The Dynamics of the Movement of Formations of Unmanned Aerial Vehicles

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Abstract: - The article presents a simulation analysis for flight in formation on the example of an unmanned aerial vehicles. The introduction presents the structure of group flights. The existing solutions in the algorithms responsible for flight of the UAV formations, focusing on the pure laws of physics, as well as research aimed at indicating the economic benefit for aviation applications were subsequently analyzed. Then a mathematical model was presented, which, optimized for three different positions in the longitudinal axis of the UAV object, allowed to obtain reliable results of the winger coordinates relative to the leader. The main goal of the article was to present simulation studies regarding the stability of the flight trajectory of unmanned aerial vehicles formations in a leader-guided control system for a group of two, three, four, five and six objects. In the final part of the article, based on the analysis of the literature on the subject of research, the mathematical model of the UAVs object created and simulation tests carried out in the field of unmanned aerial vehicle trajectory stability, final conclusions were formulated, which are reflected in practical application.

Key-Words: - Motion Dynamics, Formation, Simulation Studies, Unmanned Aerial Vehicles

1 Introduction

Coordination of unmanned aerial vehicles (UAVs) formations has attracted a lot of attention due to potentially significant benefits, which include various practical applications such as surveillance, exploration of natural resources, atmosphere research, search, rescue, reconnaissance and destruction of targets in a large area. Some of these tasks can be dangerous and will not be recommended for humans, which makes unmanned aerial vehicles ideal for this type of operation.

In order to make formation of unmanned aerial vehicles possible, an appropriate system is needed that will allow control of many objects at the same time [1], [2], [3].

UAV group control systems can be divided mainly into two types. A centralized system that synchronizes the position of any unmanned aircraft through a ground station and on an autonomous system based on decentralized control that offers greater independence and flexibility.

However, UAV group control is a complicated problem due to task coupling, a high degree of uncertainty in a dynamic environment, and limited information.

In flight control formation, major problems include stability, complexity and feasibility of restricted tasks [4], [5].

1.1 Group flight of unmanned aerial vehicles

As unmanned aerial vehicles develop, interesting views are emerging about their possible applications. In order to increase the efficiency of tasks performed by UAV, they began to use them in group flights. A group flight is defined as the flight of aircraft with specified positions relative to each other, conducted by the group commander. A flight in a formation is the intended movement of two or more flying objects that are connected by a common control system in order to achieve and maintain a specific shape of the entire formation, maintain appropriate speeds and distances through its individual members, and avoid collisions between objects. Formation flight is important during group flights, in particular when performing tasks and various types of missions in urban areas [6], [7].

The most frequently mentioned advantage of a group flight is its use in terrain searching. Each of the objects has a specific range of space monitoring, and in search missions it is important to relocate and comb the entire area as soon as possible. By giving the right shape to the formation and placing objects in a group whose observation and measurement devices will intertwine, it is possible to accurately and quickly accomplish the task in the best possible way. In order to solve the problem of UAV group control, it is first and foremost necessary to ensure an adequate degree of stability autonomy for each member of the group. Each of the flying objects must be able to reach and monitor the set speed, direction and altitude. The stability of the position of one object will determine the stability of the whole group [8].

2 Selected UAV Objects Structures

2.1 Virtual structure

This system is based on a structure in which flying aircraft are treated as rigid bodies embedded in a larger virtual structure. The whole formation is treated as one entity. Positions of objects in the system are usually defined in the structure relative to a given reference point. This formation can evolve as a rigid body in a given direction with a certain specific orientation and maintain a geometric relationship between multiple objects based on a reference point in a virtual structure. Formation guidance is in this case autonomous, performed on UAVs board, which control their relative movements in relation to the desired formation configuration and trajectory. The formation can then be conceptually operated on earth as a virtual rigid structure, as if it consisted of a single airplane structure. Individual ships control their lateral positions relative to the center of gravity of the formation, with synchronized purpose of course control [9].

A virtual structure layout with a leader can be often come across. In this system, each UAV is assigned a different virtual migration point, related to the leadership position, which is also the source reference point of the formation. Together, all migration points form a rigid virtual structure. Each object applies appropriate behaviors necessary to track its own assigned point in the structure and to avoid collisions with another formation member. To calculate the parameters of local behavior, each UAV should know the leader position to define the skeleton of the formation reference structure, and the actual position of the previous UAV in the structure. Information sharing can rely on the local ”peer-to-peer” communication chain. In this arrangement, information about the leader can be sent sequentially between one and another member of the formation [10].

The flight trajectory of formation members is given for a reference point, so the position for each object can be calculated as the virtual structure develops over time. The center of gravity of the desired formation can be defined as the reference point of the structure. When defining the structure, it can be considered that the O frame is an inertial frame, and F the formation reference frame located at the reference point.

Formation is a rigid body with the position described by the inertial system P_F, velocity V_F, direction ψ_F and angular velocity ω_F.

In addition, a reference frame i is also available, which is embedded in each member of the formation.

Each of the UAV can be represented by the position P_i, velocity V_i, direction ψ_i and angular velocity ω_i in relation to the inertial frame O or by P_{iF}, V_{iF}, ψ_{iF} and ω_{iF} associated with the reference frame of the F formation [11], [12], [13].

The equations for position dynamics and velocity for each formation member in the inertia frame of the virtual structure are as follows (1):

$$\begin{gathered} P_i^d(t) = P_F(t) + C_{OF}(t)P_{iF}^d(t) \\ V_i^d(t) = V_F(t) + C_{OF}(t)V_{iF}^d(t) + \omega_F(t) \\ \times (C_{OF}(t)P_{iF}^d(t)) \end{gathered} \tag{1}$$

where: $C_{OF}(t)$ - means the matrix of rotation of the F frame to the O frame, and the variables after superscript ^{d} represent the desired variable values for the respective formation member.

For the purposes of analysis, the case was considered with two unmanned aerial vehicles UAV1 and UAV2 placed in a virtual structure.

Then in equation (1) $V^d_{iF}(t) = 0$. For two objects in the formation, $P^d_{2F}(t) = -P^d_{1F}(t)$, if the reference point is defined as the center of gravity of the unit.

Therefore, defining $\Gamma(t) = C_{OF}(t)\, P^d_{1F}(t)$, equation (1) for UAV1 looks as follows (2):

$$\begin{gathered} P_1^d(t) = P_F(t) + \Gamma(t) \\ V_1^d(t) = V_F(t) + \omega_F(t) \times \Gamma(t) \end{gathered} \tag{2}$$

In turn, the equation for UAV2 after substitution $P^d_{2F}(t)$ and $\Gamma(t)$ takes the following form (3):

$$\begin{gathered} P_2^d(t) = P_F(t) - \Gamma(t) \\ V_2^d(t) = V_F(t) - \omega_F(t) \times \Gamma(t) \end{gathered} \tag{3}$$

In addition, when time has a fixed value $t = t_0$, where there is a non-zero value $\omega_F(t_0)$, the rapid position changes required for the aircraft to maintain the geometry will be opposite, as shown in the figure below (Fig. 1) with $\omega_F(t_0)$ being approximately on the z axis [14], [15], [16].

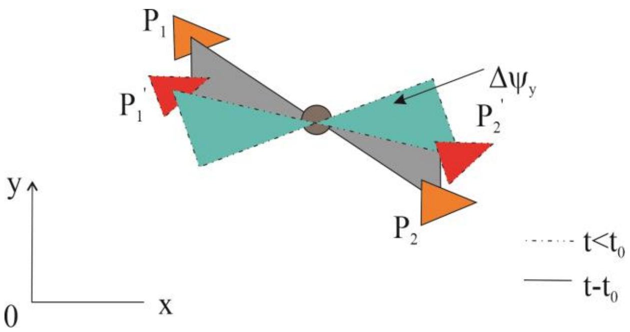

Fig. 1 Change of UAV flight direction described by the reference system

When analyzing the above system, it should be noted that in order for UAV objects in the formation to pass from P_i to P'_i, the UAV1 course change will be in the direction of $-\Delta\psi_F(t_0)$ with a higher value, while the UAV2 course change will be in the direction of $\Delta\psi_F(t_0)$ with a higher value. So the equation in the following form was obtained (4):

$$\begin{aligned} \Delta\psi_1^d(t_0) &= -(1 + K_1)\Delta\psi_F(t_0) \\ \Delta\psi_2^d(t_0) &= (1 + K_1)\Delta\psi_F(t_0) \end{aligned} \tag{4}$$

where: $K_i > 0$ is a constant value. The same analogy can be used to change positions.

Based on the desired P^d_i positions, V^d_i speeds and course changes of two objects, it can be seen that the relative values for each are opposite to the P_F reference point when it is the center of gravity of the virtual structure. It should therefore be expected that the relative position errors, if any, between the actual object positions and the reference point will also be of an opposite nature when the same trajectory instructions given for the reference point are given to both unmanned aerial vehicles [17], [18].

To eliminate relative position errors and maintain the geometry of objects during flight, you need a formation regulator. It is usually introduced using a two-loop scheme in which internal control allows to track the desired speed *(V)*, course *(ψ)* and altitude *(H)*. In the outer loop, the forming controller generates reference commands for the internal controller [19], [20], [21].

Based on the commands of the reference trajectory $T_r = [V_r, \psi_r, H_r]^T$ for the reference point $P_r = [x_r, y_r, z_r]^T$ and defined relative distances in the virtual structure, the desired position for each object can be calculated during flight $P_{di} = [x_{di}, y^d_i, z^d_i]^T$, while the actual position $Pi = [x_i, y_i, z_i]^T$ can be obtained from the GPS *(Global Positioning System)* on board the UAV facility. Using reference trajectory and actual UAV positions as input, the formation regulator generates modified trajectories for each object to preserve the geometry of the formation during flight [22], [23], [24].

The relative position errors for the i-th UAV object during flight in the inertial frame can be defined as (5):

$$\begin{bmatrix} e_{xi} \\ e_{yi} \\ e_{zi} \end{bmatrix} = \begin{bmatrix} x_i^d - x_i \\ y_i^d - y_i \\ z_i^d - z_i \end{bmatrix} \tag{5}$$

To use these relative errors in the above equation, they must be converted into errors in the formation frame using the $C_{FO}\ (t) = C_{OF}\ (t)^{-1}$ (6) rotation matrix:

$$\begin{bmatrix} e_{xiF} \\ e_{yiF} \\ e_{ziF} \end{bmatrix} = C_{FO}(t) \begin{bmatrix} e_{xi} \\ e_{yi} \\ e_{zi} \end{bmatrix}_{sd} \tag{6}$$

The command with the changed flight trajectory for the internal regulator is $T_{ci} = T_r + \Delta T_i$, where ΔT_i is calculated based on the relative position errors shown in the above equation. These corrections calculate the changes required to maintain the geometry of the formation [25], [26].

2.2 Cyclic structure

This structure is comparable to the leader-guided system. Formation control of this type of architecture is a combination of controls of individual group members. The difference between a cyclical system and a leader is that it is not hierarchical. There are also cyclical systems in which the formation is a group of many neighbours. In this case, each of the unmanned aerial vehicles flying in this group controls its flight in correlation to its neighbour's trajectory. Cyclic structures are also known, where the task of each UAV object is to maintain a very precise, fixed shape of the formation. They use rule-based controllers to generate circles, lines, and other UAV layouts. They are mainly used to control formations [27].

3 Modeling and Simulation of Group Flights

3.1 Characteristics of the tested control system

The control system used in the simulation process is a leader-guided system. This system is most often used because of the high degree of resistance to communication errors and the ability to easily add or remove subsequent members of the formation. Groups from two to six objects were examined in the simulation. The leader sends information about his position, and the other members of the formation follow him.

3.2 Control algorithm

It was assumed that the position of the leader is described by means of the reference system *(x, y, z)*. The control of the formation of unmanned aerial vehicles is based on the calculation of position errors and flight speed between the leader and the follower according to the diagram (Fig. 2).

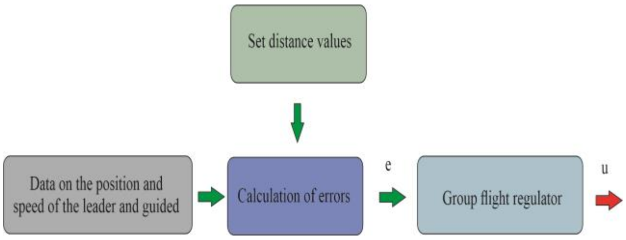

Fig. 2 Scheme of formation control system

The set distances between members should also be taken into account, which is shown in the following equation (7):

$$\begin{aligned} e_x &= x_L - x_F \\ e_y &= y_L - y_F \\ e_z &= z_L - z_F \\ e_v &= v_L - v_F \end{aligned} \tag{7}$$

where: e_x - position error in the x axis, e_y - position error in the y axis, e_z - position error in the z axis, e_v- speed difference between the leader and the follower.

Based on the calculated errors, the R matrix was created, which is the rotation matrix of the system relative to the leader (8):

$$\begin{bmatrix} e_{Rx} \\ e_{Ry} \\ e_{Rz} \end{bmatrix} = R \begin{bmatrix} e_x \\ e_y \\ e_z \end{bmatrix} - \begin{bmatrix} x_{ref} \\ y_{ref} \\ z_{ref} \end{bmatrix} \tag{8}$$

where: $x_{ref,}\, y_{ref,}\, z_{ref}$ - set distances in directions x, y, z. The output parameter u of the group flight regulator are the set values for flight control, which is expressed by the above equation (9) [28], [29], [30]:

$$u = [h_{zad} v_{zad} \psi_{zad}]^T$$
$$u(t) = k_p e_R(t) + k_i \int e_R(t)dt \tag{9}$$

where: h_{zad} - set height value, v_{zad} - set speed value , ψ_{zad} - set direction value.

The values of corrections to the speed and direction of flight are calculated according to the relation *u(t)*.

3.3 Test results of the simulation performe

The simulations were performed in the MatLab Simulink program. The control system that was used in the study is the leader-guided system.

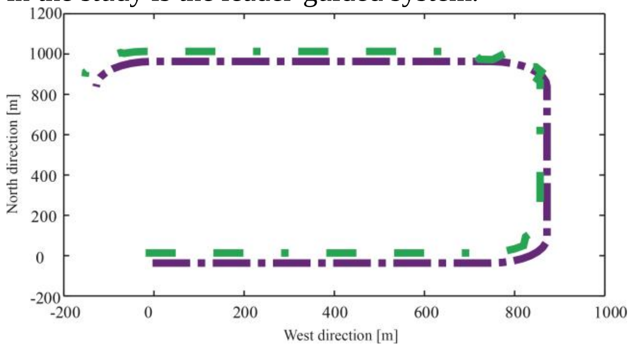

Fig. 3 Flight trajectory of two UAVs

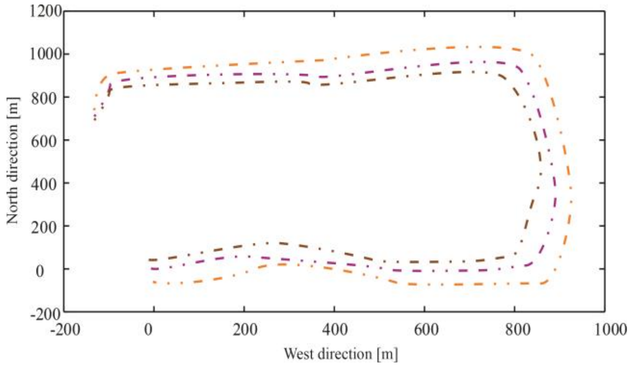

Fig. 4 Flight trajectory of three UAVs

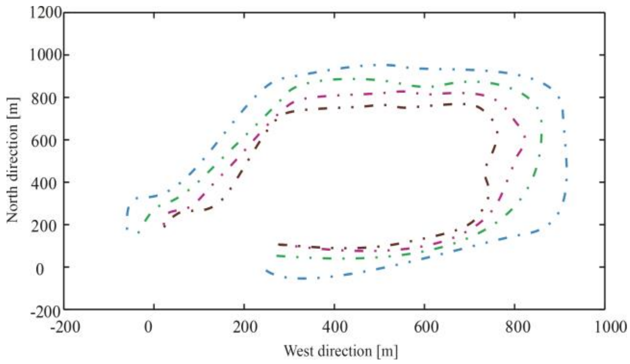

Fig. 5 Flight trajectory of four UAVs

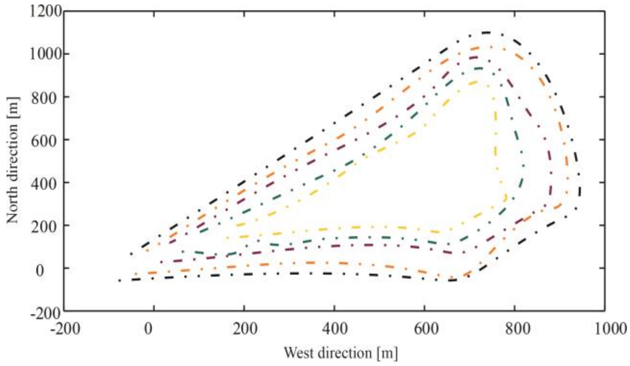

Fig. 6 Flight trajectory of five UAVs

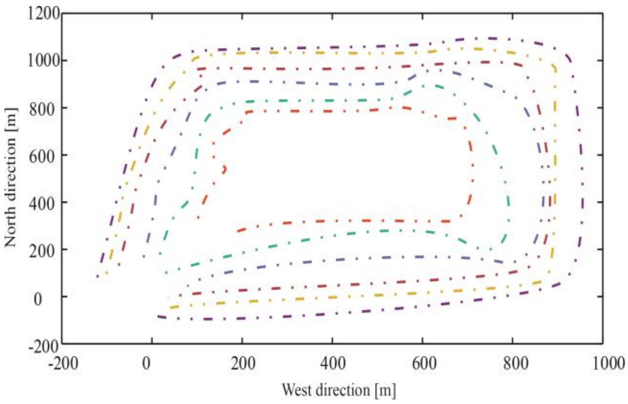

Fig. 7 Flight trajectory of six UAVs

The differences between the flight trajectory diagrams of individual members of the formation in the above figures are caused by higher oscillations of the tilt angles in the case of UAVs flying on the outside of the bend. Their trajectories cease to be parallel to others. Tracking errors are much lower when flying straight and in gentler turns.

Figure 3 shows the trajectory of leader formation with one UAV as a guide. The leading flight trajectory is marked in blue and the tracking one in green. It can be seen that during rectilinear flight both graphs overlap, but when making turns by 90 degrees a slight destabilization of the trajectory of the guided object is visible.

Figures 4-7 show the flight trajectories of more formations. It can be observed that the objects between the first and last members of the group are characterized by the lowest degree of flight stabilization in the formation [31], [32].

4 Conclusions

The main purpose of the research was to investigate the flight stability of unmanned aerial vehicles formations in groups of two to six members. Analyzing the results of the simulation performed, it can be stated that the leaders clearly follow the leader. Formation with one guided the highest degree of stability. This is because the tracker focuses solely on maintaining his position relative to the leader.

In formations with more than two members, each of the objects must not only follow the trajectory of the leader, but also watch their position relative to other members of the formation in its immediate vicinity. It can also be seen that stability decreases during dynamic maneuvers.

The presented figures clearly show that during rectilinear flight the UAV trajectories coincide with each other, while the greater the tilting angles and smaller turning radii, the greater the tracking error.

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