UDC 004.93,629.7

DEVELOPMENT OF AN AUTONOMOUS NAVIGATION SYSTEM FOR THE GROUPED COORDINATED FLIGHT OF UAV'S

Marynoshenko O.P., Pikenin O.O.
Igor Sikorsky Kyiv Polytechnic Institute

The paper considers a description of developed control system for a group of unmanned aerial vehicles (UAV) that has a software capable to continue the flight in case of failures by using alternative control algorithms. Control system is developed on vision system by using methods of image recognition. Grouped co-ordinated flight of UAV's can significantly improve the performance of surveillance processes, such as reconnaissance, image recognition, aerial photography, industrial and environmental monitoring, etc. But to control a group of UAV's is a quite difficult task. In this paper, we propose a model that corresponds to the principle of construction by the leading UAV's. In the case of using this model, the parameters of the system motion are determined by the direction of motion, the speed and acceleration of the UAV's driving. The control system based on the methods of image recognition expands the possibilities of coordinating the group of UAV's.
Keywords: image recognition, an unmanned aerial vehicle, the singular points, descriptors, vision system.

Introduction. One of the important and actual purpose of using UAVs is the application of it in mixed groups, including manned and unmanned aerial vehicles, or as a part of operating autonomously UAVs group.

To solve the navigational task for UAVs group, we use a control system based on image recognition methods. The methods of image recognition are based on tracking, identification and detection of mobile and stationary air and land objects.

To create a system, it is necessary to analyze the problem of classifying terrestrial stationary objects for constructing the flight trajectory of a group.

Statement of the problem. Formation flight control of multiple UAVs is an active topic for numerous researches (T. Soleymani, F. Saghafi, 2010; A.K. Das, R. Fierro, V. Kumar, J.P. Ostrowski, J. Spletzer and C.J. Taylor, 2002; J. Hammer, G. Piper, O. Thorp and J. Watkins, 2004; Z. Gosiewski, L. Ambroziak, 2013), with many practical application: reconnaissance, communication, search and rescue.

There are many research methods proposed for implementation of multiple UAVs control, especially for control of UAVs formation flying, such as leader following (T. Soleymani, F. Saghafi, 2010), behavior based approach (J. Hammer, G. Piper, O. Thorp, and J. Watkins, 2004), virtual leader (Z. Gosiewski, L. Ambroziak, 2013) and artificial potential functions (T. Paul, T.R. Krogstad and J.T. Gravdahl, 2008). In these methods, most appropriative is are leaders' methods.

The big problem in formation control are question of creation and full usage the neighbor-to-neighbor communication and synchronization. The well-known today methods for communication and synchronization inside of formation of UAVs are methods of usage of video information (A.K. Das, R. Fierro, V. Kumar, J.P. Ostrowski, J. Spletzer and C.J. Taylor, 2002), and methods of usage of radio transmitting data (T. Paul, T.R. Krogstad and J.T. Gravdahl, 2008).

The current development of aviation sets the task of implementation of the formation flight of unmanned aerial vehicles.

The necessity of development of technology for control of formation flying UAVs now opens a very important area: the creation of between onboard unmanned navigation systems (BONUS) for UAVs with very limited weight and volume. This need is determined by the fact that the absence of equipment onboard the UAV BONUS can greatly limit their opportunities.

Development of systems like a BONUS goes by two approaches: creation of an autonomous systems that do not depend on ground guiding systems, and onboard systems using ground-based radio beacons (T. Paul, T.R. Krogstad and J.T. Gravdahl, 2008). Each of these ways has its own advantages and disadvantages. Autonomous management system can solve the problem of formation flight without restrictions imposed by the channels for communication with ground control, as well as in radio jamming.

The main tasks. Development of a "guidance system" for an autonomous navigation system of the grouped co-ordinated flight of UAVs by using methods of image recognition. Implementation of control algorithms for recognition of mobile and stationary air and land navigation objects.

1. Model UAVs formation flying

Group of moving system – UAVs is usually regarded as a system of connected rigid bodies with significant degrees of freedom. And the number of degrees of freedom increases significantly with the increase of number of UAVs in the group that makes the model of spatial movement extremely difficult and unsuitable for solving the problem of synthesis of a coherent control of the whole set of aircrafts. In this connection, widely used is model group UAV relative motion, according to which the group is allocated carrier body (vehicle) and the transportable body. As the carrier serves the leading UAV, guided aerial vehicles (UAVs) play a role of transportable bodies. At the same time, any type of order: column, front, diamond, bearing, a wedge or a mixed order – can be viewed as a set of pairs: a master-slave. It should be noted that the formation of such pairs can be created based on two principles. In one case, the binding is carried by driven UAV marching to the leading UAV. In the second case, all driven UAVs determine their movements relative to the general for all – the leading UAV.

Without over viewing of the details and the characteristics of each method for forming a UAV system, note that in this report we consider a model that meets the principle of building by the leading UAV.

As already noted, the group traffic control problem is related to the need to study the motion of the aircraft that are in certain relationships. Therefore, in the foreground a study of their relative motion.

Two aircraft movement relative to each other is the difference between two absolute movements and has three degrees of freedom.

In considering the relative motion of the aircraft, you can use a variety of the coordinate systems. Each system has its advantages and disadvantages. The choice is determined by its specific task. However, there are general principles of selection that determine the desirability or necessity of a system of reference. Given the simplicity of the dynamics equations obtained for simplification of analysis tasks and integration of these equations for the joint analysis of UAV motion group as a reference trajectory leading UAV choose a coordinate system.

The beginning of the coordinate system has to be advice to combine with a center of mass of the driven aircraft. At the driven UAVs measurement equipment for determining of the parameters of his relative motion relatively of leading UAV are placed. So the most appropriated coordinate system is a trajectory coordinate system.

2. The structure of the "guidance system" of the grouped co-ordinated flight of UAVs

The "guidance system" is a block of control system. The structure of the control system is constructed in such way that it allows solving two subtasks of the UAVs guidance for mobile and stationary air and land navigation objects (Fig. 1). Block of control system includes an optical sensor (OS) based on a rotating sensor (Rs). OS transmits streaming video or photos of the observed scene (the Earth's surface and Space in front of UAV) on a computer system (CS), which recognize land and mobile air facilities on the basis of the generated descriptors of these objects in the navigation database. The onboard CS contains the algorithms for calculating of the angular coordinates of the selected objects. After calculating the angular coordinates CS transmits control signals to the autopilot.

3. Control system for flying of UAVs formation.

The basis of the control group assigned flight system consists of the following modules-blocks: (1) "guidance system" which includes a vision systems (video camera) and pattern recognition algorithm (for forming control information about the position of the leading UAV); (2) flight control system driven UAV which is based on control laws for driven UAV in accordance with flight program for the group of UAVs; (3) navigation system to provide the necessary control, navigation and flight information.

Video system that installed on board each of the UAV as well as pattern recognition algorithms form a guidance system. Such system, in accordance with the proposed algorithm discussed above calculates the location data of the leading UAV. The data are converted into command signals characterizing the change in distance to the leading UAV, its vertical and horizontal displacements. An example of such output signals is shown in (Fig. 2). Further guidance system generates signals on the UAV control loops for the orientation angles of the pitch roll yaw, and to control distance between the aircrafts. In such control commands are also included flight command for order form (the order of flight) of UAVs in the group. After the control system, in other words the autopilot, commands supplied to UAV control surfaces. At the same time the autopilot includes a control and stabilization circuits not only on linear and angular displacements and for the velocities and accelerations. Achieving the required parameters for transients (overshoot, decay time, minimizing errors) is provided in our proposed system using the re-

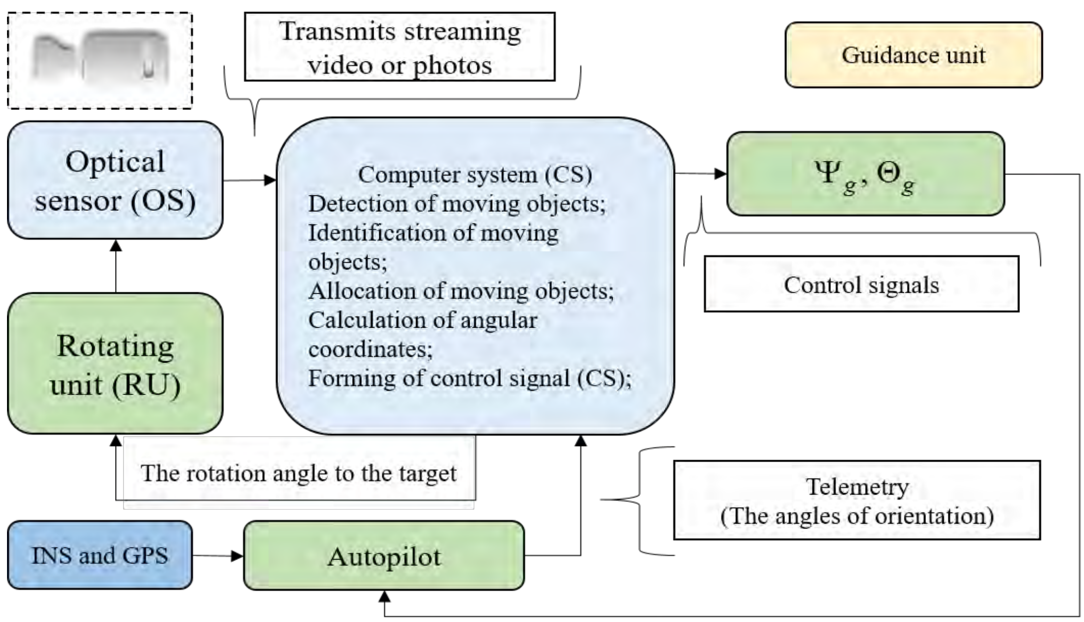

Figure 1. The structure of the "guidance system"

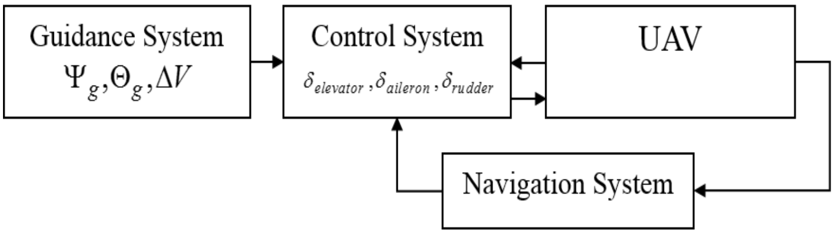

Figure 2. UAV flight control system

spective PI and PID controllers for longitudinal and lateral movement channels.

4. Method of recognition of stationary land navigation objects

Stationary land navigation objects divide into two groups: the first group of land navigation objects at an altitude of less than 1.5 km (point, areal, linear), the second group at an altitude more than 1.5 km. At an altitude of less than 1.5 km, point and linear land navigation objects we take as the basis for constructing of the flight curve (Fig. 3).

Buildings, lakes, railway stations, forests- especially important for the building of the flight trajectory as the surface area of land navigation objects (Fig.4).

Feature detection is the process where we automatically examine an image to extract features, that are unique to the objects in the image, in such a manner that we are able to detect an object based on its features in different images.

This detection should ideally be possible when the image shows the object with different transformations, mainly scale and rotation, or when parts of the object are occluded. Scale-Invariant Feature Transform, SIFT is a successful approach to feature detection introduced by Lowe. The SURF algorithm (Bay H., Ess A., Tuytelaars T., Gool L.V., 2009) is based on the same principles and steps, but it utilizes a different scheme and it should provide better results, faster.

To recognize such objects, we applied SURF algorithm (Bay H., Ess A., Tuytelaars T., Gool L.V., 2009) (Speeded-Up Robust Features) which solves two problems – finding key points and creation of their image descriptors that are invariant to scale and rotation (orientation). This means that the description of the key points will be constant, even if the navigation object will change the size and position.

SURF algorithm looks for key points and compares them with the key point's descriptors from database. Compiled navigation object will be a grouped descriptor of key points (Fig. 5).

5. Method of recognition of mobile land navigation objects

Technical means to implement the group flight of the aircraft are primarily those instruments and devices that allowing to define the parameters of

Figure 3. Detecting of point and linear land navigation objects

Figure 4. Detecting of surface area of land navigation objects

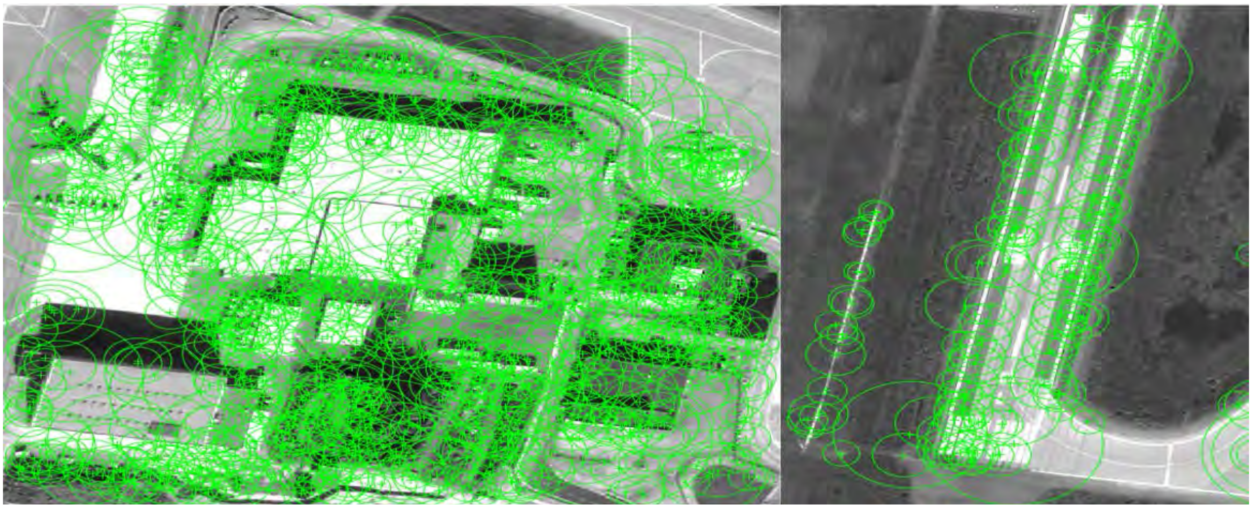

Figure 5. Descriptors of the linear and area land navigation objects

the relative motion of the aircraft. They must receive the necessary distance measuring and angle measuring information. This measuring apparatus can be based on various physical principles for the radio, optical, quantum-mechanical.

The main reasons for the growing interest in small aircraft is that they provide an inexpensive platform for electro optical (EO) and infrared (IR) cameras. Mobile land navigation objects will give us an opportunity to form the control system in a group, building a flight group and maintaining order in the ranks. To do this we have to match camera with coordinate system (Fig. 6, Fig. 7).

Supposing that the optical axis of the camera coincides with a longitudinal axis of the UAV (OX^b axis of a body fixed coordinate system $OX^bY^bZ^b$, $OX^CY^CZ^C$ – cameras local coordinate system, $OX^VY^VZ^V$ – air speed coordinate system).

It is assumed that the origin of the reference frame and the camera located in the center of gravity of the aircraft.

Guidance to the goal (leader UAV) is obtained by two angles: Ψ_{az} azimuth to goal, θ_V elevation to goal. Where:

$$R_{\Psi_{az}} = \begin{bmatrix} \cos\Psi_{az} & 0 & -\sin\Psi_{az} \\ 0 & 1 & 0 \\ \sin\Psi_{az} & 0 & \cos\Psi_{az} \end{bmatrix}$$ – matrix of rotation for azimuth;

$$R_{\theta_V} = \begin{bmatrix} \cos\theta_V & \sin\theta_V & 0 \\ -\sin\theta_V & \cos\theta_V & 0 \\ 0 & 0 & 1 \end{bmatrix}$$ – matrix of rotation for elevation;

Resulting matrix of rotation for guidance to the goal is:

$$R_b^g = R_{\Psi_{az}} * R_{\theta_V} = \begin{bmatrix} \cos\theta_V \cos\Psi_{az} & \sin\theta_V \cos\Psi_{az} & -\sin\Psi_{az} \\ -\sin\theta_V & \cos\theta_V & 0 \\ \sin\Psi_{az}\cos\theta_V & \sin\theta_V \sin\Psi_{az} & \cos\Psi_{az} \end{bmatrix}.$$

If f - is a focal length in units of pixels, then converts the pixels P in meters. To simplify the description, assume that the pixels and pixel array are squares. If the width of a square matrix of pixels in pixels is M and the v – cameras field of view is known, then the focal length f it can be written as:

$$f = \frac{M}{2\tan\left(\frac{v}{2}\right)}.$$

The position of the projection of the object expressed in the camera frame as $\left(P_{E_x}, P_{E_y}, f\right)$, where P_{E_x} and P_{E_y} define the position of the object in pixels. The distance from the origin of the camera system to a pixel position is $\left(P_{E_x}, P_{E_y}, f\right)$ $\sqrt{P_{Ex}^2 + P_{Ey}^2 + f^2}$ (as shown on the Fig. 8).

Define the ort (single vector) for the direction to the goal:

$$\frac{l^c}{L} = \frac{1}{F}\begin{bmatrix} P_{E_x} \\ P_{E_y} \\ f \end{bmatrix} = \frac{1}{\sqrt{P_{Ex}^2 + P_{Ey}^2 + f^2}}\begin{bmatrix} P_{E_x} \\ P_{E_y} \\ f \end{bmatrix} = \bar{l} = \begin{bmatrix} \bar{l}_x \\ \bar{l}_y \\ \bar{l}_z \end{bmatrix}; \quad (1)$$

The task of formation of the unit vector pointing to the leading UAV reduced to tracking of the image with leading UAV and definition of it geometric center.

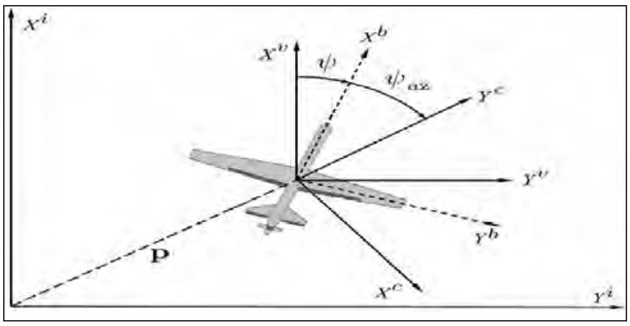

Figure 6. Matching camera with coordinate system (top view)

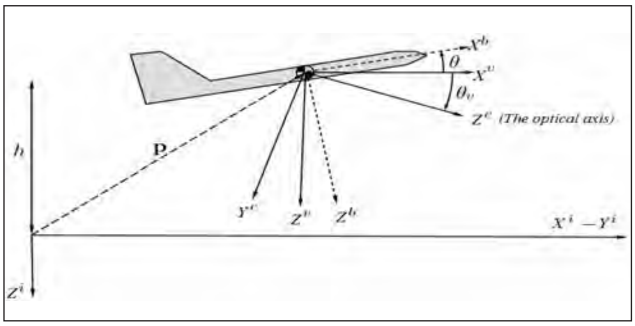

Figure 7. Matching camera with coordinate system (side view)

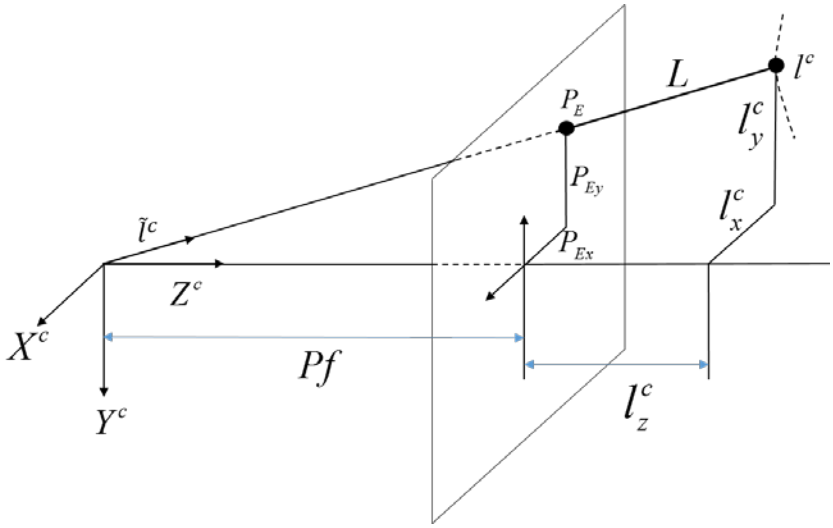

Figure 8. The camera coordinate system

6. Trajectory equation of the driven UAVs

The equations of the relative motion of the driven UAVs in the trajectory coordinate system can be represented as follows:

$$\Delta x_{gi} = x_{g1} - x_{gi}; \Delta y_{gi} = y_{g1} - y_{gi}; \Delta z_{gi} = z_{g1} - z_{gi};$$

$$\Delta Vx_{gi} = \frac{dx_{g1}}{dt} - \frac{dx_{gi}}{dt}; \Delta Vy_{gi} = \frac{dy_{g1}}{dt} - \frac{dy_{gi}}{dt}; \Delta Vz_{gi} = \frac{dz_{g1}}{dt} - \frac{dz_{gi}}{dt};$$

$$x_{gi}^{(1)} = \Delta x_{gi} \cos\theta_{vi} \cos\Psi_{azi} + \Delta y_{gi} \sin\theta_{vi} - \Delta z_{gi} \cos\theta_{vi} \sin\Psi_{azi};$$

$$y_{gi}^{(1)} = \Delta x_{gi} \sin\Psi_{azi} + \Delta y_{gi} \cos\Psi_{azi}; \quad (2)$$

$$z_{gi}^{(1)} = \Delta x_{gi} \sin\theta_{vi} \cos\Psi_{azi} - \Delta y_{gi} \sin\theta_{vi} \sin\Psi_{azi} - \Delta z_{gi} \cos\theta_{vi};$$

$$\Delta Vx_{gi}^{(1)} = \Delta Vx_{gi} \cos\theta_{vi} \cos\Psi_{azi} + \Delta Vy_{gi} \sin\theta_{vi} - \Delta Vz_{gi} \cos\theta_{vi} \sin\Psi_{azi};$$

$$\Delta Vy_{gi}^{(1)} = \Delta Vx_{gi} \sin\Psi_{azi} + \Delta Vy_{gi} \cos\Psi_{azi};$$

$$\Delta Vz_{gi}^{(1)} = \Delta Vx_{gi} \sin\theta_{vi} \cos\Psi_{azi} - \Delta Vy_{gi} \sin\theta_{vi} \sin\Psi_{azi} - \Delta Vz_{gi} \cos\theta_{vi}$$

Where: $x_{gi}^{(1)}, y_{gi}^{(1)}, z_{gi}^{(1)}$ and $\Delta Vx_{gi}^{(1)}, \Delta Vy_{gi}^{(1)}, \Delta Vz_{gi}^{(1)}$ – the coordinates and the relative speeds of the UAVs to the leading UAV in the trajectory coordinate system of the leading UAV, angles : elevation to goal θ_{vi} azimuth to goal Ψ_{azi} for each UAV in formation.

The linearization of the equations (2) provides a set of equations observation that define the trajectory of the carried UAVs in relatively to the trajectory of the leading (master) UAV.

$$\delta x_{gi}^{(1)} = c_{11}^{(i)}\delta\theta_1 + c_{12}^{(i)}\delta\Psi_1 + c_{13}^{(i)}\delta x_{g1} + c_{14}^{(i)}\delta y_{g1} + c_{15}^{(i)}\delta z_{g1} - c_{13}^{(i)}\delta x_{gi} - c_{14}^{(i)}\delta y_{gi} - c_{15}^{(i)}\delta z_{gi};$$

$$\delta y_{gi}^{(1)} = c_{22}^{(i)}\delta\Psi_1 + c_{23}^{(i)}\delta x_{g1} + c_{25}^{(i)}\delta z_{g1} - c_{23}^{(i)}\delta x_{gi} - c_{25}^{(i)}\delta z_{gi}; \quad (3)$$

$$\delta z_{gi}^{(1)} = c_{31}^{(i)}\delta\theta_1 + c_{32}^{(i)}\delta\Psi_1 + c_{33}^{(i)}\delta x_{g1} + c_{34}^{(i)}\delta y_{g1} + c_{35}^{(i)}\delta z_{g1} - c_{33}^{(i)}\delta x_{gi} - c_{34}^{(i)}\delta y_{gi} - c_{35}^{(i)}\delta z_{gi};$$

$\delta\alpha$ denotes 'small' deviations from the normal steady-state condition.

7. The mathematical model of the aircraft in the trajectory coordinate system

The vector form of the equation of motion of the aircraft as a solid body moving in space has six degrees of freedom are derived from the theorem: the theorem change of impulse, and the theorem of change of momentum of impulse.

The complete system of equations of motion of an arbitrary spatial individual UAV in trajectory coordinates are as follows (in the trajectory coordinate system are presented equation of the translational motion (force equations) of UAV). For creation of control system for formation of UAVs will be used linearized mathematic model – linearized system of equations of the UAV motion.

$$\delta \overset{\grave{U}}{V}_i = a_{11}^{(i)}\delta V_i + a_{12}^{(i)}\delta\alpha_i + a_{13}^{(i)}\delta\beta_i + a_{14}^{(i)}\delta\gamma_i + a_{15}^{(i)}\delta\theta_i + a_{16}^{(i)}\delta\Psi_i + \ldots;$$

$$\delta\theta_i = a_{21}^{(i)}\delta V_i + a_{22}^{(i)}\delta\alpha_i + a_{23}^{(i)}\delta\beta_i + a_{24}^{(i)}\delta\gamma_i + a_{25}^{(i)}\delta\theta_i + a_{26}^{(i)}\delta\Psi_i + \ldots;$$

$$\delta \overset{\grave{U}}{\Psi}_i = a_{31}^{(i)}\delta V_i + a_{32}^{(i)}\delta\alpha_i + a_{33}^{(i)}\delta\beta_i + a_{34}^{(i)}\delta\gamma_i + a_{35}^{(i)}\delta\theta_i + a_{36}^{(i)}\delta\Psi_i + \ldots;$$

$$\delta\dot{\omega}_{x_i} = a_{41}^{(i)}\delta V_i + a_{42}^{(i)}\delta\alpha_i + a_{43}^{(i)}\delta\beta_i + a_{44}^{(i)}\delta\gamma_i + a_{45}^{(i)}\delta\theta_i + a_{46}^{(i)}\delta\Psi_i + \ldots; \quad (4)$$

$$\delta\dot{\omega}_{y_i} = a_{51}^{(i)}\delta V_i + a_{52}^{(i)}\delta\alpha_i + a_{53}^{(i)}\delta\beta_i + a_{54}^{(i)}\delta\gamma_i + a_{55}^{(i)}\delta\theta_i + a_{56}^{(i)}\delta\Psi_i + \ldots;$$

$$\delta\dot{\omega}_{z_i} = a_{61}^{(i)}\delta V_i + a_{62}^{(i)}\delta\alpha_i + a_{63}^{(i)}\delta\beta_i + a_{64}^{(i)}\delta\gamma_i + a_{65}^{(i)}\delta\theta_i + a_{66}^{(i)}\delta\Psi_i + \ldots;$$

$$\delta\dot{X}_{g_i} = a_{71}^{(i)}\delta V_i + a_{72}^{(i)}\delta\alpha_i + a_{73}^{(i)}\delta\beta_i + a_{74}^{(i)}\delta\gamma_i + a_{75}^{(i)}\delta\theta_i + \ldots;$$

$$\delta\dot{Y}_{g_i} = \delta\dot{H}_i = a_{81}^{(i)}\delta V_i + a_{82}^{(i)}\delta\alpha_i + \ldots + b_{84}^{(i)}\delta u_{iT} = a_{81}^{(i)}\delta V_i = -\delta V_{i0}\theta_{i0};$$

$$\delta\dot{Z}_{g_i} = a_{91}^{(i)}\delta V_i + a_{92}^{(i)}\delta\alpha_i + a_{93}^{(i)}\delta\beta_i + \ldots + b_{94}^{(i)}\delta u_{iT} = a_{91}^{(i)}\delta V_i = \delta V_{i0}\Psi_{i0};$$

Where: V – module of air velocity; α – angle of attack; β – sideslip angle; $a_{ml}^{(i)}$ – linearized coefficients for aerodynamic forces, moments, thrust and gravity forces in trajectory coordinate system; θ – tilt angle of trajectory; Ψ – flight path angle; ω_{ij} – the angular velocities of rotation around the fixed body axis; γ, ϑ, ψ – roll, pitch, yaw angle; X_g, Y_g, Z_g – aircraft coordinates relative to normal coordinate system X_0, Y_0, Z_0; $H = -Z_g$ – altitude.

8. Method of recognition of small mobile air navigation objects

Preliminary analysis revealed that SIFT (Fazli S., Pour H.M., Bouzari H., 2009) algorithm is a potentially useful algorithm for our task. The specified descriptor is different both in terms of stability and information capacity. It is important that the characteristics of the descriptors change when the type of region is changed.

The SIFT algorithm is an algorithm of image matching that is completely invariant to affine

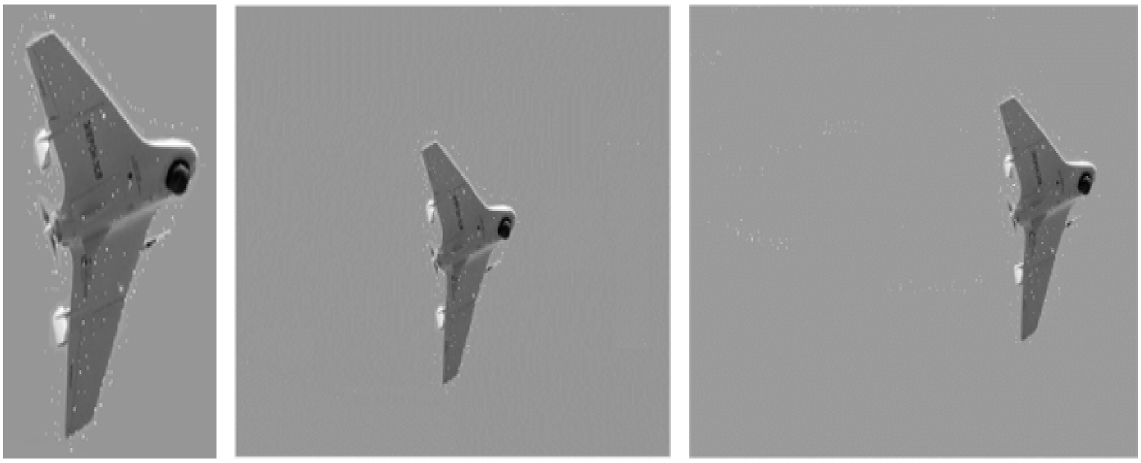

Figure 9. Descriptor model of SIFT algorithm

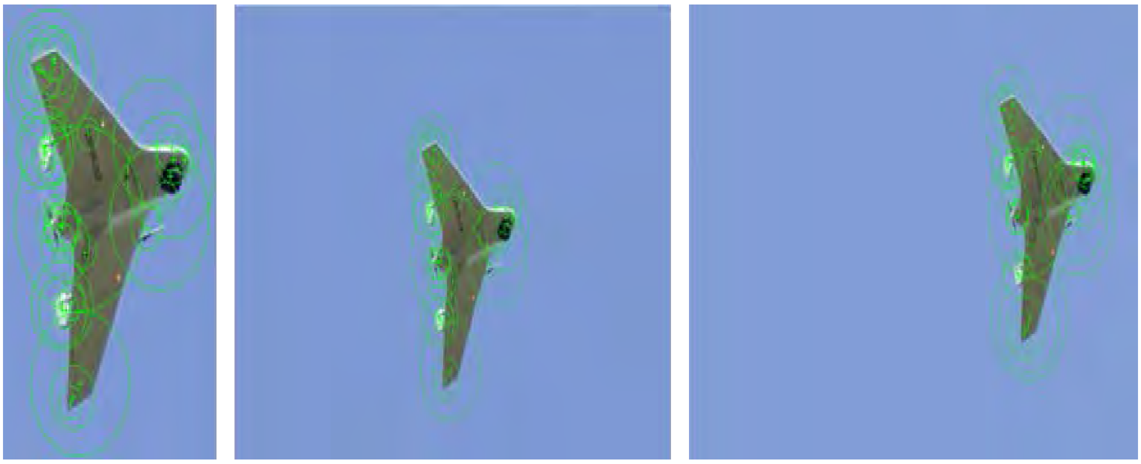

Figure 10. Descriptor model of SURF algorithm

transformations and must cover all six affine parameters. The SIFT method covers 6 parameters by normalizing rotations and displacements and modeling all scales from the current frame and complex descriptor in memory. For solving our tasks, we are interested in small-sized fast-moving objects, such as UAVs.

For testing SURF algorithm for mobile aerial moving objects we build descriptor model (Fig. 9) and compare it with the descriptor model of SURF algorithm (Fig. 10).

For the detection of the UAVs geometric center on the video frame we combined two methods, SIFT and SURF. After the addition of two algorithms we build a complex descriptor of UAVs object. The coordinates of the geometric center of the object in the frame can be calculated in accordance with the position of identified by the integrated UAVs model. This approach will provide trimming of uninformative zones by SIFT method and found false points by SURF method. Searching the geometric center of the UAVs model descriptor in the frame reduced to a simple approach: the arithmetic average of the specific points in the descriptor or using the moving average value approach. These significantly reduce the volume of calculations, which is important when we operate in real time.

For simplifying of computation we divided the frame into four segments (Fig. 11).

Describe a simple algorithm of guiding or targeting of the UAVs in formation flying. Assume the existence of the control tilts of the UAV frame than can be described in the form of control equations for azimuth and inclination angles:

$$\Psi_{az} = W_{\Psi_{az}}^{\delta_{rc}} \delta_{rc}, \Psi_{az} = W_{\theta_V}^{\delta_{ec}} \delta_{ec};$$

where δ_{rc}, δ_{ec} – commanded deflections of UAVs control surfaces, $W_{\Psi_{az}}^{\delta_{rc}}, W_{\theta_V}^{\delta_{ec}}$ – transfer functions of UAV.

The equation of optical axis is:

$$l = \frac{1}{\sqrt{P_{Ex}^2 + P_{Ey}^2 + f^2}} \begin{bmatrix} P_{E_x} & P_{E_y} & f \end{bmatrix}^T.$$

P_{E_x}, P_{E_y} – the coordinates of the geometric center of the UAV in the frame relative to the image center. Required position of axis $l_r = R_b^{gT} l$.

Next step is obtaining of required angles of azimuth and elevation to align optical axes.

$$l_r = \begin{bmatrix} l_{xr} \\ l_{yr} \\ l_{zr} \end{bmatrix} = R_b^{gT} \begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix};$$

$$l_r = \begin{bmatrix} l_{xr} \\ l_{yr} \\ l_{zr} \end{bmatrix} = \begin{bmatrix} \cos\theta_V \cos\Psi_{az} & \sin\theta_V \cos\Psi_{az} & -\sin\Psi_{az} \\ -\sin\theta_V & \cos\theta_V & 0 \\ \sin\Psi_{az} \cos\theta_V & \sin\theta_V \sin\Psi_{az} & \cos\Psi_{az} \end{bmatrix}^T \begin{bmatrix} l_x \\ l_y \\ l_z \end{bmatrix}.$$

To solve this equation of relative azimuth and elevation angles give as the following expressions for command angles:

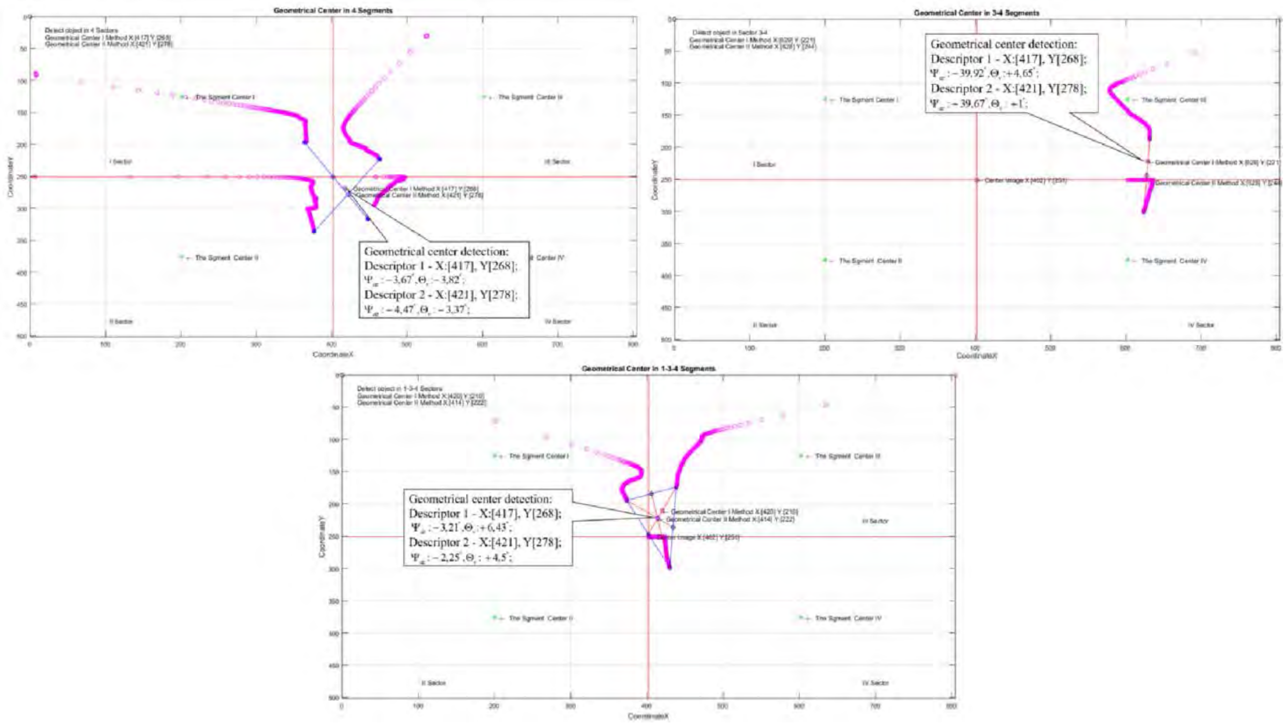

Figure 11. Position the geometric center of the frame of leading UAV

$$\theta_V c = \tan^{-1}\left(\frac{l_y}{l_x}\right), \Psi_{az} = \sin^{-1}\left(-l_z\right). \quad (5)$$

So the servo commands are:

$$\delta_e = K_e\left(\theta_V c - \theta_V\right) = K_e\left[\tan^{-1}\left(\frac{l_y}{l_x}\right) - \theta_V\right];$$

$$\delta_r = K_r\left(\Psi_{az} c - \Psi_{az}\right) = K_r\left[\sin^{-1}\left(-l_z\right) - \Psi_{az}\right]. \quad (6)$$

According to the results obtained by determination of the object geometrical center, have the information about the focal length and the exact coordinates of the object in the frame where P_{E_x}, P_{E_y} using them in (1) and generate the control signals (5).

9. Modeling the system of autonomous UAV flight control group

For the modeling of the proposed control system was selected ZAGI UAV, geometrical and a complete list of aerodynamic characteristics of this UAV was used from [12]. For the system shown in the previous figure, add the blocks with mathematic model of nonlinear behavior of UAV, (including the aerodynamic loads) instead of the "UAV" block. This module is based on a system of equations – mathematical model of UAV.

Also for the unification of the proposed control system would be necessary add to the system structure module with parameter identification of controlled object, for identification of aerodynamic derivatives, as individual parameters of each aircraft.

As the background for the creation working algorithms of guidance system are used equations (5) and (6) that describe the distance, angles of inclination and azimuth path to the leading UAV. The automatic control system (autopilot) includes control algorithms for fulfillment of flight mission (speed, altitude, direction of flight), and additional control commands concerning for creation the flight order of UAV formation.

Simulation of the proposed algorithm and the corresponding developed systems for providing UAV flight control group was conducted in MATLAB Simulink environment. As noted previously for simulation model of control system example with two flying UAVs with flying order – line along the direction of flight of a leading UAV was described. The flight carried out horizontally at a given altitude. The procedure for the flight in the group is based on the equations (3), (4).

For the simulation of the guidance system and the formation of the next commands to control the flight of the UAV has been used a model of such system. The simulation was carried with a changing of the parameters of horizontal flight of leading UAV. Horizontal vertical displacement of the leading UAV and the corresponding change in the distance between a pair of UAV took place on the second and fourth seconds of the simulation. These signals with a distance of one hundred meters correspond to the horizontal and vertical displacement of the leading UAV 2 and 1 meter respectively.

The following figure 12 presents command outputs of "guidance systems" that characterize the vertical and horizontal displacement of the leading UAV.

The response of driven UAV in the case of maintaining the flight order in the UAVs group are shown in (Fig. 12.)

As seen from (Fig. 13) the simulation results the system practically have no errors in the output parameters of the flight, as well as provided with a minimum overshoot and oscillation.

Conclusions. In this paper, an opportunity implementation of multiple UAVs control has been provided, especially for control of UAVs formation flying, using the leader following approach. Based on this obtained algorithms most appropriative methods of virtual leader behavior method will be researched and developed.

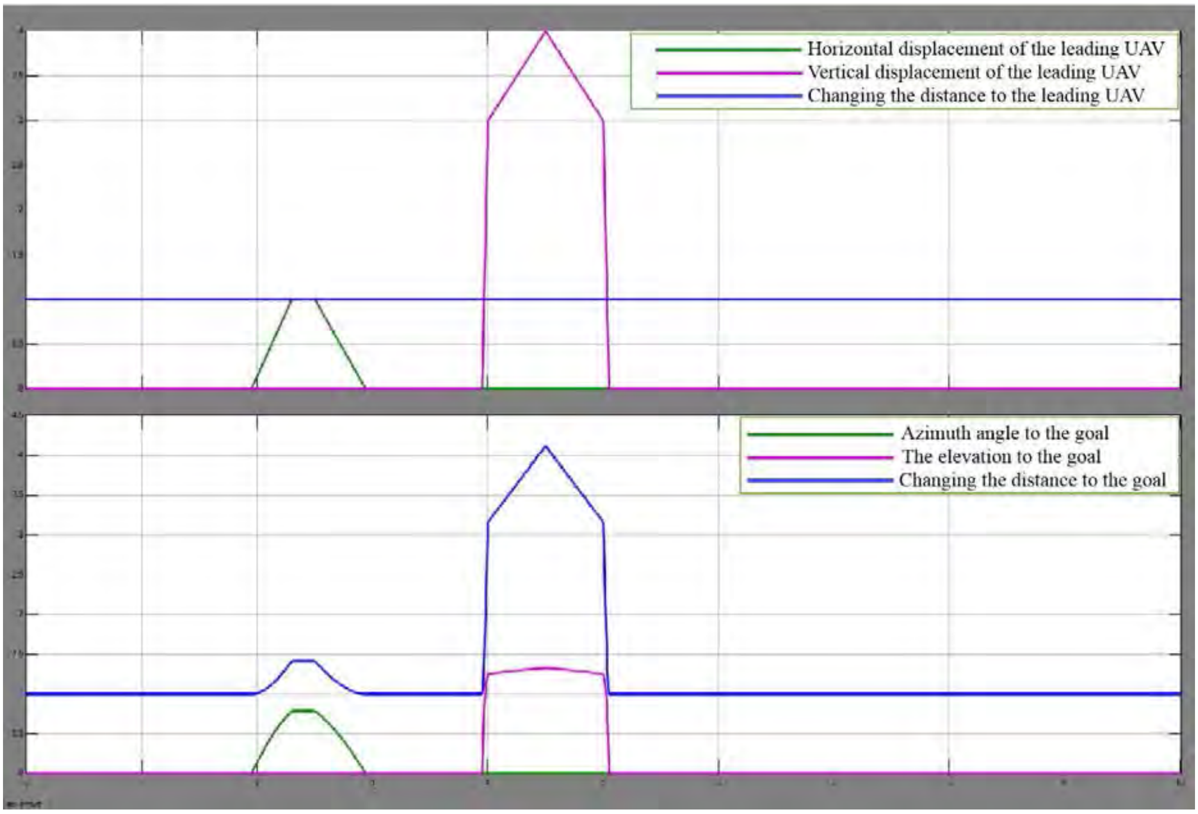

Figure 12. Command output of "guidance system"

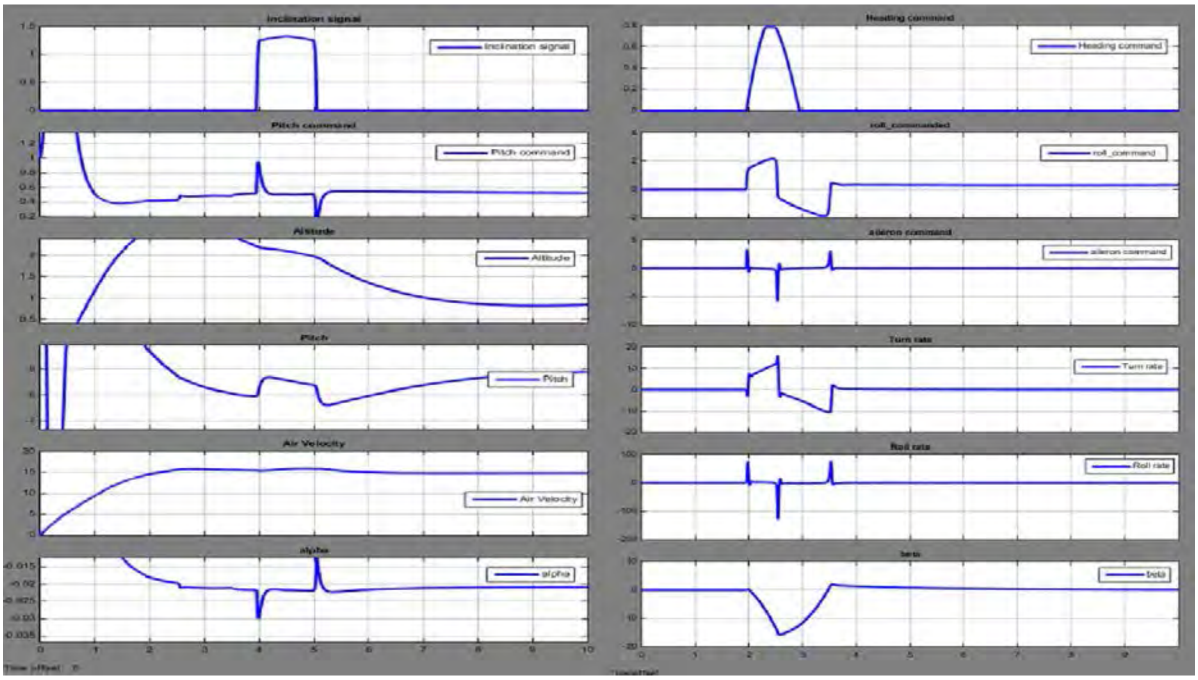

Figure 13. Reaction of the driven UAV as a response to changing of the flight parameters of the leading UAV

For the creation neighbor-to-neighbor communication and synchronization such algorithm with using of electro optical or infrared cameras and pattern recognition approaches has been proposed and realized. Also, their approach for implementation of such control system are given, as well as algorithms and principles of works, based on appropriate mathematical models.

We developed a "guidance system" for an autonomous navigation system of the grouped coordinated flight of UAVs by using recognition methods of mobile and stationary air and land navigation objects.

On the basis of the obtained results by finding the coordinates of the geometric center and the mathematical model of the camera we formed mathematical model of the control signals for UAVs "guidance system".

Acknowledgments. This work was supported by Grant-in-Aid for Scientific Research (C) no. 0115U002524, UA.

References:

1. Chao Xu, Zeping Lu, Guangquan Xu, Zhiyong Feng, Hongyan Tan, Haifeng Zhang, (2015). 3D Reconstruction of Tree-Crown Based on the UAV Aerial Images. Mathematical Problems in Engineering, Volume 2015, 8 pages.
2. Matthew B. Rhudy, Yu Gu, Haiyang Chao and Jason N. Gross, (2015). Unmanned Aerial Vehicle Navigation Using Wide-Field Optical Flow and Inertial Sensors. Journal of Robotics, Volume 2015, Article ID 251379, 12 pages.
3. Luiz G.B. Mirisola and Jorge Dias, (2009). Exploiting Attitude Sensing in Vision-Based Navigation for an Airship. Journal of Robotics, Volume 2009, 16 pages.
4. Bay H., Ess A., Tuytelaars T., Gool L.V., (2009). Speeded-Up Robust Features. Proceedings of the 9th European Conference on Computer Vision. Springer LNCS. Vol. 3951. Pt. 1, p. 404–417.
5. Fazli S., Pour H.M., Bouzari H., (2009). Particle Filter Based Object Tracking with Sift and Color Feature. Second International Conference on Machine Vision, p. 89–93.
6. J. Shin and H.J. Kim, (2009). Nonlinear model predictive formation flight. IEEE Transactions on Systems, Man, and Cybernetics – Part A: Systems and Humans, vol. 39, no. 5, p. 1116–1125.
7. T. Soleymani, F. Saghafi, (2010). Behavior-Based Acceleration Commanded Formation Flight Control. International Conference on Control, Automation and Systems 2010 Oct. 27-30, in KINTEX, Gyeonggi-do, Korea.
8. A.K. Das, R. Fierro, V. Kumar, J.P. Ostrowski, J. Spletzer and C.J. Taylor, (2002). A Vision-Based Formation Control Framework. IEEE Transaction on Robotics and Automation, Vol. 18, No. 5.
9. J. Hammer, G. Piper, O. Thorp and J. Watkins, (2004). Investigating Virtual Structure Based Control Strategies for Spacecraft Formation Maneuvers. AIAA Guidance, Navigation, and Control Conference and Exhibit, Providence, Rhode Island.
10. Z. Gosiewski, L. Ambroziak, (2013). UAV Autonomous Formation Flight Experiment with Virtual Leader Control Structure. Solid State Phenomena, Vol. 198, p. 254–259.
11. T. Paul, T.R. Krogstad and J.T. Gravdahl, (2008). Modelling of UAV Formation Flight Using 3D Potential Field. Simulation Modelling Practice and Theory, vol. 16, no. 9, p. 1453–1462.
12. Randal W. Beard, Timothy W. McLain, (2012). Small Unmanned Aircraft: Theory and Practice. by Princeton University Press.

Мариношенко О.П., Пікенін О.О.
Київський політехнічний інститут імені Ігоря Сікорського

РОЗРОБКА АВТОНОМНОЇ НАВІГАЦІЙНОЇ СИСТЕМИ ДЛЯ ГРУПОВОГО СКООРДИНОВАНОГО ПОЛЬОТУ

Анотація
У статті розглядається опис розробленої системи управління групою безпілотних літальних апаратів (БПЛА), яка має програмне забезпечення, здатне продовжувати політ в разі збоїв використовуючи альтернативні алгоритми управління. Система управління розроблена на основі системи технічного зору з використанням методів розпізнавання зображень. Груповий скоординований політ БПЛА може значно поліпшити роботу процесів спостереження, таких як розвідка, розпізнавання зображень, аерофотозйомка, промисловий і екологічний моніторинг і т. д. Але контролювати групу БПЛА – досить складне завдання. У цій статті ми пропонуємо модель, яка відповідає принципу побудови групи провідними БПЛА. У разі використання цієї моделі параметри руху системи визначаються напрямком руху, швидкістю і прискоренням руху БПЛА. Система управління, заснована на методах розпізнавання зображень, розширює можливості координації групи БПЛА.
Ключові слова: розпізнавання образів, безпілотне повітряне судно, особливі точки, дескриптори, система технічного зору.

Мариношенко А.П., Пикенин А.А.
Киевский политехнический институт имени Игоря Сикорского

РАЗРАБОТКА АВТОНОМНОЙ НАВИГАЦИОННОЙ СИСТЕМЫ ДЛЯ СГРУППИРОВАННОГО СКООРДИНИРОВАННОГО ПОЛЕТА БПЛА

Аннотация
В статье рассматривается описание разработанной системы управления группой беспилотных летательных аппаратов (БПЛА), которая имеет программное обеспечение, способное продолжать полет в случае сбоев используя альтернативные алгоритмы управления. Система управления разработана на основе системы технического зрения с использованием методов распознавания изображений. Групповой скоординированный полет БПЛА может значительно улучшить работу процессов наблюдения, таких как разведка, распознавание изображений, аэрофотосъемка, промышленный и экологический мониторинг и т. д. Но контролировать группу БПЛА – довольно сложная задача. В этой статье мы предлагаем модель, которая соответствует принципу построения группы ведущими БПЛА. В случае использования этой модели параметры движения системы определяются направлением движения, скоростью и ускорением движения БПЛА. Система управления, основанная на методах распознавания изображений, расширяет возможности координации группы БПЛА.
Ключевые слова: распознавания образов, беспилотный летательный аппарат, особые точки, дескрипторы, система технического зрения.