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Model of Control in a UAV Group for Hidden Transmitters Detection on the Basis of Local Self-Organization

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ABSTRACT

The article considers the technology of multi-UAV control of the complex of illegal transmitters detection on the basis of local self-organization. Successful detection and localization of a hidden transmitter using a group of drone scanners requires the construction of drones in the required topology. The model is based on the assumption that individual drones in a group cannot communicate with all other members and can transmit information about their location and detected hidden transmitters only to a limited number of nearest neighbors. This approach provides flexibility for individual drones to respond to changes in the current situation and effective coordination in the team. A method for constructing control laws for each of the drones based on a combination of Kirchhoff matrices, a set of mutual position vectors, and combined potential-attraction-repulsion functions is proposed. The modeling of the proposed approach to the problem of forming the structure of the mobile group of UAVs with a desired topology over the search object is carried out. The effectiveness of the approach to the search for illegal transmitters is proved.

Key words : Controllaw, detection, drone, hidden transmitter, multi-UAV system, self-organization.

1. INTRODUCTION

Detection and localization of hidden information transmission devices remains one of the most difficult tasks of information security. The widespread use of broadband data transmission media creates extremely favorable conditions for the use of covert illegal transmitters against the background of legal media networks. It is currently difficult to find another such actively used part of the radio frequency (RF) spectrum as 2.4 GHz. Wi-Fi, Bluetooth, ZigBee, analog and digital video transmitters, remote control and access systems, microwave ovens and much more work in this range. Naturally, the more used is the area of the radio frequency spectrum, the more difficult it is to control and analyze. This fact is often crucial when attackers choose an environment to disguise the operation of their covert means of obtaining information designed to intercept restricted information. This problem necessitates the automation of the search for illegal transmitters, for which robotic mobile systems are increasingly used, in particular on unmanned aerial vehicles (UAVs) [1]. Moreover, in the case of a large object, UAVs become almost the only means of controlling the electromagnetic environment, able to quickly detect and neutralize hidden audio / video surveillance (Figure 1).

Figure 1: Group of Drones for RF Monitoring [2]

1.1 Problem Statement

The level of development achieved in robotics makes relevant research not only in the field of building control systems for individual autonomous mobile devices, but also for groups of such devices. In this case, the control system, in addition to robot control, must ensure consistency of work with other members of the group. The construction of systems consisting of many autonomous components that solve a common problem is considered in the multi-agent approach. At the same time various management methods, including intellectual are applied. At the same time, the implementation of too complex intelligent methods on board a small UAV is impossible, which necessitates the use of simple and reliable methods of collective management. Such a method of the group control should optimize the individual behavior of an individual robot, aligning it with the behavior of other group members.

1.2 Related Works Overview

A significant number of publications are devoted to the problem of managing groups of autonomous objects. Thus, [3] provides a detailed analysis of UAV group management models for centralized and decentralized strategies such as "flock" and "swarm", provides control laws and evaluates the effectiveness of the group in such approaches. At the same time, the paper does not consider the adaptation of the behavior of individuals based on the experience of other members of the group. In [4], the main efforts of the UAV group are aimed at maintaining the configuration of the group, which is extremely important for effective interaction. At the same time, the issues of autonomy of drone behavior remain out of consideration. In [5] the main attention in the management processes of the group is paid to the internal interaction between its members. At the same time, the use of simplified control laws limits the functionality of the drone to perform the main task. In [6] control algorithms are presented, which provide coordinated movement of a group of drones in an indefinite three-dimensional environment with obstacles. Moreover, obstacles can be both stationary and mobile. However, the laws of motion of individuals are quite simplified and the maintenance of the configuration is provided by Delaunay triangulation without information exchange. In [7], the problem of “collecting” drones to a certain point set by the static leader of the group is solved. Drones coordinate their activities, but are not able to adapt to the experience of other individuals. In [8], the control laws are reduced to gradient methods, which allows a group of robots to go to a given area using the parameters of the gradient field without communication with other robots of the group. [9] and [10] consider control issues for a “flock” consisting of hundreds and thousands of units. At the same time, the issues of recognizing situations and correcting actions in the event of a change in the situation are not considered. In [11] an extended set of control models for a group of robots is presented on the basis of analysis by each individual of the position of the robot-neighbor and comparison of one's own position with a predetermined one. At the same time issues of self-study work are not considered. In [12] neural network control algorithms are proposed, however, the object of study in this system is stationary and the general approach does not take into account the distributed nature of the system.

The main problem that remains unnoticed by researchers is the fact that due to the low power of the transmitter, a single drone can transmit information only to its nearest neighbor and not see the overall topology of the group. Knowing only one's immediate surroundings makes it much more difficult to develop control laws for a group of drones. Thus, taking into account the peculiarities of the tasks of the UAV group related to the search and localization of hidden transmitters, the individual drone control algorithm should provide the ability to move independently in the direction of the task when interacting with other objects of the group. The system must operate both in the case of centralized control of one of the drones, and autonomously, on the basis of self-organization.

The purpose of the articleis to develop a model for the interaction of autonomous drones in a multi-UAV hiddeen transmitters detection system that would not require a global observer and would allow the implementation of a control system based on the local self-organization.

2. METHODOLOGY OF CONTROL WITH LOCAL SELF-ORGANIZATION

To implement the drone group management model, there is a special communication channel for communication between individual drones. The main information transmitted between drones is information about the current location of the neighbors of a particular UAB. This allows optimal use of the existing communication channel to achieve maximum consistency of drone operations.

Based on the approach proposed in [13,14], the problem of controlling the structure of a group of autonomous drones can be formulated as follows. Let $N=\{A_1,...,A_n\}$ is a set of drones moving in two-dimensional space with current positions $z_i(t)=\left[x_i(t),y_i(t)\right]^{\mathrm{T}},i=1,...,n$. The motion model of each drone can be described by equations

$$\dot{z}_i=u_i,\ i=1,...,n, \tag{1}$$

where $u_i=\left[u_{ix},u_{iy}\right]^{\mathrm{T}}\in\boldsymbol{R}^2$ is the speed of the *i*-drone relative to the coordinate axes.

Let $N_i\subseteq\{z_1,...,z_n\}$, $N_i\neq\varnothing, i=1,...,n$ is a subset of drone positions visible to the droneA_i. We also introduce a vector $c_{ij}=\left[h_{ji},v_{ji}\right]^{\mathrm{T}}$, $\forall j\in N_i$, which will represent the desired position of the drone A_i relative to the drone A_j in a separate formation. Thus, the relative desirable position of each drone A_i in the formation can be defined as

$$z_i^*=\phi_i(N_i)=\frac{1}{n_i}\sum_{j\in N_i}\left(z_j+c_{ij}\right),\ i=1,...,n, \tag{2}$$

where n_i is a subset power N_i. Therefore, the relative desirable position of the drone A_i can be considered as a combination of desired positions z_i relative to the positions of all elements N_i. Let also d/2 is a radius of the circle around each of the drones. The control law can be formulated as follows: for each drone A_i to find the law of management $u_i(t) = f_i(N_i(t))$ such that $\lim_{t\to\infty}(z_i - z_i^*) = 0,\ i = 1,...,n$ is a condition of convergence to the desired topology; $\|z_i(t) - z_j(t)\| \neq 0,\ \forall t \geq 0, i \neq j$ is a condition to avoid drone collisions.

As proposed in [14], the desired relative positions of the drone group in the desired topology can be represented by a graph of the structure defined as $G = \{Q, E, C\}$ which consists of:

1) sets of vertices $Q = \{A_1, A_2, ..., A_n\}$, which describe team members;

2) set of edges $E = \{(j,i) \in Q \times Q\},\ i \neq j$, which include pairs of vertices that define the relationship between drones, therefore $(j,i) \in E$ when $j \in N_i$;

3) set of vectors $C = \{c_{ji}\},\ \forall (j,i) \in E$, which determine the desired relative position between the drones *i* and *j*, that is $z_i - z_j = c_{ji} \in \boldsymbol{R}^2\ \forall i \neq j, j \in N_i$ in the desired formation topology.

If $(i,j) \in E$, then the vertices *i* and *j* are called adjacent. Degree g_i of *i*-vertex is defined as the number of adjacent vertices. The path from vertex *i* to vertex *j* is a combination of individual vertices starting with *i* and ending with vertex *j* so that serial vertices are adjacent. The *basic* graph of a structure is a graph in which $\forall (i,j) \in E$ there is an arc (j,i), even if it was not in the initial graph of the structure. The base graph is always an undirected graph. If there is a path between any two vertices of the base graph, then the structure graph is called connected. A structure graph is well defined if it satisfies the following conditions:

1) the graph is connected;

2) there are no conflicts in the desired vectors position, i.e., if $c_{ij}, c_{ji} \in C$, so $c_{ij} \neq c_{ji}$;

3) the desired position vectors define a closed structure, for example, if there are vectors $c_{jm_1}, c_{m_1m_2}, c_{mm}, ..., c_{m_rj} \in C$ then they must satisfy the condition:

$$c_{jm_1} + c_{m_1m_2} + c_{mm} + ... + c_{m_rj} = 0. \tag{3}$$

The last condition determines that the individual position vectors must form a closed polygon. Kirchhoff matrices are often used to describe the basic topological properties of structure graphs.

The Kirchhoff matrix of a graph of structure *G* is a matrix

$$L(G) = \Delta - A_d, \tag{4}$$

where $\Delta = \begin{bmatrix} g_1 & \cdots & 0 \\ \cdots & \ddots & \cdots \\ 0 & \cdots & g_n \end{bmatrix}$, where g_i is a degree of vertex *i*;

$A_d = [a_{ij}]_{n\times n}$ is an adjacency matrix, where

$$a_{ij} = \begin{vmatrix} 1, \text{ if } (j,i) \in E, \\ 0, \text{ otherwise.} \end{vmatrix} \tag{5}$$

For a connected structure graph the Kirchhoff matrix has a single zero eigenvalue, and its eigenvector is $[1,...,1]^{\mathrm{T}} \in \boldsymbol{R}^n$. Figure 2 shows an example of a structure graph. Drones are at the vertices of the graph, and edges define vectors c_{ji}. The selected elements of the Kirchhoff matrix are the degree of vertices g_i, $i = 1,...,n$.

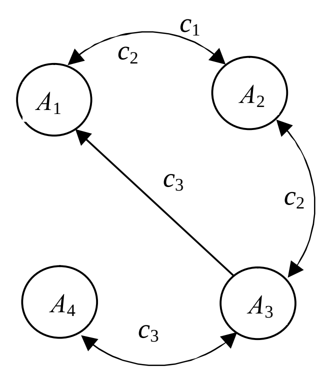

Figure 2: Example of a Structure Graph

For the structure shown in Figure. 2 sets N_i will look like: $N_1 = \{z_2, z_3\}$, $N_2 = \{z_1\}$, $N_3 = \{z_2\}$, $N_4 = \{z_3\}$ and Kirchhoff's matrix $L(G) = \begin{bmatrix} \mathbf{2} & -1 & -1 & 0 \\ -1 & \mathbf{1} & 0 & 0 \\ 0 & -1 & \mathbf{1} & 0 \\ 0 & 0 & -1 & \mathbf{1} \end{bmatrix}$. Vectors of desired positions: $c_{21} = [-1,0]$, $c_{12} = [1,0]$, $c_{31} = [-1,1]$, $c_{23} = [0,-1]$, $c_{34} = [-1,0]$. Provided the structure is closed: $c_{21} = -c_{12}$, $c_{12} + c_{23} + c_{31} = 0$.

Structure graphs can be directed or undirected. In the case of non-directional graphs of a structure, the Kirchhoff matrix will always be a symmetric semi-definite positive matrix. With the help of such graphs it is possible to describe different topologies of the UAV group when searching for hidden transmitters. Variants of different topologies have been given earlier. For example, [14] analyzes the convergence of a fully connected graph of a structure where each drone sees the position of the others. The directional graph of the cyclic pursuit structure was studied in [15], where the drone i pursues the drone and$i$ + 1, etc., and the drone n pursues the first, thus forming a chain topology. A variant of cyclic pursuit with bidirectional connections (non-directional graph) is analyzed in [16]. In [17] the graph of the structure with the virtual leader is analyzed, and for the case of "convoying" the corresponding scheme is developed in [18]. The inclusion of virtual leaders in the schemes implies that there may not be a real drone leader in the system. Such a leader can only be modeled by appropriate means to improve the properties of the system [19].

Also, an important element of the topology is its centroid. Centroid location $z(t)$ is the middle position of all drones in the group, i.e.

$$z(t)=\frac{1}{n}\sum_{i=1}^{n} z_i(t)\,. \tag{6}$$

3.CONTROL METHOD BASED ON POTENTIAL FUNCTIONS

For system (1), the virtual potential attraction function can be defined as

$$\gamma_i=\sum_{j\in N_i}^{n}\left\|z_i-z_j-c_{ji}\right\|^2,\ \forall j\in N_i,\ i=1,\ldots,n\,. \tag{7}$$

Function (7) is positively defined and reaches its minimum when $z_i-z_j=c_{ji}$, $j\in N_i, i=1,\ldots,n$. Then the control law based on the introduced attraction function can be defined as

$$u_i=-\frac{1}{2}k\left(\partial\gamma_i/\partial z_i\right)^{\mathrm{T}},\ i=1,\ldots,n,\ k>0\,. \tag{8}$$

The closed cyclic system (1) - (6) has the form

$$\dot{z}=-k\left(\left(L(G)\otimes I_2\right)z-c\right), \tag{9}$$

where $L(G)$ is a Kirchhoff matrix of the structure graph; $\otimes$ – Kronecker product symbol; I_2 – single matrix (2×2); $z=\left[z_1,\ldots,z_n\right]^{\mathrm{T}}$ – vector of drone positions; $c=\left[\sum_{j\in N_1} c_{j1},\ldots,\sum_{j\in N_n} c_{jn}\right]^{\mathrm{T}}$ – vector of mutual directions of drones location.

In [13] it was shown that in closed-loop systems of type (1) - (6) drones converge to the desired topology exponentially ($\lim_{t\to\infty}\left(z_i-z_i^*\right)=0,\ i=1,\ldots,n$), if the desired topology is based on a well-defined structure graph. The proof of this fact is based on the properties of the Kirchhoff matrix and Gershgorin's theorem on cycles [17].

Gravity-based control guarantees convergence to the desired topology, but does not guarantee collisions of individual drones. The idea of using the repulsion function is that each drone considers other drones as moving obstacles. The square of the distance between two drones is determined by $\beta_{ij}=\left\|z_i-z_j\right\|^2, \forall i,j\in N, i\neq j$. Then, the drone A_j , which could potentially collide A_i will belong to the set

$$M_i=\left\{\left.A_j\in N\right|\,\beta_{ij}\le d^2\right\}, i=1,\ldots,n\,, \tag{10}$$

where$d$ – diameter of the impact zone.

Due to the movement of drones set M_i therefore, the law of control of the structure with the avoidance of collisions on the basis of the functions of attraction and repulsion will look like (Figure3)

$$u_i=-\frac{1}{2}k\cdot\left(\partial\gamma_i/\partial z_i\right)-\sum_{j\in M_i}\partial V_{ij}/\partial z_i, i=1,\ldots,n\,, \tag{11}$$

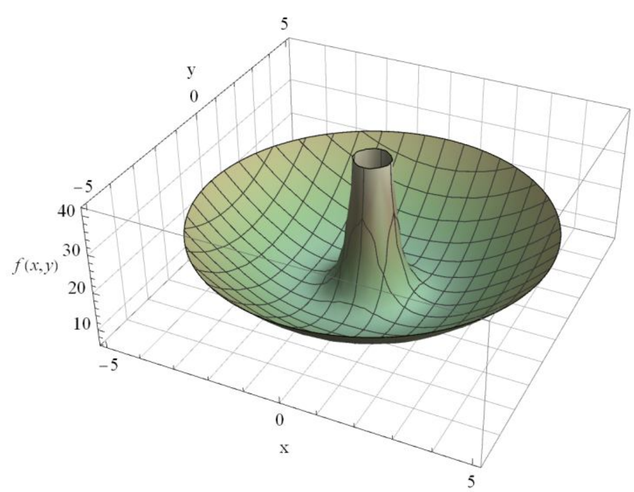

Figure 3: General View of the Attraction-Repulsion Function

where γ_i – the attraction function defined in (7); $V_{ij}\left(\beta_{ij}\right)$ – repulsion function between drones A_i and A_j, which satisfies the following properties: 1) V_{ij} is monotonically increasing, when $\beta_{ij} \to 0$ and $\beta_{ij} \le d^2$; 2) $\lim\limits_{\beta_{ij}\to 0} V_{ij} = \infty$; 3) $V_{ij} = 0$ for $\beta_{ij} \ge d^2$, $\partial V_{ij}/\partial z_i = 0$ for $\beta_{ij} = d^2$, which means each V_{ij} appears smoothly only within the zone of influence of the drone A_i. You can also show that

$$\sum_{j\in M_i} \partial V_{ij}/\partial z_i = \sum_{j\ne i} \partial V_{ij}/\partial z_i \ . \qquad (12)$$

A general function that satisfies the described properties has been proposed in [14]

$$V_{ij} = \begin{vmatrix} \eta\left(1/\beta_{ij} - 1/d^2\right)^2, \text{ if } \ \beta_{ij} \le d^2 \\ 0, \qquad\qquad\qquad \text{if } \ \beta_{ij} > d^2 \end{vmatrix} \qquad (13)$$

where $\eta > 0$. This function is also consistent with the properties of the repulsion function

$$V_{ij} = \begin{vmatrix} \eta\left(1/\beta_{ij} - 1/d^2\right)^r, \text{ if } \ \beta_{ij} \le d^2 \\ 0, \qquad\qquad\qquad \text{if } \ \beta_{ij} > d^2 \end{vmatrix}, \quad r = 2,3,4,... \qquad (14)$$

$$V_{ij} = \begin{vmatrix} \eta\left(\beta_{ij} - d^2\right)^2 \Big/ \beta_{ij}, \text{ if } \ \beta_{ij} \le d^2; \\ 0, \text{ if } \ \beta_{ij} > d^2 . \end{vmatrix} \qquad (15)$$

Simulation of the repulsion function of the form (13) at different values of d shows that its most active influence begins at $\beta_{ij} \le 1$ (Figure 4).

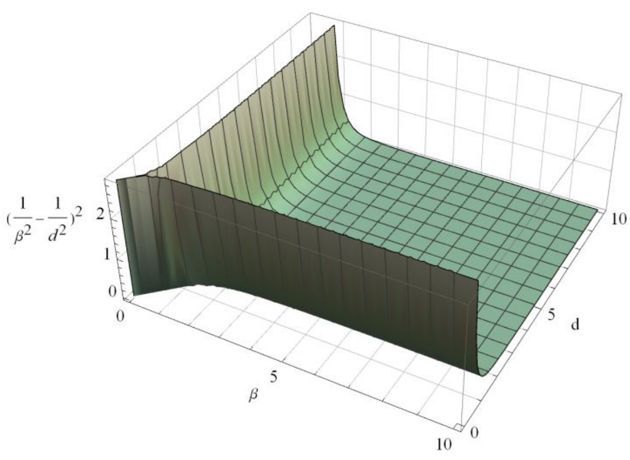

Figure 4: Dependence of the Repulsion Function on β and d

It should be noted that in general, you can write $\partial V_{ij}/\partial z_i = 2\left(\partial V_{ij}/\partial \beta_{ij}\right)\left(z_i - z_j\right)$. As $\beta_{ij} = \beta_{ji}$ then $V_{ij} = V_{ji}$ and $\partial V_{ij}/\partial \beta_{ij} = \partial V_{ji}/\partial \beta_{ji}, \forall i \ne j$. This confirms that the repulsion function is consistent with the following asymmetry property

$$\partial V_{ij}/\partial \beta_{ij} = -\partial V_{ji}/\partial \beta_{ji}, \forall i \ne j \ . \qquad (16)$$

As already mentioned, the main disadvantage of combining the functions of attraction and repulsion is that drones can get to unwanted equilibrium points of the functions. [20] proposes a method for determining these points for the case of any undirected graphs of the structure by solving the equation

$$\left(kL\left(G\right) + 2R\right) \otimes I_2 z = kc \ , \qquad (17)$$

where $L\left(G\right)$ – Kirchhoff matrix of non-directional structure graph; $c = \left[\sum\limits_{j\in N_1} c_{j1}, ..., \sum\limits_{j\in N_n} c_{jn}\right]^{\mathrm{T}}$ and

$$\left(A\right)_{ij} = \begin{vmatrix} \sum\limits_{j\ne i}\left(\partial V_{ij}/\partial \beta_{ij}\right), \text{ if } \ i = j; \\ -\partial V_{ij}/\partial \beta_{ij}, \text{ if } \ i \ne j. \end{vmatrix}$$

Such undesirable equilibrium points are formed because both drones mutually deny each other's movement when trying to move to the opposite side. The solution of such a conflict situation should be left to the operators of these drones.

Consider also the behavior of the centroid positions. To do this, use the system (1) and the law of control (11). Suppose that $k > 0$ and the desired topology is described by a well-defined structure graph. In the cyclic-closed structure (1) – (11) the centroid of the positions of the drones remains constant, i.e. $z\left(t\right) = z\left(0\right) \ \forall t \ge 0$, if the topology satisfies the condition $\left[1,...,1\right] L\left(G\right) = \left[0,...,0\right]$.

The movement of each drone R_i in a cyclic-closed system (1) – (11) described by equations

$$\dot{z}_i = -k\left(g_i z_i - \sum_{j\in N_i} z_j - \sum_{j\in N_i} c_{ji}\right) - \sum_{j\in M_i}\left(\partial V_{ij}/\partial z_i\right), \quad i = 1,...,n \qquad (18)$$

Using property (12), we write

$$\dot{z}_i = -k\left(g_i z_i - \sum_{j\in N_i} z_j - \sum_{j\in N_i} c_{ji}\right) - \sum_{j\ne i}\left(\partial V_{ij}/\partial z_i\right), \quad i = 1,...,n \qquad (19)$$

Then, the motion of the centroid positions can be applied

$$\dot{\bar{z}}_i(t)=\frac{1}{n}\sum_{i=1}^{n}\dot{z}_i=-\frac{k}{n}\left(\sum_{i=1}^{n}g_i z_i-\sum_{i=1}^{n}\sum_{j\in N_i}z_j-\sum_{i=1}^{n}\sum_{j\in N_i}c_{ji}\right)-$$
$$-\frac{1}{n}\sum_{i=1}^{n}\sum_{j\neq i}\left(\partial V_{ij}/\partial z_i\right) \tag{20}$$

Due to the fact that the graph of the structure satisfies the condition of closure (3), then $\sum_{i=1}^{n}\sum_{j\in N_i}c_{ji}=0$ and using the asymmetry property (16) then $\frac{1}{n}\sum_{i=1}^{n}\sum_{j\neq i}\left(\partial V_{ij}/\partial z_i\right)=0$. Then equation (20) can be simplified to

$$\dot{\bar{z}}_i(t)=-\frac{k}{n}\left(\sum_{i=1}^{n}g_i z_i-\sum_{i=1}^{n}\sum_{j\in N_i}z_j\right)=-\frac{1}{n}\sum_{i=1}^{n}\left(g_i z_i-\sum_{j\in N_i}z_j\right). \tag{21}$$

Multiplier $\left(g_i z_i-\sum_{j\in N_i}z_j\right), i=1,\dots,n$ refers to i-element of vector column $\left(L(G)\otimes I_2\right)z$. Then equation (21) is the sum of the elements $\left(L(G)\otimes I_2\right)z$ multiplied by $-\frac{k}{n}$. Therefore, equation (21) will be equivalent to

$$\dot{\bar{z}}(t)=-\frac{k}{n}\left([1,\dots,1]\left(L(G)\otimes I_2\right)z\right). \tag{22}$$

So it is clear that $\dot{\bar{z}}(t)=0, \forall t\geq 0$ and a centroid position determined by the initial positions of the drones $\bar{z}(t)=\bar{z}(0)$ will remain stable $\forall t\geq 0$.

The proposed improved methods of collective interaction in groups of autonomous drones generally solve the problem of group management based on self-organization algorithms, leaving the possibility of intervention in the work of the drone by the operator and thus increasing the degree of integration of human and machine intelligence.

To test the developed model, consider, for example, a system consisting of 6 drones, arbitrarily located in two-dimensional space, which task is to form a “ring” topology (Figure5). Such topology allows you to organize continuous radio monitoring to detect hidden transmitters in a certain area without gaps.In this case, the vectors of the relative positions will be c_{21}=[–2,1], c_{32}=[0,2], c_{43}=[2,1], c_{54}=[2,–1], c_{65}=[0,2], c_{16}=[–2,–1], $d=5$, $\eta=1$. The simulation results are shown in Figures6–8.

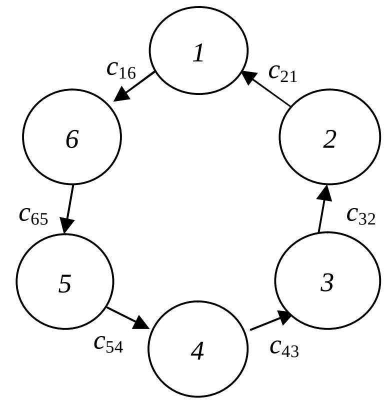

Figure 5: Graph of a Desired Topology of the System Structure

As can be seen from Figure6, the trajectories of the drones are smoothed and under the action of the attraction function the group tends to gather in the center of the location forming a desired topology. In this case, the centroid occupies a position equidistant from all initial places.

Also, it should be recalled that each of the drones moves according to a simple law of control, striving for the center of the topology (point (5,5)), maintaining contact only with the nearest neighbors.

In Figure7 drones 2 and 3 bypass the obstacle (point (1,3)), and the whole formation gathers in a desired topology slightly to the right of the centroid at the point (6,4).

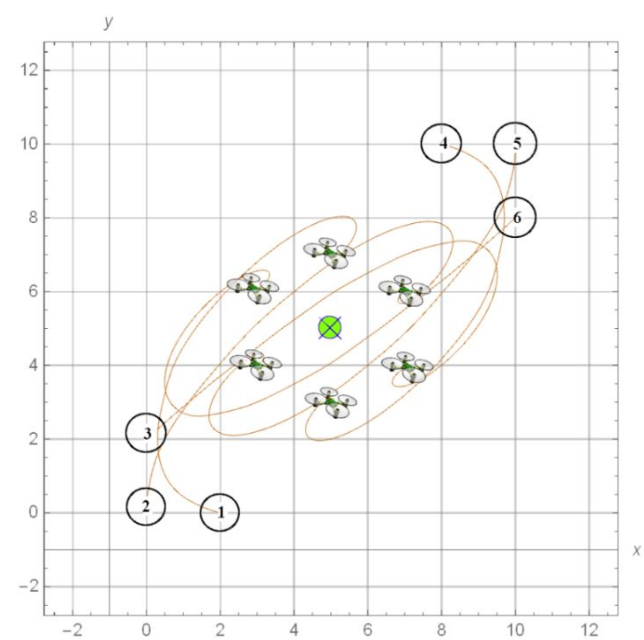

Figure 6: Movement of Drones under the action of the Attraction Function

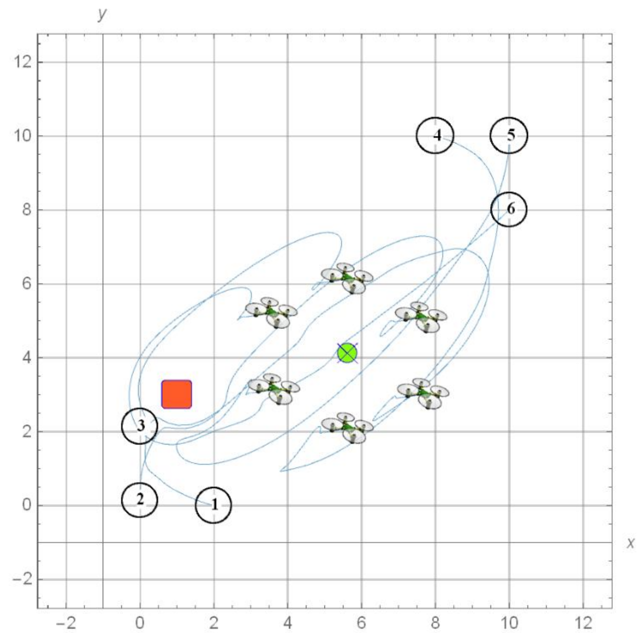

Figure 7: GroupMovement under the Attraction-Repulsion Function with Obstacle on the Trajectory

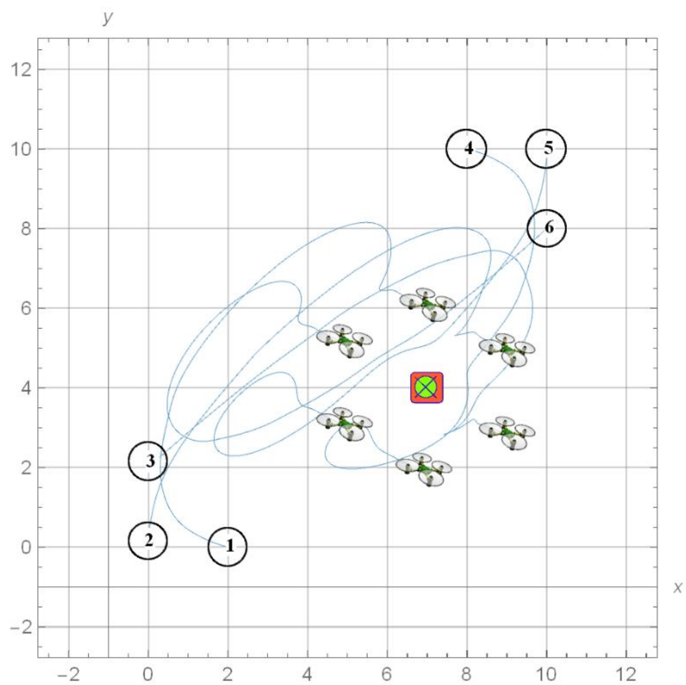

Figure 8: GroupMovement under Attraction-Repulsion Function with Obstacle in the Drone's Place

Let's complicate the task by placing an obstacle in the place where one of the drones should arrive (point (7,4)). Thus, we will not allow the group to gather to the required formation in a standard place (without significant displacing of centroid), which leads to the need for the whole group "to move" to a new place with the centroid at point (7,4) (Figure8). In this case, the most optimal for a group of drones is to move to the area with the centroid above the obstacle, because it maintains a uniform repulsion from the obstacle by all drones.

4. CONCLUSION

Thus, the developed model of autonomous drones' interaction based on local self-organization allows solving the problem of forming a desired topology in the absence of a global observer in the system. At the same time, drones do not have complete information about the location of other drones, but are guided only by the movement of certain (visible) drones of the formation, thereby reducing the total amount of information exchange in the system and realizing the principle of local self-organization. The use of potential functions and formation graphs for the analysis of such systems is very useful for describing the interaction between drones and for analytically determining the trajectories of drones.

The direction of further research in this area can be a wide range of issues of modeling the behavior of individual drones, taking into account the characteristics of the application environment.

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