for an unmanned aerial apparatus control using an intelligent control system based on artificial neural networks to reduce the control time without using the GSNS signals.

1 PROBLEM STATEMENT

Focusing on the results of well-known scientific developments in accordance with the research topic, the development of a method for constructing an intellectual system for automatic control of the UAA navigation system in the MatLab software environment remains open and requires detailed elaboration [1–10].

The task of the control system synthesis is to select the structure and the control channels parameters, which ensure the receipt of a given quality of flight control, based on dynamic properties of the UAA.

To achieve the research aim, it is necessary to solve a number of the following interrelated scientific tasks:

1. To develop method of an unmanned aerial vehicle management with using an intelligent automatic control system to minimize the error of a platform-free inertial navigation system due to the using of a fuzzy neural network system;

Suppose given the original sample as a set of functions and parameters: vector Y; spatial motion of the UAA is described by $F()$; object with $K(p)$, $W_0(p,c)$; regulator with $W_1(p,\hat{b}_1)$, $W_2(p,\hat{b}_2)$.

For a given sample of control parameters the problem of intelligent automatic control system synthesis can be presented as the problem of finding quadratic functional of intelligent automatic control system $J = \varphi(\xi(t)) = \frac{1}{2}(y(t) - y_M(t))^2 \Rightarrow \min$, where the model structure $W_{RM}()$ usually specified by the user in practice, and the set of controlled parameters $b(t) = b^*$ at $t \ge t_a$.

Learning in direct-acting systems is the result of the current numerical optimization of the main circuit. Target functionality of this optimization is selected simultaneously and as a criterion for object control and as a target condition for learning: $V(e) \succ 0, V(0) = 0;\ \dot{V}(e) \prec 0, \dot{V}(0) = 0.$

2. To apply developed realization algorithm of the advanced method of the automatic control intellectual system of the UAA navigation system construction with the help of a neural network in the MatLab software environment;

3. Perform training on the neural network in the Python 3.6 (Jupyter-notebook) software environment, as well as testing the UAA model in the ROS simulator for comparison with traditional methods.

2 REVIEW OF THE LITERATURE

Nowadays, the prospects for the development, refinement and upgrading of modern aircraft are the main focus of researches by modern scientists. From the point of view of the intelligent automatic control systems introduction for UAA complexes, it is worth noting the achievements of scientists, which are published in the works [3–10], and others.

In [11], the work of the quadcopter is investigated, and the algorithms of stabilization are proposed for the automatic control of the trajectory motion. The results of the research show a satisfactory stability of the quadcopter flight and tracking of the given trajectories, which confirms the correctness and validity of the proposed control algorithm.

The works [12, 13] investigate approaches to the implementation of the neural network regulator in the automatic control system of an unmanned aircraft apparatus. Within the framework of the work, researchers offer the structure of the neural network and simulate the result of training the neural network regulator.

In the works [14, 15] the authors offer solutions to approach the issue of automatic control of the UAA navigation system under conditions of interference. The author reveals the formation mechanisms of the flight path. The efficiency of the proposed algorithms is confirmed by calculations.

However, despite the results of scientific developments in accordance with the research topic, the question of an effective algorithm formation for the implementation method of constructing an intelligent system of automatic control of UAA navigation system using a neural network, in the MatLab software environment requires detailed elaboration.

3 MATERIALS AND METHODS

Works [1–6] offer classic methods for building UAA control systems, with the main hardware for the trajectory planning are:

– encoders;
– inertia sensors;
– devices of interception;
– barometers, compasses, etc.

The UAA traffic is controlled from the ground point by transmitting data through the radio communication channel. If for the generalization of the UAA control analysis to consider this apparatus as a "black box", it can be shown, that in the general case, the input of the apparatus enters the control signal and the influence of perturbations coming from the external environment. The source data can be considered backward radio communication with the item management and interaction with the external environment.

Tasks that are solving by the control point include the following:

– reception and processing of received information on radiocommunication;
– identifying and recognizing objects and building a map of the area;

DOI 10.15588/1607-3274-2019-1-20

– determining the coordinates of the objects and the scale of the map;

– formation of priorities and adjusting the flight plan;

– providing control of UAA movement and aerial photography.

While operating a control station under the condition of conducting a military operation, it is often necessary to timely elaborate substantiated recommendations and makes decisions on UAA control in conditions of uncertainty and fuzzy assessment criteria. Solving this problem is possible with the using of intelligent systems at all stages of the support processes of the decision making (Fig. 1).

The preparation for the work of the intellectual decision support system can be divided into the following stages:

– construction of a digital model of the area, which in the form of a three-dimensional geometric model is formed on the basis of aerial photography;

– definition of main characteristics of UAA sensors, their ranges, sensitivity and resolution;

– getting coordinates of the view point of the current image.

Working of the system begins with the determination of the orientation angle of the angular velocities of the sight line in the vertical and horizontal planes and the distance to the target using the navigation system.

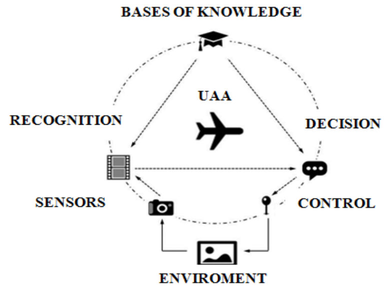


Figure 1 – Processes for supporting the decision-making of the intellectual system of the UAA

The object image is transferred to the point; which coordinates were obtained as a result of the calculation. This information is transmitted over the radio station in real time. The system compares the output images with the parameters included in the description, which leads to the problem of detection, recognition of the object.

It makes possible to form instructions and recommendations to the operator.

At the same time sensor control is conducted to target the target. The operator makes an appropriate correction to the flight plan of the UAA, which is taken into account while forming a control signal. The UAA goes into auto attendance mode. In case of error control signals are formed again according to information from the navigation system, but it takes into account the estimates received in the filtering block.

The intellectual system construction methodology of automatic control of the UAA navigation system is graphically represented as a flowchart in fig. 2.

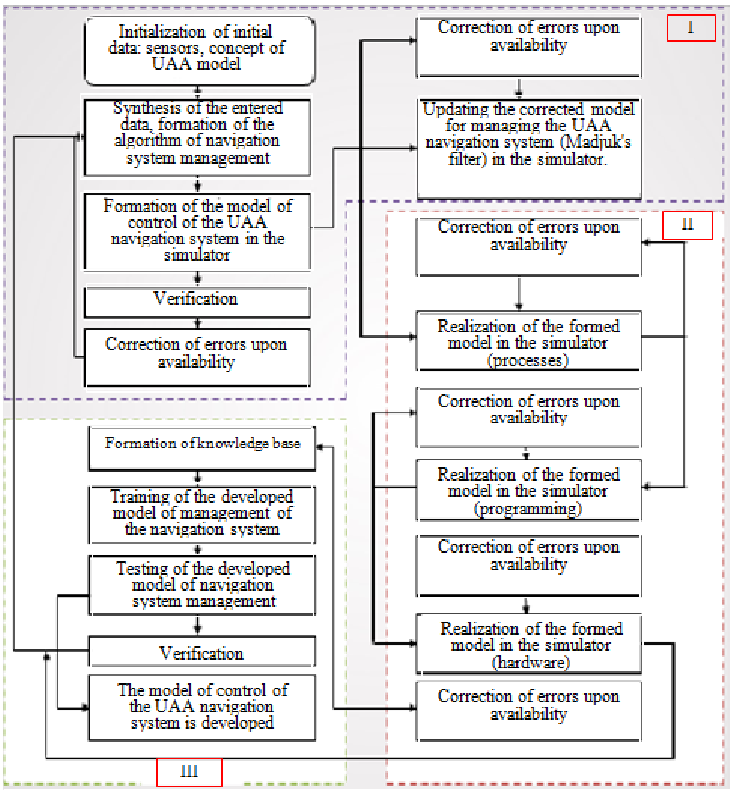


Figure 2 – Block-diagram of implementation of the methodology for building an intelligent system of automatic control of the UAA navigation system

DOI 10.15588/1607-3274-2019-1-20

The intelligence of the method is based on the using of fully automated systems. Management is based on the principle of "guidance-stabilization". The navigation method is responsible for forming the flight direction and current coordination, which is based on sensor signals, orientation and navigation systems. The result is broadcast by "Autopilot", which solves the problem of stabilization. It is mandatory to constantly check the availability of communication over the radio channel.

The first block is a unit for forming the concept of a model and analyzing the initial data. This block provides for the collection of information and its analysis. The initial information at this stage includes mathematical models of UAA, external and internal excitations that affect the UAA during operation, models and data from sensors and sensors.

In the presence of all initial data the concept is formed of a management model, the main directions of movement, obstacles in the way, the projection of displacement, etc.

The second block assumes of the model implementation in the software environment. This block is the main part within the framework of the algorithm. There is a synthesis of the general concept, the laws of management and the navigation algorithms of the system are formed and generalized.

It takes into account the operating modes and conditions of the algorithm implementation that is being developed. A general model is created using mathematical models of dynamics and excitement. The resulting models are fundamental in the overall development algorithm, based on further analysis and the formation of the final model. At each individual stage mandatory verification and evaluation of the simulation results, as well as correction, if necessary parameters of the laws of management and navigation algorithms are carried out.

The third block envisages the formation of a knowledge base, system training and testing of the developed model with the analysis of the results obtained and the final result output, on the intellectual system effectiveness of automatic control of the UAA navigation system.

Spatial motion of the UAA is described by the equations of forces, moments and kinematics of the flight. The force equation describes the movement of the CM in the vertical space:

$$F_{Yv} = mW_Y \cong Y^{\alpha}\alpha + P\alpha \pm Y^{\delta}\delta , \quad (1)$$

with this vertical acceleration at δ=0 equals

$$W_Y = \frac{Y^{\alpha} + P}{m}\alpha .$$

The UAA rotation around the CM along the OZ axis, in accordance with the basic law of the dynamics of rotational motion:

$$I_{\alpha} = I_Z \ddot{v} = M_Z^{\delta}\delta - M_Z^{\alpha}\alpha - M_Z^{\omega Z}\omega_Z . \quad (2)$$

The magnitude of the moment depends on the mass distribution with respect to the OZ rotation axis. For a circle with a radius r moment of inertia – $I_0 = mr^2$.

Relying on the work [12], the principle of receiving the transfer function of the control channel of the UAA is based on dependence $\alpha = f(\delta)$ taking into account the dynamics of UAA rotation around the axis $K(p) = \frac{\alpha(p)}{\delta(p)}$, $v = \theta + \alpha$, $v' = \theta' + \alpha'$, $v'' = \theta'' + \alpha''$, where $\omega_Z = v'$.

Angular velocity vector of UAA speed:

$$F_{Yv} = mv\theta' = \left(Y^{\alpha} + p\right)\alpha, \qquad \theta' = \frac{Y^{\alpha} + p}{mv}\alpha. \quad (3)$$

where $W_Y = v\theta'$, $T_v = \frac{mv}{Y^{\alpha} + p}$.

Then:

$$v = \theta + \alpha , \; v' = \frac{\alpha}{T_v} + \alpha' , \; v'' = \frac{\alpha'}{T_v} + \alpha'' . \quad (4)$$

The basis of the equation of the UAA rotation dynamics (2) will substitute the obtained values:

$$I_Z\left(\theta'' + \alpha''\right) = M_Z^{\delta}\delta - M_Z^{\alpha}\alpha - M_Z^{\omega Z}\left(\theta' + \alpha'\right). \quad (5)$$

Having done the transformation, we have:

$$I_Z\left(\alpha'' + \frac{1}{T_v}\alpha'\right) + M_Z^{\omega Z}\left(\alpha' + \frac{1}{T_v}\alpha\right)\delta + M_Z^{\alpha}\alpha = M_Z^{\delta}\delta . \quad (6)$$

We group members in relative terms α, receive:

$$I_Z\alpha'' + \left(\frac{I_Z}{T_v} + M_Z^{\omega Z}\right)\alpha' + \left(M_Z^{\alpha}\alpha + \frac{M_Z^{\omega Z}}{T_v}\right)\alpha = M_Z^{\delta}\delta . \quad (7)$$

Let's make Laplace's transformation:

$$\alpha' = p\alpha , \; \alpha'' = p^2\alpha , \; I_Z p^2\alpha + a_2 p\alpha + a_1\alpha = M_Z^{\delta}\delta . \quad (8)$$

where $a_1 = M_Z^{\omega} + \frac{M_Z^{\omega Z}}{T_v}$, $a_2 = \frac{I_Z}{T_v} + M_Z^{\omega Z}$.

Thus, the characteristics of the UAA control channel looks like:

$$K_{\alpha}(p) = \frac{\delta(p)}{\alpha(p)} = \frac{\frac{M_Z^{\delta}}{a_1}}{1 + \frac{a_2}{a_1}p + \frac{I_Z}{a_1}p^2} . \quad (9)$$

DOI 10.15588/1607-3274-2019-1-20

The obtained equation repeats the equation of oscillatory motion:

$$K_\alpha(p)=\frac{K_\alpha}{1+2\xi Tp+T^2p^2}. \qquad (10)$$

where $K_\alpha=\frac{M_Z^\delta}{a_1}=\frac{M_Z^\delta}{M_Z^\alpha+\frac{M_Z^{\omega Z}}{T_v}}=\frac{M_Z^\delta T_v}{M_Z^\alpha T_v+M_Z^{\omega Z}}\approx$

$\approx\frac{M_Z^\delta}{M_Z^\alpha}=\frac{S_\delta X_\delta}{S_\alpha X_F}$.

The transmission coefficient depends on the layout of the UAA, its speed and direction of movement, the boundary of the indicator from 0,4 to 0,6 dB, and the transmission coefficient shows at which angle the object $\alpha=K_\alpha\delta$ will return;

$T=\sqrt{\frac{I_Z}{a_1}}=\sqrt{\frac{I_Z}{M_Z^\alpha+\frac{M_Z^{\omega Z}}{T_v}}}=\sqrt{\frac{I_Z}{M_Z^\alpha}}=\sqrt{\frac{I_Z}{C_{Y\alpha}+\frac{\rho v^2}{2}S_\alpha X_F}}$ – constant time, that is inversely proportional to the speed pressure $q=\frac{\rho v^2}{2}$, and it is directly proportional to the mass of the UAA:

$\xi\cong\frac{1}{2T_v}\cdot\frac{I_Z}{M_Z^\alpha}\sqrt{\frac{M_Z^\alpha}{I_Z}}=\frac{1}{2T_v}\cdot\sqrt{\frac{I_Z}{M_Z^\alpha}}=\frac{Y^\alpha+P}{2mv}\sqrt{\frac{I_Z}{M_Z^\alpha}}$. The damping coefficient is determined by the damping moment $M_Z^{\omega Z}$ and lies in the range $\xi=0{,}05...0{,}15$.

At the same time, we get the pitch angle in the form:

$$\omega(p)=\frac{1}{T_v p}\alpha+\alpha=\alpha\left(\frac{1+T_v p}{T_v p}\right), \qquad (11)$$

taking into account the angles $v=\theta+\alpha$, from the original θ', i.e. $\theta=\frac{1}{T_v p}\alpha$.

Then:

$$K_v(p)=\frac{v(p)}{\delta(p)}=\frac{\frac{K_\alpha}{T_v}(1+pT_v)}{p\left(1+2\xi Tp+T^2p^2\right)}. \qquad (12)$$

The mathematical model of the constructed neural controller with a transmitted function $W(p,b,c)$ for the implementation of the proposed algorithm, the structural scheme of which is depicted in Fig. 3, has a look

$$u(t)=th\left(\sum_{m=1}^{8}w_{m1}^{(5)}th\left(\sum_{l=1}^{8}w_{lm}^{(4)}th\left(\sum_{k=1}^{10}w_{kl}^{(3)}\times th\left(\sum_{j=1}^{8}w_{jk}^{(2)}\times th\left(w_{1j}^{(1)}\varepsilon(t)+w_{2j}^{(1)}\dot\varepsilon(t)+w_{3j}^{(1)}\ddot\varepsilon(t)\right)\right)\right)\right)\right). \qquad (13)$$

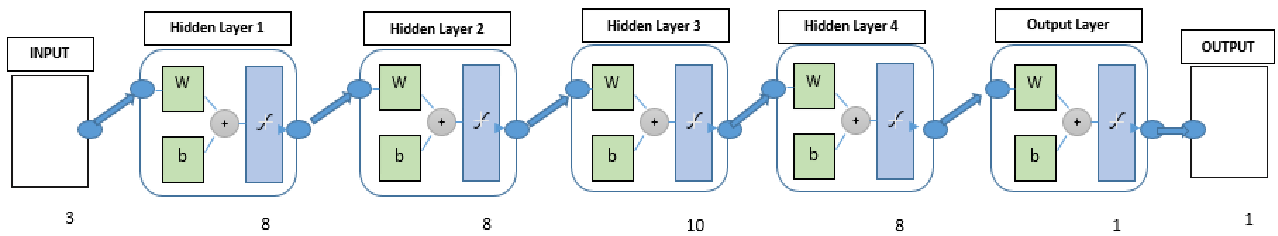


Figure 3 – Neural network model of the controller with input, 4 hidden and output layers

4 EXPERIMENTS

In the framework of this scientific research concerning the method implementation of the automatic control intellectual system of the UAA navigation system with the help of a neural network. The direct application of the solution to the problem is used in the MathLab software environment. Unlike the adaptive systems of the identification type, the systems with direct control algorithms do not contain models, which are configured according to the behavior of the main system, identifiers and evaluation devices. The information in the form of the current values estimations of the parameters and the state of the volume is not used to configure the main circuit [13]. Learning in direct-acting systems is the result of the current numerical optimization of the main circuit. Target functionality of this optimization is selected simultaneously and as a criterion for object management and as a target condition for learning.

Obligatory condition [20]:

$$\begin{cases}V(e)\succ 0, V(0)=0;\\ \dot V(e)\prec 0, \dot V(0)=0.\end{cases} \qquad (14)$$

To study the neural network, we use the algorithm of the inverse distribution of the error with the Levenberg-Marquardt training method and the activation function is a hyperbolic tangent. After training we test and validate the network in the environment of Simulink (MatLab) visual modeling. The general procedure for forming a training algorithm is formed on the basis of a parameters selection that come from the block calculation output of the parameters sum of the reference model. These parameters

DOI 10.15588/1607-3274-2019-1-20

are grouped by significance, thus forming the space of states and external control influence on the object. Signals on the output of the network that do not meet the conditions, again fall on the input of the system, thereby teaching the system.

The principle of the learning unit is based on customizing the generalized object by selecting the parameters $b(t)=b^*$ within the range of training. The error is the difference from $y_M(t)-y(t)$, and in general, the error serves as a fundamental indicator of the quality of learning. The error in its composition has information on the deviation of the key indicators $\Delta b(t)=b^*-b(t)$.

Fig. 4 shows the automatic control system structural scheme of the UAA navigation system, which includes a regulator with transfer functions $W_1(p,\hat{b}_1)$ and $W_2(p,\hat{b}_2)$, ($p=\frac{d}{dt}$ – differentiation operator), with a fixed structure and custom parameters b_1 and b_2.

Controlling object with transmitted function $W_0(p,c)$ with parameters c, where $c\in\Omega_c$, change spontaneously. Function of reference model $W_{RM}(p,b^*,c^*)$, where $c\in\Omega_c$. Error $e(t)=y_M(t)-y(t)$ serves as the main source of measurement information for the learning algorithm block. The purpose of the training is to set up a generalized object by selecting parameters $b(t)=b^*$ at $t\ge t_a$. In this case, the target functional can be chosen as a quadratic function $J(\xi)$. Calculate settings of the settings b_1 and b_2 is performed in the training block as a result of the current minimization of the quadratic functionality by the recurrence algorithm

$$b_j(t)=\gamma_j\xi(t)\frac{\partial J(p,\hat{b},c)}{\partial\hat{b}_j}g(t), \qquad (15)$$

where $\frac{\partial J(p,\hat{b},c)}{\partial\hat{b}_j}$ – determines the sensitivity of the functional for this parameter.

Then there are transfer functions of a closed system and a reference model

$$W_{CS}(p,b,c)=\frac{W_p(p,b)\cdot W_0(p,c)}{1+W_p(p,b)\cdot W_0(p,c)}=\frac{y(t)}{g(t)},$$
$$W_{RM}(p,\alpha)=\frac{y_M(t)}{g(t)}. \qquad (16)$$

Minimization of a quadratic functional:

$$J=\varphi(\xi(t))=\frac{1}{2}(y(t)-y_M(t))^2\Rightarrow\min, \qquad (17)$$

provided by the calculation of the derivative

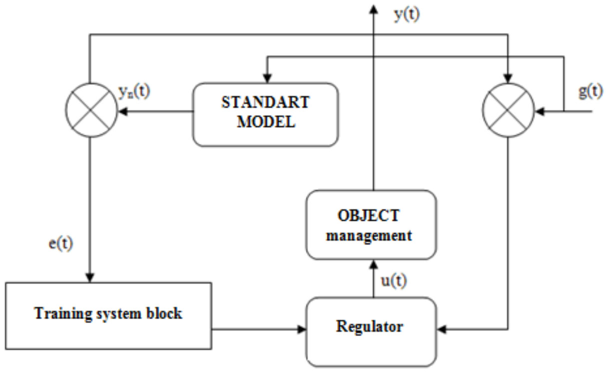


Figure 4 – The block-diagram of the system of automatic control of the UAA navigation system [3]

$$\frac{\partial J}{\partial b_j}=\frac{\partial\varphi(\xi(t))}{\partial\xi(t)}\frac{\partial\xi(t)}{\partial b_j}=\frac{\partial W_{CS}(p,c,b)}{\partial b_j}=$$
$$=\frac{\frac{\partial W_p}{\partial b_j}W_0(1+W_p\cdot W_0)-\frac{\partial W_p}{\partial b_j}W_0\cdot W_p\cdot W_0}{(1+W_p\cdot W_0)^2}= \qquad (18)$$
$$=\frac{\partial W_p}{\partial b_j}\cdot\frac{W_0}{(1+W_p\cdot W_0)^2}=C_j(p)\cdot C_0(p).$$

The functional scheme of the unit training system is shown at the Fig. 5.

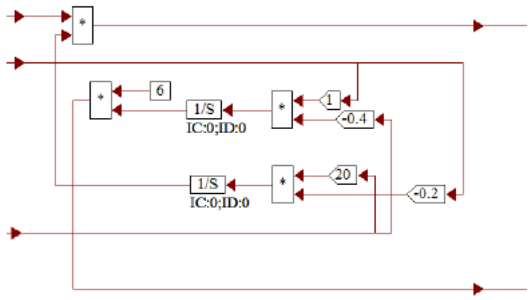


Figure 5 – Functional scheme of the unit training system (where 6 is the value from the angular rate sensor; –0,2 and –0,4 are the time delay block; + – adder of the stabilization course channel; 1/s – course channel integrator; 20 – steering gear of the steering direction)

5 RESULTS

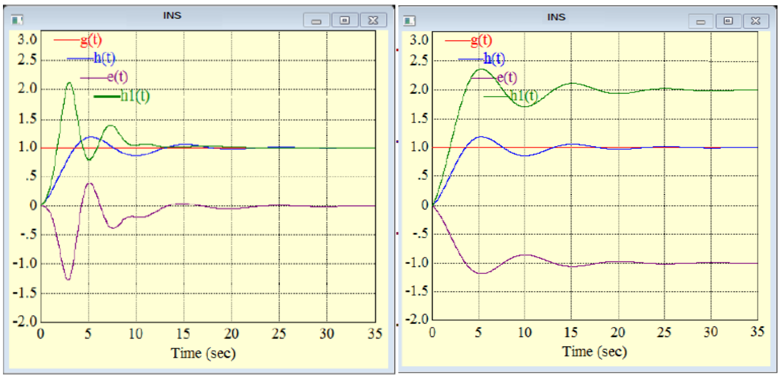
The simulation results of the proposed algorithm for the method implementation of the intellectual system of the UAA navigation system automatic control using a neural network, in the MathLab software environment, are shown in Fig. 6.

The resulting error of management using the system's learning unit is $e(t)=y_M(t)-y(t)\Rightarrow 0$, at the same time, the parameters of the controller of the intelligent automatic control system of the UAA navigation system tend to the parameters of the reference model.

In the Fig. 6: green is the object of control, blue is the reference model, violet is the error of control.

Comparing two systems of automatic control of the UAA navigation system with and without a unit training system it is worth noting that the first system has more stable performance.

DOI 10.15588/1607-3274-2019-1-20



a b

Figure 6 – The results of simulation of the proposed algorithm in the software environment MathLab: a) – with using of the training unit control system; b) – without using of the training unit control system

6 DISCUSSION

Within the framework of the work an algorithm for the method implementation of the intellectual system of the UAA navigation system automatic control with the help of the neural network in the MatLab software environment is disclosed. Structural and functional schemes of control system training are presented which are the basis of the implementation algorithm methodology of the automatic control intellectual system of direct-acting UAA navigation system.

The offered inertial navigator of automatic control flight of UAA works as with the use of MEMS sensors, that allows substantially to reduce in price the similar systems as compared to the systems [11–15].

In-process [23] an author examines a navigational, the methods of Kalman filtration are fixed in basis of that. These systems are able to provide high exactness of positioning of object substantially complicating a calculable process. In addition, such systems are bulky and outvalue considerably.

In respect of the offered system, an algorithm (Fig. 2) is fixed in basis of work of that, her exactness is arrived at by means of methods of artificial intelligence or training unit control system – technically.

From a fig. 6 we will notice that time of positioning with her use diminished substantially.

In the conditions of the use of UAA in fully autonomous behavior (in default of additional GSNS), block of UAA hours will be megascopic for lack of power expenses on the search of navigation signals and reduction of the calculable loading of navigational on the whole.

The control system described can be used as an intelligent automatic control system for UAA navigation system.

The proposed algorithm for the implementation of the methodology based on the direct control method with the help of the training unit, gives positive results in the range of normative change of parameters, greatly reduces the time and cost of design.

CONCLUSIONS

In the course of the conducted scientific research, the authors improved the methodology for building an automatic control intelligent system of an unmanned aerial vehicle, which allows to increase the efficiency of control systems for unmanned aerial vehicles up to 15% (time of decision making and positioning accuracy).

The scientific novelty. The proposed automatic control system using artificial intelligence makes it possible to provide control tasks in the mode of full autonomous flight of a UAA without regard to auxiliary positioning systems.

The testing of the work of the automatic control intellectual system of the UAA navigational system using the neural network in the MatLab software environment based on the proposed implementation algorithm.

The practical significance. The experimental results allow us to recommend the proposed algorithm for practical use in order to increase the stability of the automatic flight control system of the UAA in the autonomous operation mode.

The proposed algorithm for the implementation of the methodology based on the direct control method with the help of the training unit, gives positive results in the range of normative change of parameters, greatly reduces the time and cost of design.

The possibility of practical application of the obtained results and comparison with known methods was investigated.

The obtained scientific result is expedient to use in control systems of unmanned aerial vehicles in a complex signal-interfering environment.

Prospects for further research are to study the degree of parasitic effects of sensors on the control channel.

ACKNOWLEDGEMENTS

The staff of the authors expresses gratitude for the scientific and organizational assistance to the Honored worker of education of Ukraine, doctor of technical sciences, professor Romaniuk Valery Antonovich – deputy of head of the Military institute of telecommunications and informatization named after Heroes of Krut of scientific work and honored scientist of Ukraine, doctor of technical sciences, professor Slyusar Vadim Ivanovich – main scientist of the Central research institute of armament and military equipment of the Armed Forces of Ukraine.

DOI 10.15588/1607-3274-2019-1-20

REFERENCES

1. Information technology. Vocabulary. Part 28. Artificial intelligence. Basic concepts and expert systems : ISO/IEC 2382–28:1995. [Effective from 1995-12-15]. Geneve, 1995, 36 p.
2. Avtomatyzovani systemy. Terminy ta vyznachennja : DSTU 2226–93. [Chynnyj vid 1993-04-01]. Kyev, Derzhstandart Ukrai'ny, 1993, 86 p. (Nacional'nyj standart Ukrai'ny).
3. Subbotin S. O., Olijnyk A. O. (Ukrai'na). Pat. 18294 Ukrai'na, MPK2006 G06F 19/00. Sposib vidboru informatyvnyh oznak dlja diagnostyky vyrobiv / zajavnyk Zaporiz'kyj nacional'nyj tehnichnyj universytet. № u200603087; Zajavl. 22.03.06; Opubl.15.11.06, Bjul. №11. 4 p.
4. Akaike H. A new look at the statistical model identification, *IEEE Transactions on Automatic Control,* 1974, Vol. 19, No. 6, pp. 716–723.
5. Babak O. V., Tatarinov A. E'. Ob odnom podxode k resheniyu zadach klassifikacii v usloviyax nepolnoty informacii, Kibernetika i sistemnyj analiz, 2005, No. 6, pp. 116–123.
6. Slyusar V. I. Voyennaya svyaz' stran NATO: problemy sovremennykh tekhnologiy, *Elektronika: Nauka, Tekhnologiya, Biznes,* 2008, No. 4, pp. 66–71.
7. Slyusar V. I. Peredacha dannykh s borta BPLA: standarty NATO, *Elektronika: nauka, tekhnologiya, biznes,* 2010, No. 3, pp. 80–86.
8. Slyusar V. I. Radiolinii svyazi s BPLA: primery realizatsii, *Elektronika: nauka, tekhnologiya, biznes,* 2010, No. 5, pp. 56–60.
9. Romanyuk V. A., Stepanenko Ê. O., Panchenko Í. V., Voskolovich O. Í. Lítayuchí samoorganízuyuchí radíomerezhí, *Zbírnik naukovikh prats' VÍTÍ,* 2017, No. 1, pp. 104–114.
10. Romanyuk V. A., Stepanenko Ê. O. Zadachí sintezu topologíy merezh mobíl'noí komponenti z vikoristannyam telekomuníkatsíynikh ayeroplatform, *Zbírnik naukovikh prats' VÍTÍ*, 2017, No. 3, pp. 149–157.
11. Suyi L., Wang S. Machine health monitoring and prognostication via vibration information, *Intelligent systems design and applications : Sixth international conference, Jinan, 16–18 October 2006 : proceedings.* Los Alamitos, IEEE, 2006, P. 879.
12. Subbotin S. O. Programni zasoby syntezu diagnostychnyh i rozpiznaval'nyh modelej za precedentamy, *Suchasni problemy i dosjagnennja v galuzi radiotehniky, telekomunikacij ta informacijnyh tehnologij : VI Mizhnarodna naukovo-praktychna konferencija, Zaporizhzhja, 19–21 veresnja 2012 r. : tezy dopovidej.* Zaporizhzhja, ZNTU, 2012, P. 21–22.
13. Neagu C.-D. Using artificial neural networks in fuzzy reasoning : abstract of the dissertation ... doctor of philosophy in computer science. Galati, University of Galati, 2000, 42 p.
14. Snytjuk V. Je. Evoljucijni tehnologii' pryjnjattja rishen' v umovah nevyznachenosti : avtoref. dys. ... d-ra tehn. nauk : 05.13.06 / NAN Ukrai'ny; Instytut problem matematychnyh mashyn i system. Kyiv, 2009, 36 p.
15. Li S. Automated tool condition monitoring in machining using fuzzy neural networks : thesis doctor of Ph. Hamilton, McMaster University, 1995, 187 p.
16. Voronkin R. A. Matematicheskoe modelirovanie processov geneticheskogo poiska dlya povysheniya kachestva obucheniya nejronnyx setej pryamogo rasprostraneniya : dis. kand. texn. nauk : 05.13.18. Stavropol', 2004, 237 p.
17. Abraham A., Grosan C., Pedrycz W.. Engineering evolutionary intelligent systems. Berlin, Springer, 2008, 444 p.
18. Boguslaev A. V., Olejnik Al. A., Olejnik An. A., Pavlenko D. V., Subbotin S. A.; pod red. D. V. Pavlenko, S. A. Subbotina. Progressivnye texnologii modelirovaniya, optimizacii i intellektual'noj avtomatizacii e'tapov zhiznennogo cikla aviacionnyx dvigatelej : monografiya. Zaporozh'e, OAO "Motor Sich", 2009, 468 p.
19. Klyuev V. V., Sosnin F. R., Filinov V. N. i dr.; pod obshh. red. V. V. Klyueva. Mashinostroenie : e'nciklopediya / ped. sovet: K.V. Frolov (pred.) i dr. Moscow, Mashinostroenie, Vol. III-7, Izmereniya, kontrol', ispytaniya i diagnostika, 1996, 464 p.
20. UCI machine learning repository [Electronic resource]. Access mode: http://archive.ics.uci.edu/ml/datasets/
21. Shuvakin Yu. A. Simulation of the kinematics and flight dynamics of an unmanned aerial vehicle, *Problems of modern science and education: Olympus. Ivanovo*, 2016, No. 16 (58), pp. 44–47.
22. Lebedev A. A., Chernobrovkin L. S. under redaction of V. K. Salnik Dynamics of flight of unmanned aerial vehicles: Textbook for High Schools. Moscow, 2010, 618 p.
23. Chernodub A. N. Training of neuroemulators with use of pseudoregularization for model reference adaptive neurocontrol, *Intellektual'nye systemy*, 2012, No. 4, pp. 602–614.
24. Mu C., Wang D. Neural-network-based adaptive guaranteed cost control of nonlinear dynamical systems with matched uncertainties, *Neurocomputing,* 2017, Vol. 245, pp. 46–54.
25. Lin Z., Ma D., Meng J., Chen L. Relative ordering learning in spiking neural network for pattern recognition, *Neurocomputing,* 2018, Vol. 275, pp. 94–106.
26. Yu J., Sang J., Gao X. Machine learning and signal processing for big multimedia analysis, *Neurocomputing*, 2017, Vol. 257, pp. 1–4.
27. Lv Y., Na J., Yang Q., Wu X., Guo Y. Online adaptive optimal control for continuous-time nonlinear systems with completely unknown dynamics, *International Journal of Control,* 2016, Vol. 89, pp. 99–112.
28. Sun Y., Xue B., Zhang M., Yen G. G. Automatically Designing CNN Architectures Using Genetic Algorithm for Image Classification, *Cornell University Libreri, Electronic data,* 2018. Mode of access: https://arxiv.org/abs/1808.03818 (viewed on Aug 11, 2018). Title from the screen.
29. Zela A., Klein A., Falkner S., Hutter F. Towards Automated Deep Learning: Efficient Joint Neural Architecture and Hyperparameter Search, *Cornell University Libreri.* Electronic data, 2018. Mode of access: https://arxiv.org/abs/1807.06906 (viewed on Jul 18, 2018). Title from the screen.

Received 04.09.2018.
Accepted 25.10.2018.

DOI 10.15588/1607-3274-2019-1-20

УДК 004.852

МЕТОДИКА ПОБУДОВИ ІНТЕЛЕКТУАЛЬНОЇ СИСТЕМИ АВТОМАТИЧНОГО КЕРУВАННЯ БЕЗПІЛОТНИМ ЛІТАЛЬНИМ АПАРАТОМ

Бєляков Р. О. – канд. техн. наук, викладач кафедри Технічного та метрологічного забезпечення факультету Інформаційних технологій Військового інституту телекомунікацій та інформатизації імені Героїв Крут, Київ, Україна.

Радзівілов Г. Д. – канд. техн. наук, доцент, начальник кафедри Технічного та метрологічного забезпечення факультету Інформаційних технологій Військового інституту телекомунікацій та інформатизації імені Героїв Крут, Київ, Україна.

Фесенко О. Д. – ад'юнкт кафедри Технічного та метрологічного забезпечення факультету Інформаційних технологій Військового інституту телекомунікацій та інформатизації імені Героїв Крут, Київ, Україна.

Васильченко В. В. – начальник навчально-лабораторного комплексу кафедри Технічного та метрологічного забезпечення факультету Інформаційних технологій Військового інституту телекомунікацій та інформатизації імені Героїв Крут, Київ, Україна.

Цатурян О. Г. – старший науковий співробітник Наукового центру зв'язку та інформатизації Військового інституту телекомунікацій та інформатизації імені Героїв Крут, Київ, Україна.

Шишацький А. В. – канд. техн. наук, науковий співробітник Центрального науково-дослідного інституту озброєння та військової техніки Збройних Сил України, Київ, Україна.

Романенко В. П. – канд. техн. наук, завідувач кафедри Інституту спеціального зв'язку та захисту інформації Національного технічного університету України «Київський політехнічний інститут імені Ігоря Сікорського», Київ, Україна.

АНОТАЦІЯ

Актуальність. Воєнні конфлікти кінця XX – початку XXI ст. характеризуються застосуванням великої кількості нового озброєння, яке дозволило ворогуючим сторонам максимально дистанціюватися від безпосереднього зіткнення один з одним.

Одним з новітніх зразків озброєння на полі бою стали безпілотні літальні апарати (БПЛА), які під час воєнних конфліктів довели свою здатність значно ефективніше, ніж пілотовані літаки, вести повітряну розвідку та виконувати інші завдання бойового забезпечення, а також для завдання ударів по противнику. Одним з шляхів підвищення ефективності БПЛА є підвищення рівня технічної досконалості їх систем керування.

Створення нових підходів для проектування навігаційних систем безпілотних літальних апаратів, зокрема, на основі безплатформенної інерціальної навігаційної системи є актуальним завданням, тому що це дозволить забезпечити автоматичне керування маршрутом польоту БПЛА за відсутності коригувальних сигналів від глобальної системи супутникової навігації.

Мета. Метою зазначеної роботи є розробка методики управління безпілотним літальним апаратом із застосуванням інтелектуальної системи автоматичного керування.

Зазначена методика дозволить мінімізувати похибку безплатформенної інерціальної навігаційної системи за рахунок застосування апарату нечіткої нейронної мережі.

В роботі розроблено алгоритм реалізації запропонованої методики побудови інтелектуальної системи автоматичного управління системою навігації БПЛА з використанням апарату нечіткої нейронної мережі в програмному середовищі MatLab 7; проведено навчання нейронної мережі в програмному середовищі Python 3.6 (Jupyter-notebook), а також проведено тестування моделі БПЛА в середовищі симулятору Robot operation system (ROS) для порівняння з існуючими методами.

Метод. Для досягнення поставленої мети використано такі методи: інтелектуальні системи, теорія автоматичного управління, псевдоспектральний метод; методи на базі генетичного алгоритму та апарат нечіткої нейронної мережі.

Результати. Розроблено методику побудови інтелектуальної системи автоматичного керування безпілотним літальним апаратом для мінімізації похибки безплатформної інерціальної навігаційної системи за рахунок застосування нейронної мережі. Протестовано роботу інтелектуальної системи автоматичного управління системою навігації БПЛА за допомогою нейронної мережі в програмному середовищі MatLab на основі запропонованого алгоритму реалізації. Досліджено можливість практичного застосування отриманих результатів та порівняно з традиційними методами.

Висновки. Розроблена методика побудови інтелектуальної системи автоматичного керування безпілотним літальним апаратом показує перевагу порівняно із відомими методами за відсутності коригувальних сигналів від глобальної системи супутникової навігації.

КЛЮЧОВІ СЛОВА: інтелектуальна система автоматичного управління, навігаційна система, безпілотний літальний апарат.

УДК 004.852

МЕТОДИКА ПОСТРОЕНИЯ ИНТЕЛЛЕКТУАЛЬНОЙ СИСТЕМЫ АВТОМАТИЧЕСКОГО УПРАВЛЕНИЯ БЕСПИЛОТНЫМ ЛЕТАТЕЛЬНЫМ АППАРАТОМ

Беляков Р. О. – канд. техн. наук, преподаватель кафедры Технического и метрологического обеспечения факультета Информационных технологий Военного института телекоммуникаций и информатизации имени Героев Крут, Киев, Украина.

Радзивилов Г. Д. – канд. техн. наук, доцент, начальник кафедры Технического и метрологического обеспечения факультета Информационных технологий Военного института телекоммуникаций и информатизации имени Героев Крут, Киев, Украина.

Фесенко О. Д. – адъюнкт кафедры Технического и метрологического обеспечения факультета Информационных технологий Военного института телекоммуникаций и информатизации имени Героев Крут, Киев, Украина.

DOI 10.15588/1607-3274-2019-1-20

Васильченко В. В. – начальник учебно-лабораторного комплекса кафедры Технического и метрологического обеспечения факультета Информационных технологий Военного института телекоммуникаций и информатизации имени Героев Крут, Киев, Украина.

Цатурян О. Г. – старший научный сотрудник Научного центра связи и информатизации Военного института телекоммуникаций и информатизации имени Героев Крут, Киев, Украина;

Шишацкий А. В. – канд. техн. наук, научный сотрудник Центрального научно-исследовательского института вооружения и военной техники Вооруженных Сил Украины, Киев, Украина.

Романенко В. П. – канд. техн. наук, заведующий кафедры Института специальной связи и защиты информации Национального технического университета Украины «Киевский политехнический институт имени Игоря Сикорского», Киев, Украина.

АННОТАЦИЯ

Актуальность. Военные конфликты конца XX – начала XXI в. характеризуются применением большого количества нового вооружения, которое позволило враждующим сторонам максимально дистанцироваться от непосредственного соприкосновения друг с другом.

Одним из новейших образцов вооружения на поле боя стали беспилотные летательные аппараты (БПЛА), которые во время военных конфликтов доказали свою способность значительно эффективнее, чем пилотируемые самолеты, вести воздушную разведку и выполнять другие задачи боевого обеспечения, а также для нанесения ударов по противнику. Одним из путей повышения эффективности БПЛА является повышение уровня технического совершенства их систем управления.

Создание новых подходов для проектирования навигационных систем беспилотных летательных аппаратов, в частности, на основе бесплатформенные инерциальной навигационной системы является актуальной задачей, так как это позволит обеспечить автоматическое управление маршруту полета БПЛА при отсутствии корректирующих сигналов от глобальной системы спутниковой навигации.

Цель. Целью указанной работы является разработка методики управления беспилотным летательным аппаратом с применением интеллектуальной системы автоматического управления.

Указанная методика позволит минимизировать погрешность бесплатформенные инерциальной навигационной системы за счет применения аппарата нечеткой нейронной сети.

В работе разработан алгоритм реализации предложенной методики построения интеллектуальной системы автоматического управления системой навигации БПЛА с использованием аппарата нечеткой нейронной сети в программной среде MatLab 7; проведено обучение нейронной сети в программной среде Python 3.6 (Jupyter-notebook), а также проведено тестирование модели БПЛА в среде симулятора Robot operation system (ROS) для сравнения с существующими методами.

Метод. Для достижения поставленной цели использованы следующие методы: интеллектуальные системы, теория автоматического управления, псевдоспектральний метод, методы на базе генетического алгоритма и аппарат нечеткой нейронной сети.

Результаты. Разработана методика построения интеллектуальной системы автоматического управления беспилотным летательным аппаратом для минимизации погрешности безплатформной инерциальной навигационной системы за счет применения нейронной сети. Протестировано работу интеллектуальной системы автоматического управления системой навигации БПЛА с помощью нейронной сети в программной среде MatLab на основе предложенного алгоритма реализации. Исследована возможность практического применения полученных результатов и сравнение с традиционными методами.

Выводы. Разработана методика построения интеллектуальной системы автоматического управления беспилотным летательным аппаратом показывает преимущество по сравнению с известными методами при отсутствии корректирующих сигналов от глобальной системы спутниковой навигации.

КЛЮЧЕВЫЕ СЛОВА: интеллектуальная система автоматического управления, навигационная система, беспилотный летательный аппарат.

ЛІТЕРАТУРА / ЛИТЕРАТУРА

1. Information technology. Vocabulary. Part 28. Artificial intelligence. Basic concepts and expert systems : ISO/IEC 2382-28:1995. – [Effective from 1995-12-15]. – Geneve: ISO, 1995. – 36 p.
2. Автоматизовані системи. Терміни та визначення : ДСТУ 2226-93. – [Чинний від 1993-04-01]. – К. : Держстандарт України, 1993. – 86 с. – (Національний стандарт України).
3. Пат. 18294 Україна, МПК 2006 G06F 19/00. Спосіб відбору інформативних ознак для діагностики виробів / С. О. Субботін, А. О. Олійник (Україна); заявник Запорізький національний технічний університет. – № u200603087; Заявл. 22.03.06; Опубл. 15.11.06, Бюл. №11. – 4 с.
4. Akaike H. A new look at the statistical model identification / H. Akaike // IEEE Transactions on Automatic Control. – 1974. – Vol. 19, № 6. – P. 716–723.
5. Бабак О.В. Об одном подходе к решению задач классификации в условиях неполноты информации / О. В. Бабак, А. Э. Татаринов // Кибернетика и системный анализ. – 2005. – № 6. – С. 116–123.
6. Слюсар В. И. Военная связь стран НАТО: проблемы современных технологий // Электроника: Наука, Технология, Бизнес. – 2008. – № 4. – С. 66–71.
7. Слюсар В. И. Передача данных с борта БПЛА: стандарты НАТО // Электроника: наука, технология, бизнес. – 2010. – № 3. – С. 80–86.
8. Слюсар В. И. Радиолинии связи с БПЛА: примеры реализации // Электроника: наука, технология, бизнес. – 2010. – № 5. – С. 56–60.
9. Літаючі самоорганізуючі радіомережі / [В. А. Романюк, Є. О. Степаненко, І. В. Панченко, О. І. Восколович] // Збірник наукових праць ВІТІ. – 2017. – № 1. – С. 104–114.
10. Романюк В. А. Задачі синтезу топологій мереж мобільної компоненти з використанням телекомунікаційних аероплатформ / В. А. Романюк, Є. О. Степаненко // Збірник наукових праць ВІТІ. – 2017. – № 3. – С. 149–157.

DOI 10.15588/1607-3274-2019-1-20

11. Suyi L. Machine health monitoring and prognostication via vibration information / L. Suyi, S. Wang // Intelligent systems design and applications : Sixth international conference, Jinan, 16–18 October 2006 : proceedings. – Los Alamitos: IEEE, 2006. – P. 879.
12. Субботін С. О. Програмні засоби синтезу діагностичних і розпізнавальних моделей за прецедентами / С. О. Субботін // Сучасні проблеми і досягнення в галузі радіотехніки, телекомунікацій та інформаційних технологій : VI Міжнародна науково-практична конференція, Запоріжжя, 19–21 вересня 2012 р. : тези доповідей. – Запоріжжя : ЗНТУ, 2012. – С. 21–22.
13. Neagu C.-D. Using artificial neural networks in fuzzy reasoning : abstract of the dissertation ... doctor of philosophy in computer science / C.-D. Neagu. – Galati : University of Galati, 2000. – 42 p.
14. Снитюк В. Є. Еволюційні технології прийняття рішень в умовах невизначеності : автореф. дис. ... д-ра техн. наук : 05.13.06 / НАН України; Інститут проблем математичних машин і систем. – К., 2009. – 36 с.
15. Li S. Automated tool condition monitoring in machining using fuzzy neural networks : thesis ... doctor of philosophy / Li Shengmu. – Hamilton : McMaster University, 1995. – 187 p.
16. Воронкин Р. А. Математическое моделирование процессов генетического поиска для повышения качества обучения нейронных сетей прямого распространения : дис. … канд. техн. наук : 05.13.18 / Воронкин Роман Александрович. – Ставрополь, 2004. – 237 с.
17. Abraham A. Engineering evolutionary intelligent systems / A. Abraham, C. Grosan, W. Pedrycz. – Berlin : Springer, 2008. – 444 p.
18. Прогрессивные технологии моделирования, оптимизации и интеллектуальной автоматизации этапов жизненного цикла авиационных двигателей : монография / [А. В. Богуслаев, Ал. А. Олейник, Ан. А. Олейник, Д. В. Павленко, С. А. Субботин] ; под ред. Д. В. Павленко, С. А. Субботина. – Запорожье: ОАО "Мотор Сич", 2009. – 468 с.
19. Машиностроение : энциклопедия / [ред. совет: К. В. Фролов (пред.) и др.]. – М. : Машиностроение. – Т. III-7 : Измерения, контроль, испытания и диагностика / [В. В. Клюев, Ф. Р. Соснин, В. Н. Филинов и др.] ; под общ. ред. В. В. Клюева, 1996. – 464 с.
20. UCI machine learning repository [Electronic resource]. – Access mode: http://archive.ics.uci.edu/ml/datasets/.
21. Шувакин Ю. А. Моделирование кинематики и динамики полета беспилотного летательного аппарата / Ю. А. Шувакин // Проблемы современной науки и образования: Олимп. Иваново – 2016. № 16(58). – С. 44–47.
22. Лебедев А. А. Динамика полета беспилотных летательных аппаратов : учебное пособие для ВУЗов / А. А. Лебедев, Л. С. Чернобровкин; под ред. В. К. Сальника. – М., 2010. – 618 с.
23. Чернодуб А. Н. Обучение нейроэмуляторов с использованием псевдорегуляризации для метода нейроуправления с эталонной моделью / А. Н. Чернодуб // Интеллектуальные системы. – 2012. – № 4. – С. 602–614.
24. Mu C. Neural-network-based adaptive guaranteed cost control of nonlinear dynamical systems with matched uncertainties / C. Mu, D. Wang // Neurocomputing. – 2017. – Vol. 245. – P. 46–54.
25. Lin Z. Relative ordering learning in spiking neural network for pattern recognition / Z. Lin, D. Ma, J. Meng, L. Chen // Neurocomputing. – 2018. – vol. 275. – P. 94–106.
26. Yu J. Machine learning and signal processing for big multimedia analysis / J. Yu, J. Sang, X. Gao // Neurocomputing. – 2017. – Vol. 257. – P. 1–4.
27. Online adaptive optimal control for continuous-time nonlinear systems with completely unknown dynamics / [Y. Lv, J. Na, Q. Yang et al.] // International Journal of Control. – 2016. – Vol. 89. – P. 99–112.
28. Automatically Designing CNN Architectures Using Genetic Algorithm for Image Classification / [Y. Sun, B. Xue, M. Zhang, G. G. Yen] // Cornell University Libreri. – Electronic data. – 2018. – Mode of access: https://arxiv.org/abs/1808.03818 (viewed on Aug 11, 2018). – Title from the screen.
29. Zela A. Towards Automated Deep Learning: Efficient Joint Neural Architecture and Hyperparameter Search / A. Zela, A. Klein. S. Falkner. F. Hutter // Cornell University Libreri. – Electronic data. – 2018. – Mode of access: https://arxiv.org/abs/1807.06906 (viewed on Jul 18, 2018). – Title from the screen.

DOI 10.15588/1607-3274-2019-1-20