Accounting for the information threat level in the route-segment cost metric for UAVs in emergency situations*

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Abstract

The purpose of the article is to develop a metric for the cost of a section of unmanned aerial vehicle (UAV) routes in emergency situations, which would take into account safety (danger) indicators, in particular, information security of the UAV during the performance of a flight task. The relevance of the work is due to the high efficiency of UAVs when performing tasks in dangerous areas in emergency situations. One of the main tasks of planning the use of UAVs is finding optimal routes under conditions of decision-making time constraints and computational resource constraints. The paper considers the Shortest Path Problem and the Sales Man Problem. To solve the Sales Man Problem, it is necessary to have a matrix of the shortest paths between all possible pairs of route points. To do this, the Shortest Path Problem is first solved for all possible pairs of route points. The cost metric for the Shortest Path Problem and the Sales Man Problem is the same. The cost metric takes into account fuel and battery charge consumption, and UAV depreciation, which proportionally depend on the Euclidean metric. It is proposed to take into account in the cost metric indicators of probable hazards regarding information security incidents (regarding information channels of information transmission and internal UAV computers), hazards regarding damage to UAVs, hazards of creating or aggravating dangerous situations due to UAVs, hazards of failure to perform tasks, etc. A hazard multiplier based on logistic dependence is proposed, which is used to adjust the Euclidean metric. A procedure for preliminary preparation of arrays of Euclidean metrics, hazard coefficients, and arrays of section costs for all possible pairs of route points is proposed. Cost metrics have been successfully tested when solving the Sales Man Problem and the Shortest Path Problem. The Shortest Path Problem solution was performed with different lengths of search steps. The search step is determined by the researcher based on the limitations of computational resources and available calculation time. Higher adequacy of optimal solutions with smaller search steps has been determined.

Keywords

Model, SMP, SPP, optimization, metric, cost, danger, information security, UAV.

1. Introduction

The use of unmanned aerial vehicles (UAVs) in dangerous situations, in particular during natural or man-made emergencies, allows reducing risks to human life and health. The effectiveness of UAVs is due to the fact that they can operate in a dangerous area without the physical presence of a person. In many respects, UAVs are more functional than a person (speed, ability to move over difficult or dangerous terrain, resistance to aggressive environments, etc.). The choice in favor of UAVs among other unmanned vehicles (ground, surface) is often made due to their ability to quickly reach dangerous areas, perform surveillance from the required distance, quickly deliver cargo (medicine, water, food, etc.) and promptly adjust tasks during the flight.

UAVs can perform tasks autonomously without human intervention using built-in algorithms or artificial intelligence. It is more effective to work under the control of an operator. The cognitive

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abilities of operators enhance the positive properties of UAVs. That is why, in most cases, UAVs are controlled by an operator and require constant information communication. Loss or compromise of the UAV information channel is a danger, the impact of which must be minimized or taken into account when planning a flight mission.

One of the main components of UAV flight planning is planning the optimal route. The minimum cost of the route is most often used as the optimality criterion. The cost may include positive components (which increase the cost): Euclidean distance, fuel or battery consumption, depreciation or probable damage to the UAV, probable impact of dangerous environmental factors, threats to UAV information security, etc. The negative components (which reduce the cost) include the beneficial effects that the UAV creates at points and sections of the route, for example, performing monitoring tasks, delivering cargo, relaying signals and performing other tasks. The importance of correctly taking into account the negative and positive components of the route cost is especially important in emergency situations, when conditions and dangers change every second, which requires operational changes in flight tasks and routes. Thus, the development of models and methods that improve the quality of operational planning of UAV flights in emergency situations is a pressing task. In emergency situations, there are significant limitations on decision-making time and computational resources of decision support software systems. If these limitations do not allow finding a strictly optimal route, then a search for a suboptimal, i.e., one close to the optimal route is assumed. Route determination is implemented through two main tasks.

Shortest Path Problem (SPP) — finding the cheapest path between two route points.

Sales Man Problem (SMP) [1] — finding the cheapest route in the traveling salesman problem, which involves determining the optimal order of visiting all given route points with a return to the starting point after completing the route.

To solve the SMP, you need to have a matrix of shortest paths between all possible pairs of route points. To do this, first solve the SPP for all possible pairs of route points. An optimal or suboptimal solution can only be found if the cost metric is clearly defined. The cost metric for both SPP and SMP problems is the same.

2. Analysis of existing research

We structure known types of SPP problems, common methods for solving them, and the evolution of their development.

SPSP, Single-Pair Shortest Path — solution methods: Dijkstra A. algorithm [2] and Richard Bellman — Lester Randolph Ford Sr. — method.

SSSP, Single-Source Shortest Path – Dijkstra algorithm.

APSP, All-Pairs Shortest Paths — Floyd-Warshall method [3–7].

SPWC, Shortest Path With Constraints — modifications of Dijkstra's algorithm and Bellman's dynamic programming method.

A prominent place among other methods is occupied by Bellman dynamic programming (first reported in 1952 [8] (Figure 1). It is on the basis of Bellman dynamic programming that most of the effective methods for solving SPP were developed. The breadth of application of the Bellman method in SPP and SMP problems is due to the fact that the method was initially aimed at a wide range of problems. Bellman provided the basic recurrence formula. Ford added an effective procedure for relaxing edges. Bellman adapted his method for many optimization problems, including SPP (1957) [9]. After mutual enrichment of ideas, an improved Bellman-Ford method was prepared (1962) [10].

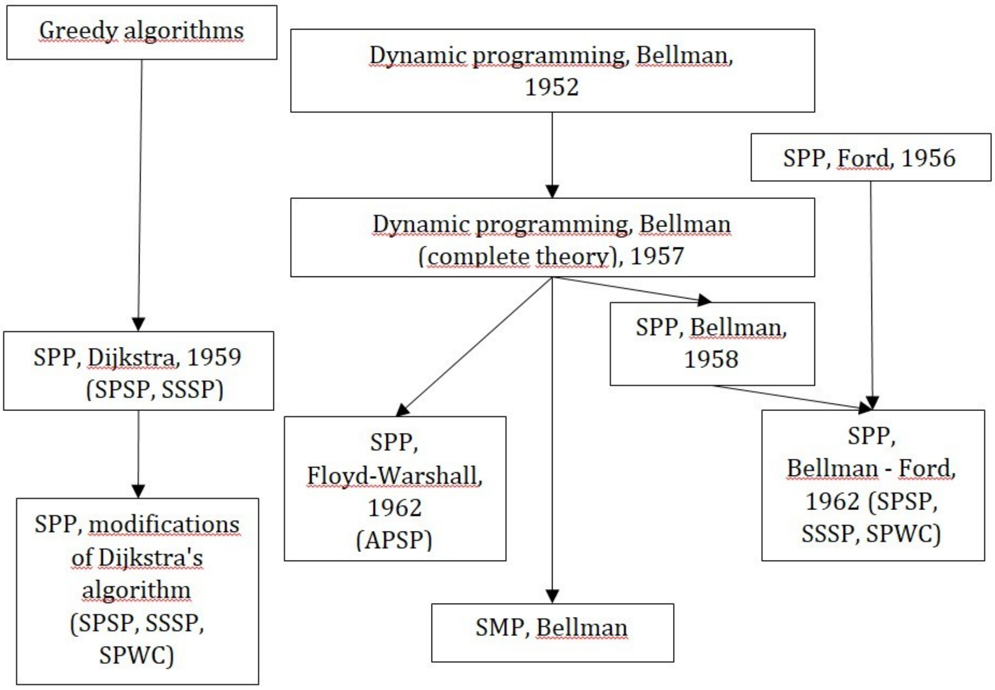

Figure 1: Evolution of SPP

The first three problems in the SPP classification are nested APSP(SSSP (SPSP)), that is, they are separate cases of each other. The SPWC problem is complicated by taking into account many constraints. As can be seen from (Figure 1), there are two main branches of SPP solution methods:

1. Methods based on Dijkstra's algorithm. Advantage: fast. Disadvantages: not accurate and do not work with negative section values.

2. Methods based on Bellman dynamic programming. Advantage: high accuracy, work with negative section values, workable under inconvenient constraints. Disadvantages: require a lot of computing resources and are inoperable in the presence of negative route cycles.

The general disadvantages of the studies that were analyzed are that they all focus on the route optimization procedure, assuming that the costs of the route sections are already known. In reality, determining the cost of a route section in conditions of danger cannot depend only on the Euclidean distance. Determining the cost of route sections turns into a non-trivial task, which begins with determining the cost metrics of route sections. The aim of the article is to develop a metric for the cost of a UAV route section in conditions of an emergency, which would take into account safety (danger) indicators, in particular, regarding the information security of the UAV during the performance of a flight task.

3. Determining the route segment cost metric

With a small error, it can be assumed that the speed of the UAV on the route is approximately the same. In this case, the expression for the UAV power required to complete the flight can be represented as [11]

$$P = P_e + P_0 + k_v V^2 + mgV_y, \tag{1}$$

$$V^2 = V_x^2 + V_y^2, \tag{2}$$

where P_e is a power of electronic control and communication systems, P_0 is a power of keeping the UAV in the air, V_x, V_y, V are horizontal, vertical and total flight speeds, k_v is a coefficient depending on the aerodynamic characteristics of the UAV, m is an UAV mass, g is an acceleration of free fall. We will find the energy consumption based on (1) and rewrite taking into account the constant flight speed and low (almost zero) flight altitude

$$E = P\,t = (P_e + P_0)\,t + k_v V\,s + mgH = ¿ \tag{3}$$

$$= (P_e + P_0)\frac{s}{V} + k_v V s + mgH = ¿ \tag{4}$$

$$= \left(\frac{P_e + P_0}{V} + k_v V\right) s, \tag{5}$$

where t is time, s is the length of the flight path, H is the flight altitude. Since, according to the assumptions made, the expression in brackets of formula (5) contains only constant values, we can consider the UAV energy consumption to be proportional to the length of the route, i.e., the sum of the costs of all sections of the route

$$CostRoute = \sum_{\substack{RouteSet,\\ i=2,N}} Cost(i, i-1), \tag{6}$$

where $RouteSet$ is an optimally ordered set of route point numbers, N, i is the total number and current route point number, $Cost(i, i\text{-}1)$ is the cost of the route section between points $i, i\text{-}1$. The basic value of the cost of the route section is the Euclidean distance between the extreme points of the route section

$$D_e(i, j) = \sqrt{(x_i - x_j)^2 + (y_i - y_j)^2}, \tag{7}$$

where x, y are the coordinates of the points, i, j are the numbers of the extreme points of the route in the initial list of route points. The energy cost and the depreciation cost of the UAV are proportional to the Euclidean distance between the extreme points of the route section

$$Cost_{D_e E, F}(i, j) = E + F = (k_E + k_F)\,D_e(i, j) \tag{8}$$

where E is the cost of battery energy and/or fuel, F is the cost of UAV depreciation, k_E, k_F are the corresponding coefficients for taking into account the costs of battery energy/fuel and UAV depreciation. In normal safe conditions of UAV use, expression (8) can be considered sufficient to determine the cost of the route section between points i, j. But in an emergency situation, it is very important to take into account the hazard indicators. Let's define the main indicators of possible dangers for UAVs:

q_{is}, M_{is} are probability and probable losses in case of information security incidents regarding information transmission channels and internal UAV computers,

q_{forUAV}, M_{forUAV} are probability and probable losses in case of damage or occurrence of danger for UAVs,

$q_{fromUAV}, M_{fromUAV}$ are probability and probable losses in case of creation or aggravation of dangerous situations due to UAVs,

q_{task}, M_{task} are probability and probable losses in case of failure to perform tasks, etc.

Next, it is necessary to aggregate the danger indicators for further use in the route section cost metric. Two approaches can be used for this.

Approach 1 (probabilistic). If we assume that all hazards with different probabilities occur simultaneously during a flight on a given route segment, then we can use the following overall hazard coefficient with a scale factor of 100:

$$k_{Hazard}(i, j) = 100\left(1 - (1 - q_{is})(1 - q_{forUAV})(1 - q_{fromUAV})(1 - q_{task})\right) \tag{9}$$

The hazard coefficient $k_{Hazard}(i, j)$ takes values from 0 to 100. It is possible to refine the dependence (9) for cases when probable events do not occur all at once, but one by one or in other combinations. But numerical modeling has shown that with the accuracy of the input data that is usually available in an emergency situation, expression (9) allows us to make an adequate decision regarding the route, taking into account the existing hazards.

Approach 2 (economic). If among the hazard indicators we also have the values of probable losses, then instead of expression (9) we can use a more economically understandable indicator of total probable losses.

$$k_{Hazard}(i, j) = 100 \frac{q_{is} M_{is} + q_{forUAV} M_{forUAV} + q_{fromUAV} M_{fromUAV} + q_{task} M_{task}}{M_{max}} \tag{10}$$

where M_{max} is the maximum possible total value of losses from probable hazards. If further analysis reveals a larger number of types of hazards (for example, information hazards will need to be detailed according to threat profiles: confidentiality, integrity, availability), then it would be more appropriate to represent dependence (10) in the form

$$k_{Hazard}(i, j) = \frac{100}{M_{max}} \sum_{h=1}^{N_h} q_h M_h, \tag{11}$$

where h is the hazard number, q_h, M_h is the probability of occurrence and probable losses in the event of occurrence of hazard number h. The choice of dependence (9), (10) or (11) for finding the hazard coefficient depends on the number of types of hazards and the availability of indicators characterizing hazards. To take into account the level of hazard in the site cost metric, we will use the logistic dependence [12] (Figure 2) and present the hazard multiplier in the form of the expression

$$SL(k_{Hazard}(i, j)) = d + \frac{a - d}{1 + e^{\frac{-2}{T}(k_{Yazard}(i, j) - s)}}, \tag{12}$$

where a, d, T, s are the parameters (constants) of the logistic dependence.

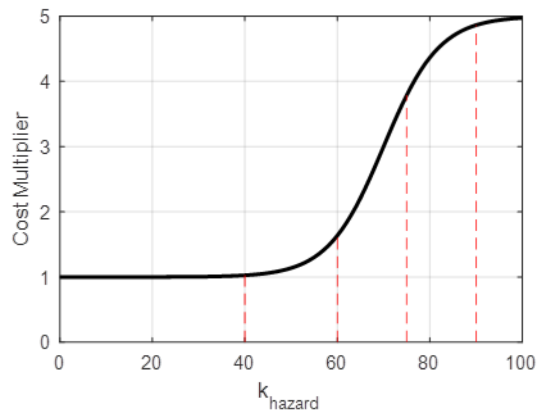

Figure 2: Hazard multiplier depending on hazard coefficient

The metric of the cost of the site, taking into account the danger and other indicators, is presented in the form

$$Cost_{\Sigma}(i, j) = SL(k_{Hazard}(i, j))(k_E + k_F) D_e(i, j). \tag{13}$$

Now we find the cost of the entire route as

$$CostRoute = \sum_{\substack{RouteSet, \\ i=2,N}} Cost_{\Sigma}(i, i=1). \tag{14}$$

To speed up the computational procedure, the matrices of values $D_e, k_{Hazard}, Cost_{\Sigma}$ for all possible pairs of route points are calculated before starting the iterative procedure of finding the optimal route. An example of a heat map for the $Cost_{\Sigma}$ matrix when solving the SMP is shown in (Figure 3).

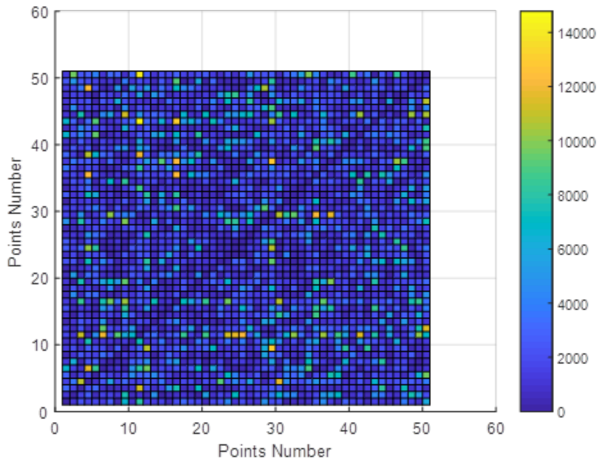

Figure 3: Heat map of the array of costs of passing route sections when solving SMP, taking into account the hazard coefficient and other indicators

Similarly, it is advisable to prepare in advance arrays of CRAx route values when solving SPP. Unlike SMP, there are no predefined route points in SPP. Only a pair of route points is given, between which it is necessary to find the optimal path taking into account all hazards, including information security incidents. The size of the cells into which the search field will be divided depends on the researcher's decision. Examples of arrays of CRAx values for SPP with different lengths of the edges of the SPP route sections (search step) are presented in (Figure 4, 5, 6) in the form of 3D surfaces. With a smaller search step (Figure 6), features are revealed that are not at all noticeable with a larger step (Figure 4). The researcher determines the optimal size of the search step taking into account the requirements for the accuracy of the solution and the available computational resources and calculation time.

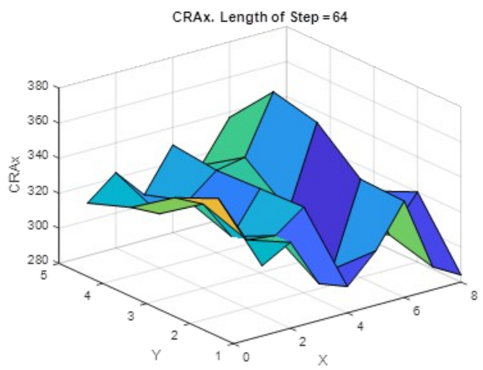

Figure 4: 3D surface of the array of values in SPP at the search step 64

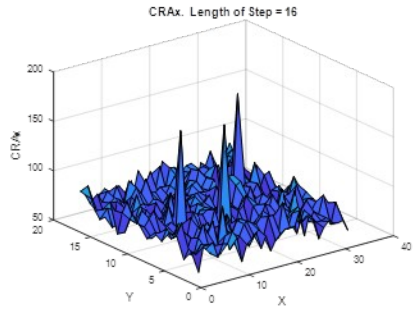

Figure 5: 3D surface of the array of values in SPP at the search step 16

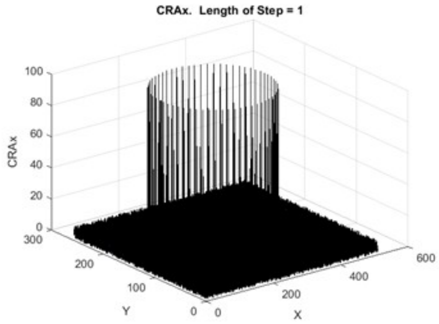

Figure 6: 3D surface of the array of values in SPP at the search step 1

4. Testing cost metrics when solving SMP and SPP

The validation of cost metrics was performed when solving SMP and SPP.

SMP was successfully solved by finding a support solution using a greedy algorithm and further improving the support solution with a stack of local variation methods. The result is a suboptimal route (Figure 7).

SPP was successfully solved using the Bellman dynamic programming method in reverse time. The result is a route that is optimal up to the selected search step length. The results of the SPP solution are presented in (Figure 8). The costs of passing sections are marked on the edges of the cells with the corresponding numbers. With a smaller search step, the resulting route is safer, since the search procedure better avoids dangerous areas and finds loopholes for safe movement of the UAV near dangerous objects, which are presented in (Figure 4, 5, 6) in the form of sharp high peaks.

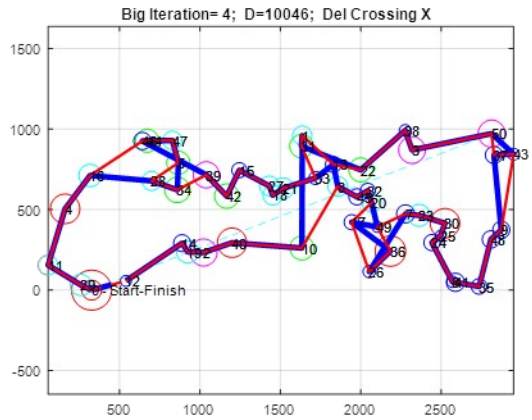

Figure 7: The optimal route for SMP

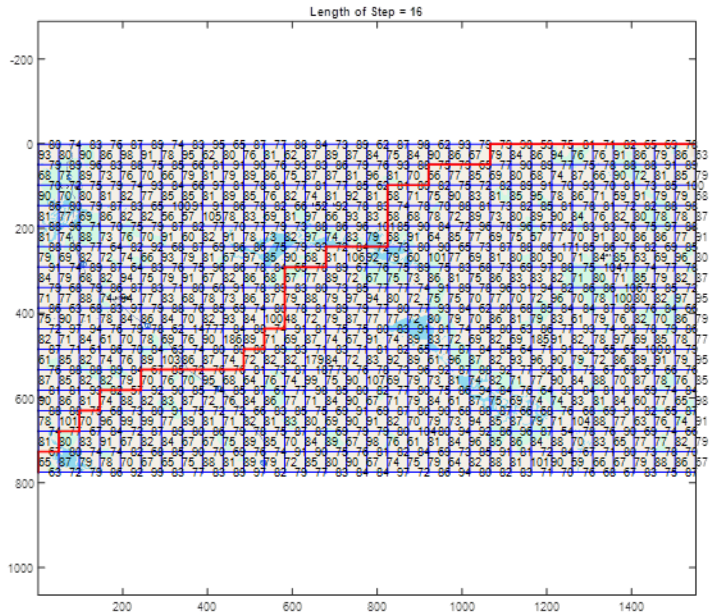

Figure 8: The optimal route for SPP

5. Conclusions

The paper considers the Shortest Path Problem and the Sales Man Problem. To solve the SMP, you need to have a matrix of shortest paths between all possible pairs of route points. To do this, first solve the SPP for all possible pairs of route points. The cost metrics for the SPP and SMP are the same.

The traditional cost metric is based on the Euclidean metric. In this work, the cost metric takes into account fuel and battery consumption, UAV depreciation, which proportionally depend on the Euclidean metric.

The work proposes to take into account in the cost metric indicators of probable hazards regarding information security incidents (regarding information transmission channels and internal UAV computers), hazards regarding damage to UAVs, hazards of creating or aggravating dangerous situations due to UAVs, hazards of failure to complete tasks, etc.

A hazard multiplier based on logistic dependence is proposed, which is used to adjust the Euclidean metric.

A procedure for preliminary preparation of Euclidean metric arrays, hazard coefficients, and an array of section costs for all possible pairs of route points is proposed.

Cost metrics have been successfully tested when solving the Sales Man Problem and the Shortest Path Problem. The solution of the Shortest Path Problem was performed at different lengths of search steps. Higher adequacy of optimal solutions was determined at smaller search steps. The search step is determined by the researcher based on the limitations of computational resources and available computing time.

Declaration on Generative AI

While preparing this work, the authors used the AI programs Grammarly Pro to correct text grammar and Strike Plagiarism to search for possible plagiarism. After using this tool, the authors reviewed and edited the content as needed and took full responsibility for the publication’s content.

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