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ORIGINAL ARTICLE

Consensus Based Formation Control of Multiple UAVs

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ABSTRACT

Autonomous vehicles are now more popular in practical fields of work and multiple vehicles can be used in a group to perform a single task that can't be performed by one. For each vehicle to stay in a group at its own specific position during motion is called formation. A quadrotor or unmanned air vehicle (UAV) can be taken as a common example of autonomous vehicle. To maintain the formation, we consider a group of vehicles inside a reference coordinate frame moving along some defined path. The idea is to make each vehicle understand the surrounding environment, distribute this information among every vehicle and with consensus choose such a path of movement to not lose the formation. Conventional techniques of formation control do not have such type of feedback due to which the formation of vehicles is lost when an obstacle is encountered in the path of one or more vehicles. Therefore, the feedback from the formation is realized in order to improve the formation accuracy. The maximum physical distance of a vehicle in formation is produced by max distance consensus unit and feedback to other vehicles to change the trajectory accordingly. Through simulations, the performance of the system is evaluated and compared with the one having no feedback.

Keywords: Autonomous Vehicles, Consensus Algorithms, Cooperative Control, Communicating Agents, Formation Control, Multi-Agent Systems.

Author`s Contribution

[1,2,3] Manuscript writing, Data Collection Data analysis, interpretation, Conception, synthesis, planning of research, and discussion

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INTRODUCTION

The problem of formation control of Multiple Unmanned Air Vehicles (Multi-UAV's) for a typical application of consensus/synchronization of complex network, has recently became a very heed area for most of research communities [1], [2] and [3]. Because of very superior qualities like small size, unsophisticated structure, expeditious manoeuvrability, and take off landing vertically, they are often employed in very dangerous environments, to perform a very complex tasks, such as surveillance in disasters, search of wilderness and extricate operation, in conjunction with [4], [5], moreover they have better efficiency in optimizing the energy management system of smart grids [6], [7] and has good services in securing them [8]. We will be more concerned to the problem of formation control in Multi-UAVs network by exploiting theory of consensus control in multi-agent system. The multi-UAV system is more advantageous and more effective [3], [5], [9], as it deals all jobs in a proper formation which is the weakness when quadrotors are dealing tasks in single. Most captivating factor in multi-quadrotors is that the overall capacity of aircraft gets enhanced which implies that they could be equipped with more devices or sensors, so that inexpedient tasks are achieved. Besides that, sharing information among multiple UAVs increases the system reliability and stability. It is known fact that the problem of stability of a UAV alone and the distributive control problem of multi-UAVs are challenging tasks, but comparatively designing and analysis of controller to keeping a proper formation of multi-UAVs is much more strenuous.

LITERATURE REVIEW

Up till now, different strategies of control have been proposed by experts and researchers from different fields to reach the goal of proper formation for a group of UAVs. Formation control application is being inspected by [5] where the method of an integral sliding mode control is presented for designing the controller of quadrotor aircraft. Keeping in view the background of optimal control method an algorithm (for designing the controller of multiple UAVs) is proposed in [10]. Based on virtual structure, the algorithm of two-levels formation is proposed in [11] for the sovereign formation of UAVs in 3D. However, [12] presented a coordination system (using a formation controller) for multiple spacecrafts. But that's not the end of era: The formation system was supposed to me more precise and collision free, for which a bounded control technique was used [13] in the design of distributed coordination controller and tested via group of UAVs. In spite the fact, that many results for the controlling of formation of multiple UAVs are being revealed in the current literature. But the question that how we could improve the performance of controller, is still a challenging issue. And this is due to certain inherent high-dimensional dynamics plus some nonlinear coupling that exists by the surrounding aircrafts, etc. Because of partial motivation from [14], [15], a consensus based protocol or algorithm is employed for maintaining the formation of multiple-UAVs and which will enable the UAV network to be in proper formation i.e. full formation control will be established.

Formation control is a vital part of cooperative control. Cooperative control is a broad field that deals with the problem of controlling multiple agent/vehicle systems to achieve common goal. An agent can be any vehicle with sensors such as camera and can communicate other agents in the group. The common goal can be surveillance, search, or exploration etc. According to [16] cooperative control system entails four basic components i.e. agent, communication network among agents, local level control algorithms and group objective(s). Among other group objectives, the formation control is to produce and keep the geometric configuration of vehicles. This configuration may be defined from the start or randomly generated according to the situation during the drive [17].

Cooperative control was first inspired from animals' behavior of flocking [18] of birds or fish. To mimic the natural behavior, an algorithm was introduced for vehicles based upon three mechanisms i.e. cohesion, separation, and alignment. Cohesion means that the vehicles remains close to one another but separated enough to avoid collision and remain aligned along a defined path. In literature, many types of formation control schemes are proposed, and are classified but one scheme based on the sensing capabilities and the interaction among agents is more well-known [17]. The types based on the said scheme are position, displacement and distance based. In position-based formation the vehicles depend upon the global coordinate system (GCS) to fix its position in the formation and there is no interaction among the neighboring vehicles. The vehicles rely heavily on sensing equipment like GPS. In displacement-based formation, the vehicles do not rely entirely on GCS but instead on a local coordinate system to find the position of its neighboring vehicles and fix its position accordingly. The vehicles also communicate with one another. In distance-based formation, the vehicle relies less on sensing capabilities and global information but interacts with the neighboring vehicles to fix its position in the formation. In these types, the sensing capabilities decreases from the position based over to displacement based, to the distance-based while the interactions among the vehicle increases as shown by the Fig. 1.

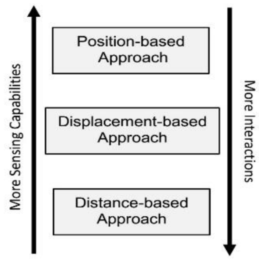

Figure 1. Classification of formation control schemes [17]

In this paper, the position-based approach is chosen for analysis. A coordinate reference frame called virtual reference frame is assumed, in which vehicles occupy specific positions to form a formation as shown in Fig.2 for six quadrotors or UAVs.

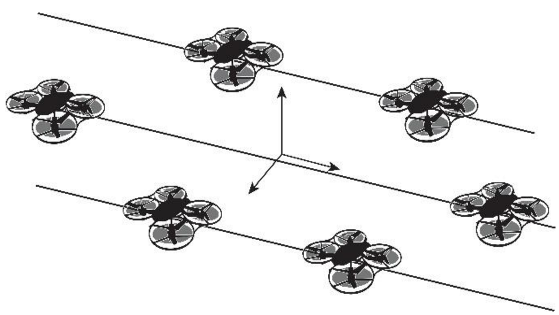

Figure 2. Six Quadrotors in formation flight

The vehicles moving in formation is attained by simply moving the virtual reference frame. This paper is organized by having mathematical formulation in Section III. The preceding section IV states the main results of simulation, and the comparison of the obtained outcomes. Finally, Section V concludes the whole paper.

MATHEMATICAL FORMULATION

This section is about discussion of network modelling and consensus algorithm in mathematical terms which lays the groundwork for cooperative control. Terminology related to Graph theory is also outlined shortly which is necessary for network modeling.

A. Network Modeling

A graph $\mathcal{G} = (\mathcal{N}, \mathcal{E})$ represents a communication network model among finite nodes, where $\mathcal{G} = \{1, 2, \dots, n\}$ denotes a finite set of nodes (or UAVs in our case) and $\mathcal{E}$ for set of edges, shows the links among the nodes in the form of pairs. Information can be passed from one node i to another j via the edge $\mathcal{E}(i, j)$ and vice versa. The nodes at the ends of an edge are neighbors. An edge $\mathcal{E}(i, j)$ starting and ending at the same node is called cycle are omitted. A path between two distant nodes consist of a sequence of edges linking the intermediate nodes. A connected graph $\mathcal{G}$ is one where all the nodes of network are linked to one another via edge or a path. If there exists a single path between every two nodes, the graph is called tree graph. A type of a tree graph with minimum number of edges linking all the nodes is specifically known as spanning tree [19]. To represent all the links between the nodes, we use adjacency matrix $A = [a_{ij}] \in \mathbb{R}^{n \times n}$, where a_{ij} = a_{ji} $= 1$ if there exists an edge $\mathcal{E}$ and a_{ij} = a_{ji} $= 0$ otherwise. For a spanning tree, the adjacency matrix A has zeros on the diagonal due to zero cycles and is symmetric. A spanning tree shall provide us a network having single active path between every two nodes. Another term to be used ahead is Degree matrix, which shows the total number of neighbors of an individual node.

$$\mathrm{D} = [d_{ij}] \in \mathbb{R}^{n \times n} \tag{1}$$

where

$$d_{ij} = \begin{cases} \sum_{j=1}^{n} a_{ij}, & i \neq j \\ 0, & i \neq j \end{cases} \tag{2}$$

Degree matrix has non-zero entries on the diagonal and zero elsewhere and shows the number of neighbors of node i [19]. From the difference of Degree matrix D and Adjacency matrix A, we get Graph Laplacian which is an important term to our notion of consensus algorithm.

$$\mathbf{L} = [l_{ij}] = \mathbf{D} - \mathbf{A} \in \mathbb{R}^{n \times n} \tag{3}$$

Our model of network shall contain an additional node (i.e. vehicle) known as Virtual Leader (VL). As its name shows it is not a physical node, but in simulation it shall contain information for reference for other nodes n and termed as followers [20].

B. Consensus Algorithm

For cooperative control, it is essential to share information among nodes and based on the sharing only, consensus is possible. Consensus means a multiagent system reaching an agreement about a common goal thru local communication [21]. Here the local communication represents neighbor-to-neighbor linkage. Mathematically, the consensus algorithm is expressed by the equation as

$$\dot{\sigma} = \omega_i(t),\ \ i = \{1,2,\ldots,n\} \qquad (4)$$

Where $\dot{\sigma}$ represents the information state of simple integrator with the input $\omega_i(t)$ at time t. As mentioned in the section 2.1, the system is composed of n agents in a network, all linked locally. As distributed linear protocol [22] is followed by individual agent

$$\omega_i(t) = -\sum_{j=1}^{n} a_{ij}\left(\sigma_j(t) - \sigma_i(t)\right),\ \ j = 1,2,\ldots,n \qquad (5)$$

Which for the whole system, can be written as:

$$\dot{\sigma}(t) = -\mathbf{L}\sigma(t) \qquad (6)$$

Where $\mathbf{L}$ indicates the graph Laplacian and $\sigma(t) = [\sigma_1(t), \sigma_2(t) \ldots \sigma_n(t)]^T$. The above equations can be translated as, each vehicle receives the locally available information of its neighbors and with it takes the average including its own values. The consensus is achieved once the condition $\sigma_1(t) = \sigma_2(t) = \cdots = \sigma_n(t)$ satisfies. In connected graph, the convergence is certain and also bounded information states. These assumptions are proved in the following discussion.

Consider i^* as index such that,

$$\sigma_{i^*}(t) = \max_i \sigma_i(t) \qquad (7)$$

then, $\forall j = \{1,\ldots,n\}$

$$-a_{i*j}[\sigma_{i^*}(t) - \sigma_j(t)] \le 0 \qquad (8)$$

Unless $a_{i^*j}(t) = 0$ or $\sigma_{i^*}(t) = \sigma_j(t)$, the inequality remains intact, which means,

$$\sigma_{i^*}(t) \le 0 \qquad (9)$$

and therefore, the increase in maximum never occurs but decreases every time it links with other non-maximum agent. The same occurs for the minimum values i.e. It never decreases but increases every time it links with other non-minimum agent. A detailed mathematical proof can be observed in [21].

MAIN RESULTS

This section discusses the simulation of consensus module/unit and then the complete formation framework simulation done with the presence and absence of active reference controller, followed by the comparisons of both simulations and wrapped up with the quantitative assessment at the end.

A. Reference Frame Consensus Unit

The individual vehicle states ξ_i are driven to the reference state ξ^r_{contr} by the consensus algorithm applied to the virtual reference frame. The reference correction is assumed not in action, therefore $\xi^r_{contr} = \xi^r$. The Euler angles α_i of ξ_i of each vehicle are plotted vs time in Fig 3, with the assumed reference value of $\alpha^r(t)$. The errors $e_{\alpha_i} = |\alpha^r(t) - \alpha_i^r(t)|$ are noteworthy and can be explained by examining the communication network. Using the error e_{α_i}, we introduce the performance criteria J as

$$J_\alpha = |\alpha^r(t) - \alpha_i^r(t)|dt, j = \{1,2,\ldots,n\} \qquad (10)$$

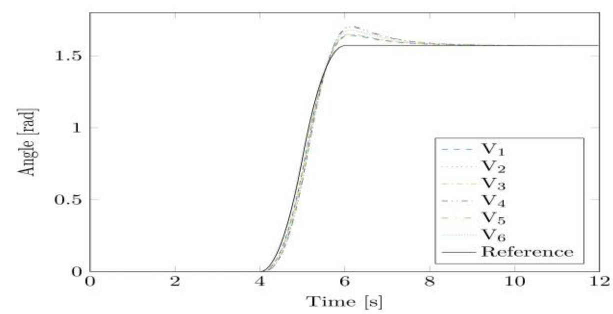

Figure 3. Consensus algorithm for α_i value of ξ_i

Fig 4 shows that the information state of fifth quadrotor varies the most as compared to other vehicles and the reason is clear as there lies other vehicles between the VL and the fifth vehicle in the network through which the information has to pass to reach the fifth vehicle. Similarly, the other vehicles depending on the remoteness from VL, the error varies. The control parameter κ influences the speed of convergence and is fixed to value of 100 to achieve the consensus faster.

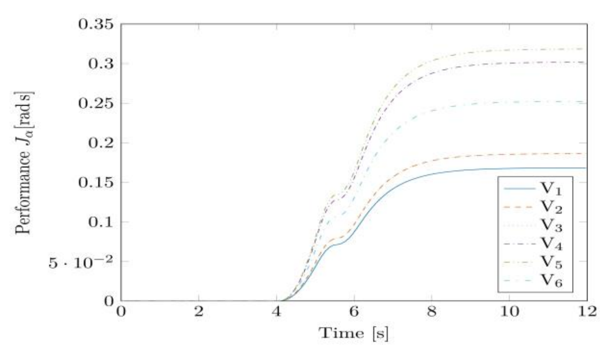

Figure 4. Comparison of performance for α_i value of ξ_i

B. Maximum Distance Consensus Unit

A formation of six vehicles in a straight line moving over a trajectory is simulated to test the algorithm. The findings for the third vehicle are shown in Fig 5, where the initial three variables of information state ζ_3 are contrasted with the global true values. No significant difference is noted between the information stored by the vehicle and the exact global positive maximum distances. This can be accounted for not including the communication delay and other restrictions during the simulation. Also, the broadcast algorithm reached consensus in a single time step, but it serves the purpose of simulation of distributed framework and its various prospects.

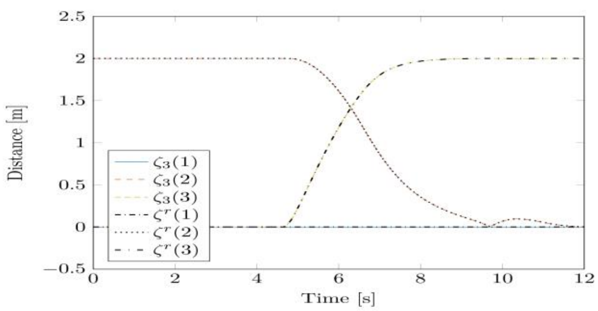

Figure 5. Max distance estimate ζ_3 of third vehicle and true values ζ^r

C. Simulation of Formation Control Structure with and Without Reference Correction

Formation Control exclusive of Reference Correction: Reference correction is excluded for simulation $c_a = 0$ and the formation of vehicles in straight line in reference coordinate frame is simulated along the proposed trajectory, which means that the information available to the vehicles is $\xi^r_{contr} = \xi^r$. For a simulation time ($t_s = 12\,s$), the vehicle positions are drawn at four different moments in Fig.6. The round and diamond symbols show the position of quadrotors referring to the desired and the actual ones, respectively. The reference coordinate frame current position is represented by the cube moving along the trajectory. The center of cube is in fact following the trajectory shown in all the pictures. It can be seen in Fig. 6a that the vehicles follow the rising motion at the start with their desired position intact. However, after a while, in Fig. 6b, it can be noted that the vehicles lack behind their desired positions once the reference frame rotation sets in. In Fig. 6c, the vehicles eventually lose formation at $t_s = 8s$, but as they approach the less steep end of the trajectory, they get in the formation again as shown in Fig.6d.

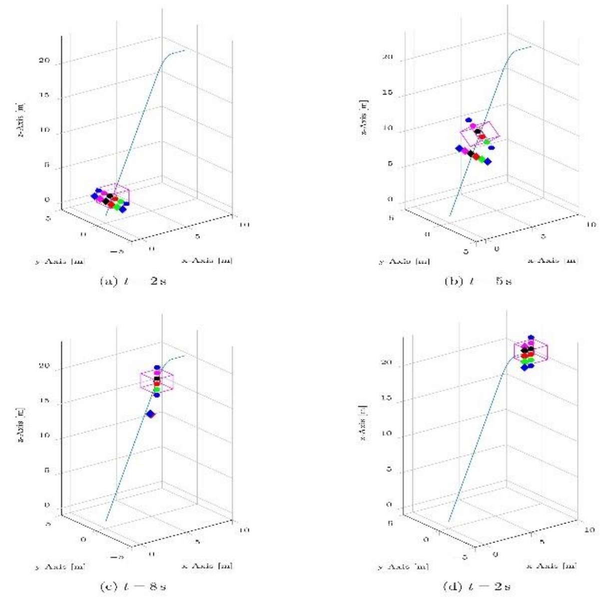

Figure 6. Position of vehicles in formation at four instants without reference correction

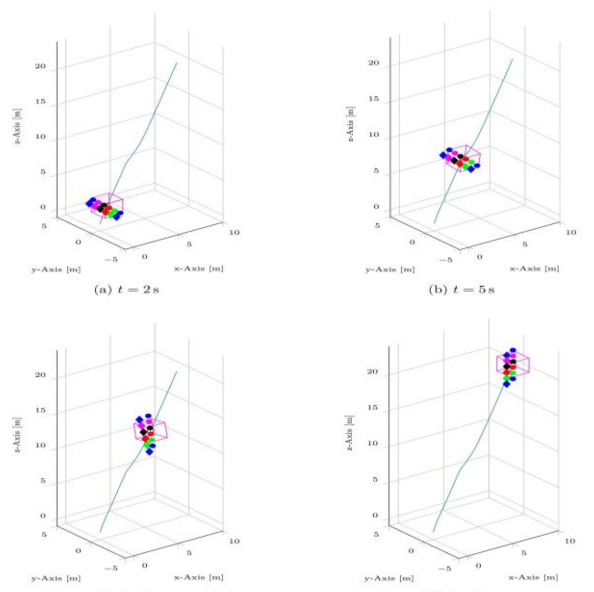

Figure 7. Position of vehicles in formation at four instants including reference correction

- *Formation Control including Reference Correction:*

Next, the simulation is carried out including the reference correction where the given trajectory is affected by the correction vector c_a. Like the previous section, the current state of formation is shown in Fig. 7 at four different instants of time. At the start of motion of vehicles in Fig. 7a, their behavior is same as the one without reference correction in Fig. 6a. As the vehicles moves forward, the different instants in Fig. 7b and Fig. 7c can be compared with the Fig. 6b and Fig. 6c, respectively. It is clear that the formation of vehicles is not lost but perfectly maintained for the whole duration.

The following Fig. 8 shows the simulation results of the controlled reference state ξ^r_{contr} vs the uncontrolled reference state ξ^r for the translational and rotational components respectively. It can be observed from these figures that the components $\ddot{z}^r$ and $\ddot{\alpha}$ are different in both which are restricted by the controller to achieve limited acceleration while the other state parameters of ξ^r_{contr} remain unaffected. The reason behind which is the correction vector c_a being non-zero only for components $\ddot{z}^r$ and $\ddot{\alpha}$.

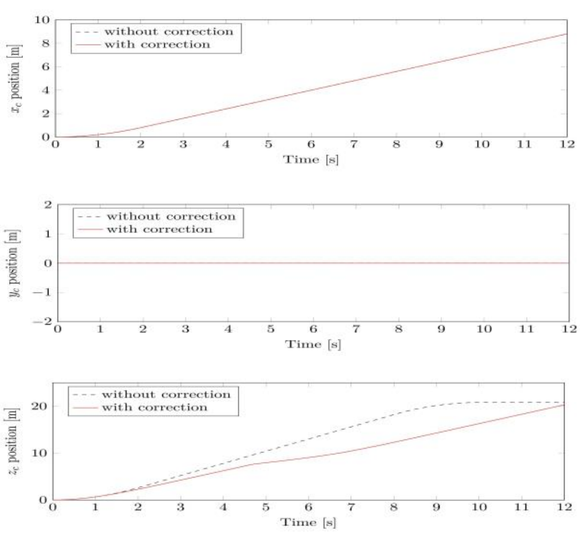

Figure 8. Controlled reference state ξ^r_{contr} vs ξ^r

The addition of formation feedback to the traditional formation control strategies is a type of novel extension. This gives us the additional information of the maximum distance of each vehicle which can be used to adjust the reference trajectory, thus providing the vehicles a better position in formation. For validation of our proposed approach, we considered a group of quadrotors which is used for simulation. The simulation results for a group of UAVs discussed so far, gives the impression, that using controlled reference trajectory does considerably improve the formation maintenance accuracy. Using the formation feedback, this work mainly contributes to the optimization of the reference trajectory in real-time. Distributed cooperative approach is used instead of the centralized approach resulting in increased robustness to agent failures. The local communication (neighbor-to-neighbor) is used, giving us the benefit of changing the formation shape, communication topology or even the number of vehicles as desired.

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