Virtual Structure in Formation Flight Control of UAVs via NOPSC Algorithm

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Abstract. This paper presents a virtual structures in multi-UAVs formation flight via consensus strategies. By using consensus strategies, each UAV can track coordination vector, the desired formation shape can be preserved accurately. For the multi-UAVs control problem, applying a novel base-on outdated and predicted state consensus algorithm (NOPSC) to ensure accurate formation maintenance through information coupling between local neighbors, and the formation control problem is transformed into each UAV tracks its desired state.

1. Introduction

At present, consistency theory has been widely studied in multiple ground mobile robots formation control, UAV formation control, AUV (Autonomous Underwater Vehicle) formation cooperative, satellite formation, spacecraft formation cooperative control in [1, 2]. A consensus-based design scheme is applied to the formation control of multiple-wheeled mobile-robot group with a virtual leader in [1]. In [3] proposes a distributed control strategy based on the consensus protocol for formation flight of unmanned aerial vehicles. In [4], the small-scale formation control of autonomous underwater vehicles (AUVs) was investigated with consensus algorithms and virtual structure. In [5] presents a general framework for synchronized multiple spacecraft rotations via consensus-based virtual structure. In [6] consensus tracking protocol with a time-varying reference state is extended to achieve the formation control.

This paper presents a virtual structures in multi-UAVs formation flight via consensus strategies. By using consensus tracking strategies, each UAV can track coordination vector. Then, the desired formation shape can be preserved accurately. Meanwhile, for the multi-UAVs control problem, applying a novel base-on outdated and predicted state consensus algorithm (NOPSC) to ensure accurate formation maintenance through information coupling between local neighbors.

2. Problem Statement and Preliminaries

In this section, some preliminary notation and properties for UAV formation flying would be introduced.

2.1 Kinematics of a UAV

The point mass model is considered for the formation flight. Each UAV is assumed to fly at a feasible constant altitude, parallel to the two-dimensional region to be surveyed. A commonly used non-linear kinematics model is described by the following differential equation:

$$\begin{cases} \dot{x}_i(t) = v_i(t)\cos\varphi_i(t) \\ \dot{y}_i(t) = v_i(t)\sin\varphi_i(t) \\ \dot{\phi}_i(t) = \omega_i(t) \end{cases} \tag{1}$$

with $i = 1, 2, \cdots n$, where $[x_i(t), y_i(t)]^T$ describes the Cartesian coordinates position vector of the i[th] UAV, $v_i(t)$, $\varphi_i(t)$ and $\omega_i(t)$ represent the forward velocity, heading angle and rotational velocity, respectively. UAV motion model feedback linearization can be obtained in the form of first-order differential system model: $\begin{bmatrix}\dot{x}_i & \dot{y}_i\end{bmatrix}^T = \begin{bmatrix}u_{xi} & u_{yi}\end{bmatrix}^T$, let $u_i = \begin{bmatrix}u_{xi}, u_{yi}\end{bmatrix}^T$ denotes the control input.

2.2 Graph Theory Notations

In a multi-agent system, the information flow between two agents can be regarded as a directed path between the nodes. Let $\boldsymbol{G} = (\boldsymbol{V}, \boldsymbol{\varepsilon}, \boldsymbol{A})$ be a directed generalized graph with the set of nodes $\boldsymbol{V} = \{v_1, v_2, \cdots v_n\}$, set of edges $\boldsymbol{\varepsilon} = \{e_1, e_2, \cdots e_n\} \subseteq \boldsymbol{V} \times \boldsymbol{V}$, and a weighted adjacency matrix $\boldsymbol{A} = [a_{ij}] \in R^{n \times n}$, where $a_{ij} > 0$ means that node *i* receives information from node *j*. The set of neighbors of node *i* is denoted by $N_i(t) = \{j \,|\, (j, i) \in \varepsilon\}$. The Laplacian matrix of the graph is defined as $\boldsymbol{L} = [l_{ij}]_{n \times n}$, the matrix $\boldsymbol{L}$ satisfies the following conditions: $l_{ij} = \sum_{k=1, k \neq i}^{n} a_{ik}$, if $i = j$; otherwise $l_{ij} = -a_{ij}$.

3. Formation control consensus algorithm

3.1 Virtual Structure

In this work, we are developing a virtual structure approach for multiple UAVs formation control.

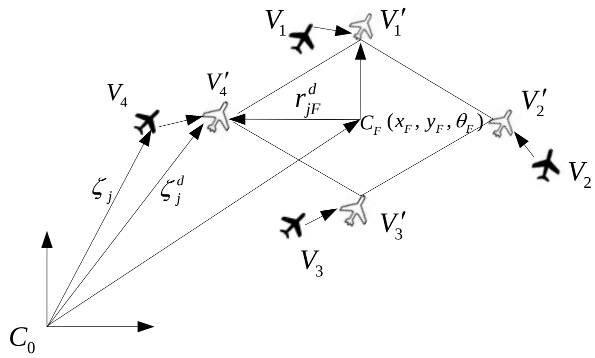


Fig. 1.A formation composed of four UAVs with a known virtual center.

Fig. 1 shows an illustrative example of the virtual structure approach with a formation composed of four UAVs with planar motions. Where C_0 represents the inertial frame and C_F represents a virtual coordinate frame located at a virtual center $\boldsymbol{\xi} = [x_F, y_F, \theta_F]^T$ with an orientation θ_F relative to C_0. In Fig. 1, V_i and V_i' represent, respectively, the i[th] UAV's actual and desired position. Let $\zeta_j = [x_j \ y_j]^T$ 、 $\zeta_j^d = [x_i^d \ y_i^d]^T$ denote the i[th] UAV's actual and desired position. And $\zeta_{iF}^d = [x_{iF}^d \ y_{iF}^d]^T$ represents the desired deviation of the i[th] UAV relative to C_F position vector. By the coordinate transformation matrix, $\zeta_j^d = [x_i^d \ y_i^d]^T$ can be described as:

$$\begin{pmatrix} x_i^d(t) \\ y_i^d(t) \end{pmatrix} = \begin{pmatrix} x_F(t) \\ y_F(t) \end{pmatrix} + \begin{pmatrix} \cos(\theta_F(t)) & -\sin(\theta_F(t)) \\ \sin(\theta_F(t)) & \cos(\theta_F(t)) \end{pmatrix} \times \begin{pmatrix} x_{iF}^d(t) \\ y_{iF}^d(t) \end{pmatrix} \tag{2}$$

3.2 Consensus Tracing Algorithm.

On the formation consensus tracing level, each UVA tracks the state of the virtual center via a consensus tracking algorithm as:

$$u_i(t) = \frac{1}{\eta_i(t)} \sum_{j=1}^{n} a_{ij}^c(t)[\dot{\xi}_j(t) - \gamma(\xi_i(t) - \xi_j(t))] + \frac{1}{\eta_i(t)} a_{i(n+1)}^c(t)[\dot{\xi}^r(t) - \gamma(\xi_i(t) - \xi^r(t))] \tag{3}$$

Where $i = 1, 2, \cdots n$ and $j = 1, 2, \cdots n+1$, and $\gamma > 0$, $\eta_i(t) = \sum_{j=1}^{n+1} a_{ij}^c(t)$.

For multi-agent formation control problem, using the following formation control strategy u_{i1}:

$$u_{i1} = \dot{\zeta}_i^d(t) - \alpha_i(\zeta_i(t) - \zeta_i^d(t)) - \sum_{j=1}^{n} a_{ij}^v[(\zeta_i(t) - \zeta_i^d(t)) - (\zeta_j(t) - \zeta_j^d(t))] \tag{4}$$

Where $\alpha_i > 0$, in order to improve the convergence rate of formation control algorithm, a novel base-on outdated and predicted state consensus algorithm (NOPSC) is studied in this work. Let $u_{i2} = \rho[(\zeta_i(t) - \zeta_i^d(t)) - (\zeta_i(t-\tau) - \zeta_i^d(t-\tau))]$; $u_{i3} = \beta \sum_{j \in N_i'} a_{ij}(\dot{\zeta}_i^p(t) - \dot{\zeta}_j^p(t))$, $\zeta_i(t-\tau) \triangleq \zeta_i(t)$, when $t \in [0, \tau)$, and $0 < \rho < 1$, β represents state prediction parameter. The introduction of state observer can be expressed as:

$$\begin{cases} \dot{\zeta}_i^p = \sum_{k \in N_i} a_{ik}[(\zeta_i(t) - \zeta_i^d(t)) - (\zeta_k(t) - \zeta_k^d(t))] \\ \dot{\zeta}_j^p = \sum_{p \in N_j} a_{jp}[(\zeta_j(t) - \zeta_j^d(t)) - (\zeta_p(t) - \zeta_p^d(t))] \end{cases} \tag{5}$$

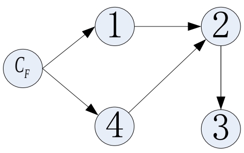
Therefore, the proposed new control algorithm can be expressed as:

$$u_i = u_{i1} + u_{i2} + u_{i3} \tag{6}$$

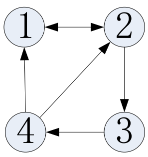
4. Experimental Results

Assuming has four UAVs formation flight in a diamond motion given in Fig.1, Diamond side length is 60m, $V_F = 5\pi\ (m/s)$, $\omega_F = \dfrac{\pi}{25}(^\circ)$, initial velocities are $V_1 = 8\pi(m/s)$, $V_2 = 7\pi(m/s)$, $V_3 = 4\pi(m/s)$, $V_4 = 3\pi(m/s)$, respectively. The UAV's desired deviation position vector that relative to C_F is $\zeta_{1F}^d = (0, 30)$ m, $\zeta_{2F}^d = (30\sqrt{3}, 0)$ m, $\zeta_{3F}^d = (0, -30)$ m, $\zeta_{4F}^d = (-30\sqrt{3}, 0)$ m. All UAVs' initial position is located at (0, 0), simulation time $t = 100s$, simulation step dt=0.01s, cycle index k and simulation time t satisfies the relationship: $t = k \times dt$, $\tau = 0.01s$.

Fig. 2 (a) and (b) respectively shows consensus tracking level and formation control level communication topology.



(a) consensus tracking level topology



(b) formation control level topology

Fig. 2 UAVs' communication topology

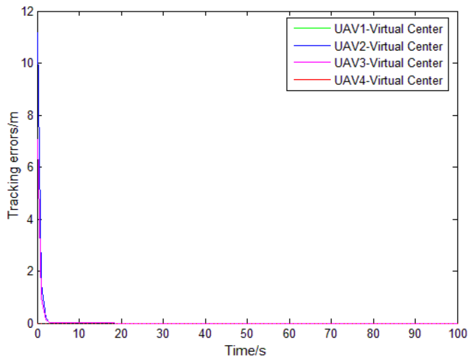
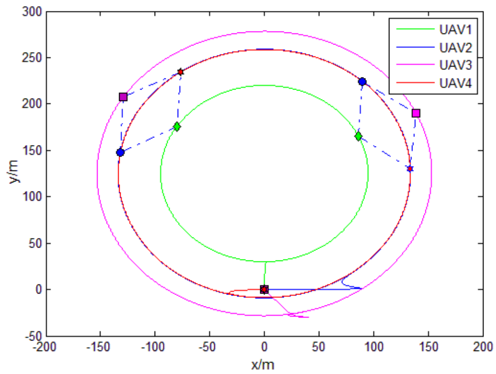
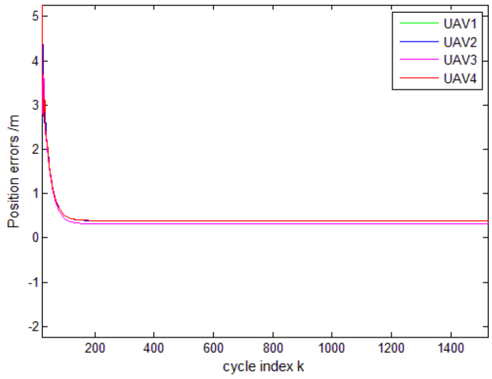
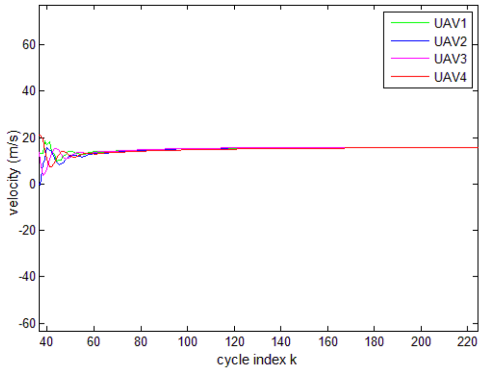


Fig. 3 Virtual center state tracking errors



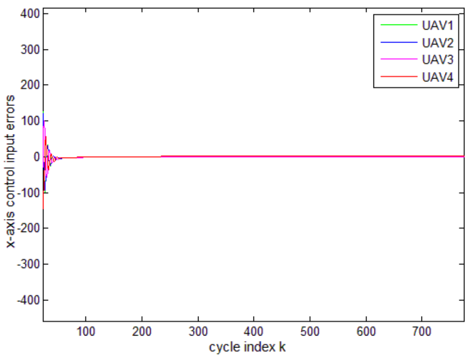


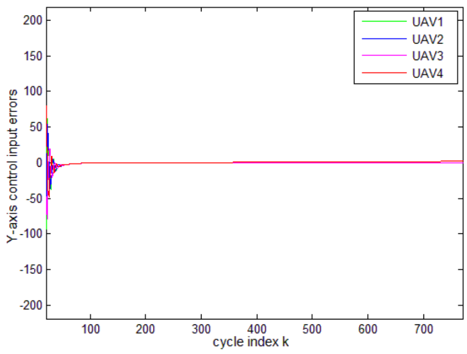
(a) UAV's final configuration and trajectories (b) position errors



(c) velocity consensus

Fig. 4 Experimental result of UAVs with a diamond formation





(a)X-axis control input errors (b) Y-axis control input errors

Fig. 5 Control input errors with $\alpha = 4, \ \beta = 20$

Table 1 Algorithm (4) and Algorithms (6) Convergence Comparison

Algorithm	Parameter	Convergence Time	Average Error
Algorithm（4）	$\alpha = 2$	3.95s	1.6806m
Algorithm（6）	$\rho = 0.5, \tau = 0.01, \alpha = 2, \ \beta = 15$	1.39s	0.7509m
Algorithm（4）	$\alpha = 4$	1.40s	1.3692m
Algorithm（6）	$\rho = 0.5, \tau = 0.01, \alpha = 4, \ \beta = 20$	0.82s	0.5905m

Fig. 3 shows the virtual center tracking errors, due to UAV1 and UAV4 know the states of the virtual center, therefor, its tracking errors are equal to zero. UAV2 and UAV3 quickly converge to zero. Note that the group is able to travel in tight formation around the circle as shown in Fig. 4(a) with relative position errors between 0.5405m and 0.6214m as shown in Fig. 4(b). Also note that velocity gradually converges to the desired velocity $V_F = 5\pi \ (m/s)$ in Fig. 4(c). Fig. 5 shows X-axis and Y-axis control input errors with $\alpha = 4, \beta = 20$. Algorithm (4) and algorithms (6) convergence comparison with different parameters shows in table 1. From the table, we can see algorithm (6) on the control effect and convergence rate are better than algorithm (4).

5. Conclusion

We propose a distributed formation control algorithm. By using consensus algorithms, the UAVs come into agreement on the position and velocity of the virtual center. The UAVs then apply a consensus-based formation control algorithm to track their desired positions and maintain the formation geometry. Simulation experimental results have shown the effectiveness of the algorithm.

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