ALTITUDE MINIMIZATION OF A GROUP OF UNMANNED LOW-FLYING VEHICLES WITHOUT USE OF A PRIORI INFORMATION ABOUT THE PHYSICAL FIELDS OF THE EARTH

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Article history:
Received 24.05.2022, Accepted 22.09.2022

Abstract

The article proposes a method for minimizing the altitude of a group of unmanned low-flying vehicles formed mainly over the lowest parts of the terrain. The input information is point slant ranges, the current parameters of the motion of the unmanned aerial vehicle and the specified end point of the route. As a result of the work, by means of computer simulation of Unmanned Arial Vehicle (UAV) motion in mountainous areas, the effectiveness of the proposed method for minimizing the altitude was evaluated. Computer simulation has shown that depending on the location of the start and end points of the trajectory, the terrain, the size of the permitted motion sector and the characteristics of the UAV, the average altitude of the trajectories of a group of low-flying vehicles decreases by approximately 150–540 m, which allows motion significantly below the tops of the terrain.

Key words

Unmanned aerial vehicle, UAV, minimizing the altitude, trajectory, low-flying vehicles.

1 Introduction

Unmanned aerial vehicles (UAV) are designed to solve tactical reconnaissance tasks, deliver cargo precisely to its destination, solutions for military, rescue, geological tasks, terrain research etc. In some cases, for example, when flying over mountainous terrain in rarefied air, it is necessary to minimize the flight altitude of the UAV. In mountainous terrain, when driving at low altitude, there is a risk of collision with the underlying surface or ground objects. The task of minimizing the height becomes more complicated if it is necessary to control a group of UAVs. If they start at the same point one after the other, it is possible to move along one route in turn. But if the launch takes place at different points and the potential UAV trajectories intersect, it becomes necessary to maintain a safe distance between them. Additionally, the task is complicated by the fact that in the absence of a priori information about the physical fields of the Earth, the UAV trajectories are determined in the process of motion. This article proposes a method for minimizing the altitude of a group of unmanned low-flying vehicles, the trajectories of which are laid mainly over lower sections of the terrain, based on data on point slant ranges, current own motion parameters and a given end point of the route. The theoretical significance of the study lies in the development of a method for minimizing the altitude of a group of low-flying UAVs without using a priori information about the physical fields of the Earth. The practical significance of the study lies in the fact that the developed method makes it possible to ensure an acceptable level of safety for low-altitude altitude of a UAV group in the absence of information about the terrain near the UAV. The object of the study is a group of low-flying UAVs. The subject of the study is the minimization of UAV flight altitudes. Research methods: in the course of the research, methods of synthesis and analysis of existing solutions were used. The reliability and efficiency of the developed method was tested by computer simulation. Currently, one of the most effective ways to minimize the height of the UAV trajectory is to move along a given trajectory, the height of which depends on the coordinates of the aircraft in the horizontal

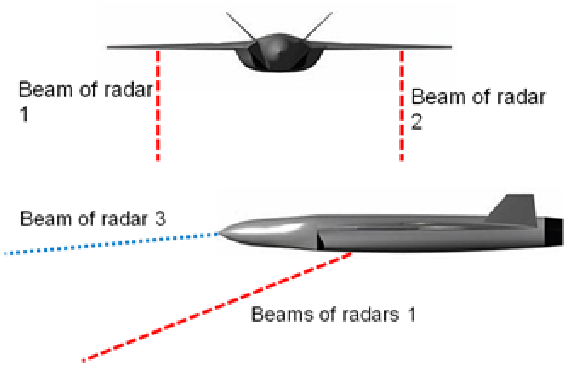

Figure 1. Scheme of placement of meters of slant ranges

plane. UAVs can use a satellite navigation system, an inertial navigation system, or both to determine the coordinates. The main disadvantage of the satellite navigation system is its high sensitivity to interference. UAVs inertial control systems have an error increasing over time due to inaccurate initial conditions, inaccurate orientation of the inertial system, measurement errors and imperfection of the position estimation algorithm. The accuracy of estimating the coordinates of an aircraft can be improved by periodically measuring the current parameters of the physical fields of the Earth near the UAV and comparing them with those stored in the memory of a computing device [Krasovskii et al., 1979]. To solve navigation problems, the terrain field is the most suitable. Navigation over the terrain field is based on the calculation of the altitude of the terrain (the difference between the absolute and geometric heights) at the current point of the UAV trajectory and its comparison with the reference map. To perform the comparison, the objective functional is calculated, which characterizes the correlation of the measured altitudes with the given ones. The current location of the UAV is determined by the extreme of the functional. Systems operating on this principle are called correlation-extreme navigation systems [[Naumov et al., 1979; Beloglazov et al., 1974]. The disadvantage of such systems is the need to use a priori information about the physical fields of the Earth, for example, a height map, which may not be known.

2 Description of the method and comparison with analogues

A known method of navigation of aircraft [Rzhevkin, 1981], which consists in:

1. Setting the terrain map
2. Measurement of the measured area of the true geometric altitude of the UAV
3. Drawing up a relief height map based on the measured area data using data on the absolute altitude and inclination angles of the UAV
4. UAV location calculation by comparing the current and reference terrain maps using correlation-extreme information processing algorithms
5. Control the motion of the UAV by correcting its location.

The disadvantage of this analogue is the need for a sufficiently accurate height map. This drawback can be eliminated by trying to lay the trajectory mainly over the lower sections of the underlying surface. Studies of a similar method for minimizing the altitude of a low-flying vehicle near a rough sea surface were carried out in [Knyazhsky, 2018; Nebylov, 2020; Knyazhsky, 2017]. The essence of the method in this works lies in the desire to move in the direction of the minimum gradient of the sea surface. The use of the proposed method of minimizing the altitude is safe if the maneuvering characteristics of the aircraft allow it to withstand the maximum gradient of the underlying surface, being at the reference (given) true geometric altitude relative to it. The reference true geometric altitude is set in such a way as to exclude the possibility of collision with an obstacle, such as a tree or building. The device for implementing the proposed method is shown in Fig. 1. On the body of the UAV, for example, on the left and right half-planes of the wing, two slant range meters spaced apart in space are fixed being inclined at a certain angle, for example, 70 degrees. about the vertical axis. Thus, in order to estimate the distance to the relief of the underlying surface at a distance that gives the greatest efficiency of the implementation of the method. The third slant ranger is attached to the front of the UAV, for example, on the nose, so that its beam is directed slightly below the horizontal axis. The angle of inclination is determined in such a way as to detect an obstacle in the direction of the UAV motion within an acceptable time interval and prevent a collision with it by raising the height.

To ensure the measurement of the slant range, its meter must have a fairly narrow radiation pattern, for example, 5-10 degrees wide. Otherwise, the readings will be averaged over the entire range of angles, radiation patterns and the result of the evaluation will be unreliable. Slant range meters can be implemented, for example, in the form of phased antenna arrays or other types of devices. Slant range measurements are carried out when the roll and pitch of the UAV are close to zero. Since these angles introduce a significant non-linear error in the measurements. Thus, before measuring slant ranges in order to make a decision on the need to start the next altitude minimization maneuver, it is necessary to complete the current maneuver. At zero bank, pitch deviations within a few degrees are acceptable for estimating the slant ranges used to determine the lateral track deviation, since a slight proportional change in both ranges to areas of incidence of patterns on the terrain is acceptable. In the case of a roll, the increase in slant ranges changes disproportionately, which causes significant errors in the assessment of the relief.

The proposed method is carried out as follows:

1. Areas of the terrain over which the UAV moves in the mode of minimizing the altitude without using the

correlation-extreme method are set (due to the lack of accurate data on altitudes);

2. The current coordinates of the UAV are estimated;

3. When an UAV enters a terrain area for which there are no accurate data on heights, at least in two directions, using the radar method, using meters 1 and 2, measure the slant ranges to the underlying surface, and also calculate the reference track angle directed to the nearest control point trajectory (or the end point of the trajectory);

4. Taking into account the current spatial position of the UAV and the measured slant ranges, the heights of the underlying surface are calculated at the signal reflection points;

5. The track angle of the UAV deviates by a specified amount in the direction of the point of the underlying surface with the lowest altitude, if, during the deviation, the difference between the new track angle and the reference angle does not exceed the specified threshold.

6. The angle of inclination of the trajectory is changed in such a way that the UAV strives to maintain the given true geometric altitude relative to the relief of the underlying surface.

7. With the help of the meter 3, the proximity of the object in the direction of motion, with which there is a risk of collision, is estimated. If the object is closer than the specified minimum allowable distance, then the flight altitude is increased until the risk of collision is eliminated (the function of preventing collision with the terrain and objects on it).

This method allows to move mainly over the troughs of the underlying surface, minimizing the average absolute flight altitude and maintaining the specified average true geometric altitude. Its implementation is safe in the absence of tall objects with unknown coordinates on the ground, with which there is a risk of collision.

3 Mathematical description of the method for minimizing the altitude of a group of low-flying uavs

The implementation of the method can be conditionally divided into four steps (functions) performed sequentially one after another:

1. The function of forming the trajectory of the UAV, laid mainly over the lower parts of the relief.

2. The function of stabilizing the true geometric altitude relative to the reference value.

3. The function of preventing collision with terrain and objects on it.

4. The function of adjusting the UAV trajectory, taking into account the motion parameters of other UAVs.

The function of forming the UAV trajectory, which is laid mainly over the lower parts of the relief, can be described by the formula

$$\begin{aligned}\gamma(t) = sector(\gamma(t-\Delta t) + D_k\cdot \\ \cdot turn\_direction(l_r(t) - l_l(t), l*), D_\psi, \gamma_v)\end{aligned} \quad (1)$$

where $sgn(x)$ is the signum function;

$$turn\_direction(l, l^*) = \begin{cases} 0, |l| \leq l^* \\ sgn(h), |l| > l^* \end{cases} \quad (2)$$

l_r is the slant range measured by the right (first) meter; l_l is the slant range measured by the left (second) meter; D_k is the value of the change in the course of the aircraft with the difference in the readings of the slant range meters; Δt is the period of taking measurements from slant range meters. The physical meaning of equation (1) is that two slant distances to the underlying surface l_r and l_l are measured, the difference between them is found, and compared with the threshold value. If the difference between the slant ranges is greater than the specified threshold, then the preliminary UAV track angle is calculated as the sum of the current UAV track angle and the specified deviation ($\gamma(t - \Delta t) \pm D_k$) in the direction of the slant range meter that showed the larger value ($D_k * turn\_direction(l, l*)$). The $turn\_direction(.)$ function returns 1 if the left meter has a smaller slant range, -1 if it has the right one. After that, the result is multiplied by the given track angle change factor. If the preliminary track angle does not go beyond the boundaries of the sector of permissible directions of motion, then the UAV track angle is rejected by the calculated value, if it does, then it is rejected by the maximum allowable value ($sector(.)$ function). This ensures the approach of the UAV to the hollows of the underlying surface. In the $sector(.)$ function, the first parameter is the UAVs preliminary track angle, γ_t is the direction to the end point of the route (target), D_{psi} is the width of the allowed movement sector. The sector of allowed directions of motion is set to prevent the UAV trajectory from drifting away from the target. Since in order to reach the goal it is necessary to choose the smallest gradient of the underlying surface in the process of motion in such a way as to continuous approach to it. To ensure the arrival at the target, the sector of allowed directions of motion narrows as it approaches the target. The function of stabilizing the true geometric altitude relative to the reference value is that the difference between the current true geometric altitude and the reference value is measured. And the height difference is corrected so that the true geometric altitude is equal to the reference one. The function to prevent collision with terrain and objects on it is defined in the description of the method (item 7). The UAV trajectory correction function, taking into account the motion parameters of other UAVs, is implemented by performing the following steps on a computing device located on the device in question:

1. UAVs are determined that are within a given radius relative to the UAV in question;

2. Each UAV from the group saves and transmits to others within a given radius its coordinates, ground speed and ground angle, the location predicted after a given period of time. The forecasting time interval is a

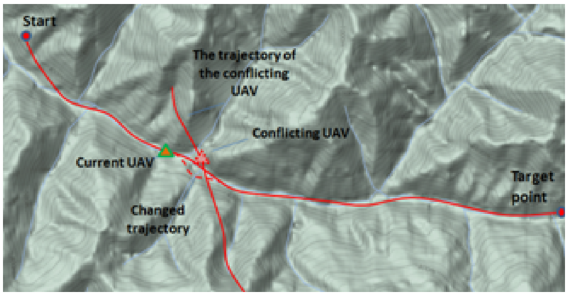

Figure 3. The result of the formation of low-altitude UAV trajectories, mainly over the hollows of the terrain, in the event of a risk of dangerous approach to another UAV.

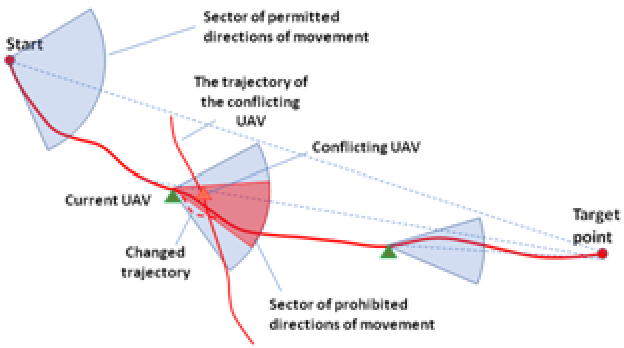

Figure 2. The principle of forming sectors of allowed (blue) and prohibited (red) directions of UAV motion.

variable parameter of the system. The location prediction is carried out using the trajectory generation function (a function corresponding to paragraph 1 in the description of the implementation of the method).

3. It is checked whether the generated trajectory approaches the predicted locations of other UAVs after a given period of time. If it gets close, then

3.1. Sectors of prohibited directions of motion are formed

3.2. If the sectors of prohibited directions of motion intersect the sectors of permitted directions of motion, then the sectors of permitted directions of motion are narrowed so as to exclude their intersection;

3.3. The trajectory deviates in the most favorable direction within the sector of permitted directions of motion. If deviation is not possible due to the risk of collision, then the direction of travel is chosen as close as possible to the recommended one.

4. The control signal is formed The principle of formation of the sector of permitted directions of movement is shown in Fig. 2.

Further, we will consider only those types of UAVs, the inertial characteristics of which make it possible to lay a trajectory, mainly over the hollows of the terrain in which the UAV moves. Such are, for example, a small highly maneuverable UAV and a quadrocopter.

4 Simulation

The effectiveness of the proposed method was evaluated by computer simulation. To simulate the relief, a map of the area of the Krasnodar Territory was taken and, on the basis of it, using coordinate transformation into a rectangular coordinate system, a matrix of heights was compiled with a step of 100 m along the horizontal plane. For clarity, the points of peaks and depressions of the relief were additionally specified. Before the start of the simulation of the motion of the UAV group, the start and end points of the motion (target) were set. During the motion with a step of 1s, the current coordinates of the UAV were measured and the slant ranges to the relief of the underlying surface were calculated. In this case, the height of the relief was interpolated at the point of contact with the underlying surface by the measuring beam. An example of the result of the formation of low-altitude trajectories of a UAV group, mainly over the hollows of the terrain, is shown in Fig. 3. For clarity, in Fig. 3 shows the curve interpolated by the points of the UAV trajectory converted from rectangular to geodesic coordinates.

Fig. 3 shows an example of the deviation of the trajectory of a UAV moving in the altitude minimization mode in the event of a risk of a dangerous approach to another UAV. Because as you get closer to the target, the sector of legal directions narrows to ensure the approach to the target, the altitude minimization is less effective towards the end of the path. The simulation results showed that depending on the location of the start and end points of the trajectory, the terrain, the size of the sector of permitted motion, the characteristics and number of UAVs in the group, the average altitude of the trajectory decreases by approximately 150–540 m, which allows moving along the hollows much lower than the tops of the relief.

5 Conclusions

The article proposes a method for forming a low-altitude trajectory of an unmanned aerial vehicle, laid mainly along low relief areas, based on data on the ranges of inclination of points, current parameters of its own motion and a given end point of the route. simulation shows that the proposed method allows to reduce the average altitude of the UAV flight path by 150–540 m.

Acknowledgements

The paper was prepared with the financial support of the Ministry of Science and Higher Education and of the Russian Federation, grant agreement No. FSRF-2020-0004, “Scientific basis for architectures and communication systems development of the onboard information and computer systems new generation in aviation, space systems and unmanned vehicles”.

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