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THE UAV FLIGHT ROUTE OPTIMIZATION BY TAKING INTO CONSIDERATION THE WIND INFLUENCE

Among external factors, the greatest influence on the dynamics of the flight has wind. It has both a chaotic turbulent component and a constant component, which may not change throughout the flight. The average speed of a constant wind component has a practically horizontal direction and significantly influences the solving of the navigational tasks. The wind speed can be taken into account as a result of the unmanned aerial vehicle (UAV) flight route planning. In recent studies and publications the wind influence was not taken into consideration when solving trajectory problems of the UAV flight. The basic calculated relations and optimization approaches of the flight program of an UAV on the route in wind conditions are determined. It is proposed to use the simplest algorithm of complete overview, when finding the best UAV flight route, where the number of route points does not exceed 20. This algorithm guarantees the exact solution finding. According to the research results, the influence of the continuous wind on the route optimality (optimal sequence of the route points passage) was not registered. The presence of the wind considerably affects the UAV overall flight time on the route.

Keywords: *route optimization, flight program, unmanned aerial vehicle, wind speed, flight dynamics, numerical methods, commercial traveler's task, efficiency of application.*

Introduction

Formulation of the problem. The task of choosing the optimal route that must pass through given points is known as a "commercial traveler's task ". The classical commercial traveler's task is that he must visit a certain number of other settlements from his hometown and go back so that the length of his journey is as small as possible. A practical example of this problem is the optimization of the flight program of unmanned aerial vehicle (hereinafter UAV) on the route. The solution of this task requires the calculation of the transition cost from one point of the route to another. The transition cost means the required time or fuel consumption (battery charge). The calculation of these parameters for UAV flight route optimization has significant peculiarities. The most of the UAVs used by Ukraine force structures, according to their characteristics, are classified as class I (micro, mini, small). Modern UAVs of this class usually have small cruising flight speed (up to 100 km/h). Among external factors, the greatest influence on the dynamics of the flight has wind. It has both a chaotic turbulent component and a constant component, which may not change throughout the flight [1]. The average speed of a constant wind component has a practically horizontal direction and significantly influences the solving of the navigational tasks. The wind speed can be taken into account as a result of the UAV flight route planning.

Analysis of recent research and publications. The difficulty of solving the commercial traveler's task depends on the number of specified points on the route n, because the number of possible route options is n! The search for the solution of this problem by precise methods, such as a complete overview, directed search with a return, the method of branches and boundaries and others, requires significant computational resources that exponentially increase with increasing number of route points. Therefore, in practice, with a significant number of route points, the heuristic (approximate) methods are more often used. This allows getting the result approximate to optimal at a reasonable time. Heuristic methods include methods of annealing imitation, genetic algorithms, methods of ant colonies, probabilistic greedy algorithms and others [2]. For example, in [3], the application of modern modification of the genetic algorithm (NSGA-III) for solving the problem of UAV flight planning in the conditions of communication constraints was considered. In [4], the comparison of Monte Carlo methods, reduction of rows and columns, and averaged coefficients for solving the commercial traveler's task during the planning of the UAV route is carried out. In [5-6] the optimal planning of the complex tasks implementation of several UAVs is considered. The article [7] considers the problem of minimizing the flight time of a small UAV on the route in the presence of a statically changing wind. In [8] the flight paths of the UAV, the piloting laws, and the deviation angles of camera for monitoring the ground object in wind conditions were obtained. The optimization of the UAV flight control for the gradient wind energy use is investigated in [9]. In the paper [10] a review of publications on the UAV flight dynamics was conducted, the formulation of tasks was analyzed and the main directions of further research on the identified themes were determined. The monograph [11] examines the problems of the UAV movement within the group. In this case, the flight path is given by one or more continuous curves without the breaking points of their derivatives (without using turning points of the route and typical points of the trajectory).

Thus, in recent studies and publications the wind influence was not taken into consideration when solving trajectory problems of the UAV flight.

The aim of this work is to solve the optimization problems of the UAV flight route, taking into account the influence of the wind and the analysis of the results.

The main material

The mathematical formulation of the problem is as follows: a complete considered graph is given $G=(V,E,D)$, where V – set of vertices $v_{ij} \in V$ which are identified with the turning points of the route; E – set of ribs $e_{ij} \in E$; D – set of ribs weight $d_{ij} \in E$. It is necessary to find the Hamiltonian cycle of minimal weight that is, the closed cycle in a graph containing all the vertices and anticipates visiting one vertex only once.

Let $P^{(k)} = \left(p_1^{(k)},...p_n^{(k)}\right)$ – version of combinatorial permutation of numbers of n elements of the vertices set $\{1,...,n\}$, where $k=(\overline{1,n!})$ – version number of combinatorial permutation; $p_i^{(k)} = (\overline{1,n})$ – the number of the route point in the k-th option of the combinatorial permutation, which must be passed at i-th stage, and $p_{n+1}^{(k)} = p_1^{(k)}$ $p_{n+1} = p_1$.

The combinatorial permutation of the numbers of the route points k^*, for which the minimum is reached, is sought:

$$\sum_{i=1}^{n} d_{p_i^{(k^*)} p_{i+1}^{(k^*)}} = \min_{k^* = (\overline{1,n!})} \sum_{i=1}^{n} d_{p_i^{(k)} p_{i+1}^{(k)}} . \qquad (1)$$

Solving the problem, the following assumptions are taken:

the weight of the graph edge is identified with the time of the UAV flight between the points of the route;

the UAV airspeed during air traffic route is permanent (cruising);

the UAV turning radius and the time required to turn the UAV into intermediate points of the route are not taken into account;

the speed and direction of the constant component of the wind during the UAV flight does not change.

In the presence of a constant component of the wind, the air and the road speed of the UAV flight do not coincide. If the control of UAV is carried out in such a way, that its course is directed to a given point ν_j, then, with the presence of a side wind, the trajectory of the flight will present an arc (fig. 1, a). In case when controlling the UAV, its road speed $\vec{W}$ will be directed on the specified point ν_j, the flight will be performed along a given path with some degree of drift (fig. 1, b).

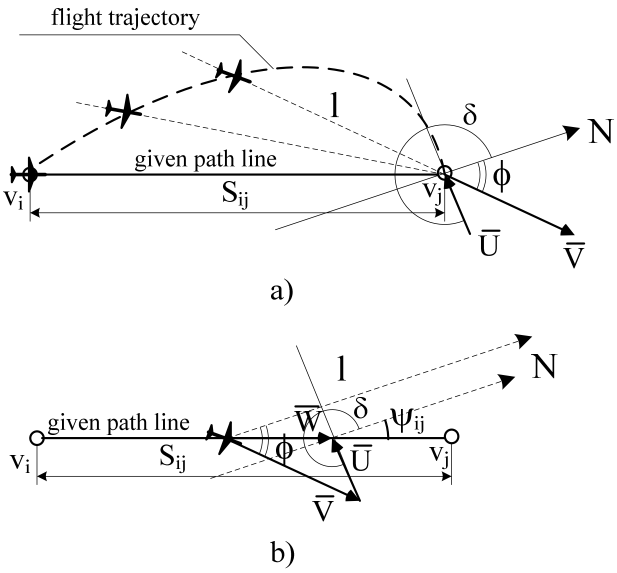

Fig. 1. The trajectory of the flight between the specified points of the route with the influence of wind

To calculate the UAV flight time between the points of the route ν_i and ν_j in the case indicated in Figure 1a, the system of differential equations are needed to solve, since the road speed and the course have been changing over time.

The system of differential equations, which describes the change in the course of the UAV and its distance to a given point, has the form:

$$\frac{d\phi}{dt} = \frac{U\sin(\delta - \pi - \phi)}{l}; \qquad (2)$$

$$\frac{dl}{dt} = -V + U\cos(\delta - \pi - \phi), \qquad (3)$$

where ϕ – the UAV course – the angle in the horizontal plane between the meridian and the longitudinal axis of the UAV; U – wind speed - the velocity of air masses as to the earth's surface; l – the distance between the UAV and the route point; V – the flight air speed - the speed of the UAV as to air; δ – navigation direction of the wind – the angle in the horizontal plane between the meridian and the direction of the wind.

The solution of the system of equations (2–3) has no analytical form, therefore numerical integration with initial conditions is required to use:

$$\phi_0 = \psi_{ij},\ l_0 = s_{ij},\ t_0 = 0,$$

where ψ_{ij} – the azimuth of j point of the route as to i:

$$\psi_{ij} = \begin{cases} \arccos\left(\dfrac{x_j - x_i}{s_{ij}}\right), y_j \geq y_i, \\ 2\pi - \arccos\left(\dfrac{x_j - x_i}{s_{ij}}\right), y_j < y_i, \end{cases} \qquad (4)$$

where x_i, y_i, x_j, y_j – the route points coordinates in a rectangular coordinate system (WGS 84);

s_{ij} – the distance between j and i points of the route and is calculated as:

$$s_{ij} = \sqrt{\left(x_i - x_j\right)^2 + \left(y_i - y_j\right)^2}. \qquad (5)$$

The UAV flight time T_{ij} between route points ν_i and ν_j is determined by the termination of the integration: $l \leq 0$.

The UAV flight time between the route points ν_i and ν_j for the scheme shown in fig. 1, b, when the flight parameters are constant, is reduced to the calculation of the ratio:

$$T_{ij} = \frac{s_{ij}}{\left|\vec{W}_{ij}\right|}, \qquad (6)$$

where $\left|\vec{W}_{ij}\right|$ – the module of the road speed.

There is a conclusion that is made out of triangle of velocities, shown on fig. 1, b:

$$\left|\vec{W}_{ij}\right| = \left|\vec{V}\right| \sqrt{1 - \left[\frac{\left|\vec{U}\right|}{\left|\vec{V}\right|} \sin(\delta - \pi - \psi_{ij})\right]^2} + \left|\vec{U}\right| \cos(\delta - \pi - \psi_{ij}). \qquad (7)$$

In general the UAV flight time T_{ij} between the route points ν_i and ν_j depends on the way of controlling it. The calculations comparison of results of the UAV flight time T_1 shows, that they are made using the system of differential equations (2–3), and T_2 – using (6–7), the difference does not exceed 3%, even at the different directions wind speed of up to 60% of the UAV speed, and 6% at 80% (fig. 2).

This allows carrying out the calculations of the flight time between the points of the route with reasonable accuracy using the simple analytical expressions (4–7) regardless of the UAV control scheme.

It is generally acknowledged that the commercial traveler's task in general is guaranteed to be solved optimally only with a complete overview of all options.

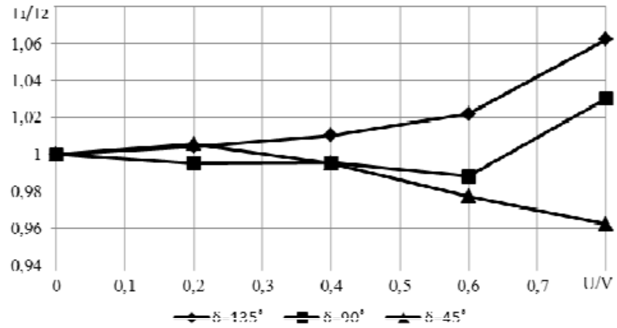

Fig. 2. Comparison of UAV flight time between the points of the route at different ways of control

But with the growth in the number of nodes, the time spent on a complete overview increases exponentially. For example, on a PC with four 2.67 GHz processors, 10 nodes are calculated on average for 5 milliseconds, 20 nodes – for 15 minutes, and the calculation of 60 nodes optimal path will take more than 6 trillion years [12]. For this obstacle avoidance with a large number of nodes, it is necessary to refuse from obtaining the accurate optimal solution and apply the "heuristic solutions", which do not guarantee the accuracy of the solution better than 1.5 of the optimal.

The number of nodes (turning points of the route) does not exceed 15-20 for the most cases of the UAV routing. There is no need to use "heuristic solutions" that require the programming of sufficiently complicated algorithms. An acceptable algorithm for optimization is a complete overview of all possible route options. In cases of more turning points of the route, it is reasonable to use approximation methods.

A number of calculations with the application of the above approach for quantitative evaluation of the wind effect on the results of the flight route optimization were carried out.

For example, it is given:

the initial (final) point of the route has coordinates $v_1(0;20)$;

coordinates of the turning points of the route $v_2(20;20)$, $v_3(25;20)$, $v_4(20;30)$, $v_5(20;10)$, $v_6(30;25)$, $v_7(30;33)$, $v_8(40;28)$, $v_9(35;20)$, $v_{10}(38;15)$;

UAV speed (aerial) $V = 30$ m/c.

Fig. 3 shows the estimated time of flight on the route with the direction of the wind $\delta = 270^\circ$ for certain initial data.

Fig. 4 shows the results of calculation of flight time on a route from the direction of the wind.

The results of the calculations indicate that the time of the flight on the closed route and the optimal sequence of passing the turning points of the route do not depend on the direction and speed of the wind.

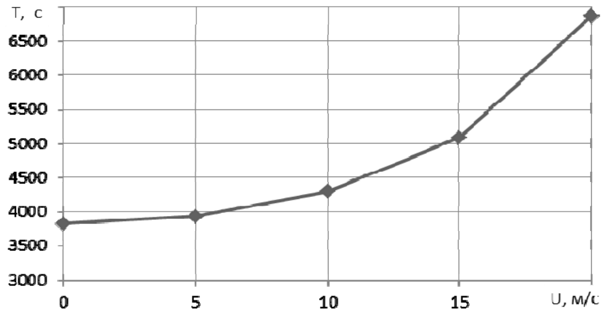

Fig. 3. Dependence of flight time on the route from the wind speed

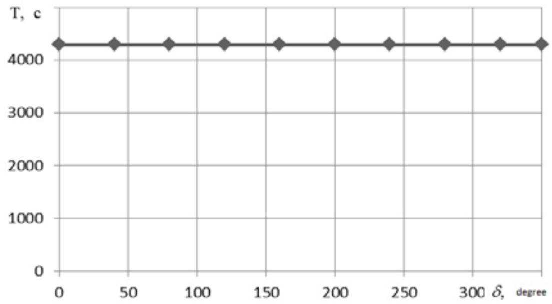

Fig. 4. Dependence of flight time on a route from the wind

The direction of passing the optimal sequence of the route points does not significantly affect the UAV estimated time of flight on the route (within the limits of calculation errors). For this example the optimal sequence of the route points passing is shown in fig. 5.

The presence of the wind considerably affects the overall UAV flight time on the route.

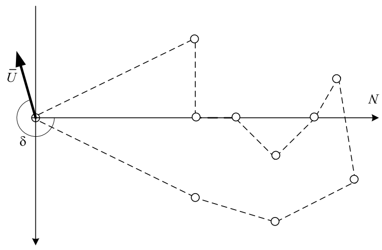

Fig. 5. The optimal sequence of the route points passing

Conclusions

1. The basic calculation relations and approaches to optimization of the flight program of unmanned aerial vehicle on the route under the wind conditions are determined.

2. It is offered to apply the simplest algorithm of complete overview when finding the optimal flight route of UAV where the number of route points does not exceed 20.

3. According to the results of the research, the influence of a constant wind on the optimal sequence of passing the points of the closed route (when take-off and landing place match) was not registered.

4. The presence of wind significantly affects the UAV total flight time on the route.

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ОПТИМІЗАЦІЯ МАРШРУТУ ПОЛЬОТУ БЕЗПІЛОТНОГО ЛІТАЛЬНОГО АПАРАТУ З УРАХУВАННЯМ ВПЛИВУ ВІТРУ

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Серед зовнішніх факторів найбільший вплив на динаміку польоту літака має вітер. Він має як хаотичну турбулентну складову, так і постійну складову, яка може не змінюватись на протязі усього польоту. Середня швидкість постійної складової вітру має практично горизонтальний напрямок і суттєво впливає на розв'язання навігаційних задач. Врахування швидкості вітру може відзначитись на результаті планування маршруту польоту безпілотного літального апарату (БпЛА). Останнім часом в дослідженнях і публікаціях не приділялась увага врахуванню впливу вітру при розв'язанні траєкторних задач польоту БпЛА. Метою статті є розв'язання задачі оптимізації маршруту польоту БпЛА з урахуванням впливу вітру та аналіз результатів. Розглянуто розв'язання задачі вибору оптимального маршруту, який повинен проходити через задані точки, ("задача комівояжера") в умовах вітру. Розв'язання даної задачі потребує розрахунку вартості переходу з одного пункту маршруту до іншого. Під вартістю переходу розуміється потрібний час або витрата палива (заряду акумулятора). Існують особливості розрахунку часу польоту БпЛА між пунктами маршруту. Отримано формули розрахунку часу польоту для двох способів управління (1 - прі дотриманні курсу на задану точку; 2 - при польоті по прямій з урахуванням зносу). Показано, що незалежно від способу керування допустимо використання простих аналітичних виразів для розрахунків з прийнятною точністю.

Пропонується, при знаходженні оптимального маршруту польоту БпЛА, коли кількість пунктів маршруту не перевищує 20, застосовувати найбільш простий алгоритм повного перебору, який гарантує знаходження точного рішення. За результатами досліджень не відзначено впливу постійного вітру на оптимальну послідовність проходження пунктів зімкнутого маршруту (коли місце зльоту та посадки співпадає). Наявність вітру значно впливає на загальний час польоту БпЛА по маршруту.

Ключові слова: *оптимізація маршруту, програма польоту, безпілотний літальний апарат, БпЛА, швидкість вітру, динаміка польоту, чисельні методи, задача комівояжера, ефективність застосування.*

ОПТИМИЗАЦИЯ МАРШРУТА ПОЛЕТА БЕСПИЛОТНОГО ЛЕТАТЕЛЬНОГО АППАРАТА С УЧЕТОМ ВЛИЯНИЯ ВЕТРА

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Среди внешних факторов наибольшее влияние на динамику полета самолета имеет ветер. Он имеет как хаотическую турбулентную составляющую, так и постоянную составляющую, которая может не меняться на протяжении всего полета. Средняя скорость постоянной составляющей ветра имеет практически горизонтальное направление и существенно влияет на решение навигационных задач. Учет скорости ветра может отличиться на исходе планирования маршрута полета беспилотного летательного аппарата (БПЛА). В последнее время в исследованиях и публикациях не уделялось внимание учету влияния ветра при решении траекторных задач полета БПЛА. Целью статьи является решение задачи оптимизации маршрута полета БПЛА с учетом влияния ветра и анализ результатов. Рассмотрено решение задачи выбора оптимального маршрута, который должен проходить через заданные точки, ("задача коммивояжера") в условиях ветра. Решение данной задачи требует расчета стоимости перехода из одного пункта маршрута к другому. Под стоимостью перехода понимается нужное время или расход топлива (заряда аккумулятора). Существуют особенности расчета времени полета БПЛА между пунктами маршрута. Получены формулы расчета времени полета для двух способов управления (1 - при соблюдении курса на заданную точку, 2 - при полете по прямой с учетом износа). Показано, что независимо от способа управления допустимо использование простых аналитических выражений для расчетов с приемлемой точностью.

Предлагается, при нахождении оптимального маршрута полета БПЛА, когда количество пунктов маршрута не превышает 20, применять наиболее простой алгоритм полного перебора, который гарантирует нахождение точного решения. По результатам исследований не отмечено влияния постоянного ветра на оптимальную последовательность прохождения пунктов сомкнутого маршрута (когда место взлета и посадки совпадает). Наличие ветра значительно влияет на общее время полета БПЛА по маршруту.

Ключевые слова: *оптимизация, приложение полета, беспилотный летательный аппарат, БПЛА, скорость ветра, динамика полета, численные методы, задача коммивояжера, эффективность применения.*