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ANALYSIS OF UNMANNED AERIAL VEHICLE FORMATION FLIGHT CONTROL METHODS

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Abstract. *The article explores different architectures, methods and approaches to control of unmanned aerial vehicles formation flight. We consider typical tasks and missions that require or may benefit from the use of multiple flight vehicles in a formation. In addition, we analyze advantages and disadvantages of each formation flight control method.*
Keywords: centralized control; distributed control; formation flight; group missions; unmanned aerial vehicle

1. Introduction

Applications of unmanned aircraft systems in multiple fields, such as industrial, military, and research have considerably increased during the past decades. Unmanned aircraft systems have proven they can improve mission performance, significantly reduce human errors, and minimize overall risk to both civilian and military personnel.

The unmanned aerial systems can be applied in a wide variety of missions that are exhaustive or dangerous for human. Surveillance missions, for instance, involve long-duration undertakings and are ill-suited for manned systems. Chemical or nuclear observation and detection missions can be dramatically dangerous for pilots that are fulfilling such tasks, and using unmanned systems can significantly decrease a hazardous influence.

Some mission are ideal fit for fulfilling by groups of unmanned aerial vehicles, such as radio signal detection, intelligence, reconnaissance, aerospace exploration, map building, search and rescue, aerial refueling. Using formations of aerial vehicles substantially increase reliability, overall fault tolerance, task performance, modularity, and extension ability.

2. Analysis of plans and forecasts of unmanned aircraft systems using in military and civilian areas

Applications of unmanned aerial systems in a military field are continuously increasing during the last years. Also, an increase in funding is projected for Unmanned Aircraft Systems during 2015 year [1].

Although the use of unmanned aerial vehicles (UAV) in recent military conflicts limited primarily by in survey (ISR) missions, it has been created the UAV, which are successfully used as a platform for the delivery and use of weapons. All this contributes to an even more substantial integration of unmanned aircraft systems in the military field.

Today, there are drones such as Reaper (Predator), for instance, standing on the service in the US Air Force and other countries. This UAV can perform strike missions and has been used successfully in Afghanistan and Iraq. The military use of UAVs continues to grow, it makes possible the creation of UAV that will be applied in the group for the suppression of enemy air defenses, radio electronic warfare, and for air combat.

Groups of UAV also widely used in civilian field. FAA, for instance, published their Integration of Civil Unmanned Aircraft Systems in the National Airspace System Roadmap [2] where the considerations and tasks needed for enabling UAV integration into the NAS are drafted for the planning purposes of the broad UAV community.

Also, the UAS Comprehensive Plan [3] shows work that has been done, and future efforts that are necessary for achieving safe integration of UAS into the National Airspace System (NAS). The UAS Comprehensive Plan sets the inter-agency goals, objectives, and approach to integrating UAS into the NAS. All the related agencies will work together to achieve these goals and may develop their own plans that are aligned to the national goals and objectives.

Teal Group, that creates a market profile along with a forecast for military and civil markets, published UAS Spending Forecast [4]. They forecasts significant spending growth for total procurement and R&D that is expected to increase from $5.2 billion to $11.6 billion over the next decade. Teal Group's ten year forecast estimates total UAS spending worldwide at $89.5 Billion.

3. Problem of formation flight control

Thus, from the UAV group tasks analysis and the world's leading organizations in the aviation field plans overview it can be seen that the relevance and importance of UAVs formation using are significantly growing.

The plans for integration of UAVs into the civilian airspace require efficient, flexible, and safe methods of group flight control. The UAV group tasks analysis shows that one of the most important and fundamental problems in cooperative unmanned systems is coordinated motion control.

4. The purpose of the work

Whereas applying of unmanned aerial systems in the different fields is continuing to increase and there are a number of different methods and approaches to control a group flight of UAV, there is no a clear methods analysis and single universal approach to control of UAV group flight.

To achieve the better understanding of UAV formation flight control problem it is necessary to analyze, classify, and outline advantages and disadvantages of the existing methods of UAVs' formation flight control. Therefore the main purpose of the article is overview and analyzing of the UAV formation flight control methods and approaches.

5. Unmanned aerial vehicle formation control methods overview.

As it was outlined above, the need for large scale and complex unmanned systems has become obvious. The crucial thing in using of UAV groups are efficient, accurate, and reliable control methods.

The majority of such systems were usually designed as a hierarchical and centralized structure with a top-down process for planning and decision making. The more number of hierarchical layers are used, the more time the system requires for the reaction to a control input or disturbance input and the less accurate and appropriate action is chosen. Also, the requirements for computing capabilities is significantly increases with the growth of the number of vehicles in the formation.

In contrast to centralized approach, distributed or decentralized control architectures reveal their main advantages when it is necessary to enhance the system, to integrate components, and to maintain the system. The main issue of distributed architectures is having to make sure, that the system are fulfilling an overall or global goal. On the other hand, the independent task execution by the system components causes problems in the area of coordination between the system agents. In this area, centralized control architectures show their main advantage.

The most studied formation control approach is the **Leader/Follower** one. The Leader/Follower architecture [5], designates one agent as as leader, while the others are designated as followers that should track the orientation and position of the leader with some offset. Leader/Follower has also can be referred to as chief/deputy, master/slave, and target/chase.

This approach uses well developed graph theory to represent the formation. Thus, the UAV formation can be defined as the directed graph where vertices of the graph represent an individual vehicle and a directed edge represents the dependency of one vehicle on another.

Mostly a single-layer leader/follower architecture is considered in which vehicles all follow the same leader. The other common architecture considered is a string or chain, in which each vehicle follows the preceding one. Also, it is worth to mention that in this approach can be more than one leader. In [6], for instance, used the terms $l - \psi$ and $l - l$ control to reflect whether the control laws are based on tracking the position and orientation of the robot relative to a leader, or the position relative to two leaders, respectively.

The team of robots can be described as follows:

$$F = (g, r, \mathcal{H}),$$

where $g \in SE(N)$ – the gross position and orientation of the lead robot in N dimensions, r is a set of shape variables that describe the relative position of the robots in the team, $\mathcal{H}$ is a control graph which describes the control strategy used by each robot and the dependence of its trajectory on that of one or more of its neighbors.

This method has a quite good robustness. If one UAV fails, it is not lead to overall group failure and only its followers are affected. Also, failure consequences can be mitigated by reassigning the leader for the affected follower UAVs. Also, Leader/Follower approach has a quite low computational requirements.

Issues of this method are that formation control relies on a graph theory and there is no reliable means to choose control graph with desired shape and plan changes depending on sensor constraints.

In the **multiple-input and multiple-output** approach the formation problem considered as a multiple-input, multiple-output [7] plant and formation control system uses a dynamic model of the whole formation. There is no dedicated leader in this architecture unlike in leader-follover one. Also, directed graphs are used in this approach to define the vehicles formation and control dependencies.

Advantage of multiple-input, multiple-output method is the proven optimality and stability properties. However, MIMO systems have a lot complexities and uncertainties that causes an increasing of computational and information requirements that are needed to implement such controllers.

The **behavior based** control method [8, 9] is based on the decomposition of the main control goal into tasks or behaviors. This approach also deals with behaviors such as collision avoidance, flock centering, obstacle avoidance, goal seeking, and formation keeping. In some cases, the individual behaviors run as concurrent asynchronous processes with each behavior representing a high-level behavioral intention of the agent [10].

In many implementations of behavior based control authors have used algebraic graph theory in order to model the information exchange between vehicles.

In [11] behaviors described as three-tuples of the form:

$$B = (r, a, F),$$

where r is the target rating function, a is the activity function, and F is the transfer function of the behavior. Additionally each behavior receives an input vector e, an activation ι, and an inhibition i and generates an output vector u.

Behavior-based control systems – in contrast to reactive systems – can store a representation of the environment which is distributed among the single components. Therefore, there is no limitation concerning the application to complex environments requiring an internal state of the system.

Issues with this method are the question of how to coordinate multiple and possibly competing behaviors running in parallel and trying to act on the same actuators, and there is possibility that behaviors will destructively interfere. Another issue can be the identification of error sources in a control that shows an emergent system behavior rather than an explicitly implemented one.

The **virtual structure** approach [12] considers every agent as an element of a larger structure. Usually, the motion of the virtual structure is done through controlling the individual vehicles by tracking their reference trajectories.

This method uses an idea that points in space maintaining fixed geometric relationships are actually behaving in the same way as points on a rigid body moving through space. If vehicles behaved in this way, they would be moving inside of a virtual structure.

Trajectory of the Virtual Structure can be represented as follows [13]:

$$I_r'^w = T(x + \dot{x}dt) \cdot R\big(\theta + \dot{\theta}dt\big),$$

where x is vector of translation, θ is angle of rotation.

This approach does not require leader selection as in other cooperative control strategies and the method is highly flexible in the kinds of geometric formations that can be maintained.

The virtual structures as well as leader/follower approaches has the issue that some algorithms that use these approaches implemented as centralized, because the trajectory of the virtual leader is generated in a central location and then must continually be transmitted to the several vehicles in the formation.

Passivity based control is used for considering the flocking of multiple agents which have significant inertias and evolve on a balanced information graph. In [14] showed that flocking algorithms that neglect agents' inertial effect can cause unstable group behavior and the passive decomposition can be used to incorporate this inertial effect. Also, a provably-stable flocking control law, which ensures that the internal group formation is exponentially stabilized to a desired shape was proposed.

Passivity approach decomposes the closed-loop group dynamics into two decoupled systems. The first subsystem, called a shape system represents the internal group formation, while second subsystem, called a locked system describes the motion of the center-of-mass. Usually, analyzing of the locked and shape systems is done separately with the help of graph theory.

Formation average is [15]:

$$M_L(q)\ddot{q}_L + C_L(q,\dot{q})\dot{q}_L + C_{LE}(q,\dot{q})\dot{q}_E = T_L + F_L,$$

Formation shape system is:

$$M_E(q)\ddot{q}_E + C_E(q,\dot{q})\dot{q}_E + C_{EL}(q,\dot{q})\dot{q}_L = T_E + F_E,$$

where q_i and $\dot{q}$ are the configuration and the velocity of the i-th agent, $M_i(q_1)$ and $C_i(q_i,\dot{q}_i)$ are the inertia and the Coriolis matrices, and T_i and F_i are the control actions and the environmental disturbances on the i-th agent, respectively.

Potential fields based control method described in [16] uses the real world charged particles properties to generate an electric or magnetic force field.

Every UAV generates it's own magnetic field regarding to it's mass and also, can sense fields generated by other UAVs. Interaction of vehicles causes attraction forces and repulsion. By analogy to the real world one sign virtual charges assign to mobile objects and obstacles in the air navigation environment, and opposite virtual sign charges assign to ultimate goals of mobile objects [17].

There are different names for this method: potential field approach, artificial potential fields, virtual force field, vector field histogram and other [18].

Mathematical model of the virtual sensors and virtual force field dynamic state:

$$X^{(n)} = f_1\left(X^{(n-k)}, P, V, G, Z, U_1\right),$$

where $X = (x, y, z)$ – vehicle coordinates in an Euclidean three-dimension space, $k = 1 \dots n-1$;

P – virtual sensors parameters vector;

V – vector of disturbances, that are in a virtual space and that are represent disturbances affecting the objects in a real navigation space;

G – vector of settings parameters of force field;

Z – vector of static and dynamic restrictions;

U_1 – vector of virtual sensors control.

Mathematical description of the goal motion of entire virtual system:

$$Y^{(m)} = f_2\left(X^{(n)}, X^{(k)}, U_2\right),$$

where, $X^{(k)}$ – vector of the goal positions of virtual sensors system;

Y – vector of goal motion dynamics of the virtual sensors in a virtual force field;

U_2 – vector of motion control.

Advantage of this method is that the topology of the potential fields that a UAV experiences are determined by the designer. More specifically, the designer creates and combine multiple field, each assigned a particular task or function to produce the UAV motion. Also, force vectors are usually computed by sensors estimating distances and directions to objects surrounding the vehicle, so potential fields can be used for UAV groups control and path planning in a complex unknown environment relying on local sensors only.

However, this method has some drawbacks, the main one being that the vehicle may get trapped in a local minimum, for example, when encountering a C-shaped obstacle. However, improved versions of this method have been developed to eliminate the local minimum and to reduce the computational load.

6. Conclusions

The last few decades have witnessed an increase of using the unmanned aircraft systems and developing of methods and approaches to group flight control. Forecasts of the leading organizations in the field of unmanned aircraft systems and aircraft manufacturers point to the growth of importance of the UAV using for industrial, military, and research tasks. Summary of the considered methods are presented in the Table 1. However, existing methods solve fragmentary tasks, that considerably increase the difficulty of choosing the right method for UAV group flight control.

Table 1. UAV formation control methods

Method	Literature	Advantages	Disadvantages
Leader-Follower	[5, 6]	Local failure does not lead to global failure, uses well developed graph theory, low computational requirements, easy to add vehicle into formation	No reliable means to choose control graph with desired shape and plan changes depending on sensor constraints
Multiple-input and multiple-output	[7]	No dedicated leader	a lot of complexities, uncertainties and high computational requirements
Behavior based control	[8 – 11]	Behaviors can run as concurrent asynchronous processes	Coordination competing behaviors running in parallel, identification of error sources
Virtual structures	[12, 13]	High-precision control, Inherently fault tolerant, no leader election required	Information must continually be communicated to the several vehicles – almost centralized architecture
Passivity based control	[14, 15]	The shape system is completely decoupled from the locked system	It is difficult to manage decoupled subsystems' interconnections
Potential fields	[16, 17]	Combining multiple objectives into one field	Local minima trap, difficult derivatives

Thus, it can be seen that the methods do not allow fully synthesize UAV formation flight control which can provide flexible and adaptive control of formation structure, smooth transition from one formation structure to another, and solve complex tasks of maintaining safe UAV formation flight control.

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Статтю присвячено розгляду та аналізу методів та підходів до управління груповим рухом безпілотних літальних апаратів. Розглянуто типові завдання та місії, які потребують використання декількох літальних апаратів, котрі рухаються у формації. Проаналізовано переваги та недоліки кожного з розглянутих підходів управління груповим рухом безпілотних літальних апаратів.
Ключові слова: безпілотний літальний апарат; груповий рух; групові завдання; розподілене управління; централізоване управління.

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Статья посвящена рассмотрению и анализу методов и подходов к управлению групповым движением беспилотных летательных аппаратов. Рассмотрены типовые задачи и миссии, которые требуют использования нескольких летательных аппаратов, которые движутся в формации. Проанализированы достоинства и недостатки каждого из рассмотренных подходов управления групповым движением беспилотных летательных аппаратов.
Ключевые слова: беспилотный летательный аппарат; групповое движение; групповые задачи; распределенное управление; централизованное управление.

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