Monitoring of a Critical Infrastructure Facility by UAVs

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Abstract

In this paper, we considered monitoring high-voltage power lines by Unmanned Aerial Vehicles (UAVs). This task has presented a set of subtasks, such as group flight control, including group formation and maintaining its structure, as well as ensuring stable and controllable flight. It is believed that a group consists of a small number of UAVs, the total number of which does not exceed 5. A feature of group control is a virtual leader presence who is always present in the group and controls the flight. This feature ensures a clear advantage over a leader-follower group, in which action is coordinated by a leader, and in case of the leader's absence, the group can lose control. The feedback on the measured coordinates of the control object is sufficient to ensure a stable flight of the group. The control signal introduced additional components by the principle of attraction/repulsion to maintain the group structure and avoid collisions. Break detection of the power line uses the built-in video recorder and Bayesian detector, which provides a minimum risk of erroneous decisions. The precision positioning devices built into the UAV are used to fix the coordinates of broken wires. Simulations and calculations confirmed these solutions.

Keywords

UAV, monitoring, control, high-voltage power line

1. Introduction

The critical infrastructure objects are banks, transport, and the power industry. Due to the great importance of the latter objects, need to pay serious attention to their condition. A possible solution could be monitoring the high-voltage power line's condition using UAVs.

To control the integrity of high-voltage power lines, the UAV must have navigation, radio communication equipment, and video cameras. The flight of the UAV is carried out at a height sufficient to be monitored by video cameras. A small group of UAVs consisting of 3-5 aircraft is used to increase the control efficiency, the route of which runs along the investigated power line. The group visually searches for power line breaks and damage to transformer substations and records their coordinates.

When moving along the route, the UAV group must be able to perform simple maneuvers such as take-off, landing, straight-line flight along the power transmission line, barrage at the place of damage, and return to the starting point.

A group flight can be with a leader, without a leader, and with a virtual leader. The main problems of a group flight organizing with a leader are ensuring the leader's availability to the team members, maintaining communication, and solving flight problems such as overcoming obstacles [1; 2]. The leader is a technically complex element of the group that affects the effectiveness of the UAV group's monitoring task.

But the leader is the weak link in the group management, and his failure makes it impossible to perform the flight task. To overcome this problem, a new leader must be chosen and management must be handed over to them. Operating without a leader involves the spatial and temporal separation of group members to organize the flight, prevent collisions, and ensure the safety of all group members.

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The advantages of such an organization are the independent performance of the assigned task by each group member, the failure of one device does not affect the final task result, and it performed by at least one device is considered completed. Problems related to the need for careful planning of the route and ensuring complete control over the actions of the group members need to be solved, especially in the case of lack of interaction at critical moments of the monitoring target task and uncoordinated activities of the group members.

In contrast to the ones considered, a group with a virtual leader can solve the task when one of the group members fails and can interact with each other to effectively solve the problem when one of the group members is lost, without losing the virtual leader. So, a group with a virtual leader compensates for the disadvantages that occur with and without a leader. As a disadvantage of such an organization, it should be noted the need to maintain some structure with the leader, according to which the coordinates of each group member are calculated. A virtual leader can also be in a group without a leader if necessary, for example, for the overcoming obstacles task. The virtual leader can be both the flight target and the group center. When performing time-consuming tasks, an organization with a virtual leader is better.

The main goal of this paper is to develop UAV control algorithms that ensure the necessary quality of video camera monitoring and control.

The paper studies the problem of monitoring high-voltage power lines by a small group of UAVs. This study consists of solutions such tasks: motion along the route; support of the group structure in maneuvers or reconfiguration when overcoming obstacles; determination of damage on the line, and fixation damage coordinates.

2. Paper review and discussion

The authors of [1] proposed a cooperative control algorithm based on a decentralized algorithm for controlling a group of quadrotors that jointly carry a general payload. The chosen control strategy consists of two stages: the first is the calculation of the control vectors of each quadrotor by pseudo-rotation of the matrix of control moments, and the second is the combination of the obtained vectors with individual control vectors created by a second-order nonlinear robust controller. The Kalman-Bucy filter evaluates unmeasured states.

The paper [2] presents three control strategies based on a behavioral approach to the group formation of wheeled mobile robots. The first control strategy used information relative location and speed of two neighboring robots. The second strategy eliminates the knowledge of the neighboring machines' speed and assumes compensation for the motion oscillation by introducing damping between robots according to LaSalle's invariance principle. The third strategy takes into account drive saturation. The last one showed faster performance when moving to a new formation. The best accuracy has the first strategy.

In [3], the authors present an overview of several deep learning and reinforcement learning methods for controlling strap-down aircraft systems. They also discuss the use of computer vision information for reinforcement learning to enable autonomous control and navigation of these systems.

The study of two types of controllers for stabilization, path tracking, and the team formation of quadrotors according to the leader-follower principle is presented in [4]. The path-tracking task and forming the leader-follower team have been implemented using the Integral Back-stepping control algorithm. In this case, two control loops are implemented: the inner loop provides the quadrotor position stabilization by the PD^2 controller, and the outer one assigns position control.

In [5], the experimental results of controlling a team of 20 micro-quadrotors with onboard orientation and control, each of which works autonomously with an external system for tracking and measuring the coordinates of the quadrotor, are presented. The architecture and algorithms for coordinating a team of quadrotors, organizing them into groups, and flying are based on the mixed-integer quadratic programming method.

In [6], three flock algorithms are presented such that algorithm two differs from algorithm one by the presence of only a navigation unit; and algorithm three by a control component under obstacles. Also introduced are potential penalty functions for the herd structure disruption if detection deviation from the lattice structure. The proposed functions provide for the execution of separation/reunification maneuvers and compression maneuvers for a large group of agents.

In [7], a scheme of a control system based on quaternions for exponential stabilization of the orientation of a quadrotor was proposed. In the controller under study, feedback and a PD2 controller that implements two derivatives for the angular velocity and the velocity of the quaternion vector compensate the Coriolis and gyroscopic moments. Despite the satisfactory results of the experiments, the sensitivity of the resulting regulator to high-frequency noise should be noted.

In [8], the control of the coordinated movement of non-holonomic mobile-wheeled vehicles connected to a network is proposed, which ensures the construction and preservation of the desired formation. The control law includes the control of both the virtual and the individual vehicles following the virtual vehicle moving along a predetermined trajectory. The management system has limited capabilities in terms of the number of managed funds.

Group control of several quadcopters in real time, which ensures safe interaction, is the paper subject [9]. The authors implemented control laws based on the consensus theory introduced by Olfaty-Saber in [6].

In [10] is proposed to use the sliding mode as an anti-perturbing control of the quadrocopter's rotational and translational subsystems. Unfortunately, the authors do not consider the issues of oscillations near the target area, which is a direct consequence of the sliding mode.

In [11], a control scheme for several UAVs has been studied, where the control is found by solving the $H\infty$ optimization problem with constraints such as the Hamilton-Jacobi inequality. The computational complexity of solving this optimization problem is overcome by using the Takagi-Sugeno fuzzy methods. In this case, the original constrained optimization problem is transformed into a constrained optimization problem in the linear matrix inequality (LMI) form and then solved by convex optimization methods.

The flight of a quadrotor in the rhythm of music is presented in [12]. The base controllers implement UAV swinging in motion and vehicle stabilization. Synchronization with music is achieved by introducing phase-locked loops, in which the correction algorithm eliminates the phase error between the music rhythm and the oscillatory movement of the quadrotor.

Problems of bipartite consensus for a multi-agent system with linear agents represented by a directed graph are studied in [13]. The authors found that two-way agreement must have a balanced graph shape and information about consensus errors.

System optimization with distributed resources using a game approach is considered in [14]. This study has proposed a system performance criterion based on its potential function, based on the corresponding cost functions of objects, which achieves global optimization.

The advantages of new technologies for vehicles in the aviation and automotive fields based on the joint control of both human operators and automation systems are discussed in [15].

Collective control of a group of mobile robots implemented on an onboard computer is considered in [16]. The study proposes a leader-follower strategy to limit the data bandwidth between each robot of the group by software implementation.

In [17], the leader-follower strategy is also used for wheeled robots following the route.

A rotary mechanism consisting of serial and parallel connections driven by servomotors as a multi-agent system is proposed in [18]. The authors have improved the particle swarm optimization algorithm used to tune the optimal parameters of the system under consideration.

A distributed protocol for the joint control of a UAV swarm, which, when the swarm configuration deviates from a fixed topology, forces the aircraft to save the structure to ensure consensus is presented in [19].

A reconfigurable wireless control system for a mechanical two-handed cooperative robotic system is presented in [20].

Some strategy of the joint control the floating means based on an intelligent approach was assigned for a towed load and developed in [21].

An integral model of the position and orientation of a spacecraft based on quaternions and the theory of systems with a variable structure, which provides a sliding mode when moving to the endpoint, was developed in [22].

An overview of some solutions for joint control of fixed-time multi-agent systems is presented in [23]. The authors also propose a classification of such systems depending on the dynamics of agents.

3. Problem statement

Ensuring the ability to perform safe, coordinated, and effectively integrated UAV flights in a single aviation transport system is the main problem of unmanned aviation. To perform UAV flights remotely piloted aviation system (RPAS) is used, which includes a UAV, a remote piloting station, and command and control lines (C2) to implement high reliability, and low delay in UAV flight and other components depending on the mission (*target task*) performed by the UAV / group of UAVs.

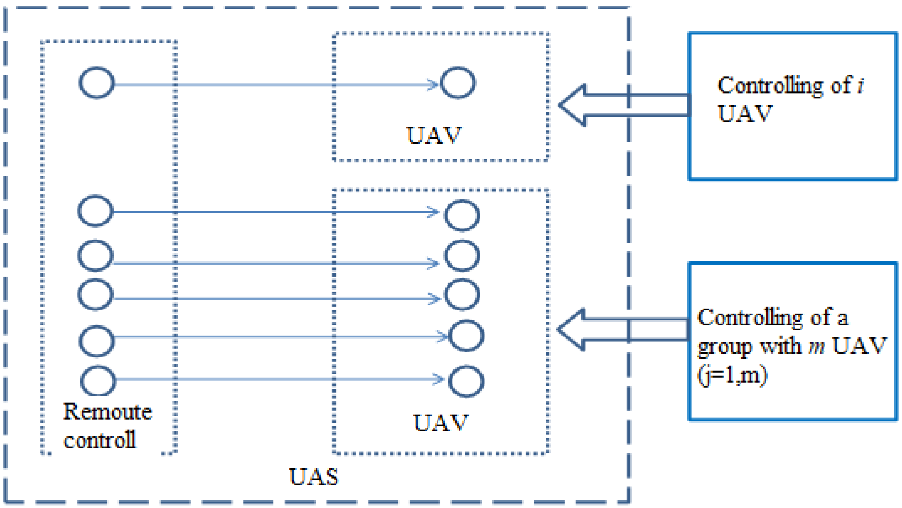

Figure 1: Single or a group UAVs control system

There are different systems of UAV control, including degrees of UAV autonomy flights and schemes to control UAV flights [24; 25]. There are the following degrees of UAV autonomy flights:

- under remote control by an operator of a UAV (remote pilot);
- under autonomously controlling using onboard computers/programming before flight;
- under autonomously controlling by UAVs onboard robots/decision-making systems.

Types of UAV flights, UAV control, and schemes to control UAVs flight:

1. the operator of UAV (remote pilot) - single UAV;
2. the group of operators – a group of UAVs;
3. the operator – UAV leader / CDR (Central Drone Repeater) – a group of UAVs;
4. the operator – virtual leader / VCDR (virtual central drone repeater) – a group of UAVs;
5. autonomous single UAV flight;
6. autonomous group UAVs flight.

A group UAV flight can be considered with a leader (UAV), without a leader, and with a virtual leader (Figure 2).

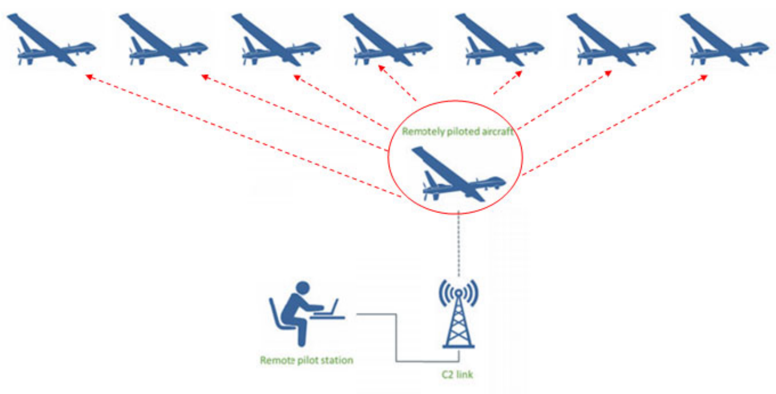

Figure 2: UAV group control system from CDR-UAV

As a general principle and requires, only one RPAS should be in control of the RPA at a given moment in time [25]. An RPA (UAV) group may be piloted during a flight or organized as an intellectual net.

The UAV group is a limited composition, consisting of 3-5 vehicles with a virtual leader. The group's movement along the route when performing the task is carried out relative to the leader, which saves computing resources for laying the route for each device. If necessary, the group's size can be increased by splitting a large group into a subgroup of the accepted size, managing only virtual leaders. However, this issue is not considered here.

Each device is equipped with means of measuring range and communication, ensuring the maintenance of a given structure and radio contact with a pair of neighboring devices and a virtual leader. The undirected graph is a structure of a type of virtual leader-follower system.

A model of a 4-engine aircraft called a quadrotor, is considered as the basis. Characteristic features of devices of this type are maneuverability and the possibility of hovering. An increase in the number of rotors affects the reliability of control and is currently considered redundant.

The mathematical model of a quadrotor is represented by a system of second-order differential equations describing the position of an individual vehicle in 3-dimensional space in the Cartesian and Euler coordinate systems in the form

$$\begin{cases} \ddot{V} = f(\dot{x}, \dot{y}, \dot{z}), \\ \ddot{\Omega} = f(\dot{\theta}, \dot{\varphi}, \dot{\psi}). \end{cases} \tag{1}$$

In this case, restrictions $|\theta|<\pi/2$, $|\varphi|<\pi/2$, $|\psi|\leq\pi$, $z>0$ are imposed on the angular and spatial coordinates.

The group occupies space in a sphere of bounded radius r, i.e.

$$D = \{| p_i - p_j | \leq r,\ \ r > 0\},\ \ i \neq j,\ \ i, j = 1,..., N, \tag{2}$$

where r is the maximum size of the formation, and N is the number of devices in the group.

The group performs the task of monitoring a high-voltage power line. The team has video cameras of the appropriate resolution to accomplish this task. When performing this task, the group must be able to move evenly and rectilinearly along the route, perform a height maneuver, and be able to turn around.

The presented task is complex and involves the solution of some subtasks:

1. Movement along the route with the ability to perform the indicated maneuvers.
2. Detection of power line breaks.
3. Fixing the coordinates of the breakpoint.

To assess the performance of these subtasks, the following quality criteria: $J1$ is the criterion for the accuracy of movement along the route has been entered. It can write in the form

$$J_1 = \int_0^T \varepsilon^2(t)dt \leq \in,\ \ \in > 0\ , \tag{3}$$

where $\varepsilon(t)$ is the deviation of the virtual leader from a route, T is the route duration in time, $T \leq T_{max}$, $\in$ is some positive value.

J_2 is the quality criterion for detecting a power line break, determined by the probability of detecting a $P_{det\mathrm{PL}}$ power line against the background of objects on the earth's surface. A break is detected if the power line tracking is lost, i.e. $P_{det\mathrm{PL}} < P_1$, where P_1 is the minimum probability of reliable power line tracking, depending on the visibility, meteorological conditions, and time of day.

J_3 is the accuracy of determining the coordinates of the break, associated with the accuracy of determining the coordinates of the virtual leader on the route.

The monitoring task is considered completed if the joint execution of these three subtasks gives a generalized criterion

$$J \geq J_{\min}\ , \tag{4}$$

where J_{min} is the minimum value of this criterion.

4. Problem solution

This section discusses the problem of high-voltage power line monitoring by the UAV group. It includes some algorithms of control, break detection, and fixing its coordinates.

4.1. Group description

The problem of managing a group of 3-5 UAVs, one of which is a virtual leader, is considered. The coordinates of the virtual leader in the case of a group of 3 vehicles with known coordinates of neighbors are determined by the middle of the segment connecting the centers of mass of the vehicles:

$$x_{vl} = \frac{x_{UAV_1} + x_{UAV_2}}{2}, \quad y_{vl} = \frac{y_{UAV_1} + y_{UAV_2}}{2} \tag{5}$$

It is assumed that the coordinates of the leader change according to a linear law and are a task for the rest of the devices of the group. The UAVs move along spaced trajectories relative to the leader, which do not go beyond a sphere of radius r.

If relation (2) is satisfied, then value $i, j = 1, 2$, the group is preserved. In this case, the virtual leader is the center of the proposed sphere, and in the plane X, Y, it is a circle of radius r, Figure 3.

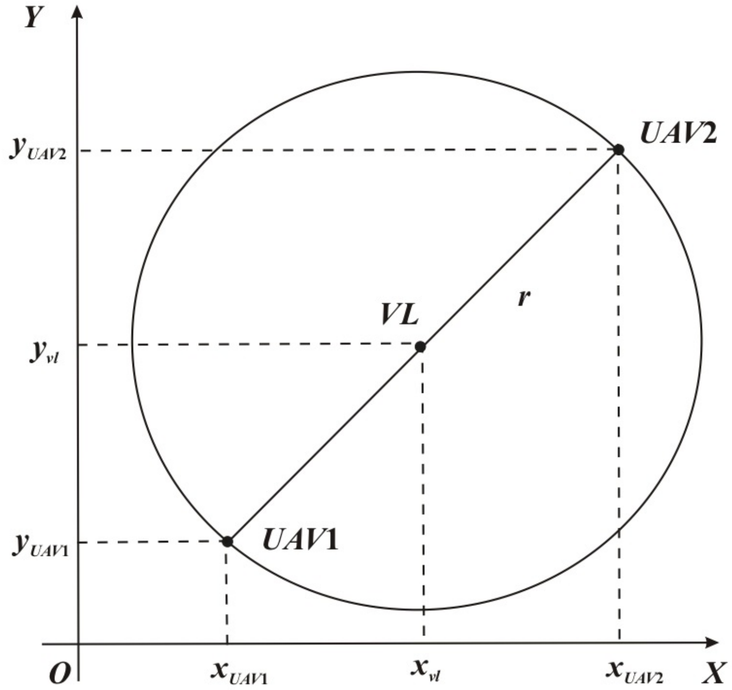

Figure 3: Coordinates of a group of 3 devices, one of them is a virtual leader

In the case of 4 devices, one of which is a virtual leader (Figure 4), the coordinates of the virtual leader are found in the condition

$$x_{vl} = \frac{x_{UAV1} + x_{UAV2}}{2} + l(r - r_1), \quad y_{vl} = \frac{y_{UAV2} + y_{UAV3}}{2} + l(r - r_2) \tag{6}$$

In equation (6), the x_{UAV1}, x_{UAV2}, y_{UAV2}, and y_{UAV3} are the coordinates of the group members forming a triangle with sides a, b, c; r is the radius of the circumscribed circle,

$$r = \frac{p}{4\cos\frac{\alpha}{2}\cos\frac{\beta}{2}\cos\frac{\gamma}{2}}, \quad p = \frac{a+b+c}{2}$$

where angles α, β, γ is the opposite to sides a, b, c; l – some positive coefficient, r_1, r_2 – distances, which are determined by the formulas

$$r_1 = \sqrt{(x_{UAV1} - x_{vl})^2 + (y_{UAV1} - y_{vl})^2},$$

$$r_2 = \sqrt{(x_{UAV3} - x_{vl})^2 + (y_{UAV3} - y_{vl})^2}.$$

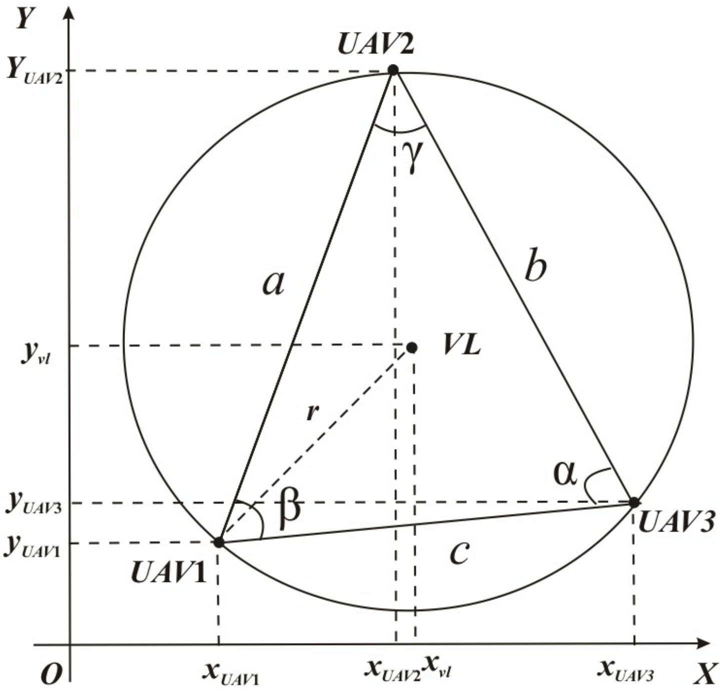

Figure 4: Coordinates of a group of 4 devices, one of them is a virtual leader

In the case of 5 devices, one of which is a virtual leader, the coordinates of the virtual leader are found from a condition similar to (5). If the group has many devices, to reduce the computational costs for control and communication should be divided into cells of 3-5 UAVs, forming a network or a grid of UAVs.

The virtual leader only determines the trajectory for the followers. A route represents a sequence of points for a virtual leader trajectory, and the segment connecting these points is a smooth function.

4.2. Object model

Consider the movement of objects along one of the coordinates, and then the object dynamics, taking into account (1), for example, along the X coordinate, can be represented by the following system of second-order differential equations:

$$\dot{x}_1(t) = x_2(t), \qquad (7)$$
$$\dot{x}_2(t) = u_x(t).$$

In the system of equations, x_1 is the output value, and x_2 is its time derivative t, $t \to T_{max}$; u_x – control on the x coordinate. At the initial moment corresponding to the start, UAV1 has coordinates

$$x'_1(0)=x_{vl}+r,\ x'_2(0)=0, \qquad (8)$$

and UAV2

$$x''_1(0)=x_{vl} - r,\ x''_2(0)=0, \qquad (9)$$

The following lemma is valid for the system of equations (7).

Lemma 1. Control action of the form

$$u_x(t) = -k_1 x_1(t) - k_2 x_2(t) \qquad (10)$$

provides stabilization of the coordinates of objects described by equation (7) with initial conditions (8), (9), if $k_2 \geq 2k_1$.

Proof. The characteristic equation for system (7) has the form:

$$p^2 + k_2 p + k_1 = 0 \qquad (11)$$

whose roots

$$p_{1,2} = \frac{-k_2 \pm \sqrt{k_2^2 - 4k_1}}{2}.$$

For the case $k_2 \geq 2k_1$, the roots are negative real different or multiple, which corresponds to a stable system according to Lyapunov, and control (10) is stabilizing and independent of the initial conditions (8), (10).

4.3. Maintaining group structure

Safe distances must be supported between group members (agents) to avoid collisions, maintain group integrity and ensure communication. It is assumed that the cell structure is not rigid, but certain geometric relationships must be provided.

The cell structure can be provided in various ways, namely by measuring and maintaining an approximately equal distance between agents, or by introducing additional forces of attraction/repulsion into the agent control law. In the latter case, the control law will be represented by the sum [30, 31]

$$u_i = u_x + u_{att} + u_{rep} \quad (12)$$

where u_x is the control by (10), u_{att} is the control action created by the forces of attraction within the group, and u_{rep} is the control action created by the repulsive forces between the agents of the group.

The control action created by the forces of attraction has the form:

$$u_{att}(\Delta x) = -grad \quad E_{att}(\Delta x), \quad (13)$$

where

$$E_{att}(\Delta x) = \frac{1}{2}\mu(\Delta x)^2. \quad (14)$$

In (14) μ is a positive coefficient, and Δx is the distance between vehicles.

The control action created by the repulsive forces has the form:

$$u_{rep}(\Delta x_i) = -grad \, E_{rep}(\Delta x_i). \quad (15)$$

where

$$E_{rep}(\Delta x_i) = \begin{cases} \frac{1}{2}\nu\left(\frac{1}{\Delta x_i} - \frac{1}{d_0}\right)^2, & if \ \Delta x_i \leq d_0, \\ 0, \ if \ \Delta x_i > d_0. \end{cases} \quad (16)$$

In expression (16) v is a positive coefficient, and d_0 is the minimum allowable distance between agents.

Lemma 2. Control action (12) is asymptotically stable.

Proof. Since the components u_{att}, and u_{rep} do not change the connection type, the proof corresponds to Lemma 1 and is omitted here.

4.4. Simulation

The control law (12) for objects (7) with initial conditions (8), (9), which work out the maneuver along the X coordinate has been studied. It is assumed that there is a pair of agents with the same parameters has been studied. The values of the coefficients of the control law are chosen from the condition of ensuring stable motion, namely k_1= 1, k_2 = 2. Initial conditions $x'_1(0)$=3, $x'_2(0)$=0, $x''_1(0)$=–3, $x''_2(0)$=0. Figures 5 and 6 show a variant of maneuver training in the presence and absence of attraction/repulsion forces.

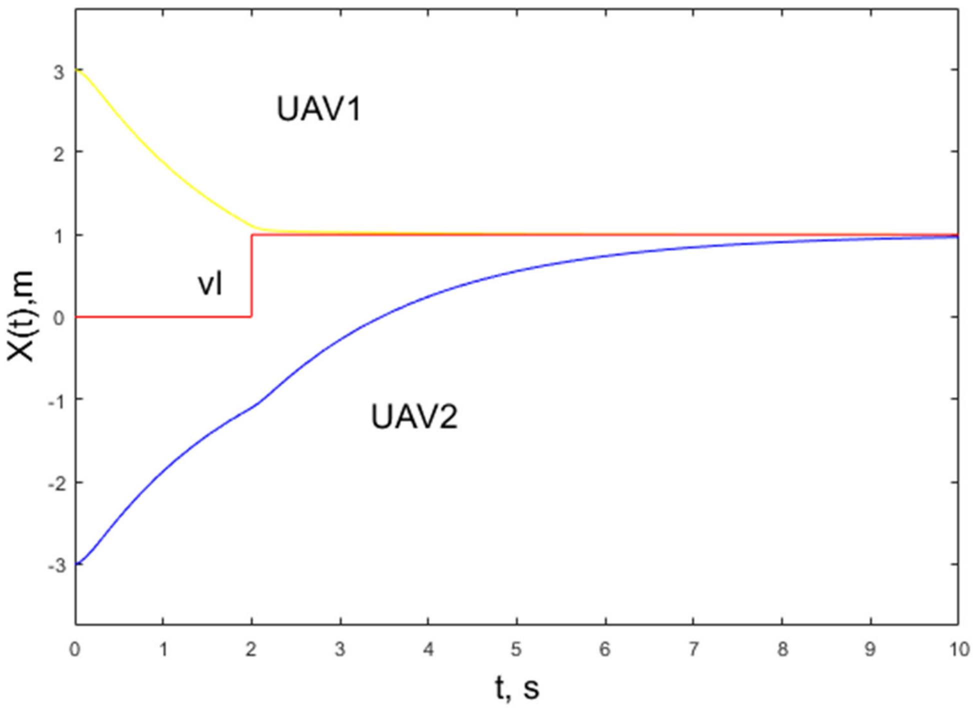

Figure 5: Trajectories of changing the *X* coordinate of a pair of agents in the absence of attractive/repulsive forces

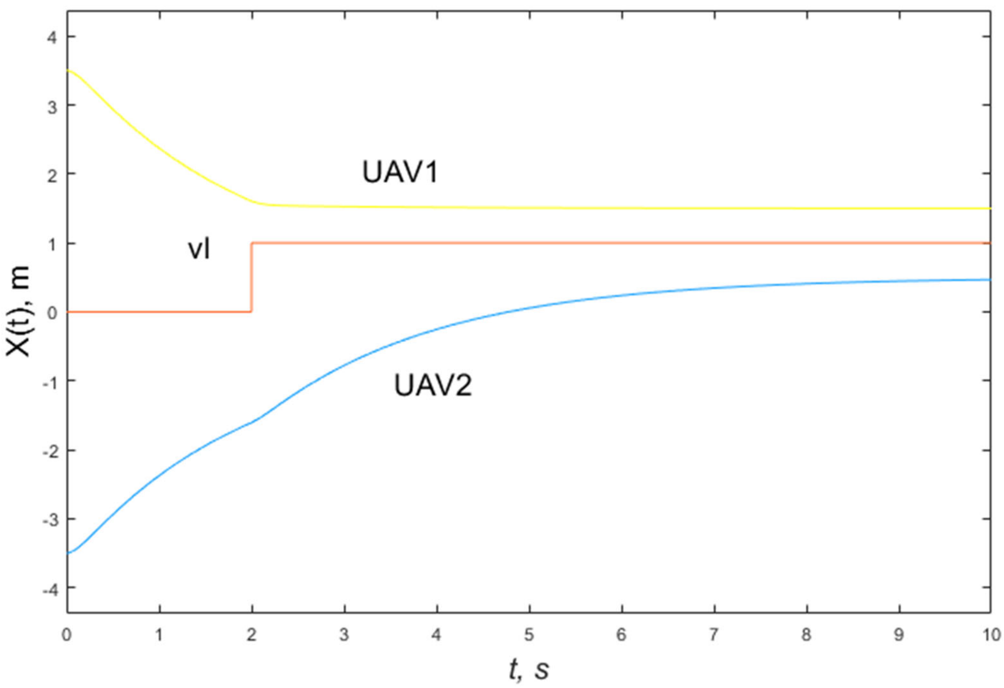

Figure 6: Trajectories of changing the *X* coordinate of a pair of agents under the action of attractive/repulsive forces

4.5. Power line break detection

It is assumed that the UAV has video recording equipment that allows you to record the state of power lines. Two possible situations are considered: there is no break A_0 and there is a break A_1. The situations are not compatible and form a complete group of events, i.e. $P(A_0) + P(A_1) = 1$.

The video signal arrives at the detector, which, based on the results of observations, the state of the power line is in the form of a signal U, Figure 7. Since it is necessary to decide on randomly received signals with a priori unknown probabilistic ones, an assumption is made about the independence of the statistical characteristics of the received signal sample $s(t)$ received against the background noise. The noise signal follows a normal distribution with zero means.

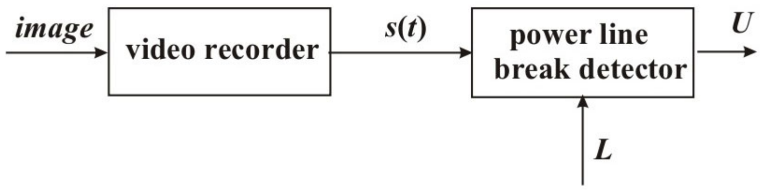

Figure 7: Principle of signal detector

The received signal appears with a certain frequency corresponding to the operation of the DVR. If a break is an absence, the signal has the probability $p(A0)$. Let us also introduce the conditional probability of an erroneous decision $p_{10} = p\ (A_1/A_0)$, i.e. deciding to break, provided that the power line is intact, then the task is to minimize the average risk

$$L = \min_{\substack{i=1,2;\\ j=1,2}} \sum_{i,j} p(A_1)p(A_j / A_i),\ \ i \neq j\ . \tag{17}$$

Deciding by (16) corresponds to the Bayesian detector. Thus, the decision to break the power line corresponds to the case when the frequency of the signal about the presence of the power line becomes less than the threshold value determined by expression (17), i.e.

$$U = \begin{cases} 1, \text{ if } p[s(t)] < L, \\ 0 \text{ if } p[s(t)] \geq L. \end{cases} . \tag{18}$$

Given the values $p(A_0)$, $p(A_1)$, $p(A_0/A_1)$, and $p(A_1/A_0)$, can determine the value of L, for example, if $p(A_0) = 0.7$, $p(A_1) = 0.3$, $p(A_0\ /A_1) = 0.8$, $p(A_1/A_0) = 0.8$, $L = 0.79$, i.e. signal frequency less than 0.79 corresponds to the break condition and the detector makes a decision U=1.

4.6. Power line break coordinates

As a rule, UAVs have a precise positioning sensor. Will assume that the coordinates of the break are associated with the geographic coordinates of the UAV, fixing this break at the time of its detection. In this case, the fixing accuracy of the coordinates of the cliff turns out to be commensurate with the positioning accuracy.

5. Algorithms for determining UAV flight routes with minimal risks and maximum safety in and around urban

There is the modern concept of Urban Air Mobility (UAM) as solutions to urban tasks using UAVs in and around urban areas, including cargo delivery, monitoring the condition of high-voltage power lines, and other services using UAV systems [26; 27]. The main problems in the UAM implementation are the coordination of UAV flights in urban areas and integration in air space, organization, and planning of safe and effective urban UAV flights. The advantages of UAVs group flight are faster coverage of fragments of the urban part and large areas and organization of UAV flights with minimal risk. The organization of a group flight with a leader is needed to ensure the leader's availability to the team members (UAVs), maintain communication, and solve flight problems related, for example, to overcoming obstacles [28; 29].

The authors have developed algorithms for determining UAV flight routes with minimal risks and maximum safety and for determining the optimal configuration of the UAV group with a set of restricted, dangerous areas and tracks of flight.

5.1. Algorithm 1

the determining UAV flight routes with minimal risks and maximum safety in and around urban:

- Determining territory for UAV flights;
- terrain analysis and obstacle evaluation [28];
- obtaining an "Obstacle Map" including the flight risks of UAV;
- GRID analysis of the territory for UAV flights. The network (grid) map creating;
- Risk assessment of GRID cells depends on the type of zone. We apply such designations: Track area means TA, Restricted area means RA, Buffer area means BA, Dangerous area means DA, Forbidden Areas means FBA, Critical objects of infrastructure means COI, Track Conflict Area means TCA, Flight area means FA;
- the UAVs group route with minimum risk at the L1 level we find as shown in Figure 8

$$W_i(y_i) = y_{i-1}(RA;\ BA;\ DA;\ FBA;\ COI;\ TA;TCA;\ FA) + \min\left(y_i(RA;\ BA;\ DA;\ FBA;\ COI;\ TA;TCA;\ FA)\right)$$

Figure 8. Fragment of the territory for estimation of minimal risk of UAVs movement

- Evaluation of the path W1 (level L1) of UAV1 as dangerous.
- Finding the route of the minimum risk for UAV group and flight planning at the L2 level and next levels (Figure 9).

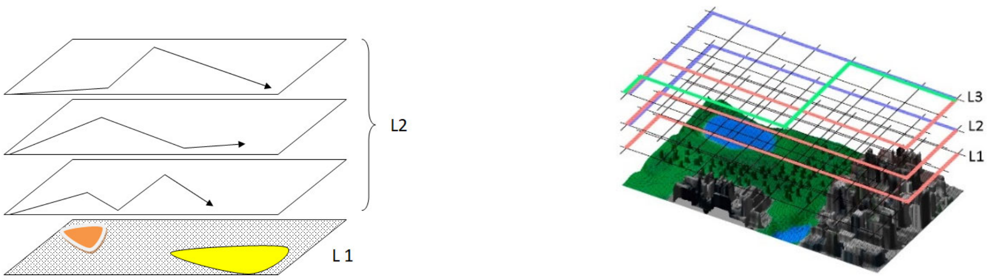

Figure 9. Fragment of the territory for estimation of minimal risk of UAVs movement

UAV emergencies and safety. The procedure for the actions of the UAV operators in an emergency according to the Manual on Flight Operations of the UAV.

5.2. Algorithm 2

UAV group optimal configuration determines, the leader of the group with a set of restricted, dangerous areas and tracks of flight.

1. The estimation effectiveness performance of the target task of using the different systems: the operator of UAV (remote pilot) - single UAV; the group of operators – a group of UAVs; the operator – UAV leader / CDR (central drone repeater) – a group of UAVs; the operator – virtual leader / VCDR (virtual central drone repeater) – a group of UAVs; autonomous single UAV flight; autonomous group UAVs flight.
2. Determination leader of the group. If there is a UAV group with control from the leader, need:

– Decomposition of the complex system on subsystems: “network topologies - the target tasks” subsystem the description of the characteristics, and estimation performance of the target task by network topologies. There are some network topologies, for example, classical topology (fully connected star, circle, tree, with a common bus, bus-star, star-circle, hybrid-pantry, etc.), free topology according to target task, and square of territory for the UAV flight.

– The evaluation of UAV’s group flight according to criteria reliability with structural redundancy; the uneven distribution of connections; structural compactness; relative distance; level of system centralizing; centrality; periphery; survivability and moment of the network.

3. Determination of UAV flight routes with minimal risks and maximum safety. Estimation of UAV flight routes using methods (GRID analyses of sector UAV flight, fuzzy logic, and EJM for estimation risk). The optimal route search with minimum risk to flight at the L1 level, planning the transition to the L2 level, etc.

4. Dynamic configuration of UAV group flight for different terrain relief or changing of obstacle altitude using geometrical modeling and covering as the most suitable configuration of UAV's team (group) for suggest improving the versatility, maintainability, and operational safety of UAVs group via the introduction of a functional framework in the form of a functional-protocol stack, on analogy with Open Systems Interconnection (OSI) model in telecommunications (Figure 9).

5. The geometric modeling method is based on the interpretation of the relative position of the UAVs on the terrain, considering forbidden/restricted zones/altitudes and other factors, such as a Discrete Network Model (DNM) of a connected surface that is built on a given contour, the topological, positional, and metric properties of which are determined by the conditions of the problem and limiting factors [29]. The DNM construction algorithm should satisfy the requirements:

- compliance to the topological, positional, and metric characteristics and formation of a group flight configuration by the target and estimated terrain characteristics;
- calculation of the optimal number of UAVs to perform the target task;
- software communication with the database.

Example of grid analysis. Overlaying a grid on a terrain fragment is presented in Figure 10.

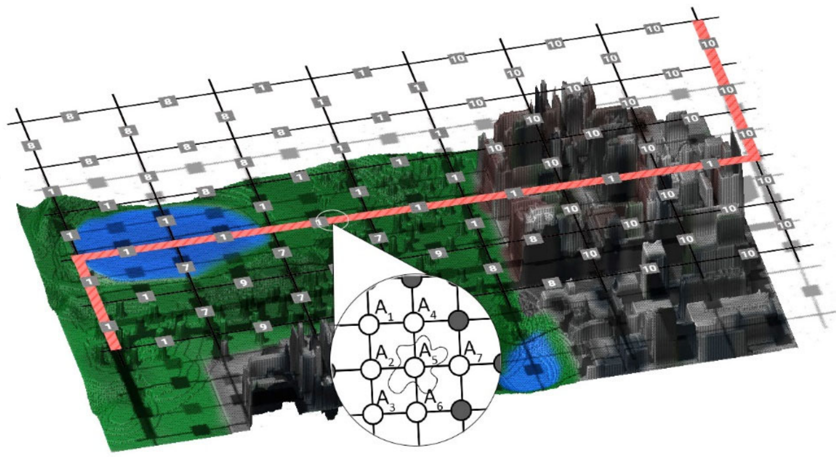

Figure 10. Fragment of the territory with coverage of the UAVs team

The coordinates of the nodes of discrete networks are determined based on the data of the structure of elementary sub-fragments. For a particular node, one can apply the following [6]:

$$\alpha_1(f^i_{j,k}) + \alpha_2(f^i_{j-1,k} + f^i_{j,k-1} + f^i_{j+1,k} + f^i_{j,k+1}) + \alpha_3(f^i_{j+1,k} + f^i_{j-1,k-1} + f^i_{j+1,k} + f^i_{j-1,k+1} + f^i_{j+1,k+1}) +$$
$$+\alpha_4(f^i_{j-2,k} + f^i_{j+2,k} + f^i_{j,k-2} + f^i_{j,k-2} + f^i_{j,k+2}) = 0$$

where:

α is the weight coefficient, the values of which are determined using the flight risk of UAVs (tension in a network), and *f* is the coordinates of network nodes (UAVs) for calculation.

Let need to evaluate a fragment of the territory before performing UAV flights. Before the UAV flight and terrain monitoring, it is necessary to decide how the flight will be performed (single or groups of UAVs). Let's have some fragment that contains both open-air spaces that include fields, spaces with natural obstructions, for example, areas with tall trees, and high-voltage power lines near the road. This territory is shown in Figure 11.

Figure 11. Fragment of the territory for performing UAV flights with coverage of UAVs group

When marking the territory, it will be necessary to note these risks. In the next stage, performed calculation of the paths with minimum risk for UAV flights according to specific types of obstructions. There are several ways to obtain initial data about obstacles. For example, one uses cartographic information providers, such as Google Maps, and Maps.me, Bing, Google Earth Pro, etc. Further, the territory marks manually if the data on it are missing or not true. Computer vision systems use to recognize the terrain obtained via satellite photos or maps. The fragment of the territory with a GRID and marked data is shown in Figure 12.

Figure 12. The fragment of the territory with a GRID and labeled data

Determination of UAV flight trajectories at other levels of the multi-level airspace, and planning of different paths of minimum risk and maximum safety depending on the flight height was presented in Figure 13.

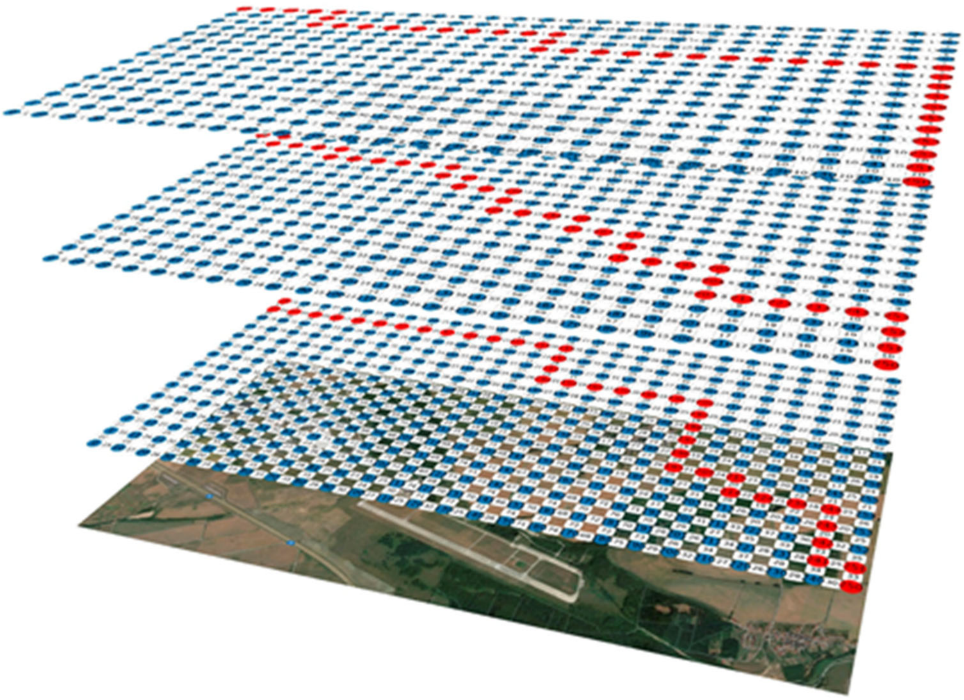

Figure 13. The fragment of the territory with a GRID and marked data at other levels of the multi-level airspace

6. Conclusion

An effective means of solving the task of monitoring high-voltage power lines can be the use of a group of UAVs. In this study, flight control algorithms, detection of breaks in power lines, and fixing the break coordinates are represented. This approach suggests using a control scheme with a virtual leader for flight control. To solve this problem, the coordinates of a virtual leader for a group of UAVs of 2-4 vehicles, which is the center of the formation, are determined. To increase the number of agents in a group, it is proposed to use a cellular structure, each cell of which is represented by a small group of vehicles. Algorithms for tracking the virtual leader are also presented, which ensure stable movement behind the virtual leader, as well as an algorithm for maintaining the required structure of the UAV during the flight to avoid collisions based on attractive/repulsive forces. Some scheme of a Bayesian detector was offered to solve the problem of detecting breaks. This approach ensures the minimum risk of erroneous decisions. Determining the break coordinates is proposed using the built-in elements of the UAV positioning system. In this study, we established that the overall effect of solving the problem of determining power line breaks depends on the performing quality of the individual subtasks. The proposed algorithms and simulation results confirm theoretical developments.

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