Вісник Тернопільського національного технічного університету
https://doi.org/10.33108/visnyk_tntu
Scientific Journal of the Ternopil National Technical University
2023, № 2 (110) https://doi.org/10.33108/visnyk_tntu2023.02
ISSN 2522-4433. Web: ***visnyk.tntu.edu.ua***

UDC 004.021.8

UAV MOVEMENT PLANNING IN MOUNTAINOUS TERRAIN

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Summary. *The principles of planning of unmanned aerial vehicle movement in mountainous terrain are described in this paper. It is emphasized that the movement of the aerial vehicle takes place along the trajectory on a certain trajectory movement model, where unmanned aerial vehicle is represented as material point, the mass of which is concentrated in the center of mass. A discrete model in the linear state space that approximates the dynamics of an unmanned aerial vehicle is proposed. The general spatial movement of unmanned aerial vehicle is divided into longitudinal and lateral movement, and the longitudinal movement is considered independently of the lateral movement, taking into account the characteristics of the flight of unmanned aerial vehicle in mountainous terrain. The selection of the polygon from a certain set of irregularities in relation to the speed limit, acceleration limit and change in acceleration of unmanned aerial vehicle in the conditions of movement in mountainous terrain is graphically presented. It is emphasized that since the corresponding heights for any point on the curved surface of the relief are unknown, in order to obtain them, it is necessary to use the interpolation of the vertices of the corresponding triangle. It is noted that while choosing certain values of the coefficients, it is possible to describe the surface of the terrain using triangles, taking into account the combinations of coordinates of each known peak, and using the combinations of undefined coefficients as variable solutions, it is possible to describe the restrictions on the bending of the mountainous terrain. It is emphasized that during trajectory movement, the unmanned aerial vehicle is presented as material point, and in a real flight over mountainous terrain, its characteristic dimensions must be taken into account in order to avoid the obstacle successfully. It is proposed to increase the dimensions by a certain amount in each direction for effective obstacle avoidance of the unmanned aerial vehicle in mountainous terrain.*

Key words*: unmanned aerial vehicle, mountainous terrain, algorithm, planning, flight, route.*

https://doi.org/10.33108/visnyk_tntu2023.02.015 *Received 15.03.2023*

Introduction and statement of the problem. The world community puts a lot of effort into the development of modernized unmanned aerial vehicles (UAVs) capable to perform the tasks assigned to them in the presence of obstacles. The development and application of UAV requires to solve a number of important problems, one of which is the provision of its autonomous flight, which can take place in various difficult terrain conditions: in urban environment (among buildings), in mountainous terrain, over desert, forest-park, water environment, etc. With the rapid development of UAVs capable of moving in complex terrain, the task of real-time flight route planning is becoming increasingly important.

In order to ensure the autonomous flight of UAV, it is necessary to solve the following key tasks: the flight route planning (FRP) prior to UAV launch and during its flight; trajectory control and stabilization of UAV during flight; determining the coordinates of UAV location in space, that is, navigation.

In the control systems of modern aircrafts, the control method with predictive models is successfully used [1]. The fundamental basis of this method is that in the UAV flight, its route is calculated gradually, and each section of the flight route is determined as the result of solving the optimization problem in the limited time interval, making it possible to reduce the calculation time [2–5].

Analysis of the available researches and publications. At present, more and more papers describing the mechanisms and principles of UAV movement planning have been published.

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Thus, in his paper [6], A. O. Berezhnyi presented the method of automated UAV flight route planning for the search of the dynamic object, which, unlike the existing ones, takes into account the uncertainty in the actions of the opposite party, forms the options of motion forecast, evaluates the dynamic characteristics of the object on each possible route of its movement, enables to reduce the uncertainty of information about these routes and to form rational route for monitoring observation objects.

K. D. Molchanov, D. I. Boiko, and N. Ye. Khatsko [7] proposed the geometric method of developing UAV route for obstacle avoidance. The authors developed the route of movement based on the given algorithm, which is capable to develop the route of UAV movement automatically with the possibility of avoiding obstacles.

Intelligent decision support system, which includes the model of dynamic objects movement, as required component is presented in paper [8]. This model makes it possible to perform location forecasting and reduce uncertainty in UAV actions.

O. M. Husak [9] revealed the principles of UAV route formation for detecting forest fires. The author presents information technology, the implementation of which is aimed at the notification of fire danger by involved non-specialized unmanned aerial vehicles in the event of the detection of forest fire center, which is based on the expansion of their information and technological capabilities, that make it possible to inform rescue services additionally improving the effectiveness of forest fire safety.

Among the foreign authors, the following papers are worth noting: Beishenalieva Aliia, Yoo Sang-jo [10], Airlangga Gregorius, Liu Alan [11], Kim M.,Pevzner L.,Temkin I. [12], Xing Peizhen, Zhang Hui, Ghoneim Mohamed, Shutaywi Meshal [13], Wang Na, Dai Fei, Liu Fangxin, ZhangGuomin [14], Izhboldina Valeriia, Igor Lebedev [15], Li Menglei, Chunhui Zhao, Hu Jinwen, Xu Zhao, Guo Chubing, Dou Zengfa [16], Gao Yang, Li Yuankai, Guo Ziqi, Tan Xiaosu [17], Peng Yingsheng, Liu Yong, Dong Li, Zhang Han [18] etc.

However, taking into account the described scientific achievements, the issue of revealing the principles of UAV movement planning in mountainous terrain remains open and requires detailed investigation.

The objective of the paper. It is necessary to reveal the principles of UAV movement planning in mountainous terrain in this paper.

Statement of the task.

- to provide the discrete model in linear state space that approximates the dynamics of unmanned aerial vehicle;
- to present graphically the selection of polygon from a certain set of irregularities in relation to the speed limit, acceleration limit and change in acceleration of unmanned aerial vehicle under the conditions of movement in mountainous terrain;
- to propose solution for the implementation of effective obstacle avoidance for unmanned aerial vehicle in mountainous terrain.

Presentation of the main investigation material. The movement of UAV follows the trajectory on a certain trajectory movement model, where UAV is represented as the material point, the mass of which is concentrated in the center of mass.

The dynamics of unmanned aerial vehicle is approximated by discrete model in linear state space and has the following form:

$$\begin{bmatrix} p \\ v \end{bmatrix}_{i+1} = \begin{bmatrix} 2 \cdot I_3 & \Delta t \cdot I_3 \\ O_3 & 2 \cdot I_3 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}_i - \begin{bmatrix} I_3 & \Delta t \cdot I_3 \\ O_3 & I_3 \end{bmatrix} \begin{bmatrix} p \\ v \end{bmatrix}_{i-1} + \begin{bmatrix} \frac{1}{2}(\Delta t)^2 \cdot I_3 \\ \Delta t \cdot I_3 \end{bmatrix} \Delta a_i$$

where $p_i = (x_i, y_i, z_i)^T$ is UAV location vector;
$v_i = (\dot{x}_i, \dot{y}_i, \dot{z}_i)^T$ is UAV velocity vector;
I_3 is unit matrix 3x3;

O_3 is zero matrix 3x3;
Δt is sampling period;
$a_i = (\ddot{x}_i, \ddot{y}_i, \ddot{z}_i)^T$ is UAV acceleration vector;
$\Delta a_i = a_i - a_{i-1}$ is acceleration change vector.

In order to simplify the expression, let us introduce the following notation:

$$A = \begin{bmatrix} 2 \cdot I_3 & \Delta t \cdot I_3 \\ O_3 & 2 \cdot I_3 \end{bmatrix},$$
$$B = \begin{bmatrix} I_3 & \Delta t \cdot I_3 \\ O_3 & I_3 \end{bmatrix},$$
$$C = \begin{bmatrix} \frac{1}{2}(\Delta t)^2 \cdot I_3 \\ \Delta t \cdot I_3 \end{bmatrix}.$$

Such parameters as: flight speed v, acceleration a, change in acceleration Δa, have certain limitations. Putting them on the planes, we get the system of equations:

$$\begin{cases} v_{min} \le \|[\dot{x}_k, \dot{y}_k]'\|_2 \le v_{max}, k = \overline{0, N}, \\ \|[\ddot{x}_k, \ddot{y}_k]'\|_2 \le a_{max}, k = \overline{0, N-1}, \\ \|[\ddot{x}_k, \ddot{y}_k]' - [\ddot{x}_{k-1}, \ddot{y}_{k-1}]'\|_2 \le \Delta a_{max}, k = \overline{1, N-1}, \end{cases}$$

where N is the number of total route planning step;
$\|\cdot\|_2$ is Euclidean norm.

Taking into account the peculiarities of unmanned aerial vehicle flight, it is convenient to divide the general spatial movement into longitudinal and lateral movement, moreover longitudinal movement can be considered independently of lateral movement.

Let us replace the given restrictions with the set of linear inequalities that define the area of the inscribed polygon, in turn, limited by a certain circle. Accordingly, the polygon is defined by a set Q of linear inequalities (Figure 1–3).

Then linear inequalities have the following form:

$$\begin{cases} v_{min} \le \dot{x}_k sin\left(\frac{2\pi q}{Q}\right) + \dot{y}_k cos\left(\frac{2\pi q}{Q}\right) \le v_{max}, q = \overline{1, Q}, k = \overline{0, N} \\ \ddot{x}_k sin\left(\frac{2\pi q}{Q}\right) + \ddot{y}_k cos\left(\frac{2\pi q}{Q}\right) \le a_{max}, q = \overline{1, Q}, k = \overline{0, N-1} \\ \Delta\ddot{x}_k sin\left(\frac{2\pi q}{Q}\right) + \Delta\ddot{y}_k cos\left(\frac{2\pi q}{Q}\right) \le \Delta a_{max}, q = \overline{1, Q}, k = \overline{1, N-1} \end{cases}$$

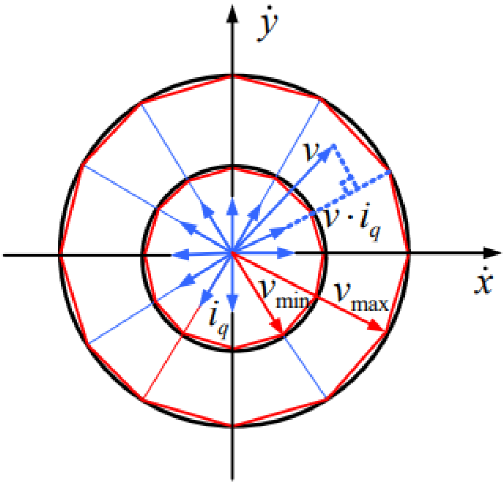

Figure 1. UAV speed limit

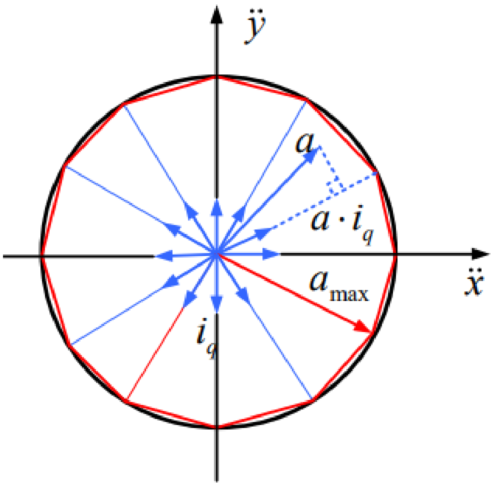

Figure 2. UAV acceleration limitations

Considering the fact that the set of all admissible solutions of the system of minimum speed limits $v_{min} \leq \|[\dot{x}_k, \dot{y}_k]'\|_2$ is not convex, the minimum speed limit is reduced to the following form

$$\begin{cases} v_{min} - \left(\dot{x}_k sin\left(\frac{2\pi q}{Q}\right) + \dot{y}_k cos\left(\frac{2\pi q}{Q}\right)\right) \leq Mc_q, q = \overline{1, Q}, k = \overline{0, N} \\ \sum_{q=1}^{Q} c_q \leq Q - 1. \end{cases}$$

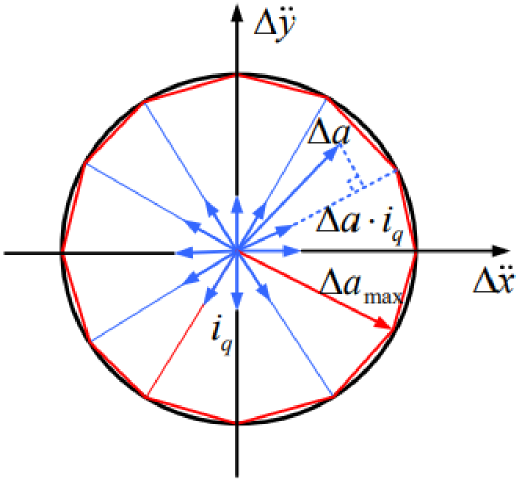

Figure 3. Limitation of UAV acceleration change

Speed limit v, acceleration a, and acceleration change in Δa in projections on the direction of z axis are written as follows:

$$\begin{cases} \dot{z}_{min} \leq \dot{z}_k \leq \dot{z}_{max}, k = \overline{0, N} \\ \ddot{z}_{min} \leq \ddot{z}_k \leq \ddot{z}_{max}, k = \overline{0, N-1} \\ \ddot{\Delta}z_{min} \leq \Delta\ddot{z}_k \leq \Delta\ddot{z}_{max}, k = \overline{1, N-1} \end{cases}$$

The relief of the mountainous terrain $z = h(x, y)$ consists of T non-intersecting and non-overlapping triangles with m vertices. Function $h(x, y)$ is piecewise affine function.

If we assume that point $p_k(x_k, y_k, z_k)$ is UAV location in the normal Earth coordinate system at time k, then coordinates (x_k, y_k, z_k) correspond to the point located on the terrain surface directly under UAV at the given time.

Limitation associated with the terrain relief bending is as follows

$$z_k \geq h_k + d_0, \forall k$$

where d_0 is linear UAV dimension.

Since the corresponding heights for any point on the curved relief surface are unknown, then in order to obtain them, it is necessary to use the interpolation of the vertices of the corresponding triangle, i.e. $h_k = h(x_k, y_k)$.

At the k-th discrete moment of time variables x_k, y_k, h_k are respectively expressed for convex surface in the form of the combination of coordinates of each known vertex as follows:

$$\begin{cases} x_k = \sum_{i=1}^{m} \lambda_{ik} x_i, y_k = \sum_{i=1}^{m} \lambda_{ik} y_i, h_k = \sum_{i=1}^{m} \lambda_{ik} h_i, \forall k \\ \lambda_{ik} \geq 0, \forall i, k \\ \sum_{i=1}^{m} \lambda_{ik} = 1, \forall k \end{cases}$$

Taking into account the combination of coordinates of each known vertex, while choosing certain values of coefficients λ_{ik}, it is possible to describe the surface of the terrain by means of triangles. Applying combinations of undetermined coefficients $\lambda_{ik}, i = \overline{1, m}$y as solution variables, it is possible to describe the limitations on bending of the terrain topography.

If the set of all points of the t-th triangle, including vertices, sides, and interior, is denoted on the convex surface by $R_t, t = \overline{1, T}$ and considered that the set D_i is the set of ordinal numbers of triangles with vertices in points P_i , i.e. $D_i = \{t: P_i \in R_i\}$. Applying limitation type:

$$\begin{cases} \lambda_{ik} \leq \sum_{t \in D_i} b_{tk}, i = \overline{1, m} \\ \sum_{t=1}^{T} b_{tk} = 1. \end{cases}$$

it is possible to confirm that at any discrete time k there is only one triangular subregion that is «active». Moreover, at this time, the corresponding logical variable $b_{tk} = 1$, other logical variables are equal to 0.

In the model of trajectory movement, UAV is represented as material point, and in the real flight over mountainous terrain, its characteristic dimensions should be taken into account in order to avoid the obstacle successfully Therefore, for the above-described limitations on UAV obstacle avoidance in mountainous terrain, the dimensions should be increased by d_0 in each direction.

Conclusions. The principles of UAV movement planning in mountainous terrain are revealed in this paper. The mathematical model of UAV movement planning in mountainous terrain, which takes into account limitations on its dynamic properties and flying over obstacles in the environment with obstacles is presented. The proposed technique for planning the spatial flight route of UAV in mountainous terrain takes into account additional limitations on the acceleration change, resulting in the stabilization of changes in he UAV dynamics of the and, and as the result, increases the accuracy of tracking the planned flight route.

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УДК 004.021.8

ПЛАНУВАННЯ РУХУ БПЛА У ГІРСЬКІЙ МІСЦЕВОСТІ

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Резюме. *Розкрито принципи планування руху безпілотного літального апарата у гірській місцевості. Наголошено, що рух безпілотного літального апарата відбувається за траєкторією на певній моделі траєкторного руху, де безпілотний літальний апарат наводиться у вигляді матеріальної точки, маса якої зосереджена в центрі мас. Запропоновано дискретну модель у лінійному просторі станів, яка апроксимує динаміку безпілотного апарата. Загальний просторовий рух безпілотного літального апарату розділено на поздовжній і бічний рух, причому поздовжній рух розглядається незалежно від бічного руху, враховуючи особливості польоту безплотного літального апарата в гірській місцевості. Графічно представлено вибір багатокутника з певного набору нерівностей відносно обмеження швидкості руху, обмеження прискорення та зміни прискорення безпілотного літального апарата в умовах руху в гірській місцевості. Підкреслено, що оскільки відповідні висоти для будь-якої точки на кривій поверхні рельєфу є невідомими, то щоб їх отримати, необхідно використовувати інтерполяцію вершин відповідного трикутника. Зазначається, що при виборі певних значень коефіцієнтів можна описати поверхню рельєфу місцевості за допомогою трикутників, враховуючи комбінації координат кожної відомої вершини, а застосовуючи комбінації невизначених коефіцієнтів у якості змінних рішень, можна описувати обмеження на обгинання рельєфу гірської місцевості. Наголошено, що під час траєкторного руху безпілотний літальний апарат представляється в якості матеріальної точки, а у реальному польоті по гірській місцевості необхідно враховувати його характерні розміри, щоб успішно уникнути перешкоди. Запропоновано збільшити розміри на певну величину в кожному напрямку для ефективного обходу перешкод безпілотного літального апарата в гірській місцевості.*

Ключові слова: *безпілотний літальний апарат, гірська місцевість, алгоритм, планування, політ, маршрут.*

https://doi.org/10.33108/visnyk_tntu2023.02.015 *Отримано 15.03.2023*