SUBSTANTIVE FORMULATION OF UAV GROUPS ROUTES OPTIMIZATION PROBLEM

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Abstract: *Submissions of several specific problems of optimizing UAV routes for individual and group use are provided. The object of the study is the problems of combinatorial optimization of routes for UAVs and their groups that collect and transmit information to control points. General formulation of the target search problem in the area was given. An analysis of how to evaluate the quality of the search and what is the criteria for its effectiveness was conducted. The formal statement and mathematical model of the UAV routing problem are presented, which deals with the stages of the operation planning and the visiting the set targets by UAVs at the same time. Algorithms, based on this mathematical model can become the basis for solving several complex technical problems: increasing the tactical and technical (minimizing the territory exploring time by the UAV group) plus technical and economic indicators (minimizing the UAVs amount) while using UAVs groups. In this case, the UAVs would act as a team, which is tasked with examining or servicing several objects. As a result of the performed works, the routing problem meaningful statement for the UAV radio network with and without retransmission of control signals from the ground control center and the possibility of the UAV autonomous movement on the part of the route has been further developed.*

Keywords: *UAV routes, combinatorial optimization, routing optimization.*

Introduction

In recent years, we have a clear trend for the unmanned vehicles usage expansion, in particular, UAVs. The worldwide experience of the UAV development, especially in such high-technology countries as the USA, Germany and Israel, shows that UAVs in the next 10-15 years will be able to perform most of the problems that are now being tackled by manned means. Already, UAVs are used to control the technical condition, safety and operation of various objects and systems, in particular in ecology, agriculture and forestry, in railway transport, and the organization of marine search and rescue operations [Ponda et al, 2015], [Austin, 2011].

The rapid expansion of UAV applications in recent years has shaped the need for new classes of problems.

Formulation of the Problem

Mathematical models and combinatorial optimization methods development for real-time problems is an actual problem, as evidenced by a large number of specialized monographs, journals and conferences, which is conditioned both by practical needs and the complexity of theoretical problems that arise. At the same time, the problem is not only finding solutions, but also saving limited resources – fuel, computing resources, time, etc. This determines the need to develop software-algorithmic tools for the creation of appropriate information technology to save UAV resources and ensure optimal routing.

This article is aimed at the development of new mathematical models and algorithms oriented to use in the construction and operation of specialized networks, the nodes of which will be UAVs, stationary and mobile ground control points of different levels.

Analysis of Recent Research and Publications

To construct criteria for optimizing UAVs operations the estimates of the search efficiency used in the theory of operations were proposed in monographs [Jaiswal, 2012], [Golden et al, 2008].

The problem of finding objects during air surveillance and research began in the 1940s based on US business performance measurement approaches, which later became part of the theory of operations research [Ventzel, 1964]. Accumulated data on combat actions allowed to highlight critical parameters for assessing the outcome of the operation, formulate performance criteria, and perform a meaningful statement of optimization problems. The solution of the problem allowed to increase the effectiveness of their own sentinel devices in time, reduce their number, identify problems in their distribution in the areas of responsibility, etc.

The listed approaches to the search organization mostly did not include the use of a group of UAVs integrated into the network to perform search operations [Kumari et al, 2020], [Ye et al, 2020], [Корольов et al, 2017], [Корольов & Огурцов, 2017], [Огурцов & Ходзінський, 2016], [Поліновський et al, 2017], [Гуляницький & Огурцов, 2020], so this remain an actual scientific problem.

The tasks of route optimization of both single UAVs and their groups ([Coutinho at al, 2018], [Horbulin at al 2020]) belong to NP-complete problems, therefore exact algorithms cannot be used in practice. This applies to even the most simple and researched tasks, when you want to find the optimal route of the single UAV between two points: start and finish (see, for example, [Zhao at al, 2018] or [Otto at al, 2018]). Researchers have proposed a number of metaheuristic methods, including ant colony optimization algorithms ([Cekmez at al, 2017], [Perez-Carabaza at al, 2018] and [Гуляницький & Рибальченко, 2018]), genetic ([Chiang at al, 2019], [Binol at al, 2018]), and artificial bee colony algorithms ([Xu at al, 2010], [Tian at al, 2018]) and particle flow optimization [Shakhatreh at al, 2017].

Moreover, additional restrictive conditions should often be taken into account (for example, flight range without recharging or refueling, load capacity, minimum turning radius, weather conditions, etc.), as it was described in [Ponda et al, 2015], [Austin, 2011], [Tsourdos at al, 2010], [Shima and Rasmussen, 2009].

In some cases, the formulation of such problems is similar to the known class of vehicle routing problems (VRP) [Toth and Vigo, 2014] [Braekers at al, 2016], in particular, VRP with several depots [Karakatič and Podgorelec, 2015], [Soto at al, 2017].

The Goal of the Work

The goal of the work – automation of UAV groups flight routes building and relaying signals between them, which allows us to increase the radius of effective action. For example, if the effective range of one UAV is 8-10 km, then using a network of several UAVs in the relay mode, you can increase the area of reconnaissance and exploration at least three times.

Research methodology – combinatorial optimization theory, combinatorial analysis.

UAV Group Operations

The authors in previous studies [Корольов et al, 2017], [Корольов & Огурцов, 2017], [Огурцов & Ходзінський, 2016], [Поліновський et al, 2017], [Гуляницький & Огурцов, 2020] considered some routes optimization problems for ground and aviation robotized systems. Below is a more detailed discussion of the management of a UAV group that is associated with the functioning of a group as a team that performs tasks with the ability to apply relay control signals.

The coordination of UAV groups flights, which execute a territory survey, the creation of images (in particular, stereo images) will allow us to control the situation. When planning a territory survey for UAVs, two types of problems can be distinguished, each of which has certain peculiarities that are important for a solution.

The general formulation of the target search problem in the area

The search problem is to scan a specific territory for an optimal way to identify objects [Корольов et al, 2017], [Поліновський et al, 2017]. Let’s assume that the region is divided into lesser areas or cells (not necessarily identical), but the probability that the target is known in the i-th area, where (i= 1, ..., N). According to the problem formulation, it is necessary to find such a division of the total amount of time t at time intervals Δt for each district in such a way as to maximize the probability of identifying the target. The problem has an analytical solution: in each region the probability of detecting a target has a uniform distribution [Jaiswal, 2012]. This is based on the assumption that the size of the area is large compared with the sector maximally explored by the UAV sensor in a stable position. The probability of detecting a target, given that it is present in area *i*, is:

$$P_i=1-\exp(-\Delta t_i/T_i),$$

where T_i is the average time to detect object in the explored area.

Then the discrete optimization problem for finding the object in the area is formulated as follows [Jaiswal, 2012]:

$$\max P=\Sigma p_i(1-\exp(-\Delta t_i/T_i))$$
$$\Sigma\Delta t_i=t,\ \Delta t_i\geq 0$$

Similar statements do not take into account the possibility of using a UAV group that will simultaneously search for an object. Also, to solve this problem, a search may be considered as optimal, and then look for spatial distribution parameters inside the group [Jaiswal, 2012].

Analysis of search quality evaluation

The problem of objects finding from the air began to be resolved during the 1940s based on the approaches to determining the process effectiveness in the United States, which later became part of the theory of operations research [Ventzel, 1964]. The accumulated data allowed us to allocate critical parameters to assess the outcome of the operation, to formulate the effectiveness criteria and to perform a meaningful statement of optimization problems. The problem solution allowed to increase the effectiveness of their sentinel agents in time, reduce their number, identify problems in their distribution in the areas of responsibility, etc.

Search efficiency criteria. Such criteria can be used to calculate the input data of the routing problem for the UAV group.

Relative search speed. Relative search speed considering the estimation of search efficiency used in the theory of operations to construct criteria for optimizing UAV search and patrolling operations [Ventzel, 1964]. The efficiency measure is introduced as the ratio of the real to theoretical achievable search speeds:

$$Z_E=V_p/V_m$$

This is, in essence, the ratio of the average density of objects we are searching for in the search area to the amount of their detection by UAVs per unit time.

Real search speed in the area. Real search speed in the area may be calculated according to the next equation:

$$V_p=(K/T)/(O/S)$$

where K is the number of detected objects, T is the period of time for which these objects were found, O – the potential number of objects we are searching for in the area, S is the cell size of the search territory.

The theoretical speed of UAV searches:

$$V_m=L\cdot V$$

where L is the effective range of the object detection by UAVs, V – the UAV movement speed.

The ratio determines the productivity of using UAV tools. A comparison of real and theoretical search efficiency is a way of tracking the performance of search operations. This measure of effectiveness is not prize-winning for immediate use during district intelligence by the UAV group, since it uses a lot of a posteriori information; in the examples of its application, the indicator is measured during the month [Ventzel, 1964].

The relative area of the surveyed territory. As the criterion of the object search effectiveness in a given territory, the average value of the explored area with the given confidence until the specified period of time can also be used [Ventzel, 1964].

The effectiveness of UAV objects search is determined as follows:

$$Z_{OS}=(\Delta S/s)\cdot p$$

where ΔS – area, explored by one UAV, s – the total area of the UAV search at a single moment, p – probability of the successful task completion. The purpose of the UAV's search is based on the analysis of independent events: the correct recognition of the target object, obstacles (bad weather etc.) absence; therefore, the probability of fulfilling the task will be their product: the probability of correct recognition of the target object p_{or} and the likelihood of avoiding the influence of the obstacle p_{oi}. So, the stability of task completion:

$$p = p_{or}\, p_{oi}$$

For a group of N UAV, which facing, for example, M bad weather condition, interfering with successful control by the operator, the Bernoulli experiments repeat theorem to determine the probability of operation success will work [Корольов & Огурцов, 2017]:

$$P_{BW\,M}=(C_N)^M W^M\cdot(1-W)^{N-M}$$

where W – the probability of losing control over UAV due to bad weather conditions. Since the UAVs mostly have a short range of activities, they will fall into the zone of the same bad weather condition, respectively, the probability of stalling control will be one-sided.

Since events such as the UAV stability control and losing this control are mutually exclusive, then:

$$p_{oi}=1-P_{BW\,M}$$

If N UAVs are involved in the search territory problem, then if UAVs detect objects independently of each other, the trajectories of the survey intersect, duplication of data is not eliminated, the effectiveness of objects search process for UAVs will be:

$$Z_{OS}=(1/S)\cdot\Sigma\Delta S\cdot(1-(1-p)^k)$$

where ΔS – the area surveyed by one UAV at a single moment of time. So, the formulas above can be used to plan the object search.

When searching for an object according to the optimal plan, the distance between the UAVs during the search process should be at least half of the target detection range [Корольов & Огурцов, 2017]:

$$B=\Sigma d_i+2L$$

where B is the width of the observation area, d_i – the distance between the UAVs during the search process, L – the maximum target range. The sum is counting according to the number of UAVs.

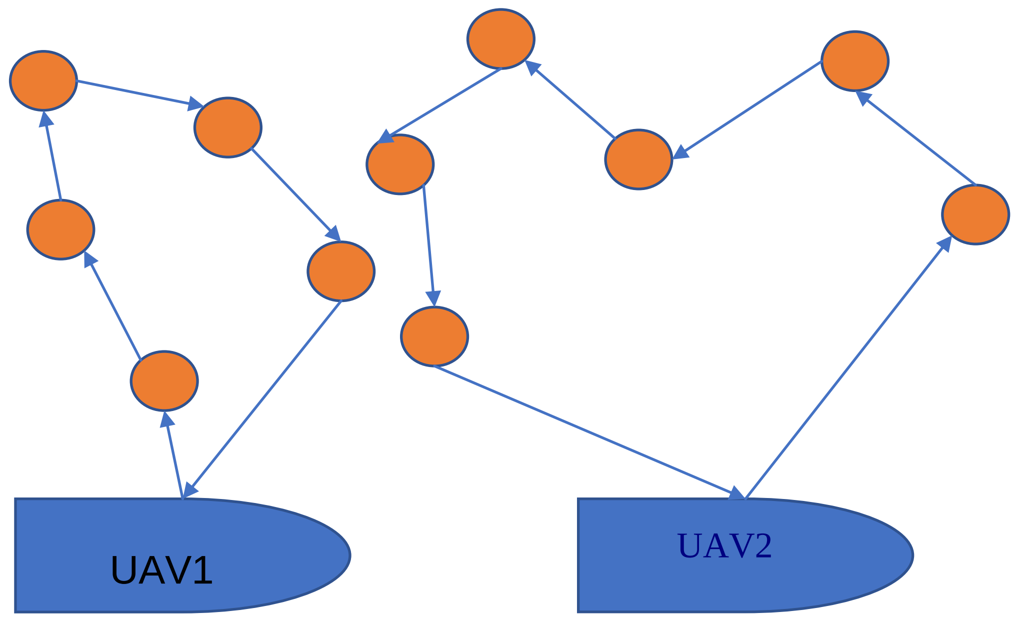
Observance of the distance value between the UAV group members by the formula above prevents the object from being skipped without re-registering the image of the surface. The given dependencies allow us to obtain initial conditions and parameters for the meaningful statement of the combinatorial optimization problem. The listed approaches to the search organization did not include the use of a group of UAVs integrated into the network to perform search operations [Корольов et al, 2017], [Поліновський et al, 2017].

The problem of a given territory general study

According to the problem terms, we have a certain territory, the area of which must be fully investigated to identify possible objects of interest. In this case, the territory may include predefined points of special interest that must necessarily be visited. Another priority when performing this problem is to cover given territory with existing UAVs as much as possible during a given time (or in the case of enough UAVs – fully research the entire territory with minimal fuel/time consumption).

For the successful performance of the tasks UAVs facing, it is necessary to solve the optimization problem of constructing routes with and without autonomous movement. During the territory study, it can be divided into smaller areas, taking into account the technical capabilities of the UAV equipment, which, for example, will correspond to the viewing angle of video recording equipment. In this case, some such problems can be reduced to building routes along with the points of centers of these smaller areas.

The problem of optimizing routes for UAV groups (without autonomous movement). According to the problem conditions, it is necessary to construct routes to each of the objects to be visited during the task execution, with a minimum travel time to the destinations and the minimum number of UAVs needed to complete the task (see image 1).



Img. 1 Example of route construction for two UAVs without autonomous movement

At the same time, each UAV is constantly under the direct control of the operator, and the UAV flew out and land at a place that we will call the depot.

Let's formalize the problem.

Incoming data.

- Maximum transmission range of the control signal;
- UAVs maximum number;

- coordinates of objects to visit;
- edge coordinates of territory to explore;
- depot coordinates;
- maximum range of UAV flight.

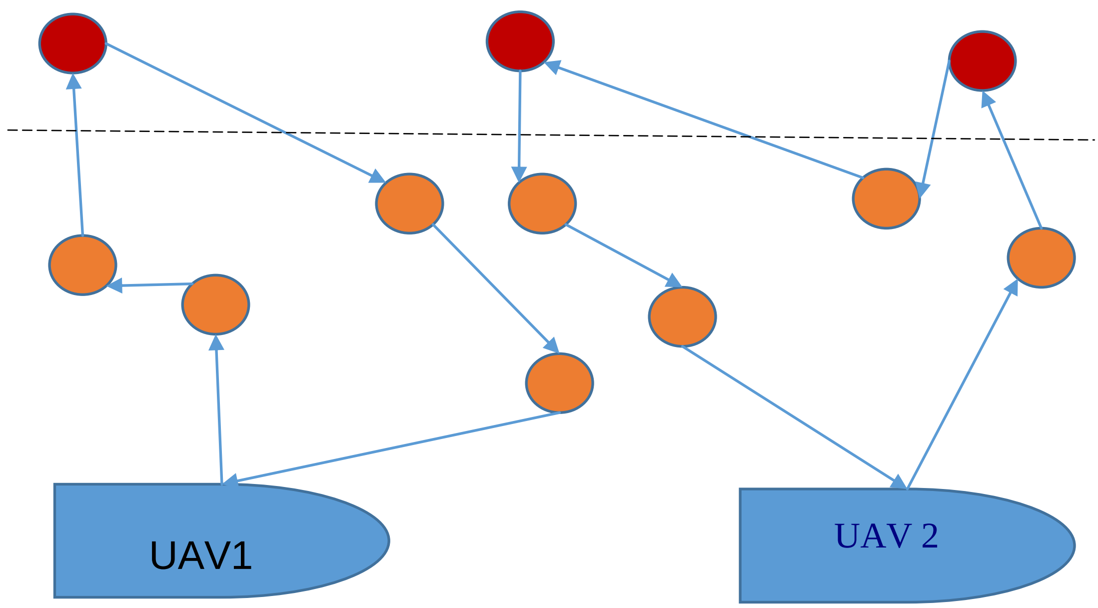
Output.

The route of each UAV with topographical binding, the route of the UAV is laid out in real coordinates and can be displayed on the area map.

Optimization Criteria.

- Minimization of the UAV routes total length;
- Minimization of the UAVs total number.

Routes optimization problem for UAV groups (with autonomous movement). Under the conditions of this problem, it is necessary to build routes to visit the objects (from the problem conditions) with the total minimum length of these routes, the minimum number of UAVs necessary for the task completion, and to determine the minimal time of autonomous movement (see image 2).



Img. 2 Example of route construction for two UAVs with autonomous movement

The autonomous movement refers to the UAV movement without the direct remote real-time control by the operator (movement on autopilot), following the predetermined flight plan.

The test area can be expanded by relaying a control signal using the UAV as a repeater.

Points of special interest, highlighted in image 2 with red color, are outside the UAV control radius and should be visited on autopilot.

Input data. Input data for the route optimization problem for UAV groups with autonomous movement:

• UAVs number;

• coordinates of objects to visit;

• depot coordinates;

• coordinates of the ground control points (operators);

• maximum range of UAV flight.

• UAV launch intervals and the number of UAVs, able to be in the air simultaneously (as supported by the control station);

• time of the UAV preparation for flight;

• bandwidth of the UAV relay equipment;

• minimum required channel bandwidth;

• maximum allowable delay for the control signal;

• the reach radius of the control signal from the ground control points.

The coordinates of the ground control points are needed to determine the maximum possible range of the UAV direct control (without signal retranslation). The UAV maximum flight range is determined by its technical characteristics (without taking into account the ability to control the UAV at such a distance).

Problem parameters.

- the maximum number of allowed retranslations;
- Frequency of UAV polls.

Criteria.

- minimizing sum length of UAV routes;
- minimizing the number of UAVs needed to complete the task;
- minimization of the number of control signals retranslations;
- minimizing the time spent outside the direct control zone;
- maximizing the amount of information being transmitted.

Output.

The route of each UAV with topographical binding, the route of the UAV is laid out in real coordinates and can be displayed on the area map.

When solving these problems three-dimensional (or, for calculations simplification, two-dimensional) coordinate grid is used.

Mathematical model

This routing problem relates to combinatorial type optimization problems that can be presented using a special graph [Корольов & Огурцов, 2017]. There are a set of points V_e to visit to avoid the refounding objects and reaching the target areas, there is a set of (depot) points V_d from which UAVs can be launched, as well as a set of points V_r where they can return.

Thus, based on these sets, a planar graph may be placed onto the map.

Let's introduce the following legend.

$G(V,E)$ – graph of the problem, where, $V=V_e \cup V_d \cup V_r$ and E is the set of graph edges;

C – matrix of integral distances (path values) C_{ij} between points v_i, v_j belong to V;

m – number of UAVs;

R_i – the route of the i-th UAV (i=1, …, m);

R – a set of routes R_i (i=1…m);

$C(R_i)$ – the cost of the route R_i (i=1, …, m);

$K(v)$ – the weight of each vertex v that belongs to V_e, which determines the importance of its attendance;

q_i – the movement resource of the UAV i (i=1, …, m).

Each point (graph vertex of the problem G) vi is given by coordinates (x_i, y_i). The routing problem consists in determining a set of m routes with a minimum total cost so that each vertex of the V_e subset is visited by only one UAV at least once. Also, the routes must begin at the vertices of the subset V_d and end at any point in the subset of V_r.

The target function in the general case is the cost of the solution of the problem:

$$F_{VRP}=(\Sigma K(v_i))/\Sigma C(R_i)$$

where $K(v_i)$ is the weight of the vertices v_i – part of the route R_i, i = 1, ..., m; $C(R_i)$ – the sum of the lengths of the route R_i paths, i = 1, ..., m.

In other words, it is necessary to find a valid solution with the maximum value of the target function on the formula above.

Conclusions and Prospects for Further Research

As a result of the performed works, further development of the routing problem meaningful statement for the UAV radio network with and without retransmission of control signals from the ground control center and the possibility of the UAV autonomous movement on the part of the route has been completed.

The general formulation of the target search problem in the area was given. An analysis of how to evaluate the quality of the search and what is the criteria for its effectiveness was conducted.

The formal statement of the UAV routing problem is presented, which deals with the stages of the operation planning and visiting the set targets by UAVs at the same time.

A mathematical model of a given problem has been built. Combinatorial optimization algorithms for this prblem can become the basis for solving a number of complex technical problems: increasing the technical (minimizing the territory exploring time) plus economic indicators (minimizing the UAVs amount) while using UAVs groups.

Implementation and practical use of the results obtained will allow us to increase the effectiveness of individual and group use of UAVs while performing different operations types and increase the maximum possible distance of UAV control by using relays.

Main directions of possible further research:

- development of combinatorial optimization algorithms for this problem;
- problems of the tasks formalization and routes optimization of a UAVs group, combined within a secure network, using the aircraft carrier;
- integral solving of the routing problem with minimization of necessary relays as an additional parameter.

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