Flight dynamics for UAV formations

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Abstract: - The purpose of this paper is to describe the flight of an Unmanned Aerial Vehicles (UAV) formation by using 6 degrees of freedom (6 DOF) models. The problem of flight formation will be approached in a simple manner, by using 3 DOF models, as well as using the complex equations that describe the movement of the 6 DOF for UAV. This theoretical development allows us to define a control structure based on direct commands, which is useful in practical applications. The work will present and will analyze the calculus results for each developed solutions. The novelty of this paper consists in definition and test of some practical solutions for an algorithm that can control an UAV formation. This algorithm allows describing the flight of a single UAV, as well as the entire formation. The conclusions will focus the practical possibility of implementing such algorithm on a UAV formation.

Key-Words – UAV, Flight, Formation, Dynamic, Control

NOMENCLATURE:

\( \alpha \) - Attack angle (tangent definition);
\( \beta \) - Sideslip angle (tangent definition);
\( \chi \) - Track angle;
\( \gamma \) - Climb angle;
\( \mu \) - Velocity rolling angle;
\( \delta_a \) - Aileron deflection;
\( \delta_e \) - Elevator deflection;
\( \delta_r \) - Rudder deflection;
\( \psi \) - Azimuth angle;
\( \theta \) - Inclination angle;
\( \phi \) - Bank (Roll) angle;
\( \rho \) - Air density;
\( \Omega \) - Angular velocity;
\( \Omega_y \) - Angular velocity in semi velocity frame;

\( \omega_x, \omega_y, \omega_z \) - Rotation velocity components along the axes of the semi-velocity frame;
\( A, B, C, E \) - Inertia moments;
\( C_x, C_y, C_z \) - Aerodynamic coefficients of force in the mobile frame;
\( C_i, C_m, C_n \) - Aerodynamic coefficients of momentum in the mobile frame;
\( C_x^T, C_y^T, C_z^T \) - Thrust coefficients in the mobile frame;
\( C_i^T, C_m^T, C_n^T \) - Thrust momentum coefficients in the mobile frame.

Force components in the aerodynamic frame:
\( L \) - Lift force; \( D \) - Drag force; \( N \) - Normal force;
\( C_D \) - Drag force coefficient;
\( C_L \) - Lift force coefficient;
\( C_N \) - Normal force coefficient;
\( g \) - Gravitational acceleration;
\( q \) - Dynamic pressure;
\( k_y, k_x, k_z \) - Trajectory matrix control coefficients;
\( k_{dx}, k_{dy}, k_{dz} \) - Position control matrix coefficients;
\( l \) - Reference length;
\( m \) – UAV mass;
\( n \) - Load factor;
\( p, q, r \) - Angular velocity components along the axes of mobile frame;
\( S \) - Reference area;
\( T \) - Thrust;
\( t \) - Time;
\( V \) - Velocity;
\( u, v, w \) - Aircraft velocity components in a mobile frame;
\( V_{sp} \) - Velocity components in Earth frame;
1. Introduction
As shown in [1], controlling UAV’s formations has become an active area of research in the last years. Similar to migrant birds, UAVs flying in a formation can experience a drag reduction due to the elevating vortexes created by the leader UAV.
This implies a possible fuel consumption reduction with important benefits for military and commercial users. Further more, a major aspect regarding flying in formations is the following: It is believed that the control of flight formations will play a fundamental role in the future aero-space scenarios, where unmanned flying vehicles will be forced to swarm in order to accomplish recognition or saving missions in hostile environments.
Finally, autonomous flight formations will be able to investigate large surfaces of ground, due to the connections between them and their capability to refuel in flight.
This paper will analyze UAV formation structures in a unitary manner using a system of control with an adequate architecture. The approach is inspired by the one proposed in [1] for controlling aircraft formations. An important result will consist in the fact that the flight parameters will be presented on a quantitative base and by doing so the objective conclusions will be made available to the designers. In particular, the ratio between the complexity and the efficiency will be hightailed.
All the simulations will be made in a non-linear workspace, without using any simplifying hypothesis. From this point of view, the paper is a novelty, because in all the other papers the dynamic is treated linear or the formation is described as a plane model.

2. Formation modeling
In order to represent each UAV from the formation a three degree of freedom material point model will be adopted. The simplified model implies only the slow stages that correspond to a problem regarding the tracking of the position and trajectory by the use of the autopilot.
Reference frame:
The UAV’s dynamic is described with the help of 3 orthogonal frame. A local frame, the $\Gamma_0$ inertia with the origin in the mass center of the aircraft, with the z axe orientated vertically up, and the semi-velocity frame, connected to the velocity vector $\Gamma_a$ also with the origin in the mass center of the aircraft, obtained by two successive rotations, the first with the angle $\chi$, the second with the trajectory inclination angle $\gamma$. In the same time we can also use the mobile frame $\Gamma$, connected to the UAV, with axes are the main inertia axes for the flying aircraft, the $Oxz$ being situate in the symmetry plane of the aircraft. We are assuming that the inertia frame $\Gamma_0$ has the axes parallel to the ones of the Earth frame bound to the ground. As usually, that the axe $x_a$ of the semi-velocity frame $\Gamma_a$ is orientated along the velocity vector $\mathbf{V}$ and the $y_a$ axe is orientated in the horizontal plane. The transformation between the inertia frame $\Gamma_0$ and the semi-velocity frame $\Gamma_a$ is given by the matrix:

$$A_{\omega \theta} = \begin{bmatrix} \cos \gamma \cos \chi & -\cos \gamma \sin \chi & \sin \gamma \\ -\sin \gamma & -\cos \chi & 0 \\ \sin \gamma \cos \chi & -\sin \gamma \sin \chi & -\cos \gamma \end{bmatrix}.$$ (1)

If we take into account the $u$ vector, the transformation relation between the inertia frames into the semi-velocity frame is:

$$u_a = A_{\omega \theta} u_p$$ (2)

3. Simplified aircraft moving equations, 3 degrees of freedom model
If we accept the evolution without sideslip angle $\beta = 0$ then, the lateral force is also non-existing $N = 0$. In the same time if we are assuming that thrust is orientate along the velocity vector, and the aerodynamic force components are obtained by a rotation with the rolling angle of the velocity $\mu$ from the velocity frame, the dynamic equations of movement for the UAV named “i” in the semi-velocity frame become:

$$\dot{V}_i = \frac{T_i - D_i}{m_i} - g \sin \gamma_i; \quad \dot{\gamma}_i = \frac{L_i}{m_i V_i \cos \gamma_i};$$

$$\ddot{\gamma}_i = -\frac{L_i}{m_i V_i} \cos \mu_i - \frac{g}{V_i} \cos \gamma_i.$$ (3)

Writing the load factor:

$$n_i = \frac{L_i}{m_i g},$$ (4)

The equations (3) become

$$\dot{V}_i = \frac{D_i - g \sin \gamma_i}{m_i}; \quad \dot{\gamma}_i = \frac{g n_i \sin \mu_i}{V_i \cos \gamma_i};$$

$$\ddot{\gamma}_i = -\frac{g}{V_i} (n_i \cos \mu_i - \cos \gamma_i)$$ (5)

where we have notated:

$D_i$ drag force, $L_i$ lift force, $T_i$ thrust, $m_i$ mass for aircraft “i”. If we use the aircraft polar coordinate, the drag coefficient is:

$$C_{Di} = C_{Doi} + k_i C_{Li}^2.$$ (6)

The drag force is:
\[
D_i = F_{0i}C_{D0i} + k_i \left( n_i m_i g \right)^2
\]

where the reference aerodynamical force is:
\[
F_{0i} = \frac{1}{2} \rho V_i^2 S_i
\]
in which \( \rho \) is the air density at a given altitude and \( S_i \) is the reference surface.

Defining the state vector \( x_i = [V_i \ \chi_i \ \gamma_i]^T \) and the input vector: \( u_i = [T_i \ n_i \ \mu_i] \), the equations (5) can be put under standard form:
\[
\dot{x}_i = f_i(x_i, u_i)
\]

(9)

4. Kinematics position

Fig. 1 The defining scheme for the UAV formation

One of the main results regarding the control system of the formation flight is the fact that it allows every UAV to maintain a certain distance from a reference point denoted in figure 1 as \( G \). This point may coincide with the formation leader (real or virtual), or the neighbor UAV, or a geometrical central point inside the formation.

For establishing a suitable mathematical model, similar to [1] we are assuming that \( r_0 \) and \( r_i \) are the position vectors of the airplane \( A \), and of the reference point \( G \) regarding the origin \( O \) of the inertia frame. \( d_i \) is the current relative distance vector between \( G \) and the airplane position \( A \). The vector of the desired position of airplane \( D \) is noted as \( \bar{r}_i \). Also, we are assuming that an orthogonal frame \( \Gamma_{\alpha} \), similar with the semi-velocity frame, is attached to the \( G \) point, which orientation is defined by the angles \( \gamma_{\alpha} \). In the same time we are defining the velocity \( \bar{V}_i \) as the velocity of the \( G \) point.

From figure 1 it result:
\[
\begin{align*}
\bar{r}_i + \bar{d}_i &= r_i \\
\end{align*}
\]

(10)

and
\[
\begin{align*}
\bar{r}_i + \bar{d}_i &= r_i - \bar{r}_i \\
\end{align*}
\]

(11)

from where we obtain:
\[
\begin{align*}
\bar{d}_i - \bar{d}_i &= r_i - \bar{r}_i \\
\end{align*}
\]

(12)

Deriving the relation (12) relation related to time in the aerodynamic frame \( \Gamma_{ai} \) we obtain:
\[
\dot{d}_i - \bar{d}_i + \Omega_{ai} \times (d_i - \bar{d}_i) = V_i - \bar{V}_i
\]

(13)

where \( \Omega_{ai} \) is the angular velocity of the semi-velocity frame \( \Gamma_{ai} \), which is relative to the inertia frame \( \Gamma_0 \). In order to evaluate these relations we can project the relations (13) after the axes of the mobile frame of each UAV:
\[
\begin{align*}
\left[ \dot{d}_i \right]_\alpha &= \left[ \bar{d}_i \right]_\alpha + \left[ V_i \right]_\alpha - \left[ \bar{V}_i \right]_\alpha - A_{\alpha i} \left[ d_i - \bar{d}_i \right]_\alpha \\
\end{align*}
\]

(14)

where the angular velocity vector has its components after the semi-velocity frame axes given by:
\[
\begin{align*}
\left[ \Omega_i \right]_\alpha &= \left[ \omega^* \omega^* \omega^* \right]^T \\
\end{align*}
\]

(15)

In addition, the anti-symmetrical matrix of rotation is:
\[
\begin{align*}
A_{\alpha i} &= \begin{bmatrix} 0 & -\omega^*_{\alpha} & \omega^*_{\alpha} \\
\omega^*_{\alpha} & 0 & -\omega^*_{\alpha} \\
-\omega^*_{\alpha} & \omega^*_{\alpha} & 0 \\
\end{bmatrix}
\end{align*}
\]

(16)

The connection between the orientation angles derivate and the angular velocity vector components is:
\[
\begin{align*}
\omega^*_{\alpha} &= \begin{bmatrix} \cos \gamma_{\alpha} & 0 & -\sin \gamma_{\alpha} \\
0 & 1 & 0 \\
\sin \gamma_{\alpha} & 0 & \cos \gamma_{\alpha} \\
\end{bmatrix} \dot{\gamma}_{\alpha} \\
\end{align*}
\]

(17)

from where we can obtain the scalar relations:
\[
\begin{align*}
\omega^*_{n_{x}} &= -\dot{\gamma}_{\alpha} \sin \gamma_{\alpha}; \quad \omega^*_{n_{y}} = \dot{\gamma}_{\alpha}; \quad \omega^*_{n_{z}} = \dot{\gamma}_{\alpha} \cos \gamma_{\alpha} \\
\end{align*}
\]

(18)

Note: In the paper [1] the problem is treated in a similar way, but the rotation matrix (1) is constructed by using three successive rotations, which represent the passing to the velocity frame, operation that makes the relations defining difficult (17) because it doesn’t clearly point out the method of obtaining the derivatives for the rolling angle \( \dot{\mu} \). We are assuming that the orientation of the “i” UAV coincides with that of the \( \Gamma_{ar} \) frame and the desired velocity \( \bar{V}_i \) is that of the reference point \( \bar{V} \). In this case we define the rotation matrices.
\[ A_{ar0} = A_{a0}(\gamma, \chi) \]  
\[ A_{ar0} = A_{a0}(\bar{\gamma}, \bar{\chi}) \] 
where \( A_{a0} \) is obtained from equation (1). Starting from the defined matrixes we can write:
\[ \bar{V}_{ar} = A_{a0}(\bar{V}_{a}) \]  
\[ V_{ar} = A_{a0}(V_{a}) \]
By using (21) and (22) we find the desired velocity in the reference frame \( \Gamma_{ai} \):
\[ \bar{V}_{ar} = B\bar{V}_{ar} \]
where we have made the notations:
\[ B = A_{ar0}A_{ar0}^{\top} \]
\[ V_{ar} = \begin{bmatrix} 0 & 0 & V \end{bmatrix} \]
By introducing the relation (22) into (14) we obtain:
\[ d_{i} - \bar{a}_{i} = \left[ V_{ar} - B\bar{V}_{ar} - A_{a0}d_{i} - \bar{a}_{a0} \right] \]
If we introduce between the stages of the UAV and the reference: \( x = [\bar{V}, \bar{\gamma}, \bar{\chi}] \), the position of the UAV regarding the reference point then the equation can also be written in the compact form like this:
\[ \dot{d}_{i} = g(x_{i}, \pi, d_{i}, \bar{a}_{i}, u_{i}) \]

5. Controlling the formation with pseudo-commands

This section of the paper will sketch the control system design. We will assume that a reaction curl of a standard autopilot will maintain the UAV in formation. Our intention is to define a law of formation control, capable of simultaneously managing two things: 1) following the trajectory and 2) maintaining the formation position. As shown in [1] we can start from the command functions after the tree axes of the semi-velocity frame:
\[ f_{1i} = -k_{y}(\dot{V}_{i} - \bar{V}) + k_{d}(\dot{d}_{i} - \bar{d}_{i}) \]
\[ f_{2i} = \frac{V}{g} k_{d}(\ddot{d}_{i} - \ddot{d}_{i}) + k_{v}(\dot{d}_{i} - \dot{d}_{i}) - k_{\gamma}(\gamma_{i} - \bar{\gamma}) \cos \gamma_{i} \]
\[ f_{3i} = -\frac{V}{g} k_{v}(\ddot{\chi}_{i} - \bar{\chi}) + k_{d}(\ddot{d}_{i} - \ddot{d}_{i}) + k_{\chi}(\dot{d}_{i} - \dot{d}_{i}) \cos \gamma_{i} \cos \gamma_{i} \]
With the help of these three functions previously defined the pseudo-commands regarding each aircraft are formed. In this manner, the velocity-rolling angle is given by:
\[ \mu_{i} = \arctan \left( \frac{f_{1i}}{f_{2i}} \right) \]
and the square sum of the last two functions (28) gives the necessary load factor:
\[ n_{i} = \sqrt{f_{1i}^{2} + f_{2i}^{2}} \]
In the end, we obtain thrust from the relation:
\[ T_{i} = f_{i}, mg \]

6. Complex movement equations of an UAV formation, a 6 degrees of freedom model

In order to describing in a complex form an UAV formation we must keep the idea previously developed of using a simplified model as reference, which should define the velocity vector of each aircraft in the formation. Supplementary, for each aircraft in particular we must write the complete system of equations, including those regarding the movement around the center of mass, which will allow us to define the real commands under the command surface’s deflection (ailerons, elevator and rudder) and the thrust control.
Therefore, for each UAV of the formation, in order to write the dynamic equations we define the aerodynamic coefficients in the mobile frame:

\[ C_x^A = \frac{X_A}{F_0}; C_y^A = \frac{Y_A}{F_0}; C_z^A = \frac{Z_A}{F_0}; \]
\[ C_l^A = \frac{L_A}{H_0^A}; C_m^A = \frac{M_A}{H_0^A}; C_n^A = \frac{N_A}{H_0^T}. \] (32)

where \( F_0 = \frac{V^2}{2} \); \( H_0^T = F_0 l \).

Similarly, if we consider the thrust and the gas-dynamic reference system: \( T_0; \ H_0^T = T_0 l \), we can define the gas-dynamic coefficients:

\[ C_x^T = \frac{X_T}{T_0}; C_y^T = \frac{Y_T}{T_0}; C_z^T = \frac{Z_T}{T_0}; \]
\[ C_l^T = \frac{L_T}{H_0^T}; C_m^T = \frac{M_T}{H_0^T}; C_n^T = \frac{N_T}{H_0^T}. \] (33)

As shown in the papers (2) and (3) the UAV’s dynamic equations are the projection equations of the force, equations that achieve from the impulse theorem, written in the Earth’s frame and the momentum equations, which comes from the kinetic momentum theorem, equations written in the mobile frame. Therefore, the force equations in the ground frame are:

\[
\begin{bmatrix}
\dot{V}_{xp} \\
\dot{V}_{yp} \\
\dot{V}_{zp}
\end{bmatrix} = \frac{1}{m} B_p \begin{bmatrix}
F_0 & C_x^A & C_x^T \\
C_y^A & F_0 & C_y^T \\
C_z^A & C_z^T & F_0
\end{bmatrix} + \begin{bmatrix}
0 \\
0 \\
0 + (-g)
\end{bmatrix}; \quad \text{(34)}
\]

Where the matrix \( B_p \) is defined using the Euler’s angles:

\[
B_p = \begin{bmatrix}
c\psi c\theta & -s\psi c\phi + c\psi s\theta s\phi & s\psi s\phi + c\psi c\theta s\phi \\
-s\psi c\theta & c\psi c\phi - s\psi s\theta s\phi & c\psi s\phi - s\psi c\theta s\phi \\
0 & -c\theta s\phi & -c\theta c\phi
\end{bmatrix},
\]

with:
\[ c\psi \equiv \cos \psi; \quad s\psi \equiv \sin \psi \]
\[ c\theta \equiv \cos \theta; \quad s\theta \equiv \sin \theta \]
\[ c\phi \equiv \cos \phi; \quad s\phi \equiv \sin \phi \]

The momentum equations around the center of mass of the UAV, written in the mobile frame are:

\[
\begin{bmatrix}
\dot{p} \\
\dot{q} \\
\dot{r}
\end{bmatrix} = J^{-1} \begin{bmatrix}
H_0^T & C_l^A & C_l^T \\
C_m^A & H_0^T & C_m^T \\
C_n^A & C_n^T & H_0^T
\end{bmatrix} \begin{bmatrix}
C_x^A \\
C_y^A \\
C_z^A
\end{bmatrix} + \begin{bmatrix}
(B - C)q + E_{pq} \\
(C - A)rp + E(r^2 - p^2) \\
(A - B)pq - E_{qr}
\end{bmatrix},
\]

where the inverse matrix for the inertia momentum is given by:

\[
J^{-1} = \frac{1}{AC - E^2} \begin{bmatrix}
C & 0 & E \\
0 & (AC - E^2) / B & 0 \\
E & 0 & A
\end{bmatrix}
\]

The kinematical equations are additional equations with allow us to obtain the linear coordinates in the earth’s frame:

\[
\begin{bmatrix}
\dot{x}_p \\
\dot{y}_p \\
\dot{z}_p
\end{bmatrix} = \begin{bmatrix}
V_{xp} \\
V_{yp} \\
V_{zp}
\end{bmatrix}, \quad \text{(37)}
\]

and Euler’s angle when the rotation velocity components are know:

\[
\begin{bmatrix}
\dot{\phi} \\
\dot{\theta} \\
\dot{\psi}
\end{bmatrix} = W_A \begin{bmatrix}
p \\
q \\
r
\end{bmatrix}, \quad \text{(38)}
\]

where

\[
W_A = \begin{bmatrix}
1 & \sin \phi \tan \theta & \cos \phi \tan \theta \\
0 & \cos \phi & -\sin \phi \\
0 & \sin \phi \sec \theta & \cos \phi \sec \theta
\end{bmatrix}. \quad \text{(39)}
\]

The ordinary differential equations (34),(36) fully describe one UAV’s movement, the rest of the parameters such as the aerodynamic angles \( \alpha; \beta \) or the angles that define the velocity frame \( \gamma; \chi; \mu \) being achieved by using direct analytical relations from the system’s state variables.

Therefore, for attack and seaside angles, which have low values that do not require a reduction to the first quadrant of the trigonometric functions, we can use the relations indicated in [3], [2]:

\[
\alpha = -\arctan(w/u); \quad \beta = \arctan(v/\sqrt{u^2 + w^2}) \quad \text{(40)}
\]

And for obtaining the velocity roll angle we can use the relation indicated in papers [2], [3]:

\[
tg \mu = \frac{c \gamma [t \phi + c(\chi - \psi) s \theta + t \gamma s(\chi - \psi) + t \phi c \theta]}{c(\chi - \psi)[1 - t \phi (t(\chi - \psi) s \theta)]}, \quad \text{(41)}
\]

with:
\[ c \gamma \equiv \cos \gamma; \quad s \gamma \equiv \sin \gamma; \quad t \gamma \equiv \tan \gamma \]
\[ c \chi \equiv \cos \chi; \quad s \chi \equiv \sin \chi; \quad t \chi = \tan \chi \]
\[ c(\chi - \psi) \equiv \cos(\chi - \psi); \quad s(\chi - \psi) \equiv \sin(\chi - \psi); \quad t(\chi - \psi) = \tan(\chi - \psi) \]
Regarding the track angle $\chi$ and the climb angle $\gamma$, although we cannot obtain them from analytical equations starting from the velocity projections in the ground frame, regarding the fact that they take values that can exceed the first quadrant, the direct expression in differential form is preferred:

$$\dot{\chi} = \frac{N}{mV} \cos \mu - \frac{L}{mV} \sin \mu + \frac{T}{mV \cos \gamma} (\sin \mu \sin \alpha + \cos \mu \cos \alpha \sin \beta)$$

$$\dot{\gamma} = -\frac{N}{mV} \sin \mu - \frac{L}{mV} \cos \mu + \frac{T}{mV} (\cos \mu \sin \alpha - \sin \mu \cos \alpha \sin \beta) - \frac{g}{V} \cos \gamma$$

(42)

This form, unlike the equations (5) indicated in [1], are written for a non-zero sideslip angle $\beta$.

For defining the necessary commands of the flight formation, we must take into account that the command signals (28) are obtained in the semi-velocity frame, and that the actual commands are formed in the mobile frame. In order to do this we will define a matrix that will successfully accomplish 3 rotations with the angles $\mu$, $\beta$, $\alpha$, matrix that can be written:

$$A_{\alpha\beta\mu} = \begin{bmatrix} c\alpha c\beta & c\mu c\alpha + s\mu s\alpha & s\mu c\alpha - c\mu s\alpha \\ -s\beta & c\mu c\beta & s\mu c\beta \\ s\alpha c\beta & c\mu s\beta - s\mu c\alpha & s\mu c\beta + c\mu s\alpha \end{bmatrix}$$

where:

$$c \alpha = \cos \alpha ; \quad s \alpha = \sin \alpha ;$$

$$c \beta = \cos \beta ; \quad s \beta = \sin \beta ;$$

$$c \mu = \cos \mu ; \quad s \mu = \sin \mu .$$

With the help of this matrix we can rewrite the specific command functions for each UAV in the formation:

$$\begin{bmatrix} g_{l1} \\ g_{l2} \\ g_{l3} \end{bmatrix} = A_{\alpha\beta\mu} \begin{bmatrix} f_{l1} \\ f_{l2} \\ f_{l3} \end{bmatrix}.$$  (44)

Starting from the command system components in the mobile frame, we can rewrite the pseudo-commands, using the mobile frame. This way, the roll angle, necessary for a non-drifting steering is:

$$\phi_{ui} = \arctan \left( \frac{g_{l3}}{g_{l2}} \right).$$

(45)

And the load factor after the z axis of the mobile frame becomes:

$$n_{zi} = \sqrt{g_{l3}^2 + g_{l2}^2}.$$  (46)

Starting from these equations, we can define the UAV’s commands, which can be written in a simplified form:

$$\delta_{ui} = -a_1(\phi_{f1} - \phi_{u1}) - a_2 P_i$$

$$\delta_{ci} = \delta_{cos} n_{zi} - b_1 q_i$$

$$\delta_{ri} = c_1 r_i - c_2 r_i$$

$$\delta_{yi} = d_i g_{l1}$$

(47)

Where $\delta_{ei}$ is the deflection angle for the elevator’s balance, corresponding to a given evolution. Based on these relations, we have obtained the results indicated in the next charts.

Fig. 4 Climbing flight, 2 aircrafts formation, complex model (6DOF)

7. Conclusions

For solving the UAV’s formation control problem we have been successively developed two models. The first one is a simplified model with 3 degrees of freedom, accordingly to the methodology indicated in [1]. The second model has a complex form, with 6 degrees of freedom, which allows the definition of the real commands needed for controlling the formation in order to do and experimental test of the model. In figures 2,3 there are presented, as a test, the spiral climb evolutions of an isolated UAV and of a formation both with a simplified model. In figure 4 there is presented the evolution obtained with a complex model.

References:

