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3-D SPACE FLIGHT FORMATION CONTROL FOR UAVS BASED ON MAS

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ABSTRACT

A Multi-Agent System(MAS) consensus based algorithm is proposed for Multi-UAVs to maintain a specified time-varying geometric configuration for formation flight in 3-D space. Use decoupling characteristics in altitude control of Multi-UAVs, formation problem in 3-D space, was decomposed altitude control and plane control. In this approach, the proposed control strategy requires only the local neighbor-to-neighbor information between vehicles. Speed, heading angle. Then height synchronization is realized and the 3-D space formation flight can be achieved, and formation transform was investigated. The simulation results show that, this method has good robustness and scalability, simple calculation and a small amount of communication, and make the formation in 3-D space become easy to implement.
Keywords: *MAS, UAV, Consensus, Formation Flight, 3-D Space*

1. INTRODUCTION

One kind of intelligent weapon system development tendencies is the autonomous formation and cooperative guidance technology of multiple unmanned aerial vehicles (UAVs) which fits for the demand of combat mission and fire distribution. Formation control technology as one of the main research in Multi-UAVs cooperative control, play important role to realize stable and safe flying for Multi-UAVs system. Recently, decentralized formation control relying on only local information interaction and allowing dynamical changing communication topologies has made rapid progress.

Numerous results have been obtained for distributed coordination of multiple agents[4-8]. For example, Lafferriere [4] studied a method for decentralized stabilization of vehicle formations using techniques from algebraic graph theory. Also, Olfati-Saber[5] considered a group of mobile second-order agents moving in the plane and introduced control laws which enable the group to achieve a common velocity while avoiding collisions. Ren[6] proposed several consensus algorithms for second-order multi-agent systems and derived sufficient conditions for state consensus of the system. Moreover, Hong[7] investigated multiple second-order agent systems with jointly-connected interconnection topologies. In engineering practice, multi-agent systems are usually subjected to various disturbances such as time-delay and the variation of network topology. Lin [8] considered consensus problems for first-order multi-agent systems with external disturbances and model uncertainty on fixed and switching topologies.

Some issues in 3-D formation control of Multi-UAVs were investigated from the view of consensus algorithms and graph theory in this paper. Consensus algorithms were introduced, and then the main results of consensus algorithms were summarized. The speed, heading angle, and height synchronization was realized which based on these algorithms, and then a decentralized control strategy based on formation graph theory were provided to form and keep the given formation, and formation transform was investigated. The rest of this paper is organized as follows. Some basic notation and useful results of the graph theory are reviewed in Section 2. The models of Multi-UAVs formation are formulated in Section 3. Section 4 offers detailed simulation results for formation flight in 3-D space of Multi-UAVs. Finally, conclusions are given out in Section 5, and some possible future directions of research are also discussed.

2. CONSENSUS PROBLEM FORMULATION AND DEFINITIONS

2.1 Graph Theory

Let $G(V,\varepsilon,A)$ be a directed graph of order n, where $V=\{\upsilon_1...\upsilon_n\}$ is the set of nodes, $\varepsilon\subseteq V\times V$ is the set of edges, and $A=[a_{ij}]$ is a weighted adjacency matrix. The node indexes belong to a finite index set $I=\{1,2,...,n\}$. An edge of G is denoted by $e_{ij}=(v_i,v_j)$. The adjacency matrix is defined as $a_{ii}=0$ and $a_{ij}\geq 0$. $a_{ij}>0$ if and only if $e_{ij}\in\varepsilon$. The set of neighbors of node v_i is denoted by $N_i=\{v_j\in V:(v_i,v_j)\in\varepsilon\}$. The in-degree and out-degree of node v_i are defined, respectively, as $d_{in}(v_i)=\sum_{j=1}^{n}a_{ji}, d_o(v_i)=\sum_{j=1}^{n}a_{ij}$. Then, the graph Laplacian with the directed graph is defined as $L=[l_{ij}]$ where $l_{ij}=d_o(v_i)$ and $l_{ij}=-a_{ij}, i\neq j$. An important fact of L is that all the row sums of L are zero and thus $\mathbf{1}_n$ is an eigenvector of L associated with the eigenvalue $\lambda=0$. A directed path is a sequence of ordered edges of the form (v_{i_1}, v_{i_2}), (v_{i_2}, v_{i_3}), . . . , where $v_{i_j}\in V$ .If a directed graph has the properties that (v_i,v_j) belongs to ε for any $(v_i,v_j)\in\varepsilon$, the directed graph is called undirected. If there is a directed path from every node to every other node, the graph is said to be strongly connected (connected for undirected graph).

2.2 Multi-agent Systems and the Concept of Consensus

The information states with agent dynamics are given by

$$\dot{x}_i=u_i \qquad i=1,2,...,n \tag{1}$$

where $x_i\in R^n$ denotes the information state of the i^{th} agent and $u_i\in R^n$ is the control input. And the consensus algorithm to reach an agreement with respect to the states of n integrator agents [1] can be expressed as an n^{th} -order linear system on a graph.

$$u_i=-\sum_{j\in N_i}a_{ij}(x_i(t)-x_j(t)) \ , \quad x_i(0)\in R^n \tag{2}$$

where a_{ij} is the (i,j) entry of the adjacency matrix of the associated communication graph at time t , and N_i represents the set of agents whose information is available from agent Σ_i at time t . The control u_i drives x_i to the average position of its neighbors.

By applying algorithm Equ.(2), we can rewrite expression Equ.(1) into

$$\dot{x}(t)=-Lx(t) \tag{3}$$

where $x=[x_1,...,x_n]^T$ denotes the aggregated state vector of the multi-agent system, and $L=[l_{ij}]$ is the graph Laplacian of the network.

The set of agents V is said to be in consensus, if $\left\|x_i-x_j\right\|=0$ for each (i,j) : $i; j =1,2,...,n$ as $t\geq t_0$. The set of agents V is said to asymptotically reach global consensus if for any $x_i(0):i=1,2,...,n$, $\left\|x_i-x_j\right\|\to 0$ as t tends to infinity for each (i,j) : $i; j =1,2,...,n$ as $t\geq t_0$. The set of agents V is said to be global consensus reachable if there exists an information update strategy (protocol) for each $x_i:i=1,2,...,n$ that achieves global consensus asymptotically for V .

If take each UAV as a node of graph , the UAV's perception and communication relationship as edge, formation flight of Multi-UAVs system can also see as a graph, which shows Multi-UAVs system information topology, then it is easy to study the problem of Multi-UAVs system cooperative control by using the powerful tools : graph theory.

3. FORMATION FLIGHT OF MULTIPLE UAVS BASED ON MAS CONSENSUS

3.1 Model of UAVs Formation Flight

We assume that each UAV is equipped with standard autopilots for heading hold and Mach hold. Let (x,y) , h , φ , θ and v denote the inertial position, altitude, heading angle, tilt angle, and velocity for the UAV respectively. Then the resulting kinematic equations of motion are

$$\begin{aligned}&\dot{x}=v\cos\psi, && \dot{y}=v\sin\psi,\\&\dot{v}=\alpha_v\left(v^c-v\right), && \dot{\psi}=\alpha_\psi\left(\psi^c-\psi\right)\\&\ddot{h}=-\alpha_{\dot{h}}\dot{h}+\alpha_h\left(h^c-h\right)\end{aligned} \tag{4}$$

where ψ^c , θ^c and v^c are the commanded heading angle, tilt angle , and velocity to the autopilots, and

α_v, α_θ, and α_ψ are positive constants. In addition, we assume that each UAV has the constraints that

$$\begin{aligned} &0 < v_{\min} \le v \le v_{\max} \\ &a_{\min} \le \dot{v} = a \le a_{\max} \\ &|\dot{\psi}| = |\omega| \le \omega_{\max} \end{aligned} \tag{5}$$

$u = \left[v^c, \theta^c, \psi^c\right]^T$ is the control input in my simulation .

In this paper, we will use UAV model equ.(4) longitudinal decoupling characteristics. The UAV formation in 3-D space, is divided into attitude control and plane formation control. This paper presents a formation based on graph theory, formation graph and consensus algorithm.

3.2 Speed Synchronization

UAV has the positive speed limit and the minimum turning radius restrictions. Before the formation, the speed and heading angle of all the UAVs should keep synchronization. Thus, all UAVs remain aggregation state, and reduce the probability of collision between each other even if there is some interference. Now we will give synchronous speed control strategy and course synchronous control strategy respectively. In order to focus on the essential issues, we will assume that altitude is held constant.

First order dynamic model of the speed of UAV: $\dot{v}_i = \alpha_{v,i}\left(v_i^c - v_i\right)$. To solve consensus of the speed problem, we use the following protocol:

$$\begin{cases} v_i^c = v_i + \dfrac{1}{\alpha_{v,i}} u_i \\ u_i = -\sum\limits_{j\in N_i} a_{ij}\left(v_i - v_j\right) \end{cases} \tag{6}$$

3.3 Heading Angle Synchronization

The i^{th} UAV can use two kinds of different path to change from the current heading angle ψ_i to the instruction heading angle ψ_i^c .One way is along the clockwise deflection, another way is along the counterclockwise deflection. Obviously the one of the two path is farther, and synchronization time will be greatly increased due to the UAV minimum turning radius limit. So in the course control, consensus algorithm based on the control strategy, should also ensure the deflection angle is less than π . To solve consensus of the heading angle problem, we use the following protocol:

$$\psi_i^c = \psi_i + \frac{1}{1+|N_i|} \sum_{j\in N_i} \left(\psi_j - \psi_i\right) \tag{7}$$

Where $\left(\psi_j - \psi_i\right)$ is the heading angle errors between adjacent UAVs, that should satisfy $\left|\psi_i^c - \psi_i\right| < \pi$ .If communication topology fixed, if and only if communication network topology contains directed spanning tree, all UAVs flight speed and heading angle can asymptotically to converge [5], then all the UAVs flight speed and heading angle tend to be the same.

3.4 Height Synchronization

Height control problem is very important for Multi-UAVs formation in 3-D space. The common control method is Leader-Follower method, by measuring their own and pilot UAV relative height to adjust their height. One of the disadvantage of this method is the tracking error may be gradually enlarged. Taking it that the longitudinal movement and lateral movement of UAV in 3-D space is completely decoupled into account, distributed control strategy based on consensus algorithm can be taken to achieve height synchronization.

In order to make all the UAVs flight height tends to be the same as given value, we use the following protocol:

$$\begin{cases} h_i^c = h_i + \dfrac{\alpha_{\dot{h},i}}{\alpha_{h,i}} \dot{h}_i + \dfrac{1}{\alpha_{h,i}} u_i \\ u_i = -c_i\left(h_i - h^*\right) - k\dot{h}_i \\ \qquad - \sum\limits_{j=1}^{n} a_{ij}\left(\left(h_i - h_j\right) + \gamma\left(\dot{h}_i - \dot{h}_j\right)\right) \end{cases} \tag{8}$$

3.5 Formation of Multi-UAVs

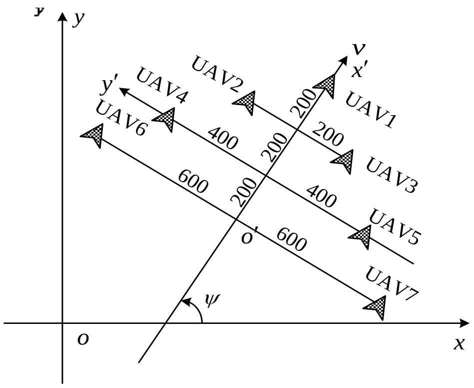

Figure 1. Uav Formation Configuration

Assuming the position, speed and heading angle of 7 UAVs as shown in Figure 2, where xoy is still ground coordinate system, and $x'o'y'$ is the UAV formation course coordinate system, and v and ψ are UAV formation speed and heading angle.

In $x'o'y'$, and its relative position matrix can be expressed as follows:

$$\left[x_{ij}^r\right]=\begin{bmatrix} 0 & -200 & -200 & -400 & -400 & -600 & -600 \\ 200 & 0 & 0 & -200 & -200 & -400 & -400 \\ 200 & 0 & 0 & -200 & -200 & -400 & -400 \\ 400 & 200 & 200 & 0 & 0 & -200 & -200 \\ 400 & 200 & 200 & 0 & 0 & -200 & -200 \\ 600 & 400 & 400 & 200 & 200 & 0 & 0 \\ 600 & 400 & 400 & 200 & 200 & 0 & 0 \end{bmatrix}$$

$$\left[y_{ij}^r\right]=\begin{bmatrix} 0 & 200 & -200 & 400 & -400 & 600 & -600 \\ -200 & 0 & -400 & 200 & -600 & 400 & -800 \\ 200 & 400 & 0 & 600 & -200 & 800 & -400 \\ -400 & -200 & -600 & 0 & -800 & 200 & -1000 \\ 400 & 600 & 200 & 800 & 0 & 1000 & -200 \\ -600 & -400 & -800 & -200 & -1000 & 0 & -1200 \\ 600 & 800 & 400 & 1000 & 200 & 1200 & 0 \end{bmatrix}$$

Where, $x_{ij}^r = x_i' - x_j'$, $y_{ij}^r = y_i' - y_j'$, $q_i' = \left[x_i', y_i'\right]^T$ is the position coordinates of the i^{th} UAV in $x'o'y'$. $r_{ij}' = \left[x_{ij}^r, y_{ij}^r\right]^T$ is the i^{th} UAV relative to expected the j^{th} UAV relative position coordinates.

The conversion relations between formation course coordinate $x'o'y'$ and ground coordinate system xoy is shown in Equ.(9). Formation diagram and the position of UAV coordinates have been given, we can calculate formation constraint conditions as:

$$q_i' - q_j' = \begin{bmatrix} x_i' - x_j' \\ y_i' - y_j' \end{bmatrix} = \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix}\begin{bmatrix} x_i - x_j \\ y_i - y_j \end{bmatrix} \qquad (9)$$
$$= \begin{bmatrix} \cos\psi & \sin\psi \\ -\sin\psi & \cos\psi \end{bmatrix}\left(q_i - q_j\right)$$

So UAV formation flight control strategies can get as follow:

$$\begin{cases} v_i^c = \bar{v}_i^c + \Delta v_i^c \\ \psi_i^c = \bar{\psi}_i^c + \Delta\psi_i^c \end{cases} \qquad (10)$$

where $\bar{v}_i^c$ and $\bar{\psi}_i^c$ are the synchronous control items of flight speed and heading angle based on consensus algorithm .The consensus algorithm form is the same as equ.(6) and equ.(7). And Δv_i^c, $\Delta\psi_i^c$ is the formation control items based on relative position feedback formation:

$$\Delta v_i^c = -k_{v,i}\sum_{j\in\mathcal{N}_i}\left(x_i' - x_j' - x_{ij}^r\right) \qquad (11)$$

$$\Delta\psi_i^c = -k_{\psi,i}\sum_{j\in N_i}\left(y_i' - y_j' - y_{ij}^r\right) \qquad (12)$$

where $k_{v,i} > 0$, $k_{\psi,i} > 0$ are positive feedback gain. When they reach a balanced state, all UAVs fly according to the given geometric configuration formation, which should have

$$\begin{aligned} & v_i^c \to \bar{v}_i^c \to v, \qquad \Delta v_i^c \to 0 \\ & \psi_i^c \to \bar{\psi}_i^c \to \psi, \quad \Delta\psi_i^c \to 0 \end{aligned} \qquad (13)$$

That is, by adopting the control strategy for the UAV system, should ensure that the communication topology graph and the formation graph of distributed control strategy to meet the convergence condition.

In order to verify the proposed distributed formation flight control strategy is effective, in the 3-D simulation example. Assuming that all the UAVs models are the same, they have the same characteristic parameters

4. NUMERICAL SIMULATION

Assume that there are 7 UAVs to form and maintain formation shown in Figure 1. The initial positions, speeds, heading angles, and height of UAVs in space are distributed arbitrarily. Initial state of UAVs is shown in the Table 1, the UAVs communication topology as shown in the Figure 2, and the weighted adjacency matrix takes as equ.(14).

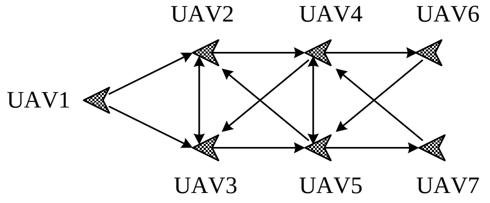

Figure 3 Multi-UAVs Communication Topology

In the first stage, all UAVs used distributed control strategy Equ.(6) and Equ.(7), so that the flight speed, and heading angle keep synchronization. The UAV1 is group Leader, its speed instruction set to be 160 m/s, and heading angle instruction set to be $-\pi/4$. After 10 seconds, the speed instruction is changed to 200 m/s. From the 20th seconds, the heading angle instruction is changed to $\pi/4$. From the 30th seconds, the flight height instruction is set to 13900. From the 40th seconds, system is switched to distributed control strategy Equ.(10) to form and keep formation shown in Figure 1.

The coefficients of distributed control strategy equ.(11) and equ.(12) are set to be $k_{v,i}=1$ 、 $k_{\psi,i}=0.001$, and we will obtain simulation results are as Figure 3 to Figure 7.

Table 1. Initial State of UAVs

	Initial positon	Initial velocity	Initial heading angle	Initial height
UAV1	(0,0)	160	$-\pi/4$	13700
UAV2	(500,-100)	221.3	$3\pi/4$	14900
UAV3	(1000,-200)	245	$-3\pi/8$	15400
UAV4	(1500,1000)	178.3	$-\pi/4$	14000
UAV5	(1000,-500)	190.7	$\pi/8$	15000
UAV6	(-100,0)	180	$-\pi/4$	12500
UAV7	(-200,-1000)	200	$\pi/8$	14400

$$A=\left[a_{ij}\right]=\begin{bmatrix}0&0&0&0&0&0&0\\1&0&1&0&2&0&0\\1&2&0&1&0&0&0\\0&3&0&0&1&0&2\\0&0&3&1&0&1&0\\0&0&0&2&0&0&0\\0&0&0&0&2&0&0\end{bmatrix}\quad(14)$$

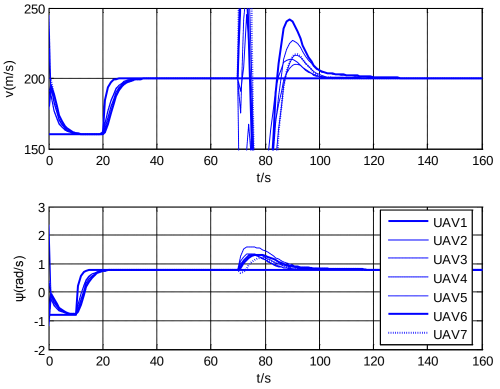

Figure 3 Change Flight Speed And Heading Angle

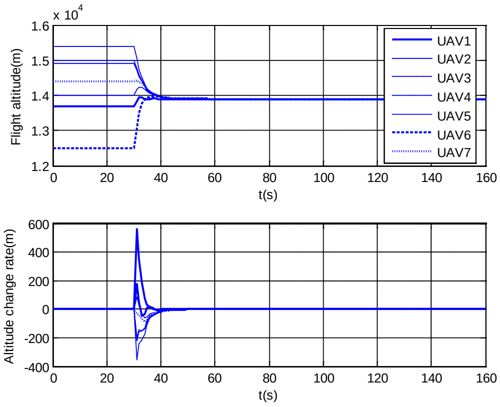

Figure 4. UAVs Flight Altitude and Altitude Change Rate

Easy to see that, when UAV1 flight speed or heading angle change, the rest of UAVs will follow the change, and tend to be consensus soon, and transient time is very short, as shown in Figure 3. So all UAVs flight speed and heading angle can keep synchronization under the distributed control strategy Equ.(6) and Equ.(7), so we can control the group leader to control the whole group.

As shown in Figure 4, all flight height quickly tends to be the same as the given value. When the operator setpoint changes, the consistent (balance) state will be broken, but soon the flight height tends to be the same as the new value.

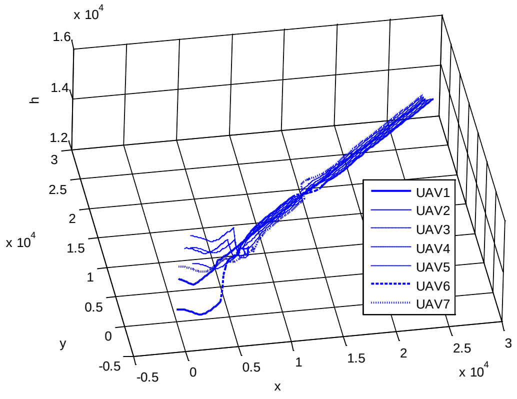

Figure 5. UAVs formation of 3-D space

By using decoupling characteristics in altitude control of Multi-UAVs, problem for formation in 3-D space, was decomposed altitude control and two dimensional control. As shown in Figure 5, the control strategy can realize the design objective, the external reference signal mutations will break the existing balance state, but does not affect the control strategy and speed up the convergence.

In the actual formation flight, when emergency, because of the change of the environment or the task, may require the formation of UAVs system adjustment or conversion. In our method, only need to be given a desired formation diagram, and rationally design of topology structure.Then the formation of transform can be realized. As shown in Figure 5, from the 40th seconds to the 100th seconds, UAV formation configuration 1 is achieved, and the amplification of the formation is shown in Figure 6 on the 100th seconds. From the 100th seconds to the 200th seconds, UAV formation configuration 2 is achieved, and the amplification of the formation is shown in Figure 7 on the 200th seconds.

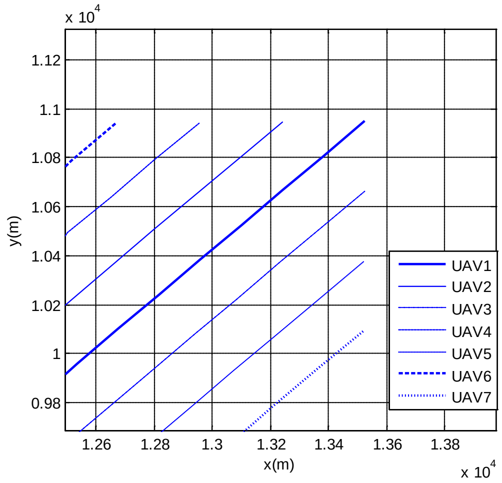

Figure 6. UAV Formation Configuration 1

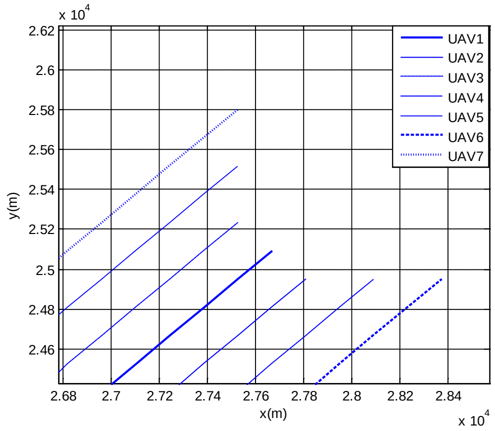

Figure 7. UAV Formation Configuration 2

5. CONCLUSION

A consensus-based algorithm is proposed to maintain a specified time-varying geometric configuration for formation flight in 3-D space of Multi-UAVs. Speed, heading angle, and height synchronization is realized and the 3-D space formation is achieved by the proposed consensus algorithm, which is shown in simulation. This research scheme laid the foundation for the application consensus algorithm for formation technology of Multi-UAVs, and some research can try in the problem for obstacle avoidance and crash avoidance in the formation control of Multi-UAVs.

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