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MANAGEMENT OF MONITORING AND CONTROL PROCESSES IN INNOVATIVE PROJECTS OF UAV PARAMETERIZATION AND SWARM FLIGHT: MODELS, STRATEGIES, ADAPTIVE SOLUTIONS

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Within the framework of managing innovative projects for the development of autonomous aviation systems, a comprehensive approach to the parameterization of unmanned aerial vehicles (UAVs) and the creation of group flight control models in swarm structures has been investigated. The aim of the work is to ensure the effective and safe operation of UAVs in a swarm by calculating their parameters and controlling group flight in a changing air environment based on a mathematical and knowledge-oriented model. The following tasks are addressed: analysis of autonomy levels, identification of critical parameters of devices, modeling of airspace with conflict assessment, and construction of airspace ontology. Analyze the levels of autonomy and control in a UAV swarm; determine the key parameters of UAVs that affect their interaction; build a mathematical model of airspace taking into account potential conflicts; develop an ontological model of airspace zones taking into account accessibility categories and restrictions. Results: The main focus is on the formation of design solutions for autonomous interaction between devices, multi-level control in a swarm, and air environment modeling. Mathematical models and a knowledge-based database have been developed to support innovative solutions for the safe operation of UAVs in dynamic environments. The results can be integrated into innovation management programs in the field of defense technologies, aviation design, and intelligent transport systems..

Introduction

Unmanned aerial vehicles (UAVs) have been in increasing demand in recent years for civil, commercial, and military applications. In military applications in particular, drones are becoming an integral part of the future battlefield [1]. Due to the limitations of the payload and energy of a single aircraft, it has been proposed to deploy swarms of drones for a variety of applications with higher mission requirements, which is changing their future application [2]. Drone swarms perform missions jointly and have the potential for rapid deployment and coverage that goes beyond the individual capabilities of single units. Currently, the number of simultaneous drone missions is estimated to be in the tens or hundreds.

The large-scale use of drones is a new innovative element of modern hybrid warfare. The formation of strike drones into swarms, the planning of their missions in waves, and the provision of adaptive control and coordination allow for the mass destruction of relevant enemy targets and contribute to the successful execution of operational and tactical actions by military leadership. The urgency of these issues is caused by the current military and political realities in Ukraine and corresponds to urgent state priorities and needs.

In the current conditions of rapid development of autonomous systems, there is a growing need for effective management of group flights of unmanned aerial vehicles [3]. Such swarm structures allow for monitoring, search, mapping, and reconnaissance tasks to be performed with minimal operator intervention. However, the effective organization of a UAV swarm requires clear structuring of the aircraft, determination of their technical and functional parameters, and the construction of interaction models in a complex, changing air environment.

New adaptive and intelligent methods for planning and controlling combat drones are one of the most important components of modern hybrid warfare, allowing for increased military effectiveness in conditions of limited time and increased risk.

The intensive development of UAVs and the expansion of their areas of application, particularly in the military sector, requires the introduction of innovative solutions in the field of complex technological systems management. One promising area is the use of UAV swarm systems, where a group of autonomous devices performs joint tasks based on distributed interaction. Effective management of such systems requires coordinated models for parameterization, data exchange, decision-making under uncertainty, and the ability to adapt to a dynamic environment.

One of the key challenges is the formalization of models of autonomy, control levels, and interaction scenarios for UAVs within a swarm. At the same time, it is necessary to model the airspace, taking into account potential conflicts and restricted access zones. To support adaptive planning and decision-making in conditions of many variables, an approach is used to construct an ontological model of flight zone categories.

In view of this, there is a need to develop a comprehensive approach to managing innovative projects related to the development of UAV swarm systems. Such projects combine elements of system analysis, mathematical modeling, engineering design, and knowledge-based technologies. The creation of an effective group flight model that takes into account changes in the air environment, potential conflicts, and restrictions on airspace availability allows for high mission efficiency.

The development of mathematical and ontological models within such projects allows for the optimization of planning, monitoring, and management processes for innovative developments in the field of autonomous aviation systems. At the same time, ensuring the safety and reliability of swarm solutions is a critically important step on the path to the practical implementation of such technologies. That is why research aimed at parameterizing UAVs and formalizing group flight control models is an important component of strategic management of innovative development in high-tech industries.

1. Analysis of autonomy, control levels, and interaction of UAVs in a swarm

The autonomy of UAVs is a measure of independence from external influences and the level of self-organization [4, 5] (Table 1). The first three levels (from 0 to 2) correspond to UAVs that require constant human operator involvement. They use systems that facilitate control, but constant analysis of the external situation is necessary. Levels 3–5 of autonomy correspond to UAVs that are already capable of moving independently and analyzing data obtained from the environment. Control of level 3 and 4 drones can be transferred to a human operator if necessary, while level 5 corresponds to UAVs that operate exclusively in autonomous mode.

Table 1

Levels of UAV autonomy

Level of autonomy	0	1	2	3	4	5
Degree of automation	None	Low	Part	Conditional	High	Full
Avoiding obstacles	None	Recognize and warn		Recognize and avoid	Recognize and orient	

Let’s consider the levels of UAV autonomy and how the implementation of autonomous UAV control looks in practice:

Level 0. No automation. The pilot has complete control over every movement. The platforms are constantly monitored 100% manually.

At zero autonomy, no function is performed by the drone independently. All tasks, including maintaining altitude and the required flight speed, are the sole responsibility of the operator. Such UAVs are very rare and are not intended for swarm use. They are mainly used for racing or are the simplest UAVs loaded with cameras for photo or video recording. Only an experienced operator can successfully control such a drone.

Practical application: UAVs for model aircraft.

Level 1. Pilot assistance. The pilot remains in control of the overall operation and safety of the UAV. However, the UAV may take over at least one vital function for a certain period of time.

The first level of autonomy involves the UAV performing only basic functions, such as automatically maintaining altitude or flight speed. Satellite or inertial navigation aids may be integrated into the control system, with data from these being analyzed by the operator or a ground station. All key flight phases, from takeoff to landing, remain under human control. Drones at this level may be equipped with sensors and cameras, but are not capable of processing the information they receive independently. They support GNSS for flight stabilization, while all inputs in terms of course, altitude, and speed are made manually. At this level, collision detection and avoidance functions are available to warn the pilot of nearby UAVs and other obstacles, but some functions depend on manual control by the pilot. Due to their limited capabilities, swarm systems cannot be created with these UAVs.

Applications: Mainly used for entertainment purposes, surveillance, photography, and videography. Or used to obtain simple recreational photos and videos.

Military applications: localization and detection, photography and videography, protection and monitoring.

Level 2. Partial automation. The pilot is still responsible for safe operation and must be ready to take control of the UAV if something happens. However, under certain conditions, the UAV can take control of the course, altitude, and speed. The pilot monitors the airspace, flight conditions, and responds to emergencies. Currently, most manufacturers are developing UAVs at this level, where the platform can assist with navigation functions and allow the pilot to relinquish some of their tasks.

At the second level of autonomy, the UAV is capable of performing certain functions without operator intervention, such as stabilizing its position, following a predetermined route, or keeping an object in the frame. However, overall flight control and decision-making remain with the human operator. Data from navigation systems (GPS, inertial sensors) can already be processed partially automatically, but tasks such as obstacle avoidance still require operator intervention.

Practical application: a pre-programmed flight path is loaded onto the autopilot and the UAV begins to perform tasks along these trajectories after takeoff. This is now common practice in mapping. Some UAVs with this level of autonomy have a built-in automatic takeoff and landing function, which makes the UAV easier to control but does not make it more autonomous.

Military applications: mapping, surveying. This level allows UAVs to be used for simple reconnaissance, monitoring, or delivery missions, but such drones are extremely limited in swarm operations.

Level 3. Conditional automation. As in level 2, the UAV can fly on its own, but the human pilot must still remain alert and be ready to take control at any time. The UAV control system transmits data to the pilot about the need for intervention, so it is a backup system. This level means that the UAV can perform all functions «under certain conditions».

At the third level of autonomy, UAVs gain obstacle recognition, which complements the capabilities of the previous level. This allows the drone to analyze its environment, but it cannot yet make decisions. When obstacles are detected, the device stops and notifies the operator of the need for intervention.

In swarm interaction, two approaches are provided for UAVs of this level. The first is control via a leader drone. In such a system, a person or ground station controls one main drone, and all others follow it, having a direct connection with the leader. At the same time, the distance from it should not exceed the stable communication range. To avoid loss of control, when communication is lost, a new leader is automatically selected from among the swarm members.

The second option is centralized control from a command center. In this case, each UAV sends all data (coordinates, speed, direction of movement, acceleration, sensor information, etc.) to the control center. The center analyzes the situation and sends commands to the drones. With this architecture, there is no interaction between the UAVs, and all decisions are made externally, not on board the aircraft.

Practical application: The UAV flies along a programmed flight path until its onboard sensors detect an obstacle. Upon detection, the UAV stops and sends an alarm signal about the object in its immediate vicinity. The pilot then manually corrects the direction and altitude before the UAV continues flying along its programmed path.

Military applications: mapping, monitoring, and cargo delivery. Swarm systems with third-level autonomy drones have sufficient functionality for mapping and security monitoring tasks.

Level 3+. Automated UAV deployment. Another way to measure UAV autonomy is to consider the operating environment. Some manufacturers have made progress in automating UAV deployment. This means that there is no human in the loop to control the flight.

Practical application: the idea is to have a UAV installed on site that frequently performs the same task (e.g., surveying a specific area twice a day). The pre-programmed flight path remains unchanged, the UAV is equipped with automated take-off and landing capabilities, and the landing site allows the batteries to be recharged and the UAV to be automatically deployed according to a set schedule.

Military applications: mapping, surveying, and protection and security.

Level 4. High automation. The UAV can be controlled by a human, but this is not always necessary. It can fly for long periods of time under certain circumstances. UAVs are expected to have backup systems, so if one system fails, it will still function. The behavior of a UAV depends on fixed built-in functionality or a fixed set of rules that dictate the behavior of the system.

The fourth level of autonomy is currently the most advanced among existing UAVs. Drones of this level are capable of independently processing information received from installed equipment and making decisions based on it. For example, when obstacles are detected, they can change their route without external commands and successfully complete their tasks autonomously. However, in non-standard or complex situations, drones may not achieve the planned result. Such UAVs can be controlled either manually or completely autonomously.

Level 4 drone swarms operate independently of ground control. Their autonomy allows them to exchange data with each other, including only with the nearest devices. This optimizes energy consumption and reduces the technical complexity requirements for each UAV. Such a swarm can include drones of different models and with different equipment. Tasks are distributed according to the capabilities of each drone and its specialization.

Bio-inspired algorithms based on the behavior of living organisms are often used to create mechanisms for interaction between drones of this level. These can be algorithms that mimic the actions of ants, bees, bats, or even simple biological particles. Despite different approaches to solving problems, they share a common idea: each drone independently searches for a way to achieve its goal using information received from other members of the swarm. Over time, as the algorithm works, the drones concentrate on the most promising objects for achieving the goal, such as the closest, most valuable, or most important according to specified criteria.

Practical application: A UAV equipped with a specific set of sensors monitors an object. In doing so, the UAV senses obstacles in its flight path and actively avoids contact by changing direction and altitude. It finds a way to complete the task while automatically changing the way it is performed.

Military applications: photography and video recording.

Level 5. Full automation. The UAV controls itself under all circumstances without waiting for human intervention. This includes full automation of all flight tasks under all conditions.

Such UAVs must use AI tools to plan their flights, in other words, autonomous learning systems with the ability to modify routine behavior functions. It is also important to remember that the fifth level of autonomy is a prerequisite for achieving two key goals in the unmanned industry: air mobility and large UAVs for cargo delivery.

The fifth level of UAV autonomy remains hypothetical and has not yet been implemented in practice. It is assumed that unmanned aircraft of this level will be able to perform assigned tasks completely autonomously in any environment, regardless of external factors. Their operation will be based on highly developed artificial intelligence technologies that will allow drones to independently analyze situations, make decisions, and adapt to changes.

The possibility of operator intervention will be implemented only as an additional backup mechanism, not as the primary form of control.

The communication architecture in swarms of drones at this level will likely be similar to that used in fourth-level UAVs: data exchange between devices will occur in a decentralized manner, with a preference for local interaction between the closest members of the swarm.

The first three levels (0 to 2) correspond to UAVs that require constant human operator involvement. They use systems that facilitate control, but constant analysis of the external situation is necessary. Autonomy levels 3–5 correspond to UAVs that are already capable of moving independently and analyzing data obtained from the environment. Control of level 3 and 4 drones can be transferred to a human operator if necessary, while level 5 corresponds to UAVs that operate exclusively in autonomous mode.

In accordance with the classification of UAV autonomy levels, let us consider *the levels of UAV control* (Fig. 1).

At the first level, interaction with the environment occurs through the control and modification of the operation of the executive mechanisms.

At the second level, the ability to control the rotation speed of the propellers is added to the control of the executive mechanisms.

Today, the simplest flight controllers include a microcontroller with a minimum set of sensors for assessing position, orientation, and altitude (accelerometers, gyroscopes, barometers), which allow you to assess the position and automatically influence the propeller rotation speeds, for example, to stabilize the position in the air and maintain altitude.

The third level controls the orientation of the UAV, whose controller is equipped with a GPS sensor that allows it to orient itself in space.

At the fourth level, linear speed control is automated. In addition to the angular speed and orientation controllers, the autopilot has a level for controlling linear speeds and position.

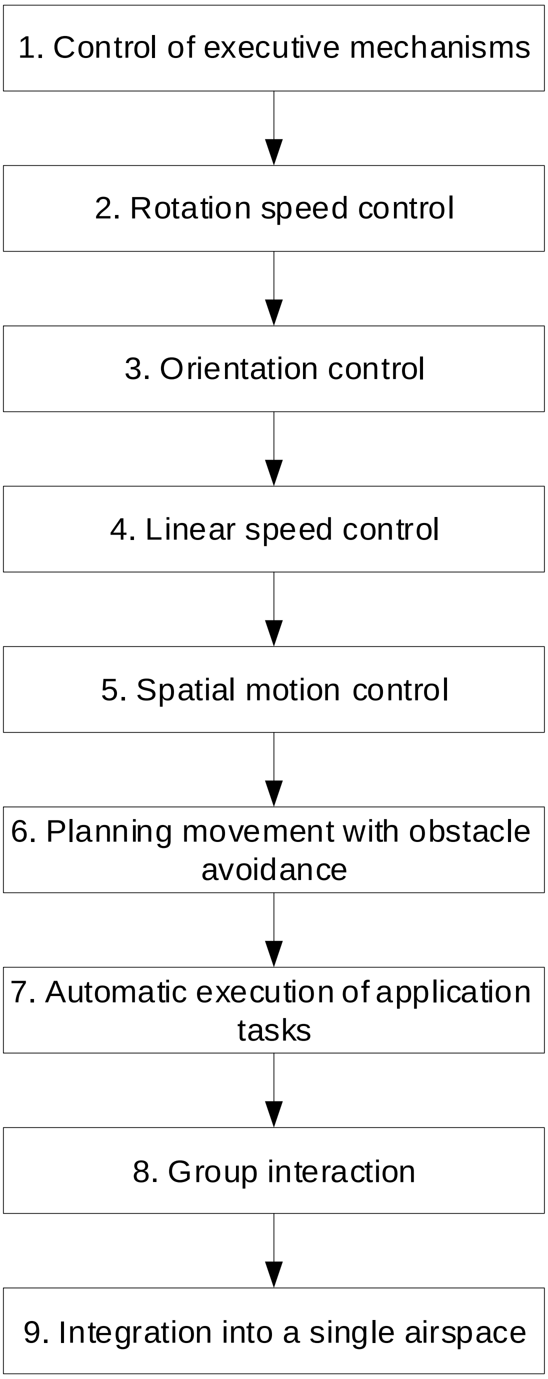


Fig. 1. Levels of UAV motion control

At the fifth level, the movement of the UAV in space is controlled by software. The principle of position control in autopilot mode is as follows: the operator sets the coordinates of a virtual point in space, the autopilot calculates the direction relative to the current coordinates of the UAV and forms a velocity vector, which is sent to the speed controller. The speed controller forms the desired angle of the UAV, which is sent to the controller responsible for the angle. A properly configured control system allows stable flight in windy weather, compensating for external influences.

At the sixth level, intelligent planning systems are integrated into the UAV control system. The UAV must be equipped with algorithms for obstacle avoidance or independent reconnaissance of complex terrain. For this purpose, an on-board computer with sensors is additionally used: cameras, lidars, radars, and other additional devices.

At the seventh level, automatic execution of applied tasks appears. The tasks of the UAV include independent route planning: for example, following any object or automatically exploring and mapping the space.

The eighth level of control is provided by group interaction between UAVs.

The ninth level involves built-in air traffic control systems, as described in [6].

Here is a classification of UAV groups based on **the types of interaction** between devices [7, 8]:

Level 1. Direct physical interaction. In this case, UAVs are connected directly to each other and their movement is limited by forces that depend on the movement of other UAVs. An example is the lifting and transport of cargo by several UAVs. From the point of view of route planning and collision avoidance, all agents can be considered as a single entity. Since the number of devices in this case is usually small, both centralized and decentralized control systems can be used.

Level 2. Formations. The devices are not directly connected to each other, and their relative positions are strictly defined to maintain the formation. Path planning can be considered for a formation of several UAVs as a single entity. Collision avoidance between devices can be built into the formation control algorithms. Scalability becomes important for this approach, and therefore decentralized control algorithms are preferred.

Level 3. Swarms of devices – a team of multiple UAVs, whose interaction algorithms ensure collective behavior. The resulting movement of the group is not necessarily a formation. Scalability is one of the most important issues in this approach, so the use of decentralized algorithms is a prerequisite.

Level 4. Cooperation. UAVs from a group plan their movement according to individual tasks that must be distributed to perform a higher-order mission in the control system hierarchy [9]. These trajectories are usually geometrically interrelated, as in the case of formations. Therefore, issues such as task allocation, high-level planning, plan breakdown into subtasks, and conflict resolution must be resolved before the higher-order mission can be executed. Accordingly, both centralized and decentralized control system architectures must be used.

Figure 2 shows a schematic interaction between the UAVs described above.

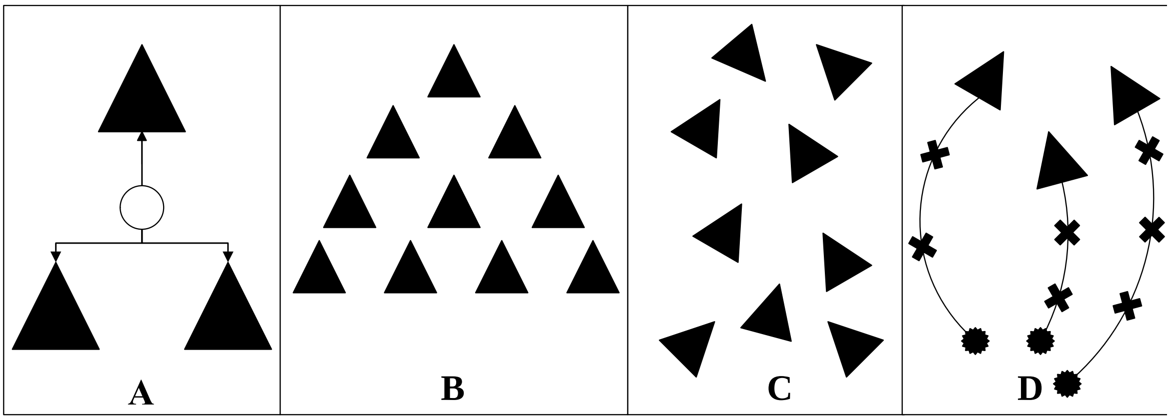


Fig. 2. Types of interactions between UAVs:
A – direct physical interaction, B – formation, C – swarm, D – cooperation

Three possible control strategies can be identified:

– centralized – remote control with a dedicated base station, the swarm leader is appointed from the central node;

– decentralized – the swarm leader is determined based on any algorithm and does not depend on the central control station;

– mixed – combines the advantages of centralized and decentralized strategies by selecting a swarm leader, if necessary, based on one of the algorithms with the transfer of control rights to the operator [10].

2. Determination of UAV parameters for group flight

For successful group autonomous flight of a group of UAVs, it is necessary to take into account: their density, the accuracy of positioning of each UAV, and the possibility and quality of communication with the control panel. An important condition is the stability of the UAV to wind gusts, turbulence, and other factors. Table 2 shows the characteristics of known quadcopter prototypes used for group flight.

A large number of quadcopters are required to create a UAV group, so it was decided to focus on the budget model CLOVER from COEX.

During the development of a quadcopter prototype based on the COEX CLOVER model, data available on the manufacturer’s website was taken into account. Based on the prototype parameters and the xcopterCalc service [https://www.ecalc.ch/xcoptercalc.php], calculations were performed to obtain realistic results regarding flight time, compatibility, and the correctness of the selected components. Thanks to the xcopterCalc component database, it is possible to vary the parameters to obtain optimal values.

Table 2

Quadcopter prototypes used for group flights

Model name	Weight, g	Brightness	Battery life, min	Positioning technology	Network connection (Wi-Fi)	Appearance
IFO	786 (without battery)	Huge LED light	25	GPS RTK	2.4 GHz and 5.8 GHz range	
EMO	540	12 lamps	35	GPS RTK	5.8 GHz WiFi	
CLOVER	1000	LED strip	15	GPS	2.4 GHz	

The service has a wide range of settings and a large database of electronic components. The main settings that must be specified for the calculation (Fig. 3):

– model weight. When selecting a screw motor unit, the calculator automatically takes into account their weight. Considering the maximum take-off weight of 1000 g specified in the prototype, let's consider a model weighing 1200 g, including the screw motor unit;

– number of screws – for the model under development, as in the prototype, for clarity, the service immediately draws the resulting configuration;

– frame dimensions – the diagonal distance between the motor axes, the size is specified as 450 mm;

– battery (lead-acid battery) – «LiPo 4500 mAh 35/50C» battery and «Nominal» charge status; the number of batteries connected in parallel is specified in the «P» field (if using a circuit with several batteries);

– regulator (ESC) – select a speed regulator from the list based on your needs – max 60A;

– in the attachments, specify the total consumption and weight of all additional equipment to be installed, for example: camera, flashlight, etc.;

– motor – select based on the intended use of the multicopter, SunnySky V4006-380;

– propeller – for the initial calculation, we will take propellers from the popular manufacturer DJI with a diameter of 254 mm, three blades, and a pitch of 127 mm.

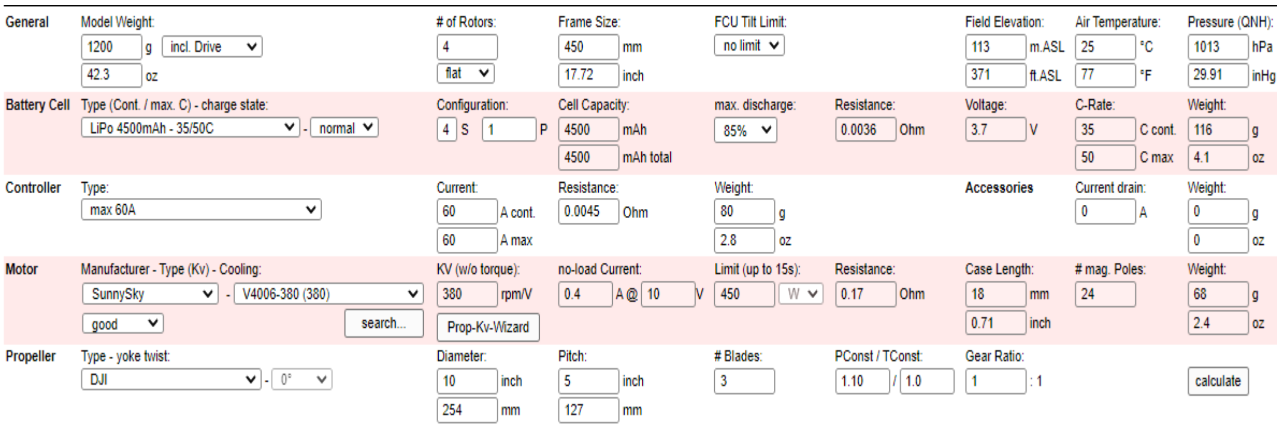


Fig. 3. Calculation parameters

Figure 4 shows the results and configuration of the multicopter. It is important to understand that the calculation is approximate and does not give guaranteed results, but it clearly shows how flight characteristics change when components and other parameters are changed. The figure shows:

– motor efficiency at optimal and maximum operating modes and in hover mode;

– propeller motor group efficiency in hover and maximum operation;

– payload, maximum roll, rate of climb, and probable time with flight range.

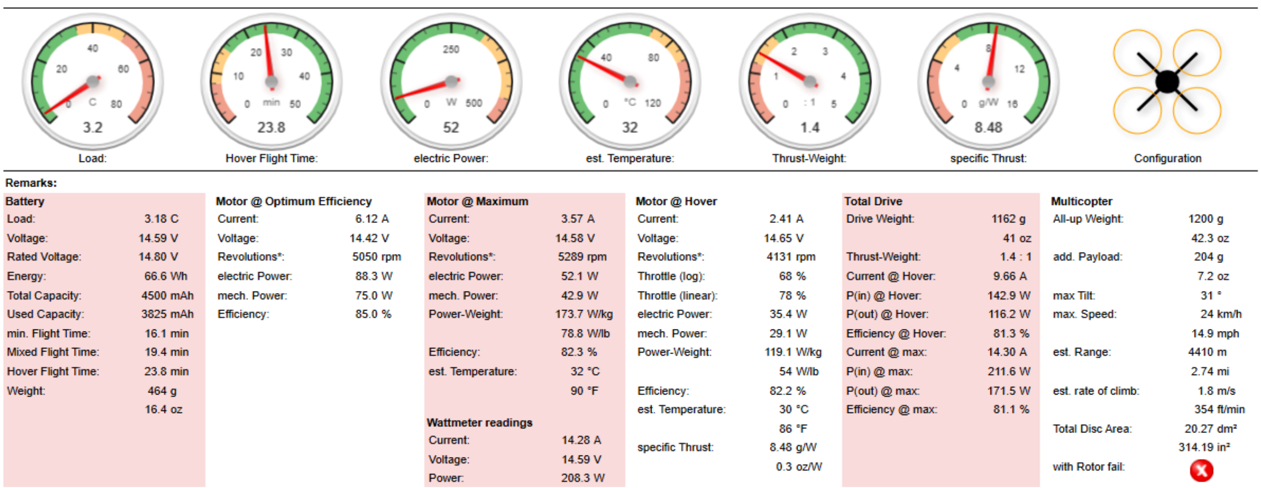


Fig 4. Calculation results

Let us consider the results of calculating the flight range using the graph shown in Figure 5. The left side of the graph shows the flight time (in minutes), the bottom side shows the speed of the UAV during flight (in kilometers per hour), and the right side shows the flight range (in meters). The green line shows the best range of flight time and distance data obtained. Depending on the weather, like if there's air resistance or not, there are two types of time and range.

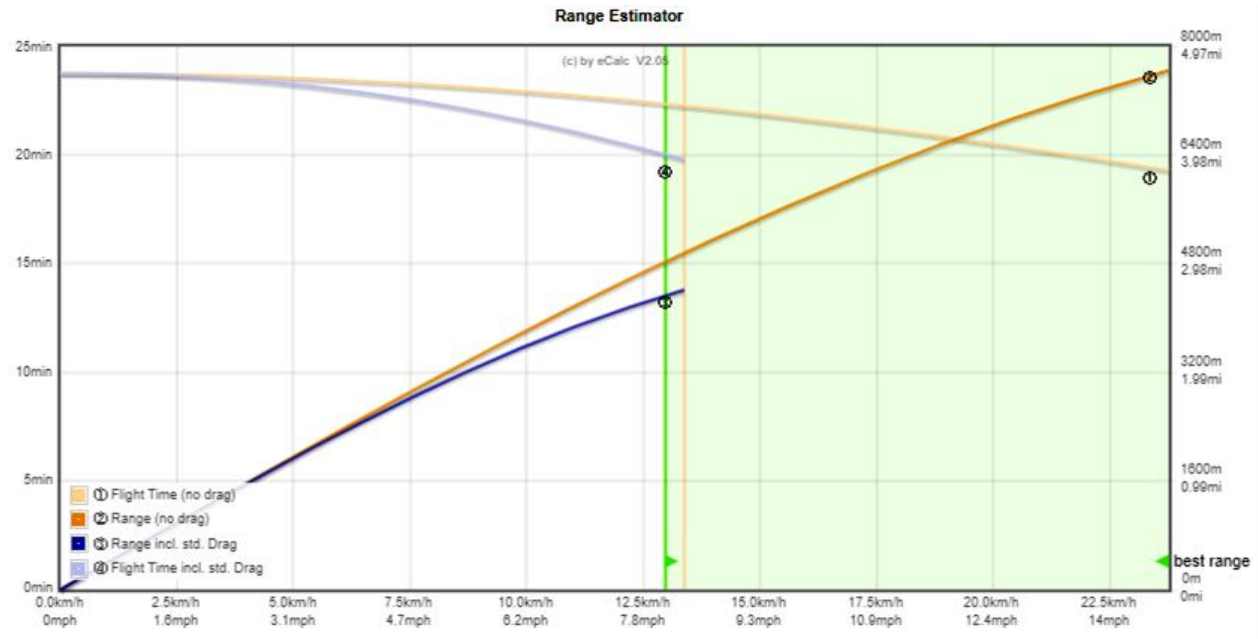


Fig. 5. Simulated graph of flight time and distance

Figure 6 shows the characteristics of the motor. The total power is marked with a circle on each characteristic curve. Based on the graph, we can see that the electric power limit of the motor can be even higher. The maximum flight time shown in Figure 5 (23.8 min) is calculated for the planned situation with the battery discharged to 85%. In reality, the flight time to avoid complete battery discharge will be no more than 19 minutes, i.e., a maximum discharge of 80%, which is sufficient for a group flight of UAVs.

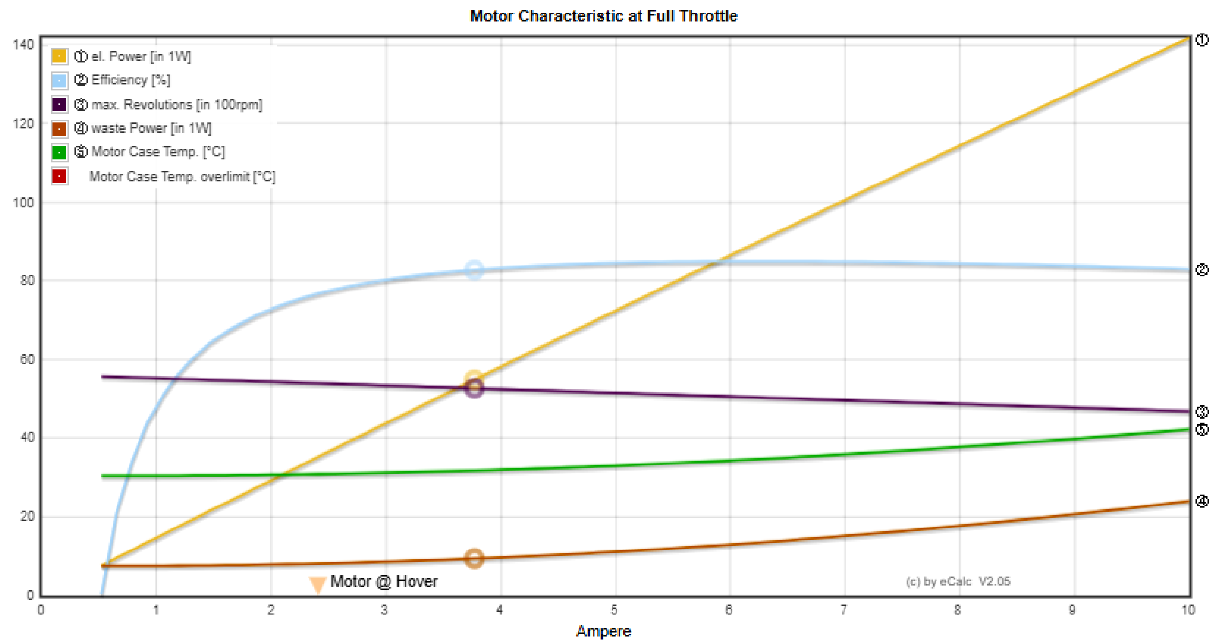


Fig. 6. Engine characteristics at full throttle

Considering that the calculation accuracy is ±15% and the UAV does not maintain a constant speed, the data obtained will differ slightly from the real scenario.

3. Mathematical models for constructing airspace maps and assessing conflicts

The increase in the number of small unmanned aerial vehicles has led to the emergence of a new task of unmanned traffic management (UTM). The main task of UTM is to estimate the throughput capacity – how many UAVs can be safely deployed with the possibility of successful management in a given airspace (AS). This task can be solved by estimating the following parameters:

– factors limiting AS capabilities, such as the emergence of intractable conflicts (if their probability is high, then measures to manage them should be identified);

– excessive UAV noise;

– interference with the UAV operator's communications (taking into account cybersecurity requirements, as encryption protocols require higher bandwidth).

The AS UTM throughput capacity assessment is based on air traffic management models and methods [11, 12], which mainly deal with flight planning from airport to airport. The UTM model differs in that it involves a larger number of aircraft and operators, a variety of flight tasks, and the ability to take off and land on unprepared sites. The limitations of the UTM model are the consideration of permitted movement zones for UAVs and restrictions on height above ground level (150 meters) [13].

Let us consider the stages of introducing UAVs into a single airspace. Based on NASA recommendations, four main stages have been identified, corresponding to levels of technological capability:

1) UAV motion control technologies for agricultural monitoring, firefighting, and infrastructure monitoring operations;

2) technologies for dynamic correction of airspace availability and management of unforeseen circumstances;

3) technologies for determining safe separation between private UAVs in moderately populated areas;

4) technologies for UAV operation in denser urban areas for tasks such as information gathering and package delivery.

Let us consider the objectives of these stages.

Stage 1. Testing of single UAV flights. Studying the demand for flights in sparsely populated areas.

Stage 2. Initial integration of UAVs into non-aggregated airspace, introduction of a basic UTM model.

Stage 3. Integration of unmanned aircraft systems (UAS) into the airspace of piloted aircraft, introduction of regional UTM.

Stage 4. Transparency in UAS management and situational awareness of all air traffic participants, creation of a centralized UTM.

Various information subsystems are used to determine flight-permitted areas and assess current traffic [14]. For example, the US Federal Aviation Administration website [15] provides maps showing flight-permitted areas, areas with flight altitude restrictions, and the possibility to register and obtain a flight license in electronic form.

To create such a subsystem in Ukraine, it is necessary to assess the probable traffic and collect information about no-fly zones.

The concept of the LiU UAV traffic probability map model is based on the following works:

– Dutch model «Metropolis» [16] – a probability model where aircraft are distributed evenly in a given AS. In general, the flight direction of UAVs is evenly distributed in a given AS circle (assuming that UAVs fly at the same altitude, i.e., the model is two-dimensional). This allows the probability of conflicts to be obtained;

– the Cal model [17] improves the previous model in terms of selecting flight end points. They are selected based on population density. In this case, each UAV flight is a line connecting the starting and ending points, raised to a given altitude.

Due to the rational selection of the throughput capacity of a given AS, limited by the number of UAVs, at which their safety decreases due to the emergence of conflicts involving three or more UAVs, the quality of UTM is improved.

To determine the intensity of UAV traffic, modeling methods are used with the application of a Poisson process model and a model for constructing and evaluating a random geometric graph.

The following input data are required to **build a map of** the studied AS for UAVs:

– region of interest R;

– flight intensity $D(g)$, given for each point $g \in R$;

– observation duration T ($T = 12$ hours, i.e., daily traffic);

– the expected number of UAV operations during the time T (the parameter N changes during the experiments).

Considering the extremely low altitudes of AS, we assume that the demand for AS is generated according to the Cal model: the start time of a flight from any point $a \in R$ is formed according to Poisson's law, according to which the intensity is proportional to the intensity of flights to a given point:

$$\lambda_s(a) = \frac{N}{T} \frac{D(a)}{\int_R DdA}. \tag{1}$$

Point b is randomly selected as the end point of the flight. Based on the given intensity of flights, the probability that the flight will end at the point $b \in R$ is

$$p(b) = \frac{D(b)}{\int_R DdA}. \tag{2}$$

The developed model calculates the point distribution of traffic. The intensity of the appearance of a UAV flying from a to b at the point $g \in ab$ is equal to the Poisson process:

$$\lambda_{ab} = \lambda_s(a)\,p(b) = \frac{N}{T} \frac{D(a)D(b)}{\left(\int_R DdA\right)^2}. \tag{3}$$

Integration for all origin-destination pairs allows us to determine the intensity of UAVs at any point g:

$$\lambda(g) = \int\limits_{ab \ni g} \lambda_{ab} dAdB = \frac{1}{\left(\int_R DdA\right)^2} \frac{N}{T} \int\limits_{ab \ni g} D(a)D(b)dAdB, \tag{4}$$

where $ab \ni g = \left\{(a,b) \in R^2 : g \in ab\right\}$ is the set of endpoints of all segments containing g.

To create a simulation model, the above model must be represented discretely: on R, we fix the grid L and the flight intensity $D(g)$, which is set for each grid cell $g \in L$. The start time of flights from any cell of the grid $a \in L$ forms a Poisson process, the intensity of which is

$$\lambda_s(a) = \frac{N}{T} \frac{D(a)}{\sum_{x \in L} D(x)} \tag{5}$$

is proportional to the intensity of flights in the cell, and the target flight cell b is randomly selected based on the density of the same probability:

$$p(b) = \frac{D(b)}{\sum_{x \in L} D(x)}. \tag{6}$$

The direct path of the UAV between cells a and b is represented by a sequence of grid cells through which the UAV passes (Fig. 7). Let's assume that the UAV spends the same time $t = l/v$ in each cell of the path, where l is the length of the cell side, v is the UAV speed.

Similarly to the continuous case for any cell $g \in ab$, UAVs flying from a to b enter cell g according to a Poisson process with intensity:

$$\lambda_{ab} = \lambda_s(a)\, p(b) = \frac{N}{T}\frac{D(a)D(b)}{\sum_{x\in L} D(x)}. \tag{7}$$

Summing up all the origin-destination pairs, we get that in general, the UAV is located in any cell g of the segment ab with intensity

$$\lambda(g) = \sum_{ab \ni g} \lambda_{ab} = \frac{1}{\left(\sum_{x\in L} D(x)\right)^2}\frac{N}{T}\sum_{ab\ni g} D(a)D(b), \tag{8}$$

where $ab \ni g = \left\{(a,b) \in L^2 : g \in ab\right\}$ is the set of endpoints of all segments containing g.

We call the graph of the function

$$m(g) = \sum_{ab\ni g} D(a)D(b) \tag{9}$$

the UAV map, which shows the probability of UAVs appearing in different cells. In general, the number of UAVs $n(g)$ that can be seen simultaneously in cell g at time t is calculated as follows:

$$\overline{\lambda(g)} = \lambda(g)t = \frac{t}{T\left(\sum_{x\in L} D(X)\right)^2} Nm(g). \tag{10}$$

In the experiments, the values of t and T do not change. Therefore, to simplify the formulas, we normalize the density to.

$$\frac{t}{T\left(\sum_{x\in L} D(X)\right)^2} = 1, \tag{11}$$

and, respectively

$$\overline{\lambda(g)} = Nm(g) \tag{12}$$

We will **evaluate UAV conflicts** using a random geometric graph model.

The Random geometric graphs (RGG) model will be used to model the number of UAV conflicts and collisions within a given traffic volume. A RGG is a graph $G(S, R)$ with a set of vertices S, which is obtained by placing n vertices randomly on the plane, with two vertices connected by an edge if the Euclidean distance between them is no more than R. *Given* a number $k > 0$, where $p_k(S,R)$ denotes the probability that $G(S, R)$ has a connectedness of size at least k:

- $p_1(S,R) = 1$, since any vertex is a connected component of size 1;
- $p_2(S,R)$ – the probability that $G(S, R)$ has an edge;

– $p_n(S,R)$ – the probability that the graph is connected;

– $p_k(S,R)=0$ at $k>n$, since $G(S,\ R)$ has only n vertices.

Suppose that R is a conflict event, e.g., two UAVs at a distance R may collide. Then, for n randomly distributed UAVs (Fig. 7), the existence of a subnetwork with connection size k in $G(n,r)$ means that k UAVs are in conflict (Fig. 8).

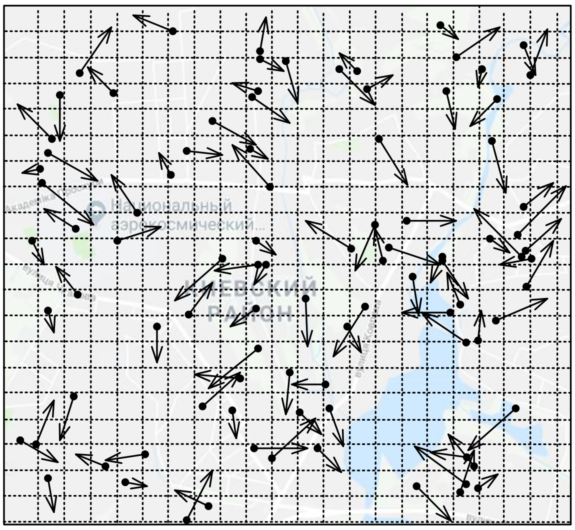


Fig. 7. UAV location map

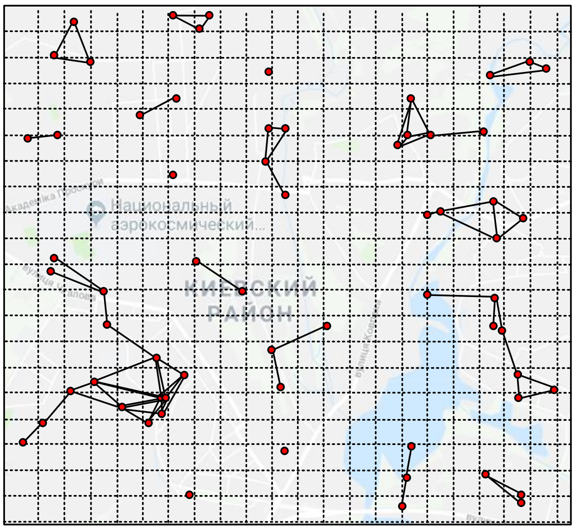


Fig. 8. Random geometric graph

With a small subnetwork size $(k=2)$, the conflict can be resolved using simple rules (e.g., the right maneuver). For $k>2$, a conflict can mean a security breach event or its probability $p_k(S,R)$.

The parameter R represents the technical capabilities of the UAV – communication quality, navigation accuracy, autopilot performance, etc. Therefore, for the practical implementation of the RGG model in the UTM system, it is necessary to find a distance R that will ensure a low probability $p_k(S,R)$. At the same time, it should be indicated what technical characteristics of the UAV can ensure this distance.

Consider the problem of estimating $p_k(N,R)$ – the probability of observing a connected component of size at least k in the daily traffic of intensity N . Fig. 9 shows a graph of modeling the probability $p_3(N,R)$ for $N=\overline{10,200000}R=\overline{5,300}$ m.

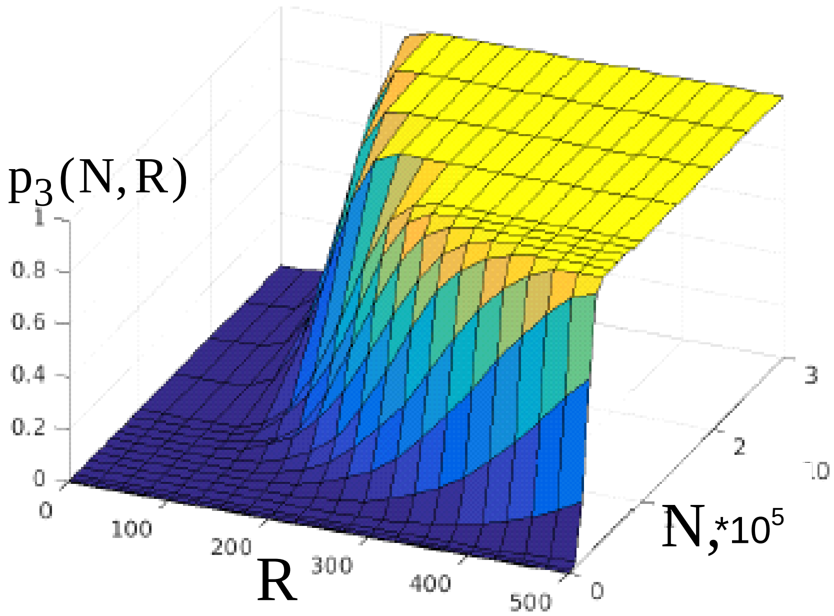


Fig. 9. Graph of probability modeling $p_3(N,R)$

Let's calculate the number of conflicts in RGG (related components) for two UAVs $(k=2)$. The total expected number of such conflicts is the sum of conflicts for all pixel pairs:

$$C = \sum_{g,g' \in L^2} C(g,g') + \sum_{g \in L} C(g) \tag{13}$$

where $C(g,g')$ is the expected number of edges between nodes (UAVs) in cells g and g',

$C(g)$ – is the expected number of edges between UAVs in cell g.

Estimating $C(g,g')$ can be difficult because it depends on the exact location of the UAVs inside the cells g and g' (Fig. 10, a). For example, r and l may be in the following relationships with each other:

– if $r >> l$ (Fig. 10, b), then this case can be ignored, since

$$C(g,g') = 0 \tag{14}$$

every time the cells g and g' are located «further than r« from each other and

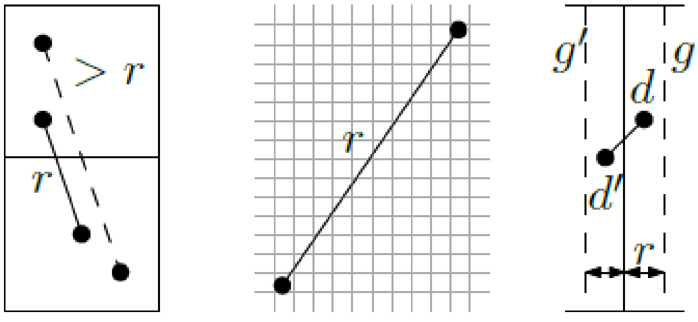
$$C(g,g') = \frac{1}{2} \overset{\Sigma}{\sum_{n,n'}} n,n' \Pr\{n(g)=n\} \Pr\{n(g')\} = n', \tag{15}$$

for the cells g and g' located «closer than r«. At $r = 500$ m and $l = 150$ m, this event does not occur, since the condition $r >> l$ is not fulfilled;

– if $r \sim l$, you can reduce the grid so that the new cell size is $l' << r$, but calculations on the refined grid may take too much time;

– if $r << l$, edges between UAVs can exist only for neighboring cells g and g'. Moreover, the probability of such an edge is low (Fig. 10, c), since each UAV must fall into a band of r-width near the cell boundary with probability

$$(rl)/l^2 = r/l. \quad (16)$$



a) b) c)

Fig. 10. Types of edges on the graph between nodes located in different cells

In addition, the distance between UAVs located near the cell boundary should be less than r (which gives an additional probability coefficient r/l).

In general, the probability of an edge between cells is $(r/l)^3$ (e.g., for $r = 5$ m, $l = 150$ m, it is about 10^{-4}) and, accordingly, the sum of edges between cells in (13) can be neglected.

Thus, we consider the sum of edges in the cells in formula (13) to obtain the expected number of conflicts. For a UAV at a given moment, the expected number of edges in cell g is $\frac{1}{2}n(n-1)\frac{\pi r^2}{l^2}$. Since the time of the UAV's movement in the cell is t, the total number of edges is

$$C(n) = \frac{1}{2}n(n-1)\frac{\pi r}{l} \quad (17)$$

Previously, it was believed that the number of UAVs in cell g $(n(g))$ according to the Poisson distribution law is $Nm(g)$. Thus, the expected number of edges in cell g is:

$$C(g) = \sum_n C(n)\Pr\{n(g) = n\} = \frac{\pi r}{2l}\sum_n n(n-1)\Pr\{n(g) = n\} =$$
$$= \frac{\pi r}{2l}\left(E\left[n^2(g)\right] - E\left[n(g)\right]\right) = \frac{\pi r N^2 m^2(g)}{2l}, \quad (18)$$

where $E[n(g)] = Var[n(g)] = Nm(g)$.

When summing $C(g)$ over the entire grid during the entire simulation time, using the sum of discrete moments T/t, we obtain the expected number of conflicts during the flight:

$$C_d = \frac{\pi r N^2 T}{2lt} \sum_{g \in L} m^2(g). \tag{19}$$

Let's assume that a UAV collision occurs at $r = 5$ m. From the UAV map, we obtain the average flight duration:

$$\tau = \frac{1}{V|L|(|L|-1)\left(\sum_g D(g)\right)^2} \sum_{a,b \in L^2} |ab| D(a) D(b) \approx 2000c, \tag{20}$$

where $|L|$ is the total number of cells.

If we take into account the expected number of flight hours $H = N\tau$, we can see that this indicator will grow linearly, while the number of collisions C_d will grow quadratically. For example, for $N = 2457$, the expected number of conflicts is $C_d = 0.001$. Thus, it is possible to calculate the acceptable value of traffic intensity at which appropriate UTM measures are required.

4. Ontological model of flight zone categories

The probability of UAV conflicts in conditions of geometric variability of existing static obstacles, such as buildings and terrain, should be assessed taking into account the zones allowed for flight. To do this, we will create a model of no-fly zones.

To build a map of the zones allowed for flight, we built an ontological model of the regulatory document of the State Aviation Service of Ukraine «Temporary Procedure for the Use of the Airspace of Ukraine» [18].

The Protégé platform was chosen to build the ontology, which is a free, open ontology editor and a framework for building knowledge bases.

The structural elements of the ontology are arranged in a hierarchical order, with the relevant information needed at the lowest level of the hierarchy.

Let:

– a finite set of categories is given

$$C = (c_1, c_2, c_3, c_4),$$

where c_1 – forbidden zones,

c_2 – flight restriction zones,

c_3 – danger zones,

c_4 – temporarily reserved zones;

– a given feature space

$$P = P_1 \times P_2 \times \ldots \times P_i \times \ldots \times P_N,$$

where P_i is the set of features of the values of the i-th feature;

– is a finite set of elements of order

$$D = d_1, d_2, ..., d_i, ..., d_K.$$

– a feature function is given

$$f : D \to P, \ (fd_i) = (p_1, p_2, ..., p_{Ni}),$$

is the feature description of the structural element d_i;

– is an undefined function

$$\Phi : D \times C \to \{0,1\},$$

which for each pair $(d_i c_j)$ determines whether this element d_i, which has a feature description (fd_i), belongs to the category c_j.

The following are the features used to define the categories:

[airspace] [list of categories] [categorized accordingly] [*] → c_1

For d_i to be included in a category, a list of characteristics is needed to determine whether the category is a subclass or a concept:

The following are the features for defining concepts and subclasses of certain categories:

[*] [flights are performed] [without | not] [list of attributes] → d_1

[*] [flights are not performed] [list of signs] → d_1

[Flight restriction areas] [list of features] → d_2

[Dangerous areas] [list of signs] → d_3

where d_1 – signs of prohibited areas,

d_2 – signs of restricted areas,

d_3 – signs of hazardous areas.

Below are the signs for defining subclasses of categories:

[*] [main streets] [list of features] → e_1

[*] [operations zones] [list of features] → e_2

[*] [roads of national importance] [list of features] → e_3

[*] [designated objects] [list of features] → e_4

These concepts were divided into subclasses of categories because each concept describes one separate object, but they are connected by one common feature.

Based on the above features, the main categories and category subclasses were identified, on the basis of which the ontological model will be developed:

a) restricted areas:

– storage facilities for fuel, oil, gas, other hazardous substances and liquids, etc;
– penitentiary institutions;
– taxiways of airfields;
– places of accidents and disasters;
– power lines;
– pre-trial detention centers
– railways
– product pipelines;
– other important state and potentially dangerous facilities;
– power plants
– runways; and
– taxiways of heliports;
– state borders;
– industrial zones;
– sea ports;
– railway stations;
– central streets (cities, towns, villages);
– areas of operations (special, police, anti-terrorist);
– roads of national importance (international, national, regional, territorial);
– objects designated by state authorities (the Ministry of Defense of Ukraine, the Ministry of Internal Affairs of Ukraine, the State Border Guard Service of Ukraine, the Security Service of Ukraine, the National Police of Ukraine, the National Guard of Ukraine, the State Protection Department, other military formations and law enforcement agencies established in accordance with the laws of Ukraine and in respect of which security is provided);

b) flight restriction zones:

– training grounds (bombing, firing, missile launches, use of military explosive devices, neutralization of ammunition by means of their explosion, landing)
– areas of firing to influence hydrometeorological processes in the atmosphere;

c) hazardous areas: the space above the high seas.

All categories and attributes are hierarchically linked by the IS-A relationship, as each higher-level attribute is a generalization of the lower level.

Based on these categories and concepts, an ontological model was built, which is shown in Fig. 11.

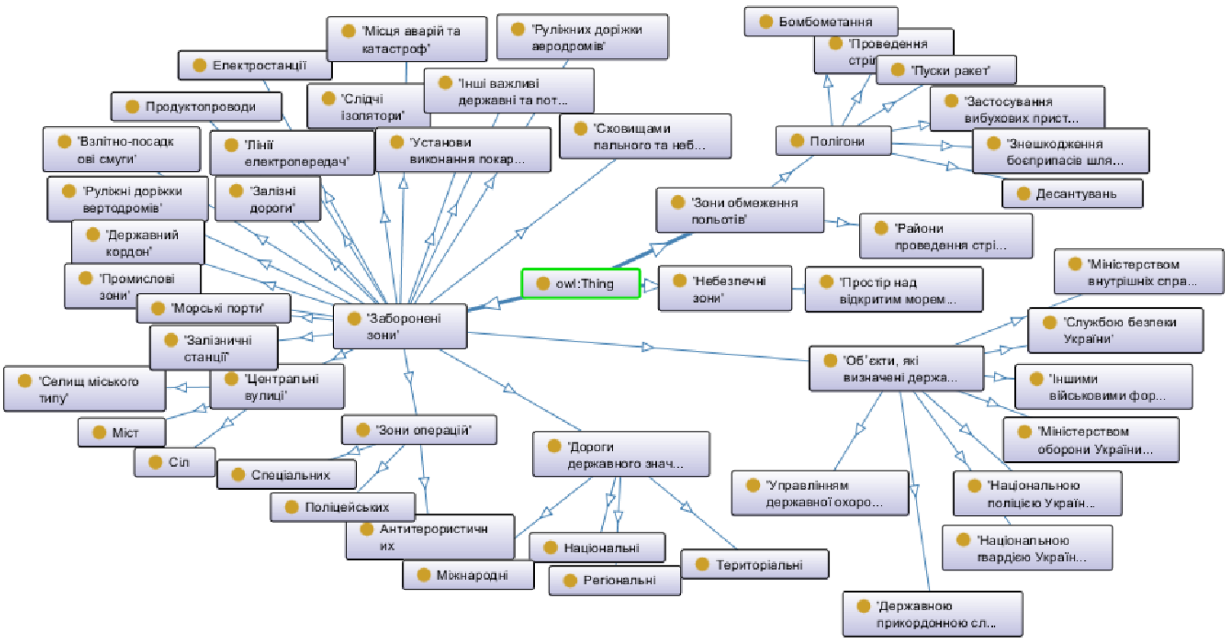


Fig. 11. Ontological model of flight zone categories

Using the developed ontological model, software was built that displays prohibited, restricted, and dangerous areas on the map. The basic scenario of the program's operation in a generalized form will consist of the following steps:

Step 1. Obtain data from the ontological model and save it to the program's knowledge base.

Step 2. Process the data using map queries. An important question is whether the existing electronic map can provide information on flight zones and how relevant this information will be. During the development of the software product, testing was only performed on available maps.

Step 3. Save the data.

Step 4. Output the data using an external service.

In this case, the external tools are Google API and a database server (Fig. 12).

The resulting map will enable the construction of a random geometric graph model for simulating the number of conflicts and collisions between UAVs within a given traffic volume, taking into account the areas permitted for flight. In addition, using the model developed in [10], it is possible to estimate the probability of UAV conflicts in a heavily built-up environment (Fig. 13).

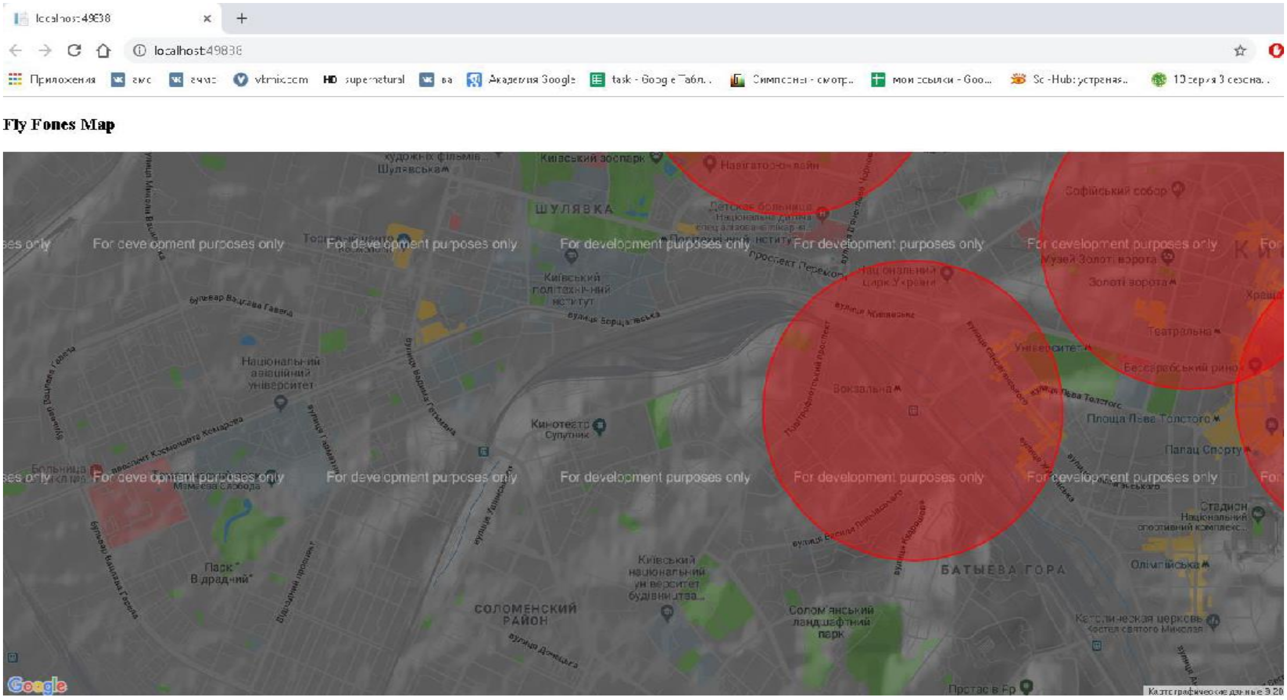


Fig. 12. Map showing flight zone categories

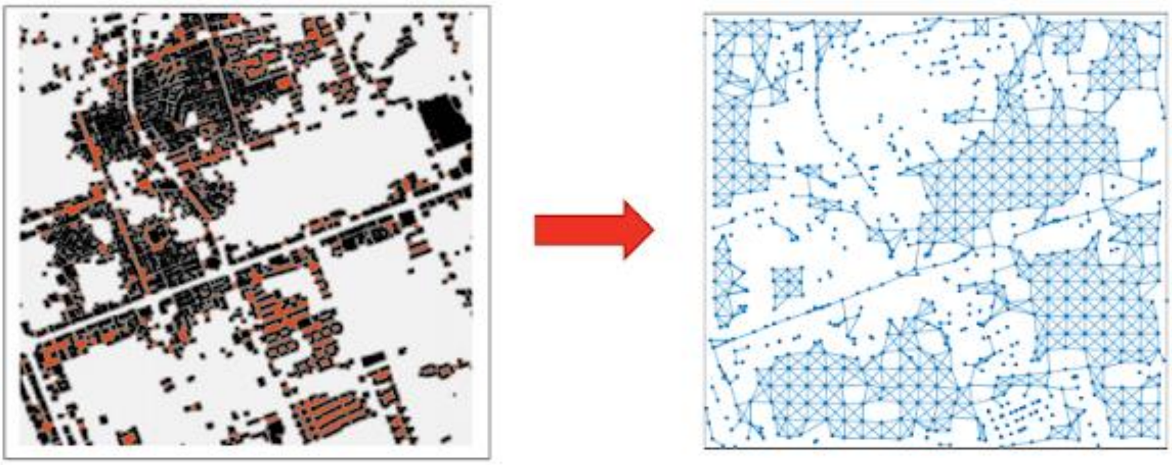


Fig. 13. Structuring of a heavily built-up urban environment

Conclusions

The levels of UAV autonomy and practical applications, including military applications at each level, are considered. In accordance with the classification of UAV autonomy levels, control levels are considered. UAV groups are classified based on the types of interactions between devices.

Based on data on the parameters of prototypes and the xcopterCalc service, calculations were performed to obtain realistic results regarding flight time, compatibility, and the correctness of the selected components. Thus, parameters were determined that ensure adaptive behavior in a swarm when environmental conditions change. Graphical results of flight range and engine performance calculations are provided.

The parameters for assessing throughput capacity as the main task of unmanned traffic control are considered. According to NASA recommendations, four main stages corresponding to levels of technological capability have been identified. The concept of a probabilistic traffic map model for small UAVs has been applied. A generalized model of swarm interaction of UAVs has been constructed, which takes into account a multi-level control system and data exchange between devices. Modeling methods using a Poisson process model are used to determine the intensity of UAV traffic. A mathematical model of conflicts in airspace has been proposed, which allows predicting and avoiding collisions. UAV conflicts were assessed using a random geometric graph model.

An ontological model describes categories of airspace to support automated decision-making. Using the developed ontological model, software was created that displays prohibited, restricted, and dangerous areas on a map. The resulting map will enable the construction of a random geometric graph model for simulating the number of UAV conflicts and collisions within a given traffic volume, taking into account the zones permitted for flight.

The proposed parameterization method and mathematical and perception-oriented models contribute to improving the efficiency and safety of group flight of UAVs in a partially structured or changing air environment. The results obtained can be applied in the planning of military missions for the implementation of autonomous swarm strategies.

Thus, the work is aimed at determining the parameters of UAVs for group use, developing models for assessing air conflicts, and creating a conceptual basis for the implementation of a fully autonomous swarm. Establishing the relationships between the technical characteristics of UAVs, their behavior in a swarm, and the parameters of the air environment is the basis for further practical implementations.

їхньою поведінкою в рої та параметрами повітряного середовища є основою подальших практичних впроваджень.

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