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# Air Defense Planning from an Impact of a Group of Unmanned Aerial Vehicles based on Multi-Agent Modeling

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## ABSTRACT

The paper discusses the methodology of forming an air defense plan to counteract a group of drones based on multiagent modeling. It is shown that the application of traditional planning methods does not take into account the peculiarities of the defense of objects against large groups of air targets in case of their simultaneous application. The use of a multiagent paradigm for modeling is considered, which considers the defense process as an interaction of two groups of agents: attack and defense. The air situation model is based on the application of agents with simple control methods and the use of cohesive and repulsive functions. The air defense model includes adequate air defense agents' response to air targets. The conclusion about the possibility of multi-agent air defense planning was confirmed by modeling of an infrastructure object defense from attack of a group of drones.

**Key words :** Air Defense, Drone, Group Behavior, Multi-Agent, Planning, Unmanned Aerial Vehicle.

## 1. INTRODUCTION

Over the last decade the number of small drones (UAVs) applications has increased rapidly. At the same time, the smallest UAVs (drones) are becoming more intelligent and technically sophisticated. Not surprisingly, in this case, they can increasingly be used not only with good intentions but also for terrorist attacks. Drones, simple and cheap, are now available to a variety of armed groups. The largest-scale drone attack was launched in September 2019. Its target was large oil refineries in Saudi Arabia. As a result of the attack, oil production has fallen by 5.7 million barrels a day, which is 5% of world production, and its price has jumped by 10% [1]. Network coordination technologies now allow terrorists to use not only single drones, but also their groups, consisting of dozens of units coordinated across time and space. This further complicates the task of counteracting such UAV groups in protecting critical infrastructure as it requires the concerted management of a large number of forces and resources.

### 1.1 Problem Statement

Various mathematical methods can be used for air defense planning of an infrastructure object: operations research, probability theory methods, scheduling theories, mathematical analysis, game theory, statistical analysis, statistical modeling, etc. [2]. However, the main disadvantage of such methods is the overly generalized presentation of the entire “UAV Group - Air Defense” system, which negates the final result and renders the plan inappropriate. Therefore, there is a need to use more detailed “multi-agent” game modeling methods. Submission of individual elements of the system in the form of independent “agents” allow to analyze the behavior of each of the studied objects in more detail and to plan the “defense agents” application more rationally.

A common problem of air defense planning for an important infrastructure object is the need to forecast UAV group actions. The specific variant of the air defense counteraction to a group of drones will depend on the possible location of individual UAVs in the space above the infrastructure object. Therefore, it is obvious that the overall planning task will be based on two models: 1) the model of the air situation forecast, and 2) the model of air defense counteraction.

### 1.2 Related Works Overview

In order to develop a model of the air situation forecast, the UAV team should be considered as a set of agents that coordinate their actions to fulfill a common goal. By interacting locally, intellectual agents – UAVs create so-called collective intelligence that is capable of self-organization and complex behavior, even if each agent's strategy is simple enough. The first publications in this field refer to the research of Craig Reynolds. Observing bird's behavior, he proved that the interaction of birds in a flock requires only a few simple rules of behavior [3]. In [4] theoretical bases of application of robotic groups are stated. Studies [5]–[7] describe some particular cases of constructing spatial group formations based on information about a limited range of neighbors. Model [8] describes the movement of search agents in the decision support system. The "Diffusion Bomb Task" [9] gives an idea of how to defeat an enemy air defense system (air defense system) by an autonomous group. [10] describes the UAV group motion model, which most fully complies with the principles of decentralized management, is easily scalable and, at the same time, easy to apply.

The main approaches to air defense organization are laid down in guidance documents such as ATP 3-01.8 Techniques for Combined Arms for Air Defense [11] and Joint Publication 3-01 Countering Air and Missile Threats [12]. However, these documents do not disclose options for modeling of the air defense counteraction, leaving these issues for the decision of commanders. In turn, individual counteraction models are reported in [13], although without the possibility of numerical estimation of counteraction parameters. More detailed models can be seen in [14], which include Tracking models and Bayesian models for target recognition. At the same time, such approach is not sufficient to plan the defense of an object in the case of a group UAV strike. [15] discusses a multi-agent approach to missile defense planning. At the same time, agent activities are only implemented for planning procedures without taking into account the UAV group parameters. The procedures for planning air defense in real time are well modeled in [16]. At the same time, the main criterion for such planning is only the "non-conflict of the plan", which is inaccessible when protecting important objects. The best method for combining with the multi-agent planning model of the air situation in terms of planning is the method described in [17], which provides for the deployment of an air defense system depending on the variant of actions of the group of aircraft. At the same time, some elements of this model need to be refined.

The purpose of the article is to develop a methodology for forming an air defense plan for a critical infrastructure object from a group of unmanned aerial vehicles based on multi-agent modeling.

## 2. THE MODEL FOR AIR SITUATION FORECAST

### 2.1 Multi-Agent Approach to Air Situation Modeling

UAV group application leads to the proportional growth of information transmitted through the control channels in dependence from the UAVs number. Therefore, developers use decentralized control methods, which minimize the transmission of information in the control channels and manage the group as the only "integrated" UAV. Group control consists of two independent tasks: the decomposition of a group task into individual performers and the concerted execution of a group task in space and time. From the point of view of defense, the spatial position of individual drones is the most significant factor in the planning of defense actions. Therefore, to form a defense plan based on multi-agent modeling, it is most appropriate to take as a basis the problem of the spatial position of the UAV group.

The group $R$ consisting of $N$ UAVs is considered. Each UAV $r_i \in R$ ($i$=1…$N$) must be capable of performing the following functions: determining its location (absolute or relative); keeping in touch with its neighbors in the local group within the low-power transmitter range $d_{adj}$; dynamic (re-)planning of its own route based on the information received.

The task of the group, within the scope of this article, is to move from the start point with $X_{base}$ coordinates to the $X_{aim}$ destination, and each UAV must be informationally connected to the group and be able to avoid interference of neighbor UAVs and enemy active objects.

### 2.2 UAV Group Movement

The coherent group motion model is based on the potential method, which determines that each UAV is drawn to its destination and to the neighbors of the local group (which are recognized by onboard sensors). In addition, each UAV repels obstacles and neighbors to ensure flight safety. In general, the model can be represented in vector form:

$$\vec{V}^i = \vec{V}^i_{aim} + \vec{V}^i_{coh} + \vec{V}^i_{rep} + \vec{V}^i_{AAD}, \qquad (1)$$

where $\vec{V}^i$ – the resulting velocity vector of UAV $r_i$; $\vec{V}^i_{aim}, \vec{V}^i_{coh}$ – velocity vectors of approaching to the target and neighbors respectively; $\vec{V}^i_{rep}, \vec{V}^i_{AAD}$ – velocity repulsion vectors from neighbors and obstacles, respectively.

Let's look in detail at the first component $\vec{V}^i_{aim}$ of model (1), which is responsible for moving the UAV to the target. Fig. 1 shows two UAVs and their trajectories from the start point to the destination point with coordinates (30,10).

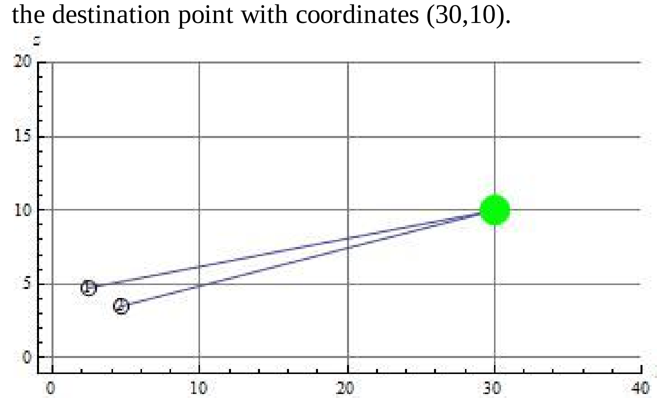


**Figure 1:** The trajectories of the movement of two UAVs to the target

The motion of each UAV in this case is described by a system of equations:

$$\vec{V}^{i}_{aim}=\begin{cases}\dfrac{\partial x_i(t)}{\partial t}=-\dfrac{\partial}{\partial x_i(t)}k_{aim1}d_{aim}\\ \dfrac{\partial z_i(t)}{\partial t}=-\dfrac{\partial}{\partial z_i(t)}k_{aim1}d_{aim}\\ x_i(0)=x_{base}\\ z_i(0)=z_{base}\end{cases} \quad (2)$$

where $X_{base}=(x_{base},z_{base})$ – coordinates of the starting point; $X_i(t)=(x_i(t),z_i(t))$ – current UAV coordinates; $X_{aim}=(x_{aim},z_{aim})$ – target point coordinates;

$d_{aim}=\sqrt{k_{aim2}+(x_i(t)-x_{aim})^2+(z_i(t)-z_{aim})^2}$ – the current distance between the *i*-th UAV and point $X_{aim}$; $k_{aim1},k_{aim2}$ – the model parameters responsible for the speed-of-destination module and the deceleration when the target is reached, respectively.

Dependencies of velocity projections on time according to the parameters $k_{aim1},k_{aim2}$ are shown in Fig. 2-4.

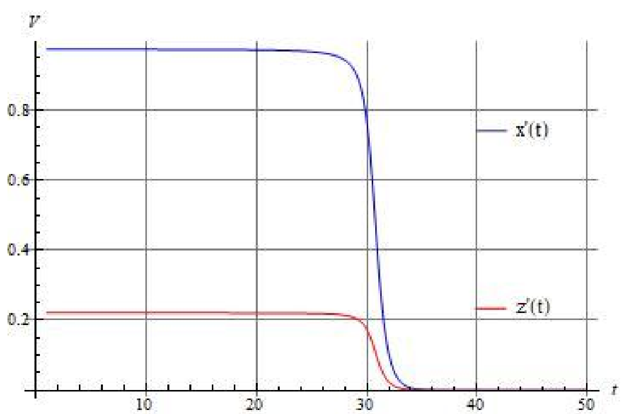


**Figure 2:** $k_{aim1}=1, k_{aim2}=0.5$

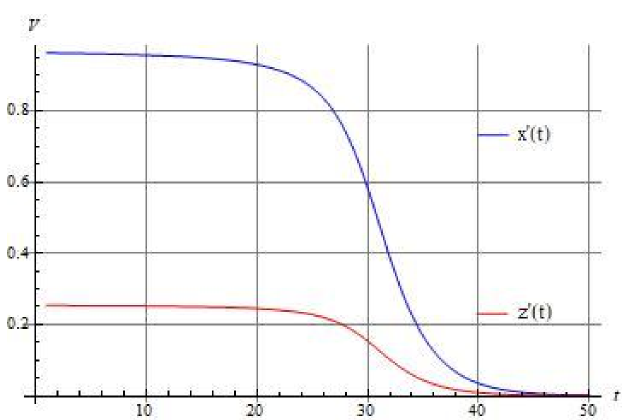


**Figure 3:** $k_{aim1}=1, k_{aim2}=10$

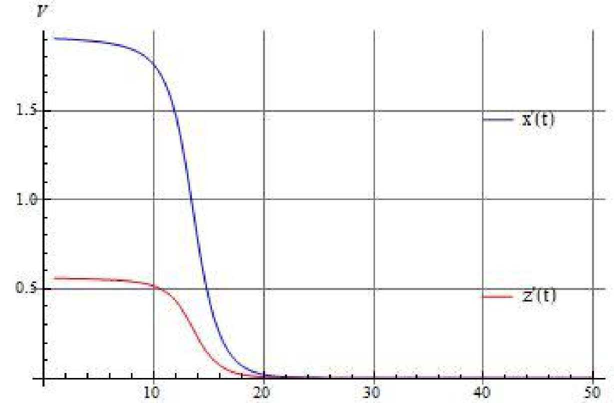


**Figure 4:** $k_{aim1}=2, k_{aim2}=10$

### 2.3 UAVs Action Forecast

UAV action in a group involves a role distribution. So today, more and more actions of drone groups are reminiscent of the actions of groups of people or military formations. Such groups have their own intelligence, radio-electronic jamming, impact forces, and others. In this case, the agents which perform the main task will have sufficient information about the forces that opposes them. Thus, UAVs will know in advance the location of the air defense facilities and will be able to bypass them.

Therefore, we include in the model (1) a fourth component $\vec{V}^{i}_{AAD}$, describing the circumvention of the area of damage by air defense. Jointly the first and fourth components of the model give the result shown in Fig. 5. Two UAVs go to the target bypassing the enemy air defense zones.

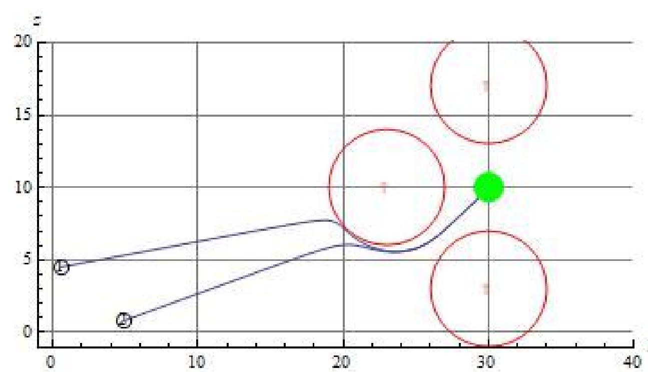


**Figure 5:** The trajectories of the movement of two UAVs to the target, taking into account the circumvention of enemy air defense zones

In this case, the model of the UAV movement will look like $\vec{V}^{i}=\vec{V}^{i}_{aim}+\vec{V}^{i}_{AAD}$. The vector of the velocity of repulsion of UAV $r_i$ from the set of zones of enemy air defenses is supplied by the system of equations:

$$\vec{V}^{i}_{AAD} = \begin{cases} \dfrac{dx_i(t)}{dt} = -\sum_{a=1}^{nAAD} \dfrac{\partial}{\partial x_i} \dfrac{k_{AAD}}{d_{ia}^{P_{AAD}}} dt \\ \dfrac{dz_i(t)}{dt} = -\sum_{a=1}^{nAAD} \dfrac{\partial}{\partial z_i} \dfrac{k_{AAD}}{d_{ia}^{P_{AAD}}} dt \end{cases} \quad (3)$$

where *nAAD* – the number of enemy air defense zones; $X_a = (x_a, z_a)$ – coordinates of the center of the impact area; $d_{ia} = \sqrt{(x_i(t) - x_a)^2 + (z_i(t) - z_a)^2}$ – current distance between UAV $r_i$ and the impact area $X_a$; $k_{AAD}, P_{AAD}$ – model parameters that are responsible for the radius of the impact area and the rate of repulsion from it.

Components two and three $\vec{V}^{i}_{coh}, \vec{V}^{i}_{rep}$ models (1) provide flight safety and information coherence for the group at the same time. The attraction to neighbors does not allow UAV to exceed the distance of the transmitter $d_{adj}$, and repulsion – ensures flight safety by preventing dangerous distance between neighboring UAVs.

The results of simulation of motion of two UAVs with respect to joint attraction and repulsion are shown in Fig. 6-8.

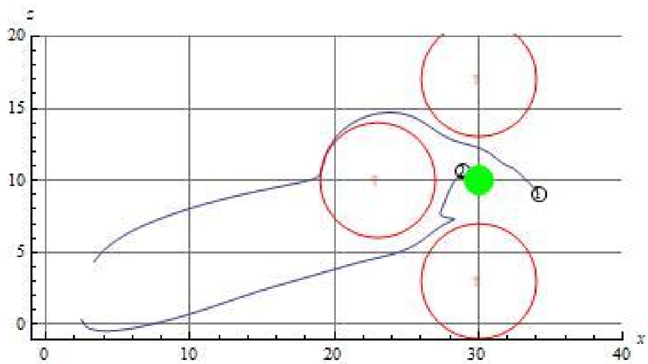

**Figure 6:** The trajectories of motion of two UAVs ($r_1$, $r_2$) to the target with regard to information coherence $d_{adj}$ <12 and bypassing obstacles

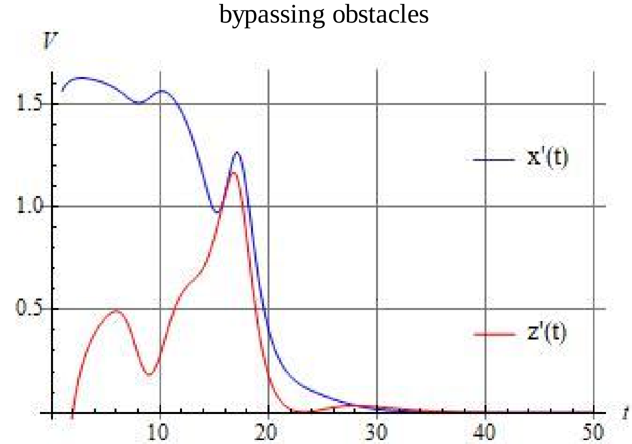


**Figure 7:** Projections of UAV velocities $r_2$

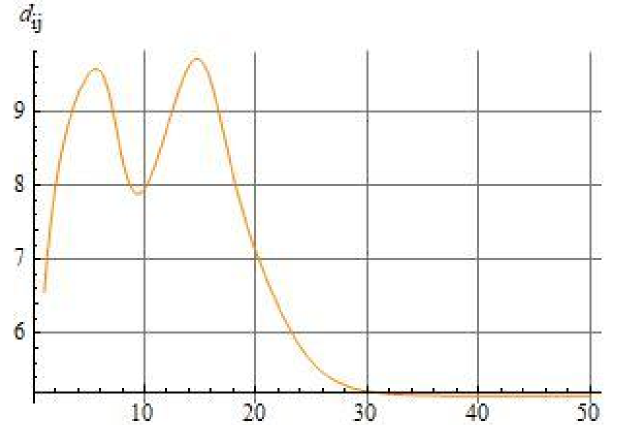


**Figure 8:** The current distance between UAVs $r_1$ and $r_2$

The cohesion and repulsion in model (1) is described by the following systems of differential equations:

$$\vec{V}^{i}_{coh} = \begin{cases} \dfrac{dx_i(t)}{dt} = \sum_{j=1}^{nUAV} \dfrac{\partial}{\partial x_i} \dfrac{k_{coh}}{d_{ij}^{P_{coh}}} dt \\ \dfrac{dz_i(t)}{dt} = \sum_{j=1}^{nUAV} \dfrac{\partial}{\partial z_i} \dfrac{k_{coh}}{d_{ij}^{P_{coh}}} dt \end{cases}, \quad (4)$$

$$\vec{V}^{i}_{rep} = \begin{cases} \dfrac{dx_i(t)}{dt} = -\sum_{j=1}^{nUAV} \dfrac{\partial}{\partial x_i} \dfrac{k_{rep}}{d_{ij}^{P_{rep}}} dt \\ \dfrac{dz_i(t)}{dt} = -\sum_{j=1}^{nUAV} \dfrac{\partial}{\partial z_i} \dfrac{k_{rep}}{d_{ij}^{P_{rep}}} dt \end{cases}, \quad (5)$$

where nUAV – number of neighbors; $X_i, X_j$ – coordinates of interacting UAVs; $k_{coh}, P_{coh}$ – model parameters responsible for the distance and speed of cohesion to neighbors; $k_{rep}, P_{rep}$ – model parameters responsible for distance and repulsion rate from neighbors; $d_{ij} = \sqrt{k_{cr} + (\varsigma + x_i(t) - x_j(t))^2 + (\varsigma + z_i(t) - z_j(t))^2}$ – the current distance between the *i*-th and the *j*-th UAV; $k_{cr}$ – model parameter responsible for acceleration in repulsion and deceleration in cohesion to neighbors; $\varsigma$ – accidental measuring error of distances between UAVs $r_i$ and $r_j$.

The ability to scale the model is confirmed by the simulation. The results of application of the group with $N = 20$ UAVs are shown in Fig. 9. The start of the UAVs is in the square (0,0)-(5,5), the target point has coordinates (20,20). At the 30th step of model time, there is a distribution of the group around the target point, which is approaching to equal distribution.

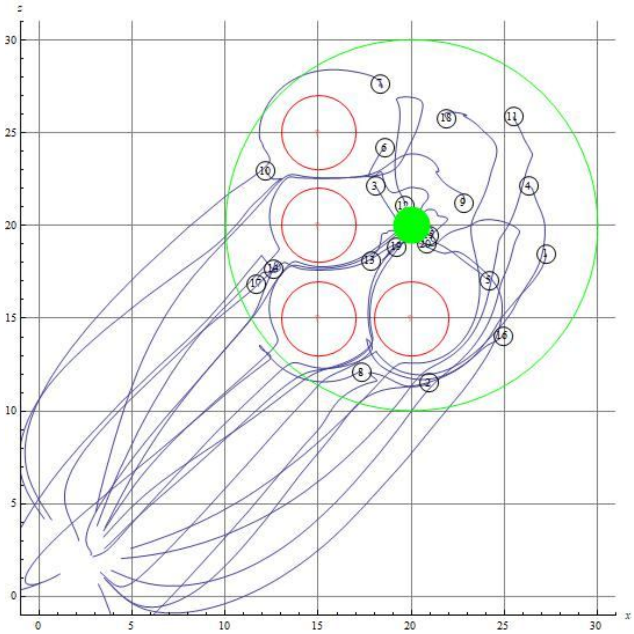

**Figure 9:** The trajectories of the movement of twenty UAVs

## 3. THE MODEL OF MULTI-AGENT AIR DEFENSE

Planning of the air defense deployment is a process that requires consideration of many factors, including terrain, type of enemy attack, enemy purposes, air raids, trajectory of enemy's flight and air defense tactics, intelligence capabilities etc. In the case of counteracting a group of small UAVs for air defense of an important infrastructural object, the topology of the air defense fascilities on the terrain will be extremely important. The specific position of every counter mean must take into account the particularities of the object itself and the surrounding area.

In short, the problem of planning the air defense of an infrastructure object is the correct deployment of a certain amount of air defense fascilities in optimally selected locations around the designated area on the ground. Attack and defense are two aspects of one problem, this is why the multiagent attack model should provide a similar multiagent air defense model.

The article assumes that the object is protected by a system that includes:
- air defense missile and artillery complexes including fully automated turrets with motion detection [18];
- radar stations;
- control point of the air defense system.

In this case, each element of the air defense system can be characterized by different performance indicators, in particular:
- effective range of impact $d_t$, wherein $t$ is the number of the type of a separate air defense system;
- the average probability of impact for the defense system $s_t$.

### 3.1 Model of Deployment of Air Defense System Facilities

Elements of an object's air defense system can be placed at several predefined deployment points. The set of possible deployment points is determined in advance based on prior information (reconnaissance). The following features are taken into account in this process:
- parameters of the terrain around each deployment point;
- engineering infrastructure of the area.

Only one element of air defense system can be deployed at any single deployment point from $D$ – set of all possible deployment points.

### 3.2 Model of Interaction of UAV Agents with Air Defense Agents

The content of the air defense plan for an infrastructure object should include measures to counteract the UAV group air raid. Applying a multi-agent approach, let's determine that a separate air defense (missile or artillery) unit must be assigned to each unit of attack (UAV). Thus, the overall operation of the system can be described as the interaction of UAV agents with agents of the air defense system.

Choosing the best deployment points for a defined number of air defense means selecting pairs that include:
(1) the deployment point number of the air defense facility from the set of valid deployment points and
(2) the number of air defense facility type assigned to that deployment point that maximizes a specific function of the performance criterion (evaluation).

To evaluate the effectiveness of the assignment, it is assumed that this evaluation function must consider two factors:
- potential air defense deployment points should be selected so that the distance from the point to the center of the object being defended is maximized (the earlier the enemy's air target is impacted, the less likely the mission's success is for that air target; moreover, it is possible to hit the air target repeatedly);
- the choice of the specific point of deployment of the air defense facility must take into account the effectiveness of the air target hit by the air defense facility;
- the choice of deployment points for air defense facilities should take into account the expected distribution of the attack probability, that is, the uneven appearance of UAVs in different areas on the approaches to the object.

The following function, which selects a pair (the point of deployment of the air defense facility and the specific air defense facility), meets these requirements:

$$d(j,t)=\begin{cases}\sum_{n=1}^{N} s_t p_n z_{jnt}; \left| z_{jnt} \neq -\infty;\ p_n > 0;\ \exists n=\overline{1,N}; \right. \\ -\infty; \left| \forall n=\overline{1,N}; z_{jnt} = -\infty. \right. \end{cases} \quad (6)$$

$$j \in D,\ t \in \left\{\overline{1,T}\right\}.$$

where $z_{jnt}$ – indicator of combat ability ($z_{jnt}$ = 1, if there is a possibility of targets impact in a certain area and $z_{jnt}$= $-\infty$ otherwise); $p_n$ – the probability of hitting by the enemy from $n$ direction (the UAV agent is in the zone $n$); $s_t$ – efficiency (probability of impact) of the system $t$; $N$ – the total number of impact areas by UAVs.

The choice of the best points for the deployment of air defense facilities, is based on optimization by the matrix of assignments $V=\left[v_{jt}\right]_{J\times T}$, the elements of which have the following meaning:

$$v_{jt}=\begin{cases}0, \text{air defense mean } t \text{ is not assigned to point } j; \\ 1, \text{air defense mean } t \text{ is assigned to point } j.\end{cases} \quad (7)$$

The solution to the problem is to find some matrix $V^*=\left[v_{jt}\right]_{J\times T}$, which maximizes function

$$f\left(V^*\right)=\sum_{j\in D}\sum_{t=1}^{T} v_{jt}^* d(j,t). \quad (8)$$

### 3.3 An Algorithm for Selecting the Best Points to Deploy

To solve the optimization problem (8), we propose the following algorithm for deploying air defense facilities to cover an important infrastructure object.

1. Determining the center of the defense area of an important object *S*.
2. Modeling UAV routes and identifying the most vulnerable areas of attack (formulas (2)–(5)).
3. Identification of potential UAV meeting areas by means of air defense.
4. Determination of allowable deployment points for air defense equipment.
5. Determination of effective defeat points for air targets by air defense means of specific types deployed at those points where impact of air targets is possible ($z_{jnt}$ = 1).
6. Determining the value of the evaluation function $d(j,t)$ for the following admissible pairs: the admissible points of deployment of the means and the number of the type of means of air defense in accordance with formula (6).
7. Selecting the best deployment points according to the formula (8).

### 3.4 An Example of Multi-Agent Interaction of Air Defense with UAVs

To evaluate the capabilities of the multi-agent approach, we will perform simulations according to the already considered example (Fig. 9). The results of the application of the group of $N$ = 20 UAVs and $T$ = 8 air defense systems for an object defense are shown in Fig. 10.

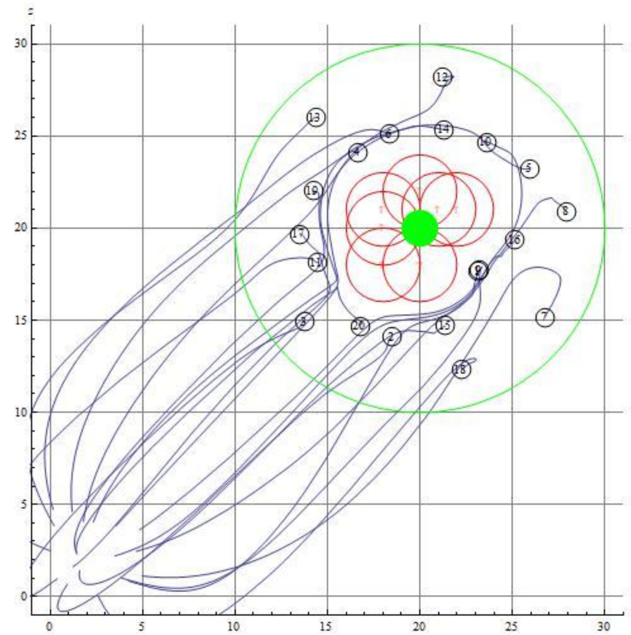

**Figure 10:** Results of air defense modeling

The start of the UAV is still in the square (0,0) (5,5), the target point has the coordinates (20,20). At the 30th step of model time, there is a distribution of a group around a target surrounded by air defenses located at points with coordinates: (18,18), (18,20), (18,21), (20,22), (22, 21), (20,18), (21,21), selected by the optimization algorithm.

This demonstrates the possibility of a multi-agent approach to planning the air defense of infrastructure. The advantage of the method is that iterations can investigate a significant number of attack options and, accordingly, choose the optimal distribution of air defense to repel the attack.

## 4. CONCLUSION

Increasing complexity of modern UAVs has led them to be increasingly used by terrorist groups for illegal activities. The general problem of planning the air cover of an important infrastructure object is the need to anticipate the actions of the UAV group in the area of the object. Air defense planning is based on the optimal deployment of air strikes against terrain. The use of a multi-agent approach makes it possible to determine the most feasible option for deploying air defense in pre-selected potential positions. Thus, on the basis of the multi-agent approach, the technique of forming a plan for air cover of a critical infrastructure object from a group of unmanned aerial vehicles is implemented.

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