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MODELING WAVES OF A STRIKE DRONES SWARM FOR A MASSIVE ATTACK ON ENEMY TARGETS

This article solves the relevant task of studying military operations on a massive wave attack by a swarm of strike drones against enemy targets in a combat zone (CZ) of a military conflict. This research solves operational and tactical tasks for planning active actions on the battlefield by applying a massive strike on enemy targets by a swarm of combat drones (kamikaze drones). Therefore, the topic of the proposed publication is relevant; it analyzes and explores the sequence of logistical military actions to plan a massive attack using waves of strike drones. The purpose of this study is to create a set of models for applied information technology that will allow planning logistical actions for the effective use of a strike drone swarm to conduct a massive wave attack on enemy targets. This article analyzes problems associated with the formation of a swarm of drones, splitting the swarm into groups, and forming waves for active combat operations on the battlefield. Enemy targets will be attacked by strike drones in the waves formation, which makes it possible to carry out further successful operational and tactical actions. This study assesses the combat capability of a swarm of drones required to defeat enemy targets in a military conflict zone. It creates a systematic representation of the sequence of actions taken to plan a massive drone swarm attack, considering the combat capability *and number of drones. With the help of military experts, the composition of the actual CZs is formed, in which the targets must be hit in the first place. The swarm of drones is rationally divided into groups that are directed to a set of targets in the CZs, considering the* combat capability *of drones to defeat targets. Waves of strike drones are planned to maximize damage to enemy targets. This research analyzes possible directions of drone movement toward enemy targets despite military threats. The models form flight routes of drones swarming to enemy targets under the conditions of possible anti-drone actions. An agent model was created using the Any Logic platform to simulate drone flight and form the routes of the drone swarm groups. This article presents an illustrated example of planning logistical actions to use waves of strike drone swarms for a massive attack on enemy targets. The scientific novelty of this study is related to solving the relevant problem of preparing and planning logistical actions for a massive attack on enemy targets using waves of strike drones by creating a set of optimization and simulation models that contribute to the effectiveness of further military attack operations on the battlefield. The results of the study could be used by military leaders to plan the use of a drone swarm to launch a massive attack on enemy targets in a military conflict zone.*

Keywords: *massive attack by a swarm of strike drones; waves of a strike drone swarm; distribution of a drone swarm into groups; planning of flight routes of a strike drone swarm; optimization planning models; agent-based simulation of drone movement.*

1. Introduction

The massive use of strike drones in local conflicts is a new innovative element that requires research to effectively plan drone attacks in modern hybrid warfare [1, 2]. The deployment of strike drones in a swarm allows for massive destruction of enemy targets and contributes to the successful implementation of operational and tactical actions of the military leadership [3, 4]. To effectively use a swarm of strike drones, it is necessary to analyze the combat capability of enemy targets, the required drone strikes, and the formation of groups of drones to attack targets [5, 6]. The large-scale use of strike drones in the form of waves can change the nature of hostilities and ensure the success of further tactical military operations on the battlefield [7, 8]. The formation of a drone swarm to defeat actual enemy targets requires new research, which contributes to their rational use in the combat zone (CZ) of a military conflict [9, 10].

Therefore, a study is proposed that uses modeling to plan the combat actions of a drone swarm to conduct a massive attack on a set of relevant enemy targets.

1.1. Motivation

The use of a drone swarm is most effective for massive destruction of enemy targets [11, 12]. Dividing a swarm of drones into groups, each of which is associated with a set of enemy targets in the CZ, contributes to the success of combat operations and ensures maximum damage to the enemy. Military

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practice has shown that planning attacks by a swarm of drones in the form of wave sequences ensures surprise and maximum damage to the enemy [13, 14]. To effectively use a swarm of drones, it is necessary to systematically analyze the set of CZs and identify the enemy's relevant targets for the next attack. The targets in each CZ are geographically localized, which contributes to the success of the attack by a group of strike drones [15, 16]. To use drones, it is necessary to assess their combat capability (combat capability, NATO terminology) to successfully defeat localized enemy targets. One of the most challenging tasks of using a swarm is to plot a flight route for a drone swarm despite possible enemy anti-drone warfare [17, 18].

Therefore, the topic of the proposed study is relevant because it models the logistics of using a drone swarm in the form of waves to deliver a massive blow to enemy targets.

1.2. State of the Art and problem statement

There are many problems associated with the effective use of drone swarms in the form of waves in modern hybrid warfare [19, 20]:

1. Formation of a drone swarm depends on the number of enemy targets [21, 22].
2. Grouping a set of strike drones to attack targets in the CZ [23, 24].
3. Planning waves of strike drones considering the completeness of defeating enemy targets [25, 26].
4. Planning and routing of strike drones to targets and their distribution into groups despite enemy anti-drone operations [27, 28].

A new innovative element of hybrid warfare in the form of a drone swarm for massive destruction of enemy targets by waves requires the development of new models and information technology research [29, 30].

Thus, the use of drone swarm waves contributes to the successful implementation of the operational and tactical plans of the military leadership on the battlefield.

1.3. Objectives and methodology

There is a contradiction between the possibilities of a drone swarm being effectively used to massively defeat enemy targets and the imperfection of existing methods and models, the lack of systematic analysis of problems related to the formation of a drone swarm, dividing them into groups, and planning waves of drone flight routes to inflict maximum damage on the enemy. This contradiction is the subject of the proposed publication, which presents models for creating an information technology to plan combat operations using waves of combat drone swarms to maximize the destruction of enemy targets.

The goal of this study is a systematic analysis of logistical actions to form a strike drone swarm, create a set of models for dividing the swarm into groups, consider the set of combat zones in which enemy targets are located, form waves of strike drones, and plan the flight routes of the strike drone swarm to the targets.

In accordance with the research goal, it is necessary to solve the following tasks:

1. Form the set of combat zones necessary to defeat enemy targets with a swarm of strike drones.
2. Divide a drone swarm into groups that are associated with multiple enemy targets in combat zones.
3. Form of waves of strike drones for massive destruction of enemy targets.
4. Create a model for planning the flight routes of strike drones to enemy targets.
5. Provide an illustrated example of modeling a massive attack by a drone swarm on enemy targets in a combat zone.

The mathematical methods and models, used to study combat operations with strike drone swarm waves, include system analysis, combinatorial methods, integer (Boolean) optimization, and agent-based simulation modeling.

2. Formation of the combat zones necessary to defeat enemy targets with a swarm of strike drones

To form a set of CZs that will be attacked by a swarm of strike drones in a field of military conflict, it is necessary that the combat capability P_M of the drone swarm exceeds the required combat capability P_Q to defeat targets in the selected CZ set ($P_M \geq P_Q$). To maximize the combat capability P_M of an strike drone swarm, it is necessary to ensure min (P_M-P_Q, $P_M \geq P_Q$). When forming the set of possible CZs to be attacked by drones, a binary counter is used to form the possible CZs. For example, the number of CZs in a military conflict zone from which it is necessary to form an optimal set to defeat relevant enemy targets with strike drones, N=4. Then, there are possible variants of the composition (variants count $S=2^N-1=15$):

1. 0001	9. 1001
2. 0010	10. 1010
3. 0011	11. 1011
4. 0100	12. 1100
5. 0101	13.1101
6. 0110	14. 1110
7. 0111	15. 1111,
8. 1000	

where «1» – means the use of the i-th CZ as part of the combat zones, the targets of which will be attacked by a swarm of drones;

«0» – otherwise.

For example, the 11th variant of the CZ composition includes the first, third, and fourth combat zones.

To find min (P_M-P_Q, $P_M \geq P_Q$), we use the integer (Boolean) programming method. Let's introduce a Boolean variable z_k:

$$z_k = \begin{cases} 1, \text{ if } k\text{-th variant of CZ composition is used;} \\ 0, \text{ otherwise.} \end{cases}$$

Taking into account z_k let's present P_Q in the form:

$$P_Q = \sum_{k=1}^{2^{N-1}} P_{Qk} z_k = \sum_{k=1}^{2^{N-1}} \sum_{i=1}^{n_k} P_{Qki} z_k, \quad (1)$$

where P_{Qk} – is the combat capability required to defeat the k-th possible CZ composition;

P_{Qki} – combat capability required to defeat targets in the i-th CZ, which is part of the k-th CZ composition;

n_k – is the number of CZs included in the k-th variant of the CZ composition.

It is necessary to minimize (P_M-P_Q, $P_M \geq P_Q$) to fully utilize the available combat capability of strike drone swarm P_M to attack enemy targets:

$$\min(P_M - P_Q) = \min(P_M - \sum_{k=1}^{2^{N-1}} P_{Qk} z_k) = \\ = \min(P_M - \sum_{k=1}^{2^{N-1}} \sum_{i=1}^{n_k} P_{Qki} z_k), \quad (2)$$

if the following conditions are met:

$$P_M \geq P_Q, \sum_{k=1}^{2^{N-1}} z_k = 1, \quad (3)$$

which means the mandatory selection of the k-th variant of the CZ composition to conduct an attack with a swarm of drones.

If the enemy will actively use anti-drone warfare, then to find a rational option for solving the min (P_M-P_Q, $P_M \geq P_Q$) problem, it is necessary to consider the risks of strike drones reaching each i-th CZ to defeat targets located there. Let us assume that the intelligence means and further analysis by military specialists of the circumstances in the CZ of a military conflict formed risk assessments (ri) of achieving targets for each i-th CZ. Then, the risk (R_k) of achieving the goals in the k-th composition of CZ will be:

$$R_k = \sum_{i=1}^{n_k} r_{ki}. \quad (4)$$

The final risk (R):

$$R = \sum_{k=1}^{2^{N-1}} R_k z_k = \sum_{k=1}^{2^{N-1}} \sum_{i=1}^{n_k} r_{ki} z_k. \quad (5)$$

It is necessary to minimize (P_M-P_Q, $P_M \geq P_Q$), considering the risks of reaching the targets by a swarm of drones:

$$\min(P_M - \sum_{k=1}^{2^{N-1}} \sum_{i=1}^{n_k} P_{Qki} z_k), \quad (6)$$

if the following conditions are met:

$$R \leq R', R = \sum_{k=1}^{2^{N-1}} \sum_{i=1}^{n_k} r_{ki} z_k, \quad (7)$$

$$R_M \geq R_Q, \sum_{k=1}^{2^{N-1}} z_k = 1, \quad (8)$$

where R' – acceptable risk of reaching the enemy's targets.

3. Dividing a swarm of strike drones into groups associated with a set of enemy targets in combat zones

To conduct a massive strike in the combat zones of a military conflict, where enemy targets are concentrated, using a swarm of strike drones, the combat capability of the drone swarm must exceed the necessary combat capability to defeat enemy targets ($P_M \geq P_Q$). To do this, we will use the combat characteristics of each j-th drone: drone flight range (l_j), combat capability (p_j), to reach the targets in the i-th CZ by the j-th drone (t_{ij}). The set of drones used to create a drone swarm can include different types of drones. The division of drone swarms into groups will be made by considering the CZs to which the drone groups will be sent. To divide the set of drones into groups, we use the method of integer (Boolean) programming. Let's introduce variable x_{ij}, which takes the following values:

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$$x_{ij} = \begin{cases} 1, \text{ if } & \text{j-th drones is used in i-th group;} \\ 0, \text{ otherwise.} \end{cases} \quad (9)$$

Then, considering the combat capability of the drones, for each i-th group of drones that is used to defeat targets in the i-th CZ, the combat capability of the group will be:

$$P_{Mi} = \sum_{j=1}^{M} p_j x_{ij}, \quad (10)$$

where M – number of strike drones allocated for the attack.

When creating the i-th group of drones, it is necessary that the combat capability $P_{Mi} \geq P_{Qi}$, where P_{Qi} – combat capability required for massive destruction of targets in the i-th CZ.

When forming the i-th group of strike drones, it is necessary to consider the parameters l_j, t_{ij} for each j-th drone that is used in the group.

One of the important factors for effective combat operations using a swarm of drones is the time (T), which must be minimized to ensure the success of a sudden massive attack by combat drones on enemy targets. Therefore, it is necessary to find:

$$\min T, T = \sum_{i=1}^{N} \sum_{j=1}^{M} t_{ij} x_{ij}, \quad (11)$$

where N – number of CZs in the area of military conflict.

To find minT, the following restrictions must be taken into account:

$$P_{Mi} \geq P_{Qi}, P_{Mi} = \sum_{j=1}^{M} p_j x_{ij}, i = \overline{1, N},$$
$$\sum_{i=1}^{N} x_{ij} = 1, j = \overline{1, M}. \quad (12)$$

4. Formation of strike drone waves for massive enemy target destruction

The enemy's use of anti-drone weapons makes it difficult to completely defeat selected targets and leads to partial (incomplete) defeat of targets. In such cases, a second massive strike using a swarm of drones is needed. Therefore, waves of strike drones are introduced. The number of waves depends on the complete destruction of the enemy targets. To form new groups of drone swarms and distribute them to the targets remaining in the i-th CZ, for each k-th wave it is necessary to:

$$P'_{Mik} \geq P'_{Qik}, \quad (13)$$

where P'_{Mik} – is the combat capability of the i-th group of drones required to defeat the targets remaining in the i-th CZ for the k-th wave of the drone swarm launch;

P'_{Qik} – combat capability required to defeat the targets remaining in the i-th CZ for the k-th wave of the drone swarm launch.

Values P'_{Mik}, P'_{Qik} are formed with the help of military specialists after receiving data on the number of affected drones and the state of enemy targets that are not completely affected. They are formed by military specialists based on intelligence data (for example, with the help of reconnaissance drones), as well as data based on operational circumstances in the combat zone after an attack.

It is necessary to minimize the time required for drone swarms to reach the remaining targets in the area of military conflict for the k-th wave of drone launch:

$$\min T_k, T_k = \sum_{i=1}^{N_k} \sum_{j=1}^{M_k} t_{ij} x_{ij}, \quad (14)$$

where T_k – the time required to reach the targets in the k-th wave of the drone swarm launch;

N_k – the number of targets left to be destroyed in the k-th wave of drone launch;

M_k – is the set of drones that will be used in the k-th wave of strike drone launch.

To determine the distribution of the drone swarm in the k-th wave into groups to defeat the targets remaining in the i-th CZ, the following requirements must be met:

$$P'_{Mik} \geq P'_{Qik}, P'_{Mik} = \sum_{j=1}^{M_k} p_j x_{ij}, i = \overline{1, N_k}, \quad (15)$$

$$\sum_{i=1}^{N_k} x_{ij} = 1, j = \overline{1, M_k}. \quad (16)$$

The number of waves $k = \overline{1, V}$ depends on the ability of the military leadership to form a set of drones M_k to re-engage targets remaining in the CZ of the military conflict, as well as on the planned operational and tactical decisions on the battlefield at the moment.

When forming waves of drone launches, it is necessary to consider the fact that the enemy may intensify anti-drone operations. In this case, it is necessary to use the risks of reaching the enemy's targets as an optimization indicator for dividing a swarm of drones into groups. Therefore, we minimize the risks of reaching the targets with strike drones in the k-th wave:

$$\min R_k, R_k = \sum_{i=1}^{N_k}\sum_{j=1}^{M_k} r_{ij} x_{ij}, \quad (17)$$

where r_{ij} – is the possible risk of reaching the target in the i-th CZ by the j-th strike drone.

When optimizing risks, the following requirements should be taken into account:

$$P'_{Mik} \geq P'_{Qik}, P_{Mik} = \sum_{j=1}^{M_k} x_{ij} p'_j, k = \overline{1, N_k},$$
$$\sum_{i=1}^{N_k} x_{ij} = 1, j = \overline{1, M_k}. \quad (18)$$

5. Strike drones flight routes modeling

When planning the movement of a drone swarm to the CZ, where the enemy's actual targets are located, it is necessary to consider the division of the swarm into groups. To do this, mark the flight zones (FZ) in which the swarm will be divided into groups. This division can be performed several times along the drone's flight route. This leads to the challenging task of forming flight routes for a drone swarm, considering its division into groups. To solve this problem, we use simulation event modeling. The main events in the simulation modeling are as follows:

1. Launching a swarm of strike drones (launch).
2. Reaching the distribution zone by a swarm (distribution zone).
3. Dividing a swarm of drones into groups (splitting).
4. Reaching enemy targets by a group of drones (defeat).

To plot a flight route for a swarm of strike drones, it is necessary to form a set of flight zones in the form of a map with navigation points for flight control and possible route changes. At the same time, it is necessary to consider the possible emergence of military threats and the use of anti-drone weapons by the enemy. Therefore, we need such auxiliary events as:

5. The swarm (group) reaches the flight control zone (control).
6. Emergence of a threat (threat).
7. Change of route (change).

To create a simulation event model, the Any Logic agent-based modeling platform is used, in which the next agents were created:

1. Flight zone set formation agent (formation).
2. A drone movement sequencing agent based on flight zones (route).
3. Drone swarm launch agent (launch).
4. A swarm agent for reaching the zone of division into groups (division).
5. Swarm division agent for dividing a swarm of drones into groups (splitting).
6. Enemy target destruction agent in CZ (destruction).
7. Reaching the control zone by a swarm of drones' agent (control).
8. Threat agent (threat).
9. Route change agent (change).
10. Modeling control agent (management).
11. An agent for collecting statistics based on the results of modeling (statistics).

To simulate the occurrence of a threat, the model uses a random generator with different distribution laws of random variables. Therefore, to generate modeling results and their statistical averaging, it is necessary to conduct multiple simulations. Fig. 1 shows a block diagram of the agent model.

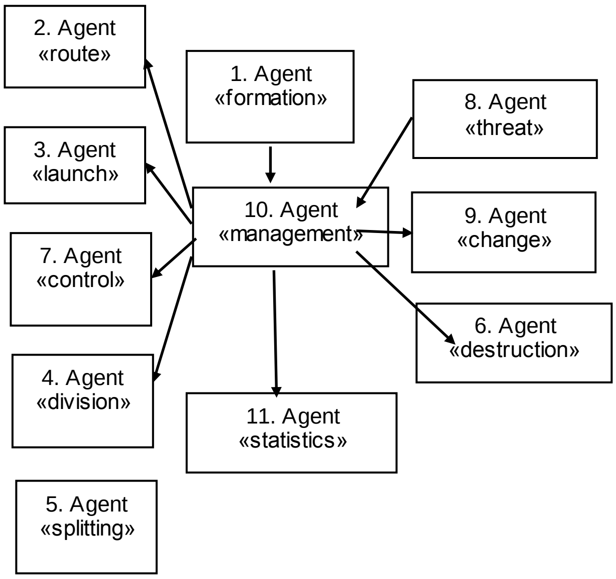

Fig. 1. Block diagram of the agent model

The modeling output has the following results:

1. Flight routes of strike drone groups to enemy targets.
2. The time required to reach the enemy targets (including each possible wave of drone launches).
3. The impact of threats on flight times and changes in flight routes.
4. Number of strike drone waves to destroy enemy targets.
5. The required number of strike drones to destroy enemy targets (taking into account waves).

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The developed agent-based simulation model [31] allows the prediction and planning of combat actions of a strike drone swarm for a massive attack on enemy targets in the combat zones of a military conflict.

6. An illustrated example of modeling

The illustrated example demonstrates the effectiveness of the proposed approach for planning a drone swarm attack on enemy targets. Suppose the set of CZs in a military conflict consists of three CZs. Then, the number of possible CZ composition variants for using a massive attack (see p.2) $S=2^N-1=2^3-1=7$.

For each i-th CZ, the combat capability of P_{Qi} (Table 1), which is necessary to defeat targets in the i-th CZ, was previously estimated by conducting reconnaissance. Five identical strike drones (M=5) with a total combat capability of P_M=30kg of explosives (six kg per drone) were allocated to conduct a massive attack on enemy targets in conditions of limited capabilities.

To ensure the maximum use of the combat capability of the allocated strike drone set, considering the combat capability required to defeat enemy targets, we search for min (P_M-P_{Qk}), where $P_M \geq P_{Qk}$ (see p. 2). The minimum difference value in combat capabilities, for the selected set of drones (M = 5), considering the difference values in Table 1, corresponds to the 3rd variant of the CZ composition, in which the second and third CZ of the military conflict are used to attack enemy targets with a swarm of strike drones ($P_M > P_{Q3}$, $P_M - P_{Q3} = 2$). Note that the 5th and 7th variants of the CZ composition cannot be used for drone attacks because $P_M < P_{Q5}$, $P_M < P_{Q7}$.

Table 1

Combat capability

№	CZ composition variant	The required combat capability for destruction (P_{Qk})	Difference in combat capabilities (P_M-P_{Qk})
1	001	12	18
2	010	16	14
3	011	28	2
4	100	20	10
5	101	32	-2
6	110	18	12
7	111	48	-18

The elected CZs consisted of two CZs (the second and third). Therefore, to attack targets in these CZs, it is necessary to form two groups of strike drones from the swarm (see p.3). We consider that drones in a swarm are identical, so to meet the requirements $P_{m2} \geq P_{Q2}$, $P_{m3} \geq P_{Q3}$, corresponding to the superiority of the combat capability of drones over enemy targets, we will form the number of drones to defeat the targets of the second CZ m_2=3 (P_{m2}=18, P_{Q2}=16, P_{m2}-P_{Q2}=2), and for the third CZ the number of drones m_3=2 (P_{m3}=12, P_{Q3}=12, P_{m3}-P_{Q3}=0), where is the number of allocated strike drones $M=m_2+m_3=5$.

Next, it is necessary to plan the flight of the drone swarm to two selected CZs to defeat enemy targets (see p.5). To do this, we will form a map of drone flights in the shape of a flight zones set in which we will conduct flight control and possible division of a strike drone swarm into groups. Fig. 2 shows, in the form of a graph G, a set of drone flight zones (the vertices of the graph G correspond to control points, and the edges correspond to possible flight paths).

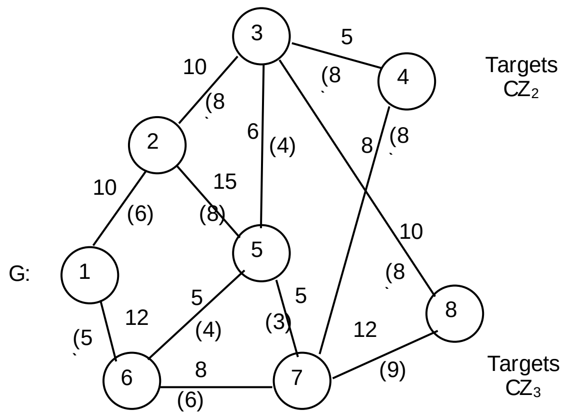

Fig. 2. Formation of strike drone swarm flight routes

Each edge of the graph G is estimated by the time t_{ij} of the drone flight between the i-th and j-th flight control points (in minutes):

$$t_{12}=10,\ t_{23}=10,\ t_{34}=5,\ t_{25}=15,\ t_{53}=6,\ t_{16}=12,\ t_{65}=5,\ t_{57}=5,\ t_{38}=10,\ t_{74}=8,\ t_{78}=12,\ t_{67}=8.$$

The swarm of drones will be divided into two groups to fly to the targets in CZ_2 and CZ_3 in flight zone 5. Movement up to the 5th flight zone, considering the minimum time (minT), corresponds to the found route: 1-6-5 (T=17). Then, after the drone swarm is divided, one group of drones (m_2=3) moves to CZ_2. For this group, minT corresponds to the route: 5-3-4 (T=11). The second drone group (m_3=2) flies to CZ_3. For this group, minT corresponds to the route: 5-3-8 (T=16).

Let's say that after the drone attack, not all enemy targets in CZ_2 were hit. The enemy still has a combat capability that needs to be destroyed by drones P'_{Q2}=8. To defeat the remaining enemy targets, it is necessary to form a second wave of strike drones in the form of a group of two drones (P'_{m2}=12, $P'_{m2} > P'_{Q2}$, P'_{m2}-P'_{Q2}=4) (see p.4).

To minimize the flight time (minT) of strike drones, which is important in the context of intensified enemy anti-drone warfare, it is necessary to fly drones along the following route: 1-2-3-4 (T=25). To find the minimum flight time of strike drones (minT), we will use the original algorithm for minimizing the movement time, which is presented in the publication [30]. If new conditions increase the risk of strike drone flights to enemy targets, it is necessary to assess the possible risks of flight routes before launching drones (risks are presented in column G in brackets with points 0-10):

r_{12}=6, r_{23}=8, r_{34}=8, r_{25}=8, r_{53}=4, r_{16}=5, r_{65}=4, r_{57}=3, r_{38}=8, r_{74}=8, r_{78}=9, r_{67}=6.

To find a route with minimal risks of strike drone flight to targets in CZ_2 (minR), we will use the developed algorithm presented in [30]. The following flight routes were found with minimal risk of strike drone flights to targets: 1-6-7-4 (R=19)

7. Discussion

This article presents an example to demonstrate the effectiveness of the proposed approach for planning military operations using swarm waves of strike drones. The analysis of combat zones (CZs) is carried out, and possible CZ compositions are formed for planning an attack by strike drones. An example finds the optimal composition of the CZ, considering the value of the required combat capability of attack drones to defeat enemy targets. This study generates a set of drone flight control zones in the form of a flight control map and possible division of the swarm into groups. It models the flight routes of drone groups to enemy targets in the CZ. It is shown that one wave of attack drones was not enough, so a second wave was formed. Due to the enemy's active anti-drone warfare, a new flight route to enemy targets was found with minimal risk of military threats.

The use of a logically linked model complex allows planning of the combat actions of a strike drone swarm for wave attacks on enemy targets in a military conflict zone.

A formal representation of the methodology used to plan combat operations for a massive attack by waves of combat drones against enemy targets consists of the following steps:

1. Formation of possible combat zone compositions for rational selection of attack directions by a swarm of strike drones.
2. Optimizing the division of the swarm into groups that will fly toward enemy targets in designated combat zones.
3. Plotting flight routes for strike drones, minimizing the time to reach enemy targets, in the context of anti-drone warfare.
4. Formation of strike drone waves for complete destruction of enemy targets.
5. Simulation of massive wave attack by strike drones on enemy targets.

The complex of developed models was implemented on the Any Logic agent platform using interactive simulation of the main events related to the planning of a drone attack. The results of this study are relevant for the military in the context of modern hybrid warfare, in which a swarm of strike drones is an innovative element. This makes it possible to plan a massive strike on enemy targets using waves of strike drones.

Future research will focus on the creation of applied information technology for military specialists. It will work on the operational and tactical levels of planning combat operations using a swarm of strike drones. The next focus will be the formation of relevant flight routes to enemy targets, which will contribute to the effectiveness of combat operations on the battlefield.

8. Conclusions

This study focuses on the modeling of combat operations in the form of a massive attack on enemy targets using waves of strike drone swarms.

This article analyzes existing problems associated with the formation of a drone swarm and optimization of the CZ composition for a massive attack by a drone swarm. This study creates a systematic representation of the logistics sequence for planning a massive attack by a swarm of strike drones. It generates relevant enemy targets in combat zones that need to be hit by a drone swarm. The swarm of strike drones was rationally divided into groups, considering the necessary combat capability to defeat enemy targets. Drone flight routes were selected for combat zones to minimize time and risks. Waves of strike drones were formed to inflict maximum damage on the enemy. This article models the movement of strike drones under the conditions of enemy anti-drone warfare. It provides an illustrated example of drone swarm waves usage to defeat enemy targets in combat zones.

The proposed approach allows us to analyze the capabilities of a strike drone swarm to be used in massive wave attacks on enemy targets, which contributes to effective military operations on the battlefield.

Contribution of authors: a systematic representation of the logistics sequence for a massive wave attack on enemy targets by a swarm of strike drones – **Oleg Fedorovych**; selection of relevant combat zones for a massive attack by groups of strike drones – **Dmytro Krytskyi**; distribution of drones by enemy targets, taking into account the combat capability of strike drones – **Oleksandr Leshchenko**; agent-based simulation of a massive attack by strike drones – **Olena Yashina**; illustrated example of modeling – **Yuliia Malieieva**.

Conflict of interest

The authors declare that they have no conflict of interest in relation to this research, whether financial, personal, authorship, or otherwise, that could affect the research and its results presented in this paper.

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Data availability

The manuscript contains no associated data.

Use of Artificial Intelligence

The authors confirm that they did not use artificial intelligence methods while creating the presented work.

All the authors have read and agreed to the published version of this manuscript.

References

1. Yaacoub, Jp A., Noura, H., Salman, O., & Chehab, A. Security analysis of drones systems: Attacks, limitations, and recommendations. *Internet of Things*, 2020, vol. 11, article 100218. 39 p. DOI: 10.1016/j.iot.2020.100218

2. Chen, W., Zhu, J., Liu, J., & Guo, H. A fast coordination approach for large-scale drone swarm. *Journal of Network and Computer Applications*, 2024, vol. 221, iss. 103769, 12 p. DOI: 10.1016/j.jnca.2023.103769.

3. Orfanus, D., De Freitas, E. P., & Eliassen, F. Self-organization as a supporting paradigm for military UAV relay networks. *IEEE Communications letters*, 2016, vol. 20(4), pp. 804-807. DOI: 10.1109/LCOMM.2016.
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4. Chen, W., Liu, J., Guo, H., & Kato, N. Toward robust and intelligent drone swarm: Challenges and future directions. *IEEE Network*, 2020, vol. 34(4), pp. 278-283. DOI: 10.1109/MNET.001.1900521.

5. Tahir, A., Böling, J., Haghbayan, M. H., Toivonen, H. T., & Plosila, J. Swarms of unmanned aerial vehicles—A survey. *Journal of Industrial Information Integration*, 2019, vol. 16, iss. 100106. 7 p. DOI: 10.1016/j.jii.2019.100106.

6. Tian, W., Zhao, Y., Hou, R., Dong, M., Ota, K., Zeng, D., & Zhang, J. A Centralized Control-Based Clustering Scheme for Energy Efficiency in Underwater Acoustic Sensor Networks. *IEEE Transactions on Green Communications and Networking*, 2023, vol. 7, iss. 2, pp. 668-679. DOI: 10.1109/TGCN.2023.3249208.

7. Prymirenko, V., Demianiuk, A., Shevtsov, R., Bazilo, S., & Steshenko, P. The impact of the joint use of false aircraft targets in a group of combat unmanned aerial vehicles on the results of destruction. *Radioelectronic and Computer Systems*, 2022, vol. 3, pp. 132-140. DOI: 10.32620/reks.2022.3.10.

8. Wang, F., Huang, J., Low, K.H., Nie, Z., & Hu, T. AGDS: adaptive goal-directed strategy for swarm drones flying through unknown environments. *Complex Intell. Syst.*, 2023, vol. 9, pp. 2065-2080. DOI: 10.1007/s40747-022-00900-9.

9. Liu, C., Sun, S., Tao, C., Shou, Y., & Xu, B. Sliding mode control of multi-agent system with application to UAV air combat. *Computers & Electrical Engineering*, 2021, vol. 96, part A, article no. 107491. 13 p. DOI: 10.1016/j.compeleceng.2021.107491.

10. Wu, Y., Wu, S., & Hu, X. Multi-constrained cooperative path planning of multiple drones for persistent surveillance in urban environments. *Complex & Intelligent Systems*, 2021, vol. 3, pp. 1633-1647. DOI: 10.1007/s40747-021-00300-5.

11. Kritsky, D. N., Ovsiannik, V. M., Pogudina, O. K., Shevel, V. V., & Druzhinin, E. A. Model for intercepting targets by the unmanned aerial vehicle. In Advances in Intelligent Systems and Computing, 2020, vol. 1019, pp. 197-206. DOI: 10.1007/978-3-030-25741-5_20.

12. Jawad, Y., Hashem, H., Jukka, H., Hannu, T., & Juha, P. Formation Maintenance and Collision Avoidance in a Swarm of Drones. *3rd International Symposium on Computer Science and Intelligent Control*, 2019, pp. 1-6. DOI: 10.1145/3386164.3386176.

13. Sabziev, E. A control algorithm for joint flight of a group of drones. *Scientific Journal of Silesian University of Technology. Series Transport*, 2021, vol. 110, pp. 157-167. DOI: 10.20858/sjsutst.2021.110.13.

14. He, D., Yang, G., Li, H., Chan, S., Cheng, Y. & Guizani, N. An effective counter measure against UAV swarm attack. *IEEE Network*, 2020, vol. 35, iss. 1, pp. 380-385. DOI: 10.1109/MNET.011.2000380.

15. Chamola, V., Kotesh, P., Agarwal, A., Naren Gupta, N., & Guizani, M. A comprehensive review of unmanned aerial vehicle attacks and neutralization techniques. *Ad hoc Netw*, 2021, vol. 111, article no. 102324. 20 p. DOI: 10.1016/j.adhoc.2020.102324.

16. Shahid, S., Zhen, Z., Javaid, U., & Wen, L. Offense-Defense Distributed Decision Making for Swarm vs Swarm Confrontation While Attacking the Aircraft Carriers. *Drones*, 2022, vol. 6, iss. 10, article no. 271. 21 p. DOI: 10.3390/drones6100271.

17. Yan, J., Xie, H., & Li, J. Modeling and optimization of deploying anti-UAV swarm detection

systems based on the mixed genetic and monte carlo algorithm. *IEEE International Conference on Unmanned Systems*, 2021, pp. 773-779. DOI: 10.1109/ICUS52573.2021.9641465.

18. Zhao, J., Zhang, J., Li, D., & Wang, D. Vision-based anti UAV detection and tracking. *IEEE Transactions on Intelligent Transportation Systems*, 2022, vol. 23, iss. 12, pp. 25323-25334. DOI: 10.48550/arXiv.2205.10851.
19. Chen, Y., Zhang, H., Fu, X., & Xu, J. Robustness analysis and modeling of UAV cluster system based on complex network. *2nd International Conference on Computer Science, Electronic Information Engineering and Intelligent Control Technology*, 2022, pp. 743-748. DOI: 10.1109/CEI57409.2022.9950164.
20. Lappas, V., Shin, H-S., Tsourdos, A., Lindgren, D., Bertrand, S., Marzat, J., Piet-Lahanier, H., Daramouskas, Y., & Kostopoulos, V. Autonomous Unmanned Heterogeneous Vehicles for Persistent Monitoring. *Drones*, 2022, vol. 6, iss. 4, article no. 94. 27 p. DOI: 10.3390/drones6040094.
21. Carli, R., Cavone, G., Epicoco, N., Di Ferdinando, M., Scarabaggio, P., & Dotoli, M. Consensus-based algorithms for controlling swarms of unmanned aerial vehicles. *International Conference on Ad-Hoc Networks and Wireless, Lecture Notes in Computer Science*, 2020, vol. 12338, pp. 84-99. DOI: 10.1007/978-3-030-61746-2_7.
22. Fan, D. D., Theodorou, E. A., & Reeder, J. Model-based stochastic search for large scale optimization of multi-agent UAV swarms. *IEEE Symposium Series on Computational Intelligence*, 2018, pp. 2216-2222. DOI: 10.48550/arXiv.1803.01106.
23. Sanders, A. W. *Drone swarms*. US Army School for Advanced Military Studies Fort Leavenworth United States: Fort Leavenworth, 2017, KS, USA. 40 p. Available at: https://apps.dtic.mil/sti/citations/AD1039921 (accessed 12.12.2023).
24. Tianfeng, F., Xiaojing, M., & Chi, Z. Development status of anti UAV swarm and analysis of new defense system. *Journal of Physics: Conference Series*, 2023, vol. 2478, iss. 9. 14 p. DOI: 10.1088/1742-6596/2478/9/092011.
25. Xu, Z., Hao, F., Wang, Y., & Bai, Y. Swarm Operation System and Its Intelligent Development. *Journal of Physics: Conference Series*, 2023, vol. 2460, article no. 012148. 7 p. DOI: 10.1088/1742-6596/2460/1/012148.
26. Li, J., Rombaut, E., & Vanhaverbeke, L. A systematic review of agent-based models for autonomous vehicle sin urban mobility and logistics: Possibilities for integrated simulation models. *Computers, Environment and Urban Systems*, 2021, vol. 89, article no. 101686. 20 p. DOI: 10.1016/j.compenvurbsys.2021.101686.
27. Pasek, P., & Kaniewski, P. A review of consensus algorithms used in Distributed State Estimation for UAV swarms. *IEEE 16th International Conference on Advanced Trends in Radioelectronics, Telecommunications and Computer Engineering (TCSET)*, 2022, pp. 472-477. DOI: 10.1109/TCSET55632.2022.9766903.
28. Phadke, A., Medrano, F. A., Sekharan, C. N., & Chu, T. Designing UAV Swarm Experiments: A Simulator Selection and Experiment Design Process. *Sensors*, 2023, vol. 23, iss. 17, article no. 7359. DOI: 10.3390/s23177359.
29. Blais, M.-A., & Akhloufi, M. A. Reinforcement learning for swarm robotics: An overview of applications, algorithms and simulators. *Cognitive Robotics*, 2023, vol. 3, pp. 226-256. DOI: 10.1016/j.cogr.2023.07.004.
30. Fedorovich, O., Lukhanin, M., Prokhorov, O., Slomchynskyi, O., Hubka, O., Leshchenko, Y. Simulation of arms distribution strategies by combat zones to create military parity of forces. *Radioelectronic and Computer Systems*, 2023, vol. 4, pp. 209-220. DOI: 10.32620/reks.2023.4.15.
31. Schiffmann, O., Hicks, B., Nassehi, A., Gopsill, J., Valero, M. A Cost–Benefit Analysis Simulation for the Digitalisation of Cold Supply Chains. *Sensors*, 2023, vol. 23, article no. 4147. DOI: 10.3390/s23084147.

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МОДЕЛЮВАННЯ ХВИЛЬ РОЮ УДАРНИХ ДРОНІВ ДЛЯ ПРОВЕДЕННЯ МАСОВАНОЇ АТАКИ ПО ЦІЛЯХ ПРОТИВНИКА

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Формується та вирішується актуальна задача дослідження військових дій щодо масованої хвильової атаки роєм ударних дронів по цілях противника в зоні бойових дій (ЗБД) воєнного конфлікту. Дослідження, яке проводиться, пов’язане з вирішенням оперативно-тактичних завдань щодо планування активних дій на полі бою шляхом нанесення по цілях противника масованого удару роєм бойових дронів (дрони-камікадзе). Тому, актуальна тема запропонованої публікації, в якій аналізується та досліджується послідовність логістичних військових дій, щодо планування масованої атаки за допомогою хвиль ударних дронів. Метою дослідження є створення комплексу моделей для прикладної інформаційної технології, яка дозволить планувати логістичні дії щодо ефективного використання рою ударних дронів для проведення масованої хвильової атаки по цілях противника. Аналізуються проблеми, які пов’язані з формуванням рою дронів, розбиттям рою на групи, формування хвиль для проведення активних бойових дій на полі бою. Цілі противника будуть атаковані ударними дронами у вигляді хвиль, що дає спроможність проводити подальші успішні оперативно-тактичні дії.. Оцінюється бойовий потенціал рою дронів, необхідний для ураження цілей противника в зоні воєнного конфлікту. Створюється системне представлення послідовності проведених дій щодо планування масованої атаки рою дронів з урахуванням бойового потенціалу та кількості дронів. За допомогою військових фахівців формується склад актуальних ЗБД, в яких необхідно вразити цілі у першу чергу. Проводиться раціональний розподіл рою дронів на групи, які будуть спрямовані в множину цілей в ЗБД, з урахуванням бойового потенціалу дронів для їх ураження. Плануються хвилі ударних дронів для максимального ураження цілей противника. Аналізуються можливі напрямки руху дронів до цілей противника, в умовах військових загроз. Формуються маршрути польоту рою дронів до цілей противника в умовах можливих протидронових дій. Створюється агентна модель на платформі AnyLogic для імітації польоту дронів та формування маршрутів груп рою дронів. Наведено ілюстрований приклад планування логістичних дій щодо використання хвиль рою ударних дронів для масованої атаки по цілях противника. Наукова новизна дослідження пов'язана з вирішенням актуальної проблеми підготовки та планування логістичних дій щодо проведення масованої атаки по цілях противника, за допомого хвиль ударних дронів, шляхом створення комплексу оптимізаційних та імітаційної моделей, що сприяє ефективності проведення подальших військових атакуючих дій на полі бою. Результати дослідження доцільно використовувати військовим керівництвом щодо планування використання рою дронів для нанесення масованого удару по цілях противника в зоні воєнного конфлікту.

Keywords: масована атака роєм ударних дронів; хвилі рою ударних дронів; розподіл рою дронів за групами; планування маршрутів польоту рою ударних дронів; оптимізаційні моделі планування; агентне імітаційне моделювання руху дронів.

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