Consensus-based Robust Clustering and Leader Election Algorithm for homogeneous UAV clusters

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Abstract. In this study, a consensus-based robust clustering and leader election algorithm is presented for homogeneous Unmanned Aerial Vehicle(UAV) clusters. It can adaptively cluster and elect leader of each cluster of UAVs if any UAV can fail anytime and communication network changes dynamically. The algorithm is based on a distributed consensus algorithm, combining the sensing capabilities with the autonomous decision-making capabilities of the UAV to realize adaptive, scalable and robust clustering, leader election as well as group member management for UAV clusters.

1.Introduction
As UAV technology is leaping forward, UAV has gradually become practical and changed from a highly sophisticated technology to a general consumer goods. Thanks to the rapid development of UAV technology, the cost of a UAV is directly reduced. Yet a UAV has limited payload and can only carry limited sensors, whereas a larger payload will increase the cost. Accordingly, it is more cost-effective to organize a group of UAVs smaller in payload, enabling UAVs to allocate the load and cooperate to complete tasks that a single UAV cannot perform. In this example, each UAV can be regarded as an individual with independent but limited sensing and decision-making capabilities. Thus, it is an important research program to robustly stratify UAVs into groups with members meeting a specified range, and to automatically elect the leader in each UAV cluster if any UAV can fail anytime, which is our main work.

In Section 1 of this study, the relevant research background is described. In Section 2, the relevant research work is presented. In Section 3, modelling and simulation methods for homogeneous clusters of UAVs based on limited communication capabilities are introduced, including UAV attributes and UAV behavior rules, core algorithms and simulation flow. In Section 4, the simulation experiment and the design, analysis and verification of the experiment are presented. It primarily covers the initial environment of the simulation experiment, one experiment, repeated experiment, comparison, analysis and verification. Finally, we summarize the study and look forward to future work.

2.Related work
The UAV cluster control methods now primarily include: centralized control and distributed control. The way of centralized control is easy to implement but insufficiently robust. To solve the problem of centralized control, artificial potential fields [1], mimicry physics [2], biological clustering behavior [3] and digital pheromone [4] have been employed recently to distribute the control of UAV clusters.
Though the distributed control methods have higher adaptability, reliability and scalability, they reduce controllability and do not adapt to human intervention. Thus, centralized control and distributed control should be combined, through which distributed control is adopted for basic group behaviors e.g., formation flying, obstacle avoidance and collision avoidance. Besides, centralized control is adopted for more advanced behaviors (e.g., information sharing, task scheduling, distributed computing, etc.).

The consensus on distributed systems focuses on addressing the consistency of distributed system. In 1978, Leslie Lamport introduced distributed Replica State Machine (RSM) system to address the consistency between replicas by maintain the consistency of sequence of external instructions [5]. The conclusion of the FLP Impossibility (FLP Impossibility) in 1985 verified that in the asynchronous communication scenario, there is no algorithm that can ensure non-failed processes to achieve consistency even if there is only one process failure (fail-stop) [6]. The Paxos algorithm [7] is a well-known algorithm in distributed consensus algorithms. The Paxos algorithm is almost equivalent to distributed consensus, and other distributed consensus algorithms are variants of the Paxos algorithm. Yet the Paxos algorithm has always been considered difficult to understand, and it is hard to implement. Thus, in response to the problems of the Paxos algorithm, in 2013 Diego Ongaro developed a distributed consensus algorithm—Raft algorithm [8] that is easier to understand and implement. Though the Raft algorithm is also a special case of Paxos algorithm, the Raft algorithm is designed to be relatively simple and easy to understand and achieves the same performance as the Multi-Paxos algorithm. It is a vital step to practically implement the distributed consensus algorithm from theoretical research.

The UAV clusters, as a typical distributed system, will be more robust by integrating consensus algorithm. The clusters are units that form a consensus, where a distributed system consensus algorithm is employed to elect the cluster leaders. Following the distributed system consensus algorithm, a highly adaptive, robust and scalable UAV clustering and leader election algorithm is yielded.

3. Modelling and simulation

To be specific, the cluster leader serves as the coordinators. It is capable of integrating UAVs’ perception, communication, computation, and storage resources in the cluster and coordinate UAVs in the cluster to complete more complex tasks. In emergency situations, when the cluster leader fails, the members of the cluster can respond promptly and re-elect a new cluster leader. The cluster leader can not only directly communicate with a member within its communication distance but also communication with a member outside its communication distance by frame relay. Bridging communication can fully exploit the UAVs’ communication capability and the entire perception and communication capabilities at cost of limited losses of reliability and robustness.

Practically, UAVs have limited communication capabilities (e.g., a valid communication distance and a certain amount of communication capacity). This study studies the homogenous UAV cluster, so each UAV has the same communication distance and communication capacity. Practically, the communication capabilities of UAVs are impacted by various environmental factors, and the ability to communicate in different directions is also not the same. To simplify the problem, this study assumes that the UAVs’ communication capabilities will not change with its location, and its communication capabilities are the same in all directions. Accordingly, each UAV can directly communicate with a group of UAVs that are less than the amount of communication capacity within a circle centered on the radius of its communication distance. Bridging communication is viable only when the cluster leader is live, and a UAV in the cluster not within the communication distance of the cluster leader can communicate with the cluster leader by frame relay through intermediate UAV without considering other complications or changes due to bridging communication.

3.1 Definitions
Neighbors: A UAV’s neighbors refer to a collection of other UAVs within a circle that is itself centered on its communication distance radius.

Cluster leader: a UAV act as a coordinator of control, perceptions, communications, and other resources in a UAVs cluster.

Group: the basic unit for forming consensus (election cluster leader) is a UAV team formed by a cluster leader UAV and other UAVs led by it.

Temporary group: prior to forming a consensus, i.e., the temporary group before the election of the cluster leader.

Group members: the collection of all UAVs in the same group, the cluster leader also pertains to the group members.

Temporary group members: the collection of UAVs in temporary group before the election of the cluster leader.

Stable scale: the predefined range of group members capable of maintaining the stability of the group, including that the lower limit of stable size is the minimum number of group members needed for its task, and the upper limit of stable size is the number of the most group members that stably exist with limited communication capabilities.

Isolated group: a group with a number of members fewer than the minimum stable size.

Stable group: a group that has a group size (including upper and lower limits) within a stable scale.

Crowded group: a group with more members than a stable upper limit.

Unstable group: an isolated group or a crowded group.

Unfilled group: a group with fewer members than the stable upper limit of the group size.

Filled group: the team with the group size equal to the stable upper limit of the scale.

Hop: the times of information being processed to wireless signal in a single direction by UAVs participating in a communication when the group member communicates with the cluster leader.

3.2 Features and rules

This study should model and simulate UAVs with limited communication capabilities. The UAVs have the three characteristics as follows:

- Each UAV has its own independent decision making, computing capabilities and independent communication capabilities, whereas its own perception and communication capabilities are limited. It can get the information of local neighbors and directly communicate with neighbors.
- The failures of individual UAVs or communication failures between them will not impact the operation of the entire cluster with the distributed control in UAV clusters. Thus, it has better flexibility, robustness as well as scalability.
- Each UAV considers its own interests and overall interests as its own decision-making and action criteria. UAVs are more inclined to group actions rather than acting alone and must also avoid the collision between each other.

Due to the distributed control of UAVs, the following rules are satisfied in the flight control of UAVs.

- The UAV initially has its own flight direction.
- The UAV can sense and learn the direction of the surrounding UAVs.
- The UAV should keep a certain distance from other UAVs.
- UAVs cannot be too far away from the center of the group. If they are far from the center, they should accelerate to the center.

To make the cluster leader election algorithm achieve convergence with higher efficiency, the following rules are added to the control of UAVs.

- Each UAV or group should try to avoid being an isolated UAV or an isolated group. Thus, isolated UAVs and isolated groups should seek peers and flight faster.
- The unfilled groups, isolated UAVs and isolated UAV groups are mutually attracted.
Isolated UAVs are preferred to join a stable group with fewer group members, followed by isolated group with more group members.

Filled groups are mutually exclusive to other UAVs and groups.

Stable groups are mutually exclusive.

3.3 States transitions

Fig. 1 shows the flow of states transitions, where M denotes the upper limit of the stable size, N is the lower limit of the stable size, and N\(\leq M\). Next, the attributes, behavioral policies and states transitions of UAVs are detailed according to Fig. 1. Each state is detailed, followed by the interpretation of simulation process.

First, each UAV is in the same state: passive state. A passive state UAV will not actively communicate with the neighboring UAVs and avoid occupying the number of communication channels around it. Some of the passive social state UAVs will enter active state after a random wait known as the social window period, actively contact their neighbors, attempt to become temporary cluster leader, establish temporary groups, and further become cluster leader and form a group. The passive state UAV first in the central location of the UAV cluster should become a cluster leader since it is easier to contact more UAVs. Accordingly, in the design of social window period, the UAVs in local centers should have more advantages, i.e., shorter social window period. Some UAVs do not have neighbors or group members will enter an isolated state. Instead of trying to become a cluster leader, their behavioral strategy is to try to find neighbors and join one of them. It will thus pass through two intermediate states, i.e., Applicant and Intern. The ultimate goal of all groups is to become stable groups. On that basis, the isolated groups will also try to find isolated UAVs or other isolated groups and subsequently merge into stable groups.

The passive state UAV has a social window period. At the end of the social window period, passive social UAVs will make judgments based on the status of their neighbors. If there are neighbors around, they will enter an active state, otherwise they will enter an isolated state. If the passive state UAV receives an organization from an active state UAV during the social window, it will provide a commitment to the drone as its own temporary cluster leader and set a commitment period and subsequently enter the temporary group member state. The active state UAV will send a request to the neighbor to build a group. If a neighbor UAV gives a promise, the active UAV will enter the temporary cluster leader state. Otherwise, it will turn to isolated state.
UAVs in temporary group member state have promise and promise period. During the promise period, if its promised cluster leader accepts it into the group, the UAV enters the state of the group member. Otherwise, the UAV will enter a passive state. A UAV transited from a passive state to a temporary group member does not have the right to be elected. A UAV changed from group member state to temporary group member state has the right to be elected.

Temporary cluster leader UAVs have temporary group members and term. During the term of the temporary cluster leader, the temporary cluster leaders will turn to cluster leaders after the temporary cluster leaders confirm the temporary group members to be group members once the number of current group members (including the temporary cluster leaders) exceeds 2 UAVs.

UAVs in the group member state have group members, cluster leader, heartbeat period as well as the right to be elected. If a group member does not receive the heartbeat from the cluster leader during the heartbeat period, it will consider that the cluster leader has failed and turn to a temporary group member state and enter the campaign period. After the end of the campaign period, it will enter the candidate state and send election requests to the neighboring group members. Temporary members should promise the request if receiving a candidate’s election request during the election campaign.

Cluster leader UAVs have group members, interns and term. During the term, the cluster leader UAV continuously synchronizes the group members’ information to each group member. If a group member fails, the cluster leader UAV will remove the failed group member from the group members’ set and notify other group members. The cluster leader UAV will synchronize the group members’ information to the interns, and subsequently turn the state of the interns into a group member and synchronize the information to other group members. The term of a cluster leader UAV depends on the size of the cluster. The term of the cluster leader will continue once the size of the cluster is a stable scale. If it is an isolated group, its term will consider the situation of the surrounding UAV clusters. The cluster leader’s term will not continue if there are other cluster leaders within the communication distance, and the other cluster are not smaller than the size of their group. Otherwise, it will continue.

An isolated UAV has a social window period. At the end of the social window period, isolated UAVs will select appropriate action strategies in accordance with their neighborhood situation. Isolated UAVs first check whether there are neighbors. If there are no neighbors, they will remain isolated. If there are neighbors, they will first detect whether there are members of the unfilled group in the neighbors. If there are any, they will enter the applicant state. Otherwise, they will sense whether there are passive state or isolated state UAVs nearby. If true, they will enter passive state. Otherwise, they will remain isolated state. If an isolated UAV receives a group request from an active state UAV during a social window period, it should be ensured that the active state UAV will be its temporary cluster leader and set a promise period. Subsequently, the temporary group member state will be entered.

The UAV in the applicant state further perceives the neighbors. The UAV will select the best if there are group members from different groups in the neighbor. In the applicant state, the UAV is preferred to select the stable group. If there are multiple stable groups, the stable group with fewer members will be preferred. If there is no stable group, applying to join an isolated group will be considered. If there are multiple isolated groups, it will prefer isolated group with more members. The applicant applies to a group member as its introducer to join the group. When the cluster leader receives the applicant’s request, it will be confirmed as an intern, and the applicant’s state will turn to intern state, give a promise and set up an internship period.

Intern UAVs should synchronize group information (e.g., including group members, etc.). If the intern is confirmed by the cluster leader as a group member during the internship period, it will be changed to a group member. Otherwise, it will be turned into an isolated state after the internship period.
4. Experiments and analysis

4.1 Experiment preparation
The cluster leader election algorithm of this study decides to implement and simulate experiments on the NetLogo simulation platform. It has achieved favorable experimental results. First, initialize the environment. A cluster of 150 UAVs was created and randomly distributed in (-20, -20, 20, 20) spaces. Each UAV had a random initial direction. Based on UAV’s parameters, we select a typical set of parameters as an example that can be changed as needed. The maximum communication distance for the UAV is set at 4, the maximum communication capacity at 39, the lower limit for the stable size of the UAV group at 13, the upper limit of the stable size at 26, and the failure rate of the non-clustered UAV at 5/1000000. The failure rate of UAVs is (size (group members) *2+3)/1000000. Following the rules of behavior of the UAV and UAV clusters described in the previous section, we set different speeds of UAVs in different states. The speed of the cluster leaders of stable groups and crowded groups is 1/2 of the default speed. The speed of the cluster leaders of the isolated group maintains the default speed. The speed of group member except leader is 1.25 times of speed of the leader. When the hop rises, the UAV increases the speed. The speed of isolated UAVs is twice the default speed, and other UAVs keep the default speed.

4.2 Simulation experiment
The first step is to initialize the environment.

![Image](image.png)

Figure 2. The initial environment of the simulation platform.

Fig. 2 shows the interface of the simulation platform, including parameter controls, button controls, switch controls, monitoring windows, graph windows as well as simulation window. There are 150 UAVs randomly distributed in the space of simulation window. Each UAV has a random initial direction.

The second step, start the simulation.
Figure 3. The first phase of the simulation.

The first phase, the random distributed UAVs forms many isolated UAV groups in relatively dense space in the simulation window. The graph Group suggests that the number of groups has reached a peak and subsequently decreases with time; the graph Breakdown shows the of the total number of group breakdown increasing with time; the graph Passive shows the number of UAVs in each state with time. The number of UAVs in the passive state decreases promptly and tends to zero. On the contrary, the UAVs of the group members grows rapidly and finally becomes stabilized, and the number of cluster leaders and the total number of groups are the same. The graph Hops shows different hops at different times. The number of UAVs, 0-hop UAVs first decreases promptly and subsequently turns stabilized, 1-hop UAVs first increases promptly and then becomes stabilized, and 2-hops UAVs increases with time, whereas UAVs more than 2-hops is not even existed.

Figure 4. Simulation phase 2.

In the second phase showed in Fig. 4, the isolated groups in the simulation window are close to each other and merged to form some stable groups. The graph Group suggests that the number of isolated groups and the total number of groups at this stage have decreased with time, and the number of stable groups has increased with time.
In the third stage, the UAV clustering reaches a basically stable state, and cluster grouping tends to be optimal. With the decrease of the number of isolated groups, the probability that an isolated group can find a group to merge with becomes smaller. Yet as the simulation continues, the grouping of UAV clusters will eventually tend to be optimal. The graph in the graph window shows that all data tends to be stable.

Finally, the simulation ends, and the data of the simulation experiment is collected and recorded.

4.3 Repeated experiments

We repeat the simulation on the same UAV parameters and recorded the data 100 times, considering the number of stable groups, the total number of groups, the total number of group breakdown, and the time to achieve the ideal clustering. Fig. 6 shows the number of stable groups and the total number of groups. It is suggested that during the 100 times of simulation, the number of stable groups and the total number of groups is concentrated on 6, 7, and 8, and the highest frequency is 7. It is suggested that though we did not directly set how many clusters to divide the UAVs, the algorithm can adaptively cluster the UAV into the appropriate number of groups. This verifies the flexibility and scalability of the algorithm. A total of 31 UAVs failed during the 100 times of simulation, whereas it had no impact on the entire cluster, proving the robustness of the algorithm.
Fig. 7 shows the histogram of the frequency of the number of breakdown by the UAV during the 100 times of simulation when the clustering group reaches the ideal condition. The number of breakdown ranges from 120 and 170 times. This data shows that when the simulation started, there are a large number of isolated groups, and many merges remain incomplete or unsuccessful when the isolated group is merged. After the failure, it is likely to continue multiple attempts to merge, which increase the number of breakdown of the groups. Fig. 8 shows the time when the clustered group reaches the ideal conditions in 100 times of simulation. The unit is tick and the simulation end time is distributed between 500-2500 ticks. The number of group breakdown and the simulation end time can to some extent reflect the efficiency of the algorithm, but it is closely associated with the random initial state. Besides, since there is also a high randomness in subsequent group merges, the number of group breakdown and the simulation end time are the combined results of efficiency and randomness.

5. Conclusions
In this study, a consensus-based robust clustering and leader election algorithm for homogeneous clusters of UAVs is presented. It can adaptively solve the cluster leader election problem of a homogeneous cluster of UAVs with limited communication capabilities when the topology of the communication network changes dynamically and further improve the coordinated control of the UAV cluster. In this study, we study the feasibility of the algorithm by performing repeated simulation experiments on the simulation platform and prove that the algorithm has the characteristics of adaptability, scalability and high robustness. This study continues to study the efficiency and convergence of the algorithm and proves that the algorithm can reach an ideal situation of UAV clusters within a limited time. The next step we will focus on two aspects. On the one hand, we will continue to adjust and optimize the algorithm, and improve the efficiency of the algorithm. On the other hand, we will employ the algorithm to the dynamic changed network and reach a local consensus to achieve highly robust and highly reliable distributed systems.

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