

# Teleoperation of Cooperative Control of Multiple Heterogeneous Slave Unmanned Aerial Vehicles via a Single Master Subsystem for Multi-Task Multi-Target Scenarios

Yushing Cheung  
Stevens Institute of Technology

Jae Chung  
US Army RDECOM-ARDEC

## ABSTRACT

This paper proposes a control method to remotely operate cooperative multiple heterogeneous slave unmanned aerial vehicles (UAVs) via a single master robot to perform different tasks on different targets in one mission. The UAV team is formed by different automated aircrafts. They are equipped with a vehicle-task-target pairing algorithm to be assigned their proper tasks and targets when moving in a leader-follower formation to track and perform assigned targets and tasks, respectively.

The proposed leader-follower formation control method is modified based on a potential field algorithm to guide the UAV team or sub-team. In the UAV team, only a single leader vehicle is teleoperated by a human operator while all other follower vehicles autonomously form the formation regarding the leader movement. Therefore, the number of long distance transmission links between UAVs is reduced to minimize the possibility of occurrences of large communication delays.

Besides, the vehicle-task-target pairing algorithm is derived from the proven auction algorithm for a multi-task multi-target case, which optimizes effects-based vehicle-task-target pairing based on a heuristic algorithm. The pairing method for the vehicle-task-target pairing is developed to produce a weighted attack guidance table (WAGT), which includes the benefits of assignments of robotic combinations (subteams) to tasks and targets. Therefore, the optimal robot-task-target pairs are computed based on WAGT with the heuristic algorithm.

Finally, comparative simulation studies are performed to illustrate efficacy of the proposed teleoperated UAV team for multi-task multi-target scenarios to highlight the improvement of the teleoperation of the UAVs in terms of task efficiency.

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## INTRODUCTION

Obvious advantages of collaborative multiple Unmanned Aerial Vehicle (UAVs) systems are to enhance working efficiency when tasks need to be accomplished by collaboration that cannot be performed by a single UAV. One of the important issues in collaborative control of multiple UAVs is formation control. A significant amount of research work has been proposed to resolve the issue of the formation control of a group of vehicles [2, 3, 4]. As found from the research papers [2, 3, 4], many control approaches, e.g.

leader-follower strategy [2] virtual structure approach [3], and behavior-based method [4], have been developed to enable the UAV team to keep a formation while avoiding obstacles and tracing targets. In the virtual structure approach, all the UAVs have a rigid geometric relationship based on virtual points or virtual agents. Due to its rigid geometric relationship, the environment where the UAV team goes through should be large enough; otherwise, the UAV team would be jammed. However, in practical applications, e.g. life rescues, military surveillance, nuclear plant repair, and etc, the environment is so highly unstructured that the

UAV team formation is greatly distorted to penetrate a very narrow passage to reach targets. In the leader-follower strategy, one UAV is considered as a leader and the others are followers which track the leader [6]. The UAV team formation can be changed when the followers are able to move regarding the leader's positions and velocities. Nonetheless, because the UAV team movement is totally guided by the single leader motion, the UAV team fails if the single leader breaks down. Hence, the robustness and reliability of the multi-UAV system are decreased. In the behavioral structure, tracing a target with obstacle or collision prevention is an important issue. In addition, each of the UAVs in the team is properly controlled to achieve its desired behavior [6]. Several control methods such as potential field, neural network, fuzzy control, and so on have been proposed to deal with this issue [6, 7, 8]. Potential field based control method about repulsion from obstacles and attraction to targets is well known in this area of research. In [6], the repulsion is adopted to make UAVs avoid obstacle or collision with other objects. Nevertheless, when UAV approaches the obstacle or objects in the potential field, since the resultant vector of the UAV motion is equal to the repulsive vector from the obstacle or the objects, it may not get around the obstacle or the objects and may reach a local minima position.

Besides, another issue about collaboration of the UAV team in the unknown environment is the lack of the capability of highly adaptation to different environments. This is very important for field applications such as life rescue, outer space operation, military reconnaissance, and etc because the applications require a team of two or more UAVs to navigate for a single mission about multi-target and multi-task scenarios in the unknown environments. Furthermore, in the applications, due to the limitations of the current sensors and computer decision-making technologies, navigation of the UGV team in the unknown environments prohibits the use of fully autonomous systems [7]. Therefore, it is required that human decision making be involved in the UAV systems. Teleoperators, in which a human operator is an integral part of the control, are suggested to integrate the human decisions to the control loop of the systems. The teleoperator consists of master and slave subsystems. The human operator remotely controls the UAV team, i.e. the slave subsystem that locally works on tasks in the unknown environment, via another subsystem, the master subsystem that reads human commands and reflects sensory data from the slave subsystem to the human operator. The teleoperator that involves cooperative multiple slave UAVs can be classified into two types of the teleoperation systems based on different numbers of the master-slave subsystems, Single-master Multi-slave System (SMMS) [7] and Multi-master Multi-slave System (MMMS) [8]. However, only the SMMS teleoperation system [7] can be used to minimize the required human resources but amplify the human effort; therefore, it has been considered in this paper.

Besides, from a practical point of view, the SMMS teleoperation is so complicated that it is always performed to fulfill a single mission that has multi-tasks and multi-targets. In order to improve the work efficiency, the slave UAV team is suggested to be regrouped into subteams, which enables the slave UAVs to execute multi-tasks on multi-targets properly and simultaneously. Some methods and solution algorithms have been developed in research work [8] of task-target-vehicle allocations. Nonetheless, most of the research work was not able to produce optimal solutions of the task-target-vehicle allocations for existence of multiple tasks and targets within one mission in the unknown environments.

Therefore, in this paper, the primary objective is to propose a control method for a SMMS teleoperation system to control the UAV team to execute multiple tasks on multiple targets in the unknown environments. The proposed control method is able to integrate Component (1) modified potential field based leader-follower formation control method [9-10] and Component (2) vehicle-task-target pairing method based on weighted attack guidance table (WAGT). The proposed control method with Component (1) and (2) enables the SMMS teleoperator to solve the multi-task multi-target problem of the UAV team when the work environment is uncertain. Component (1) computes UAV team leader-follower formation in which a human operator can concentrate on controlling a leader UAV when follower UAVs autonomously move regarding the positions and velocities of the leader. Moreover, Component (1) enables the UAV team to move in a leader-follower formation to avoid obstacles as positive ions and attract to its target positions as negative ions as if UAVs as positive ions were bonded together with bonding strengths varying according to their roles in an artificial potential field. For example, the bonding strength for leader-follower 1 is stronger than that for follower 1-follower 2 and so on. As soon as the leader UAV teleoperated by the human operator is approaching the region of interest, Component (2) dynamically calculates the weighted attack guidance table (WAGT) in which optimal solutions of vehicle-task-target assignments are found and generated. With the optimal solutions of vehicle-task-target assignments, the UAV team excluding the leader UAV is automatically split into many UAV subteams, each of which has the most suitable functionalities of UAVs to deal with its assigned tasks and the most vehicles closest to its assigned target positions. After all the subteams are formed with Component (2), all subteam UAVs approaches their assigned target positions while avoiding obstacles with Component (1) until all tasks are completed.

The rest of this paper is organized as follows. Section 2 develops the leader-follower formation control method for multiple UAVs based on an artificial potential field algorithm. Section 3 proposes the vehicle-task-target pairing method to assign UAVs to different tasks for different targets. In Section 4, the control method is proposed to integrate the proposed formation control and pairing algorithm for the SMMS teleoperation in multi-task multi-target scenarios. In

Section 5, the work efficiency of the SMMS teleoperation system with the proposed control method was evaluated through simulation studies. Section 4 concludes this paper and shows future research directions.

## LEADER-FOLLOWER FORMATION CONTROL BASED ON ARTIFICIAL POTENTIAL FIELD

Formation is defined as a geometric disposition of vehicles in the environment. A common reference in order to specify the position of every vehicle that forms a team in the formation is prescribed. Three techniques, (1) leader-reference, (2) neighbor-reference, and (3) unit-center reference, have been proposed in the following ones explained in [3], as described in Figure 1.

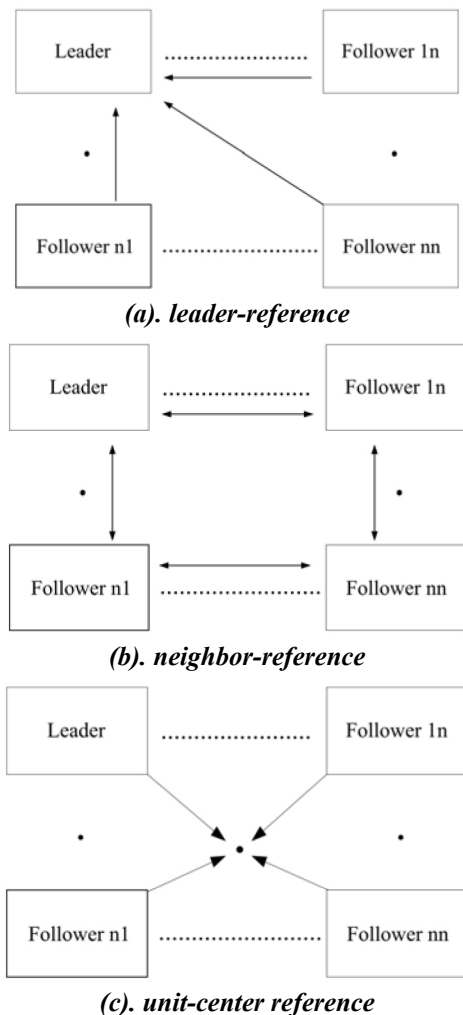


Figure 1. multi-vehicle formations

(1) leader-reference: the position of one of the vehicles is taken as the reference for the others, in order to calculate the desired position for each one. (2) neighbor-reference: the vehicles assume the position of the closet partner as the reference to calculate its own position. (3) unit-center

reference: the unit-center location of the group is calculated by each one of the vehicles and is taken as the reference to calculate its desired position.

Global information about the positions of all vehicles is required in advance to form (3), but the global information does not always exist in a real system. On contrary, for teleoperation, only (1) and (2) are suitable for formation control of the team of vehicles because they have the benefit that local information is needed to be fed back from local sensors mounted on the vehicles to sense their positions when the local information is available. Moreover, (1) is better than (2) because more communication links between the vehicles are needed in (2) than (1), which causes larger transmission delays in the system. Therefore, in this paper, the leader-follower formation is proposed; nonetheless, as mentioned previously, the whole team fails if only one vehicle, the leader, in the team breaks down. Thus, this paper proposes that the leadership is able to be online switched over between vehicles in the team wirelessly by a human operator at a remote site.

Besides, most of the UAV team remotely controlled by the human operator who identifies the obstacle location on-line by receiving the delayed feedbacks can avoid the obstacles. However, the human operator feels fatigue while maintaining situational awareness for a long time. Moreover, the team formation is needed to be automatically adapted when the team penetrates a narrow area where only one vehicle is allowed to pass through each times. Hence, the robotic intelligence is needed and added to make the formation control intelligent enough to move the UAV team in changing environments even if the human operator is not aware of the UAV team when the UAV team is remotely controlled by him or her. Several robotic intelligences, such as artificial potential field, virtual structure, neural network, fuzzy control, and so on, have been proposed to deal with the problem as mentioned previously. Nevertheless, only the artificial potential field enables the UAV team to adapt the formation properly to avoid obstacles and get through a narrow passage by only having local feedbacks from sensors mounted on UAVs when UAVs do not necessarily spend a long time learning their desired behavior. Therefore, in the following, the artificial potential field based formation control is described in detail to explain how it is supposed to work in our approach.

## Artificial Potential Field Based Formation Control

In order that the UAV team autonomously avoids the obstacles and keeps a distance from other neighboring vehicles simultaneously while tracking the target, the approach that the most commonly has been used is potential field based formation control. Nonetheless, the potential field based formation control has the local minima problem [5], which can hold the vehicles in a specified formation while in motion. Therefore, the potential field with a prioritized

bonding between team vehicles is proposed in this paper. The strength of the bonding to keep a constant distance between vehicles varies depending on which two vehicles are connected. For example, the bonding between Leader and Follower 1 is the strongest when the one between Follower  $n$  and Leader is the weakest if there are the  $n$  number of vehicles. Thus, the formation becomes more adaptive due to the attraction from the target and repulsion from the obstacle, but no vehicle in the team is left behind due to the vehicle-vehicle bonding with different strengths.

At any time instant, the vehicles can be visualized as particles with negative charge moving in a potential field. Each obstacle is viewed as a particle with negative charge while the target is seen as a particle with positive charge. Hence, the vehicle is repulsed from the obstacle while attracted to the target in the potential field. In addition, with the prioritized vehicle-vehicle bonding, the follower keeps a constant distance from the neighboring vehicles when the leader tracks the human position commands closely. In the potential field, the vehicle path is generated by summing up the attraction, repulsion, and prioritized bondings if the vehicle is a follower or human position commands if the vehicle is a leader.

### Repulsion from obstacles

The repulsive force  $U_o$  derived from the obstacle potential functions is written in Eq.(1).

$$U_o = \varphi(-k_e \partial D_1 - b_e \partial V_1) \quad (1)$$

where  $\partial V_1 = \dot{x}_{si} G / \partial x_o^2$ ,  $\partial D_1 = H / \partial x_o^2$ .  $\partial x_o$  is the distance between the obstacle and vehicle.  $x_{si}$  is the position of the vehicle.  $\varphi$ ,  $G$ ,  $H$ ,  $k_e$ , and  $b_e$  are positive parameters.

### Attraction to targets

Besides the repulsive force, the attractive force  $U_T$  derived from the target potential functions for the  $i^{th}$  vehicle is written in Eq.(2).

$$U_T = \gamma_i \partial x_T \quad (2)$$

where for  $i = 1 \dots n$ ,  $n$  is the number of UAVs, and  $\gamma_i$  is the positive tuning gains for the  $i^{th}$  vehicle.  $\partial x_T$  is the distance between the vehicle and target(s). The  $i^{th}$  vehicle can be a leader or one of the follower vehicles in the team.

### Bonding between vehicles

Except the attraction and repulsion functions, for the followers, the prioritized vehicle-vehicle bonding  $U_f$  is needed to maintain the formation, as shown in Eq. (3).

$$U_f = -k_{ij}(r_{smin i} - \partial x_{si}) \quad (3)$$

where for  $i = 1 \dots n$  and  $j = 1 \dots n$ ,  $i \neq j$ ,  $k_{ij}$  is the positive parameter. The bonding strength varies because of different

vehicle combinations according to the two vehicle priority numbers. For instance, the Leader-Follower 1 bonding,  $k_{L1}$ , is larger than the Follower 1 - Follower 2 bonding  $k_{12}$  when the Follower  $n$  - Leader bonding,  $k_{nL}$  is the smallest.  $r_{smin i}$  is the desired distance that the vehicle needs to keep from the neighboring vehicles.  $\partial x_{si}$  is the measured distance between vehicle and vehicle. During the teleoperation, the leader is online selected, and the target is identified by the human operator based on his or her experience. The obstacle(s) are detected and avoided by UAV according to the repulsive function in the potential field. The target is tracked by the vehicle according to the attraction function in the potential field. Follower's path is generated by combining the vehicle-obstacle repulsion, vehicle-target attraction, and vehicle-vehicle bonding forces. In addition, Leader's path is produced by integrating the vehicle-obstacle repulsion, vehicle-target attraction, and human position commands. Due to the vehicle-vehicle bonding forces with their varying strength, the probability of occurrences of the local minima problem [1] is reduced.

Nonetheless, as said in the previous section, even if a team of UAVs is being teleoperated in the leader-follower formation based on the artificial potential field, the team cannot be enabled to handle a multi-task multi-target scenario efficiently by tackling all tasks on all targets successfully and simultaneously. Therefore, the vehicle-task-target pairing method is proposed to enable the teleoperation system to split the team into subteams that especially perform the assigned task on the assigned target. In the following section, how to adopt and formulate the proposed vehicle-task-target pairing method in the team is described in details.

## VEHICLE-TASK-TARGET PAIRING METHOD

In fact, the concept of the proposed vehicle-task-target pairing method is that all team vehicles act largely independently in terms of planning for themselves but are able to take into account team resources by working on the tasks with other team members. With the pairing method proposed in this paper, the leader vehicle in the teleoperation system not only takes any human command from the master vehicle but also works as an auctioneer to send and show all bid data e.g. target locations and their base prices that are also online shared by all other vehicles called team followers. Any team vehicle is online appointed as the leader vehicle by the human operator via the master subsystem if the original one fails. All follower vehicles act as bidders to form a subteam by themselves in order to maximize a sum of all follower bid values and bid on the targets when the corresponding task on the targets is performed by the cooperation of the subteam. In the subteam, the bidder with the maximum bid value is selected as a subteam leader that is responsible for monitoring and coordinating all subteam member actions. According to the largest bid proposed by the subteam, the auctioneer, the leader vehicle, decides which subteam wins