

Force-directed formation and guidance for large scale swarming system of micro air vehicles

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ABSTRACT

This paper proposes a force-directed method for formation and guidance of large scale swarming system, consisting of hundreds or even thousands of MAVs, in which two independent communication channels are configured, so that local repulsion and global aggregation can be coordinated to control the behavior of the whole swarm. Local repulsion force is committed to ensure all MAVs stay within a safe distance of each other as the swarm constantly adjusts, while global aggregation force is employed for guiding the whole swarm. By arranging multiple leaders in proper way, swarm guiding, reshaping, partitioning and merging can be supported in a consistent way. Besides, the calculation of local repulsion force only depends on relative location and angle information, so that the safety of the swarm can be enforced even without depending on the precisely positioning information, which is extremely important for the applicability of the proposed scheme in real environments. Finally, the simulation demonstrates that local repulsion and global aggregation may work together well, leading to a stable formation of MAVs, with enough freedom of control guided by leaders.

1 INTRODUCTION

Due to its potential applications in battlefields and disaster scenes[1], Micro Air Vehicles (MAVs), as a class of miniature unmanned aerial vehicles (UAVs) that have size restriction, have gained many attentions from industry and academic[2]. For single MAV, the mission abilities are limited, such as for reconnaissance and surveillance. In order to increase mission success rates and enlarge field of view, hundreds or even thousands of low-cost MAVs fly as a flock to replace an expensive multifunction UAV, and achieve a desired formation pattern to meet various task's requirements, which is called formation flight control of MAVs[3].

At present, the methods of formation control can be classified into leader-follower method [4][5], virtual structure method [6], artificial potential field based method[7] and consensus-based method [8][9]. Leader-follower method refers to the control mechanism where one or several MAVs serve as leaders, and the rest of MAVs follow the leaders' trajectory according to a certain formation to perform a series of required tasks, but most of these methods only consider a small scale of swarms, at most with dozens of vehicles[10][11]. The idea of virtual structure[12] is to regard the multi-agent formation as a rigid body, but it is usually challenging to maintain the virtual structure in a consistent way, which limits the scalability of the swarm[6]. Artificial potential function-based method adopts a mixture of attractive and repulsive potential field for guiding the swarm[13], which is widely used to solve obstacle avoidance problems in a complex environment. In contrast, consensus-based method is abstracted from the swarming behaviors of animals[14][15][16] and most researches formulate the swarm as a consistency problem [17], but most local operations, which depend on multi-hop packet transfers, have a remarkable control delay and do not allow for too much freedom of control and guidance[18].

Moreover, most of existing formation models depend on accurately positioning information, which is hard to obtain through traditional communication channels in real environments due to the problem of bandwidth constraints, interference and noisy, especially when a large number of MAVs are involved with high mobility. [19] used a monocular on-board camera for detecting and estimating the pose of micro aerial vehicles. [20] proposed a vision-based tracking scheme to achieve the formation tracking, which uses a Kinect installed on each agent as the sole sensor to get UAV's status, but there are problems of visibility constraints because of the limited vision range of Kinect.

This paper proposes a force-directed method for formation and guidance of large scale swarming system, maybe consisting of hundreds or even thousands of MAVs. The basic idea is to mandate the safety distance between neighbors through local repulsion force, while global aggregation force is employed for guiding the behavior of the whole swarm with enough freedom. Two independent communication channels

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are configured for each MAV, so that the formation of the swarm can be constructed through the balance of local repulsion and global aggregation. Since it is not easy to obtain accurately positioning information, the calculation of local repulsion only uses the information of relative position and relative angle of neighbors, which greatly improves the feasibility of the proposed scheme in the real application's environments.

2 SYSTEM MODEL

2.1 Problem description

Compared with UAV, Micro Air Vehicle (MAV) has a smaller size but the swarm size of MAVs is usually much bigger, even up to hundreds or thousands, which makes it rather challenging to keep formation and guidance for such a swarming system of MAVs.

We assume that all MAVs have the same hardware configuration, in which each MAV has two independent communication channels. One channel works in the short-range mode, configured for supporting for information exchange between neighboring MAVs, so that local repulsion can be committed to ensure that all MAVs stay within a safe distance of each other as the swarm constantly adjusts. The other channel works in the long-range mode, which may cover the range of whole swarm. By using the long-range channel to broadcast the location and speed of leaders to every other MAVs, each MAV will predict the state of leaders and apply a global aggregation force to itself, so that leaders can be followed in an autonomous way.

Thus, the key point of the proposed scheme is to make formation by balancing the local repulsion and the global aggregation, and, at the same time, to allow the swarm of MAVs to have enough freedom for easily being guided through commands.

2.2 Formation of MAV swarm

Each MAV calculates the repulsion force from its neighbors according to the neighbors' state information obtained through the short-range channel, and calculates the global attraction force from its leader according to the leader's state information obtained through the remote channel. By balancing the repulsion force and the attraction force to control each MAV state, a stable UAV formation centered at the leader can be established, as shown in Fig. 1.

2.2.1 Repulsion force

A repulsion force is employed to ensure a safe distance between every two of MAVs, so that collisions can be avoided. Through the short-range channel, a MAV, i , is able to obtain the state information of its neighbors within the communication range, so that a repulsion force, $F_{i,j}^{(R)}$, can be calculated for each of the neighbors, as follows.

$$F_{i,j}^{(R)} = -F_R \times x_{i,j}^\alpha * \vec{d}_{i,j} \quad (1)$$

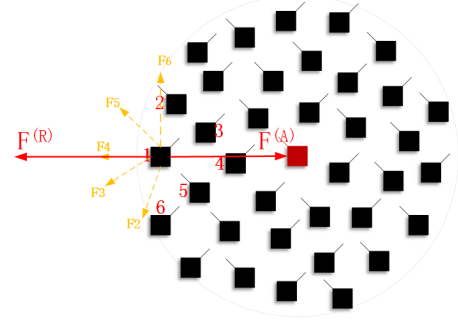


Figure 1: Balanced force for formation of MAVs

where $x_{i,j}$ is the distance between i and j , $\vec{d}_{i,j}$ the unit vector indicating the direction from i to j , and F_R the fixed repulsion force that can be pre-configured, and α the repulsion coefficient for tuning the effects of the distance. In case that $\alpha = 2$, Eqn.(1) indeed follows the Coulomb's inverse-square law, analogous to Isaac Newton's inverse-square law of universal gravitation.

2.2.2 Aggregation force

In order to aggregate MAVs into a swarm, an aggregation force is also needed. We assume that one or more MAVs play the role of leaders, which keep broadcasting their own state information periodically to all other MAVs through the long-distance channel. Based on the state information of leaders, each MAV calculates the attraction force from its leader.

$$F_i^{(A)} = F_A \times x_i^\beta * \vec{d}_i \quad (2)$$

where x_i denotes the distance between MAV i and the leader, $\vec{d}_i$ the unit vector from MAV i to the leader, F_A the fixed attraction force, and β the attraction coefficient, for tuning the effects of the distance.

2.2.3 Convergence of resultant force

By considering the total effects of repulsion force and aggregation force, each MAV, i , controls its kinematic state based on the resultant force, F_i , as follows.

$$F_i = F_i^{(A)} + \sum_{j \in V_i} F_{i,j}^{(R)} \quad (3)$$

where V_i indicates the set of neighboring MAVs that are located in the communication range of i . When F_i is 0, a balance state is reached. Otherwise, the repulsion force dominates the kinematic state of i when $F_i < 0$, or the aggregation force dominates. When almost every MAV falls into the balance state, i.e., $F_i = 0$, we say that the whole swarm reaches a equilibrium state.

2.3 Guidance of MAV swarm

In real application's environments, the formation of MAVs is usually needed to be adjusted frequently for meeting the requirements of various tasks.

2.3.1 Swarm guiding

Since each MAV is attracted by the aggregation force of its leader, the swarm may be guided by controlling the state of the leader, so that the swarm follows the flight trajectory of the leader. By collecting the state information of leaders through the short-range channel, each MAV may predict the moving direction of its leader. When the distance that the leader moves is little, the swarm can fly smoothly. Otherwise, if the distance changes too fast, e.g., x_i exceeds a specified threshold, X , an interpolation is usually useful for reducing or avoiding the turbulence of the swarm. As shown in Fig. 2, the coordinate position of the leader is "1" at the previous moment, and it is "4" at this time. In case that the distance between "1" and "4" is very large, linear interpolation is performed on "1" and "4" to smooth the transition by inserting two intermediate points "2" and "3". Then, each MAV will update the location of the leader from "1" and "4" in a specified rhythm, so that a smooth guidance of the swarm can be achieved.

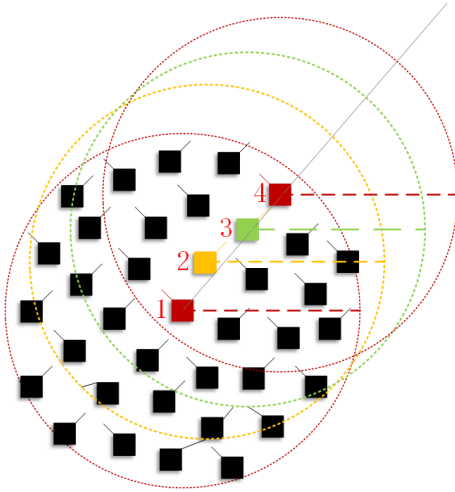


Figure 2: Guidance of MAV swarm

2.3.2 Swarm reshaping

When only one leader is employed, the shape of the swarm always tends to be like a circle in two-dimension space or a ball in three-dimension space. If a different shape is needed, one of the easiest ways is to use multiple leaders, so that the shape of the swarm may be adjusted by controlling the locations of these leaders. As shown in Fig. 3, by assigning

multiple leaders, a specified flight path may be achieved for the swarm.

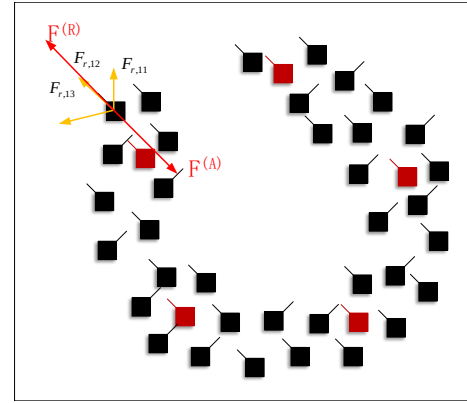


Figure 3: Reshaping of MAV swarm

2.3.3 Swarm partitioning and merging

Due to various requirements of applications, if the number of leaders changes, swarm partitioning or merging are usually involved, as shown in Fig. 4.

Swarm partitioning may take place when the number of leaders increases. When the number of leaders is more than one, a membership between MAVs and leaders must be specified, so that each MAV knows which leader is what it should follow. In this case, all leaders periodically broadcast not only their state information but also the membership information, so that the swarm may be partitioned by reassigning the membership.

Note that the membership only influences the calculation of aggregation forces, while the calculation of repulsion forces stays the same for every two neighboring MAVs, so that safe distance between every two of MAVs can be always maintained. Though multiple leaders may result in interferences on the long-range channel. As the number of leaders is often small, the interference usually can be overcome or avoided by properly configuring the channel resources.

In contrast, when the number of leaders decreases, the merger of swarms will take place. Similarly, membership can be actively adjusted via the long-range channel, and new balance of repulsion force and aggregation force can be rebuilt after swarms complete the merging process. In some cases, due to the failure or the crash of some leaders, some MAVs may fail to receive the broadcast messages from its leader, so that a merger process takes place passively. Usually, it can be treated as a backup mechanism by enabling each MAV to automatically follow a new leader, in case that it fails to receive the broadcast message from its original leader within a certain period of time.

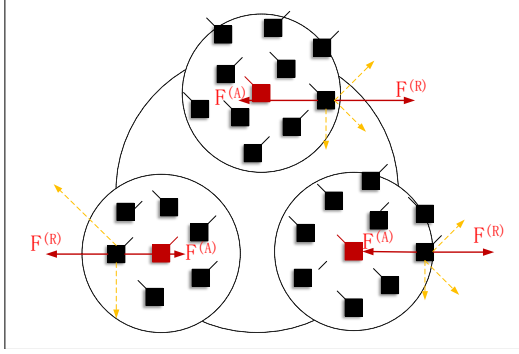


Figure 4: Division and merger of MAV groups

3 PERFORMANCE EVALUATION

In order to investigate the characteristics of the proposed scheme, we implemented both two-dimensional(2D) and three-dimensional(3D) versions parallelly and evaluated the performance by varying parameters.

3.1 Simulation setting

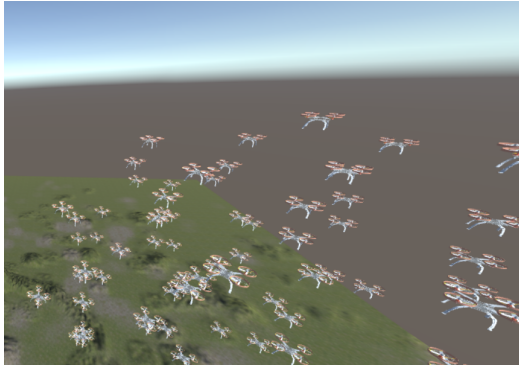


Figure 5: A snapshot of the simulations with 100 MAVs

We implemented a 2D simulation of MAV formation in C# programming language with Microsoft Visual Studio, and a 3D simulation with Unity, which is a 3D game development engine for high-quality 3D interactive supports[21]. The two versions of simulation were implemented by using the same algorithms with the same parameters, and the only difference is that mathematical representations and operations of vectors were performed in a 2D and 3D way, respectively.

In Unity, as shown in Fig. 5, all MAVs are instantiated from the same resource file of a MAV model with different parameters. Each MAV is configured as a rigid body, with parameters, “mass”, “drag” and “angular drag” to be 1, 0.1 and 0.05, respectively. The communication radius is 1000 meter in default. We define a metrics, neighbor distance, for a MAV as the distance that it has from its nearest neighbor as follows.

$$D^{(i)} = \min_{j \in V_i} \text{dist}(i, j) \quad (4)$$

where V_i is the set of neighbors for MAV i .

Then, the minimum value of $D^{(i)}$ indicates the safe distance that the swarm has in the equilibrium state.

$$D_{min} = \min_{j \in V} D^{(i)} \quad (5)$$

where V is the set of all MAVs.

Correspondingly, the maximum value of $D^{(i)}$ reflects the maximal degree of freedom that a MAV may have in the swarm.

$$D_{max} = \max_{j \in V} D^{(i)} \quad (6)$$

3.2 Results

We firstly compare 2D version and 3D version to validate the correctness of the algorithm implementation. Fig.6 and Fig.7 show the snapshots of the simulation scenario with one hundred MAVs with $F_A = 1000$ and $F_A = 10000$, respectively. From the figure, we can see that Fig.6 has a less intensive distribution of MAVs than Fig.7, because the formation of MAVs is based on the balance of local repulsion force and global aggregation force. Since F_A indicates the fixed repulsion force, a larger F_A leads to a less density of MAVs, which is consistent with Eqn. (1).

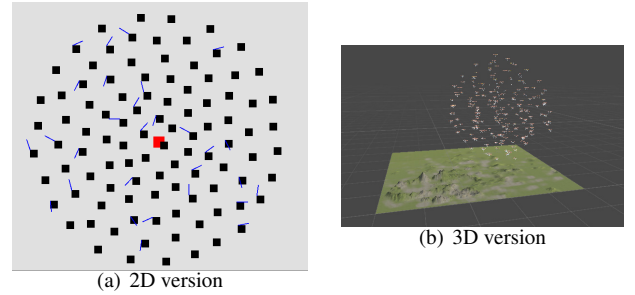
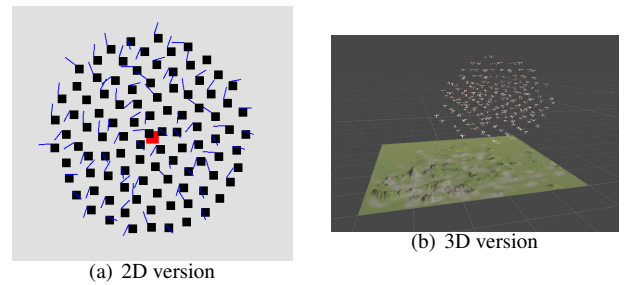
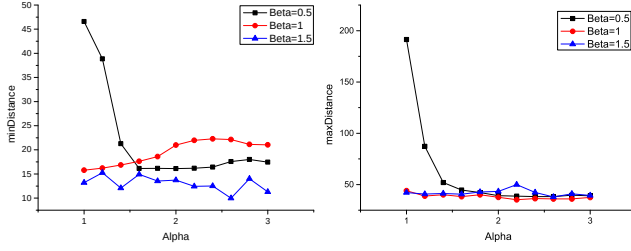
Figure 6: Formation of MAVs with smaller F_A Figure 7: Formation of MAVs with larger F_A

Fig. 8, Fig. 9 and Fig. 10 show the minimum and maximum of neighbor distance varying with parameters, α , β and

the communication range of MAV, respectively. From the picture, we observed that the minimum of neighbor distance is always larger than zero, which means that there is no collision between any two MAVs throughout all simulations.



(a) Minimum distance

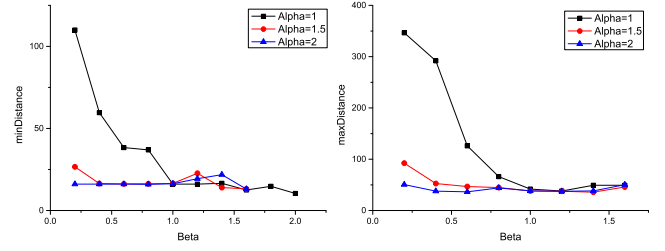
(b) Maximum distance

Figure 8: Neighbor distance varying with alpha

From Fig. 8(a), we can see some interesting results. Firstly, the minimum of neighbor distance first decreases rapidly and then increases slowly as the α increases when $\beta = 0.5$. The decreasing tendency can be explained that a smaller α results in a larger repulsion force. However, since the leader is located at the center of the swarm, when α increases further, the spanning diameter of the whole swarm decreases. Thus, increasing α further results in that the minimum of neighbor distance decreases. Secondly, when $\beta = 1.5$, the minimum of neighbor distance has a large fluctuation with the increasing of α . The aggregation force to a MAV is great when the β is large, but the increase of α will reduce the repulsion force of the MAV. Thus, the fluctuation demonstrates that the balance of repulsion and aggregation is closing to a critical point, on which any small random factors may result in an imbalanced effect. Correspondingly, as shown in Fig. 8(b), the maximum of neighbor distance has similar tendencies, but three curves tend to be close to the same value as α increases, which means that α has little effect on the freedom of swarm. Thirdly, when $\beta = 1$, the minimum of neighbor distance increases slowly with the increase of α , which reflects that the effects of α become less obvious.

In Fig. 9(a), with the increase of β , the minimum of neighbor distance shows a downward trend, which is steep when α is 1, but not when α is 1.5 and 2. This is because when α is large, the repulsion force between MAVs will be very large, at this time the effect of increasing attraction caused by β is not obvious. Correspondingly, as the α increases, the maximum of neighbor distance in Fig. 9(b) have similar tendencies to those in Fig. 9(a) due to the same reason.

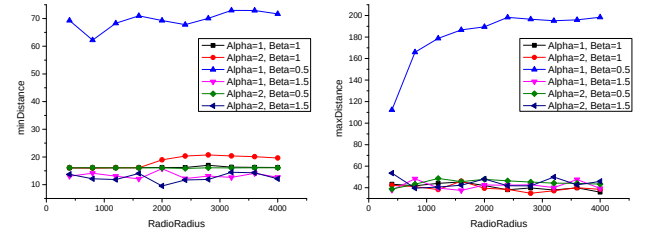
In Fig. 10(a) and Fig. 10(b), when $\alpha = 1$ and $\beta = 0.5$, the minimum and maximum of neighbor distance are both large, which indicates that the MAV formation is dispersed. When α and β are on other combinations, the values of neighbor distance are relatively stable, because there are more MAVs in



(a) Minimum distance

(b) Maximum distance

Figure 9: Neighbor distance varying with beta



(a) Minimum distance

(b) Maximum distance

Figure 10: Neighbor distance varying with radio radius

the communication range of each MAV, and thus the change of the communication range has a little effect, relatively.

4 CONCLUSION

In this paper, we present a force-directed method for formation and guidance of large scale swarming system, in which hundreds or even thousands of micro air vehicles are able to construct a swarm with enough freedom of control and guidance. Two independent communication channels are configured, so that local repulsion and global aggregation can be coordinated to control the behavior of the whole swarm. By arranging multiple leaders in proper way, swarm guiding, reshaping, partitioning and merging can be supported in a consistent way. Besides, the calculation of local repulsion force only depends on relative location and angle information, so that the safety of the swarm can be enforced even without depending on the precisely positioning information, which is extremely important for the swarm deployed in the real environments.

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