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A Case Study on Local Decentralized Air Traffic Protocol for Multiple Multicopters

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***Abstract*—For a multiple multicopter system, the increase in the number of multicopters may lead to severe trap problems. These will abort missions, crash multicopters, or even injure people. To solve the trap problem and guarantee the mission of each multicopter, an Air Traffic Management (ATM) system should build. In this paper, a local decentralized air traffic protocol for multiple multicopters is proposed to solve the trap problem and complete a series of tasks in a local low altitude airspace. Based on the Artificial Potential Field (APF) method, the protocol is designed in the form of a state machine to coordinate the motions of multiple multicopters. Finally, some simulations are performed to show the effectiveness of the proposed protocol in a case study.**

***Index Terms*—multicopters, trap, artificial potential field, decentralized control, air traffic protocol**

I. Introduction

It is widely acknowledged that multicopters are utilized to perform some missions such as search and rescue [1], military surveillance [2], agricultural application [3], observation and surveillance [4], payload delivery [5] and target tracking [6]. To handle these missions, it is preferred to employ multiple multicopters instead of a single one. Although using multiple multicopters can divide the total mission into several local tasks and relieve the burden of the single multicopter, the high-level decision-making may be complex. Thus, all these missions share a general need for Air Traffic Management (ATM) to coordinate the motions of multicopters.

ATM is an aviation term comprising all systems that assist aircraft to depart from a take-off place, traffic airspace, and land at a destination. It is based on the network-based architecture [7]. However, it suffers from perceived drawbacks such as systematic indirect routing between the take-off place and destination. Traditionally, the main effect of ATM is to keep a prescribed separation among all multicopters by using centralized control. The centralized control often results in a significant communication delay between the ground station and multicopters, deteriorating the performance of the systems and lacking scalability.

Until the Global Positioning System (GPS) is applied, the precise localization of the aircraft can be obtained easily. As a consequence, free flight [8] is proposed by airlines and Federal Aviation Administration (FAA) to remove the routing constraints imposed by the conventional, fixed-route system. It is a developing air traffic control method with distributed control. Parts of airspace are reserved dynamically and automatically in a distributed way by using computer communication to ensure necessary separation among multicopters.

The airspace is utilized by far inferior aircraft than it can accommodate, especially the low altitude airspace such as farmlands. There are only multicopters in the low altitude airspace. Such an airspace may be allocated temporarily by a high-level ATM for a special task within a given time interval. As for coordinating the motions of multiple multicopters in a local low altitude airspace, similar to [9], we have to manage the motions of multicopters so that they can complete their tasks and avoid collision. The coordination of multiple agents has been addressed partly using different approaches, various stability criteria and numerous control techniques [10], [11], [12].

Recently, Artificial Potential Field (APF) is a widely-used method on account of its ease-of-use. It uses the negative gradient of mixing of attractive and repulsive potential functions to produce vector fields that ensure the convergence and collision avoidance, respectively. Based on the APF method, a distributed feedback control strategy is proposed for distributed cooperative control and collision avoidance of multiple kinematic agents in [13] and [14]. A preliminary high-level architecture framework for ATM in the context of the aviation transportation enterprise is designed in [15].

However, in reality, there exists a practical engineering problem that the increase in the number of multicopters may lead to severe trap problems by using the APF method. To deal with the trap problem, the high-level decision-making needs to be optimized, and the control strategy is realized by using a state machine because of its ease-of-use, modularization and extensibility. In this paper, based on the APF method, a protocol is proposed in the form of a state machine to coordinate the motions of multiple multicopters in a local low altitude airspace. The major contribution in this paper is to design a local decentralized air traffic protocol for multiple multicopters to escape out of the trap, avoid collision and complete a series of tasks as well.

The remainder of this paper is organized as follows. Section II describes the preliminaries and problem formulation. In Section III, a local decentralized air traffic protocol is proposed. Finally, a case study of multiple multicopters is presented to demonstrate the efficiency of the proposed protocol in Section IV, and Section V gives the conclusion and future research plan.

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II. Preliminaries and a Case Study Problem Formulation

A. Airspace Definition

A schematic diagram of the horizontal airspace is shown in Fig. 1, the airspace is structured similarly to the road network. The airways play a similar role to the roads, and the free flight areas are some separated areas such as farmlands. In our case study, the free flight areas are connected by two airways with the width $2r_{\mathrm{h}}$ and centerlines through $\mathbf{p}_{\mathrm{h},1}$ and $\mathbf{p}_{\mathrm{h},2}$, $\mathbf{p}_{\mathrm{h},3}$ and $\mathbf{p}_{\mathrm{h},4}$, respectively. There are two static obstacles in the Free Flight Area 2 which are modeled as disks at center $\mathbf{p}_{\mathrm{o},k}$ with radius $r_{\mathrm{o},k}$, $k = 1, 2$. Assume that the height of each obstacle is boundless so that multicopters can only fly around it instead of over it. Multicopters are only permitted to fly within airways and free flight areas. Except for the obstacles, airways and free flight areas are denoted by $\mathcal{A}$.

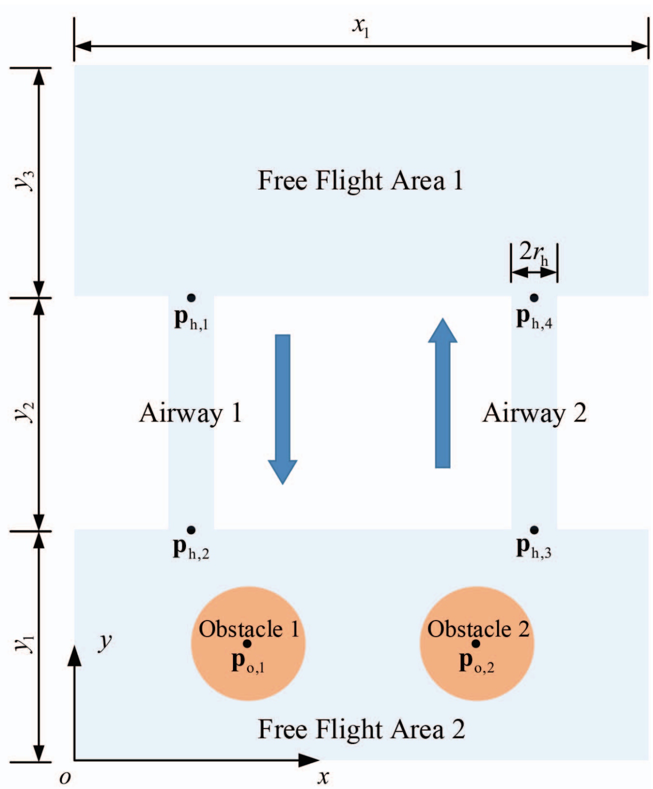

Fig. 1. A schematic diagram of the horizontal airspace in the case study.

B. Multicopter Model

Define a set of multicopters as $\mathcal{Q} = \{Q_1, Q_2, ..., Q_M\}$ and the waypoint positions of the ith multicopter as $\mathcal{T}_i = \{\mathbf{T}_{i,1}, \mathbf{T}_{i,2}, ..., \mathbf{T}_{i,N_i}\}$, i = 1, 2, ..., M. Those waypoint positions are arbitrarily selected from the area $\mathcal{A}$ in Fig. 1. To make the multicopters work well, it is assumed that the M multicopters at the same altitude satisfy the following kinematic model

$$\dot{\mathbf{p}}_i = \mathbf{v}_i \tag{1}$$

where $\mathbf{p}_i \in \mathbb{R}^2$ and $\mathbf{v}_i \in \mathbb{R}^2$ are the position and velocity of the ith multicopter, respectively. It is assumed that those M multicopters satisfy the following control model

$$\dot{\mathbf{v}}_i = -l_i\left(\mathbf{v}_i - \mathbf{v}_{\mathrm{c},i}\right) \tag{2}$$

where $\mathbf{v}_{\mathrm{c},i} \in \mathbb{R}^2$ is the velocity command of the ith multicopter. The control gain $l_i \in \mathbb{R}_+$ depends on the semi-autonomous autopilot that the ith multicopter uses, which can be obtained through flight experiments.

C. Problem Description

There is an unanticipated phenomenon during the early case study. One multicopter can arrive at its waypoint successfully. While two or more multicopters taking part in the mission may get trapped, namely they have not reached the corresponding waypoint but velocities are zero. Let $r_{\mathrm{a}} \in \mathbb{R}_+$ and $\mathbf{T}_{i,\mathrm{now}} \in \mathbf{T}_i$ be the avoidance radius and the current waypoint position of the ith multicopter, respectively. Mathematically, given a $\varepsilon \in \mathbb{R}_+$, a multicopter gets trapped if

$$\|\mathbf{T}_{i,\mathrm{now}} - \mathbf{p}_i\| > r_{\mathrm{a}} \text{ and } \|\mathbf{v}_i\| < \varepsilon. \tag{3}$$

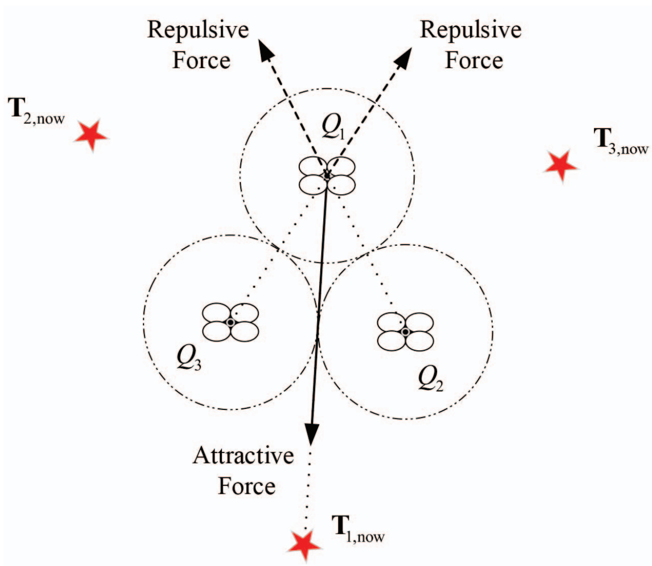

Fig. 2. Three multicopters are trapped for multicopters avoidance.

As depicted in Fig. 2, the unanticipated force balance is the main reason why multicopters Q_1, Q_2, and Q_3 get trapped. Besides, the trap problem also appears at the entrance into airways due to the dense waypoints. To avoid the static obstacles, two multicopters may get trapped due to the opposite fly direction. If the speed of a multicopter through the exit of airway is too fast, it will turn back to the waypoint. However, those subsequent multicopters fly at the front of it so that all the multicopters get trapped at the exit of airway. All of these issues make the velocities of trapped multicopters zero, and their positions are not close to waypoints so that the current task may never be finished.

D. Control Objective

The control objective of this paper is to coordinate the motions of multiple multicopters including avoiding collision with any obstacle and other multicopters, arriving at the waypoint and keeping in the area $\mathcal{A}$. There are some descriptions:

- In the free flight areas, the motions of multiple multicopters are coordinated to achieve convergence to spatial destinations, obstacle avoidance and inter-agent collision avoidance.
- In the airways, the motions of multiple multicopters are coordinated to achieve convergence to spatial destinations, inter-agent collision avoidance and keeping within airways.
- About convergence, while a multicopter completes its task, which means the multicopter arrives at the waypoint and its velocity is zero, it hovers at the current position.

In general, If there are multicopters trapped, how to escape out of the trap is the main problem this paper concerns. If not, the control objective is same as the original one. Specifically, the ith multicopter is required to fly from $\mathbf{T}_{i,N_o}$ to $\mathbf{T}_{i,N_{o+1}}$ in order, $o \in \{1,2,...,N_i\}$. Finally, it is required to hovers at the last waypoint $\mathbf{T}_{i,N_i}$. If $\|\mathbf{v}_i\| < \varepsilon$, and the distance between a multicopter and the current waypoint is less than r_a, then the waypoint is changed to the next one. Mathematically, the waypoint is changed to the next one if

$$\|\mathbf{T}_{i,\text{now}} - \mathbf{p}_i\| \leq r_\text{a} \text{ and } \|\mathbf{v}_i\| < \varepsilon. \tag{4}$$

In the whole process, each multicopter is required to satisfy the following constraints

$$\left\|\mathbf{p}_i - \mathbf{p}_j\right\| \geq 2r_\text{a} \tag{5}$$
$$\left\|\mathbf{p}_i - \mathbf{p}_{\text{o},k}\right\| \geq r_\text{a} + r_{\text{o},k} \tag{6}$$
$$\mathbf{p}_i \in \mathcal{A} \tag{7}$$

where i, j = 1, 2, ..., M, $i \neq j$, and k=1,2.

Based on the constraints and objective above, we aim to design a local decentralized air traffic protocol.

III. A Local Decentralized Air Traffic Protocol

A. Basic Principles

There are some basic principles before introducing the proposed protocol. The APF method applies the negative gradient of mixing of attractive and repulsive potential functions to produce vector fields that ensure the convergence and collision avoidance, respectively. The waypoint is assigned attractive potential, while the obstacles, other multicopters and the edge of the airway are assigned repulsive potentials. As shown in Fig. 3, those dashed arrows and solid arrows are representative of the forces derived from repulsive potentials and attractive potentials, respectively. Thus, a multicopter in the field will be attracted towards the waypoint, while being repelled by the static obstacles, other multicopters and the edge of the airway.

To solve the trap problem caused by the APF method, first we use a term *group* to define the set of trapped muticopters. If $\left\|\mathbf{p}_i - \mathbf{p}_j\right\| < r_\text{a}$, $i \neq j$, we say that the ith multicopter and the jth multicopter are connecting. If $\left\|\mathbf{p}_i - \mathbf{p}_j\right\| < r_\text{a}$, $\left\|\mathbf{p}_j - \mathbf{p}_n\right\| < r_\text{a}$, $i \neq j \neq n$, we say the ith multicopter and the nth multicopter are reaching. If there is a trapped multicopter, those multicopters connected with or reached with it form a *group*.

Then, we assume that there is an important one who owns the highest priority in each *group*, and the others in the same *group* make way for it. Note that the priority of the multicopter is related to the distance between its current position and waypoint in this paper. To minimize performing time, it is defined that the multicopter with the furthest distance has the highest priority. Based on those principles, a possible method is to make the multicopter independently judge its status and adjust the control scheme according to the status. Thus, we can start to design the protocol in the form of a state machine.

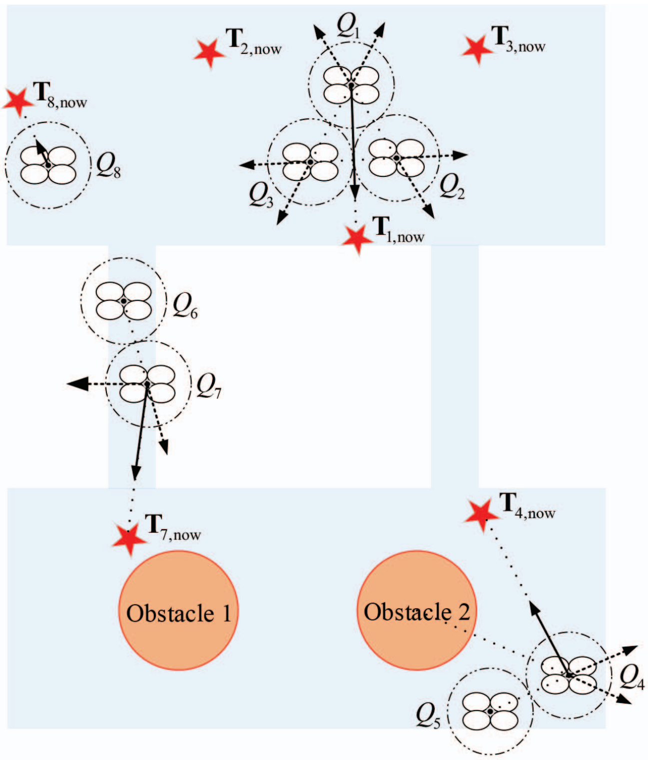

Fig. 3. A force diagram of multicopters in different states.

B. State Definition

The velocity command $\mathbf{v}_{\text{c},i}$ depends on the current state of the ith multicopter. According to the different tasks, we define five states as follows:

- *Standby State*. If no task or not prepare well, then a multicopter hovers at the current position. For example, there is no task for multicopter Q_8 at point $\mathbf{T}_{8,\text{now}}$ shown in Fig. 3. Then it hovers at $\mathbf{T}_{8,\text{now}}$ according to the control law

$$\mathbf{v}_{\text{c},i} = -\text{sat}\left(\mathbf{p}_{\text{wp},i}, v_{\text{m},i}\right) \tag{8}$$

where $v_{\text{m},i} \in \mathbb{R}_+$ is the maximum speed of the ith multicopter. Similar to [16, p. 234], the function sat is a saturation function which keeps the flying direction the same if $\|\mathbf{v}_i\| > v_{\mathrm{m},i}$. The variable $\mathbf{p}_{\mathrm{wp},i}$ plays an important role in arriving at the waypoint. As shown in Fig. 3, the waypoint $\mathbf{T}_{8,\mathrm{now}}$ assigned attractive potential attracts the multicopter Q_8 by the action of attractive force with the solid line.

- *Free Flight State*. If a multicopter performs the task on free flight areas, then it is required to arrive at the waypoint, meanwhile avoiding collision with any obstacle and other multicopters as well. For example, there is a task for multicopter Q_4 to fly to the point $\mathbf{T}_{4,\mathrm{now}}$ on the Free Flight Area 2 shown in Fig. 3. Then it flies according to the control law

$$\mathbf{v}_{\mathrm{c},i} = -\mathrm{sat}\left(\mathbf{p}_{\mathrm{wp},i} + \mathbf{p}_{\mathrm{r}1,i}, v_{\mathrm{m},i}\right) \tag{9}$$

where $\mathbf{p}_{\mathrm{r}1,i}$ is used for collision avoidance. As shown in Fig. 3, the waypoint $\mathbf{T}_{4,\mathrm{now}}$ assigned attractive potential attracts the multicopter Q_4 by the action of attractive force. While the Obstacle 2 and the multicopter Q_5 assigned repulsive potentials repels Q_4 by the action of repulsive forces indicated by the dashed lines.

- *Airway Flight State*. If a multicopter performs the task within airways, then it is required to arrive at the waypoint, meanwhile avoiding collision with other multicopters and keeping within airways. For example, there is a task for multicopter Q_7 to fly to the point $\mathbf{T}_{7,\mathrm{now}}$ through the Airway 1 shown in Fig. 3. Then it flies according to the control law

$$\mathbf{v}_{\mathrm{c},i} = -\mathrm{sat}\left(\mathbf{p}_{\mathrm{wp},i} + \mathbf{p}_{\mathrm{r}1,i} + \mathbf{p}_{\mathrm{r}2,i}, v_{\mathrm{m},i}\right) \tag{10}$$

where $\mathbf{p}_{\mathrm{r}2,i}$ is used for keeping the multicopter within airways. As shown in Fig. 3, the waypoint $\mathbf{T}_{7,\mathrm{now}}$ attracts the multicopter Q_7. The multicopter Q_6 and the edge of the Airway 1 are assigned repulsive potentials so that Q_7 is repelled by them.

- *Avoidance Flight State*. If a multicopter gets trapped and its priority is not the highest in its *group*, then it performs the pure avoidance control scheme. For example, as shown in Fig. 3, the multicopter Q_1 flies to point $\mathbf{T}_{1,\mathrm{now}}$, while the multicopter Q_2 and Q_3 following an opposite direction fly to point $\mathbf{T}_{2,\mathrm{now}}$ and $\mathbf{T}_{3,\mathrm{now}}$, respectively. They are trapped due to repulsive forces of each other and attractive forces of waypoints as same as those shown in Fig. 2. Then Q_1 which owns the highest priority in this *group* flies according to the control law (12), and Q_2 and Q_3 flies according to the control law

$$\mathbf{v}_{\mathrm{c},i} = -\mathrm{sat}\left(\mathbf{p}_{\mathrm{r}3,i}, v_{\mathrm{m},i}\right) \tag{11}$$

where $\mathbf{p}_{\mathrm{r}3,i}$ performs the pure avoidance control. As shown in Fig. 3, Q_1 is attracted towards $\mathbf{T}_{1,\mathrm{now}}$ and repelled by Q_2 and Q_3. To breaking the force balance, Q_2 and Q_3 entering into *Avoidance Flight State* ignore the attractive forces to make way for Q_1. Thus, they all escape out of the trap.

- *Degradation Flight State*. If a multicopter gets trapped and it owns the highest priority in its *group*, then it flies according to the control law

$$\mathbf{v}_{\mathrm{c},i} = -\mathrm{sat}\left(\mathbf{p}_{\mathrm{wp},i} + \mathbf{p}_{\mathrm{r}3,i}, v_{\mathrm{m},i}\right). \tag{12}$$

C. Event Definition

- AIRWAYSTART. Set its value to 1 if the multicopter is required to perform the task through the airway; otherwise 0.
- AIRWAYOUT. Set its value to 1 if the multicopter finishes its current task through the airway; otherwise 0.
- TRAP. Set its value to 1 if the multicopter gets trapped; otherwise 0.
- PRIORITY. Set its value to 1 if the multicopter possesses the highest priority in its *group*; otherwise 0.
- TASKDONE. Set its value to 1 if the multicopter finishes its current task; otherwise 0.
- CLEAR. Set its value to 1 if no other multicopters stay around the multicopter; otherwise 0.

D. Flight Protocol

Based on the states and events above, a local decentralized air traffic protocol is designed. The protocol dictates that each multicopter governs its operation through a decision state machine shown in Fig. 4, where TCi represents the transition condition, i = 1,...,8.

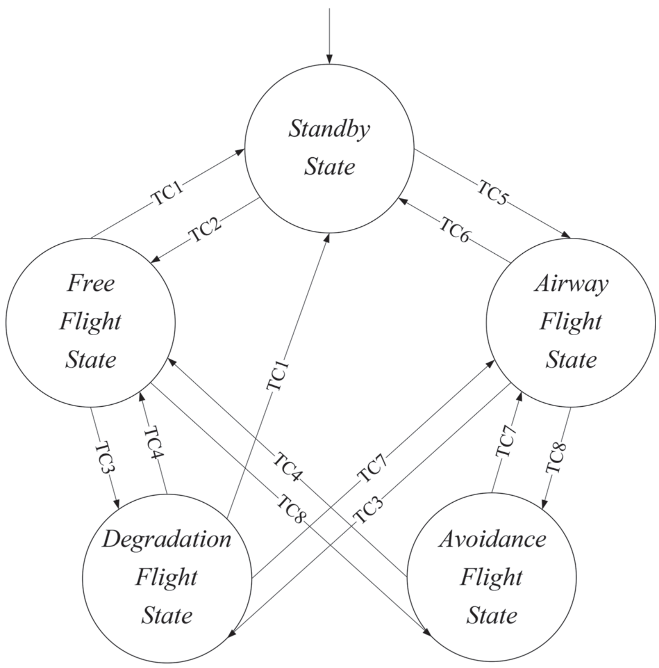

Fig. 4. Decision state machine for state selection of each multicopter.

- TC1: TASKDONE=1. When the task is done, the multicopter enters into *Standby State*.
- TC2: TASKDONE=0 & AIRWAYSTART=0. When the task is not done, and the multicopter is not required to

complete the task through the airway, it enters into *Free Flight State*.

- TC3: TRAP=1 & PRIORITY=1. When the multicopter gets trapped, and it owns the highest priority in its current *group*, it enters into *Degradation Flight State*.
- TC4: AIRWAYSTART=0 & CLEAR=1. When there are no other multicopters around, and the multicopter is not required to complete the task through the airway, it enters into *Free Flight State*.
- TC5: AIRWAYSTART=1 & TASKDONE=0. When the task is not done, and the multicopter is required to complete the task through the airway, the multicopter enters into *Airway Flight State*.
- TC6: AIRWAYOUT=1. When the multicopter finishes the task within airways, it enters into *Standby State*.
- TC7: AIRWAYSTART=1 & CLEAR=1. When there are no other multicopters around, and the multicopter is required to complete the task through the airway, it enters into *Airway Flight State*.
- TC8: PRIORITY=0 & TRAP=1. When the multicopter gets trapped, and its priority is not the highest in its current *group*, it enters into *Avoidance Flight State*.

IV. A Case Study

A. Simulation Setup

A sequence of simulations by Matlab R2017a are carried out to verify the feasibility and correctness of the designed protocol above. The general framework of each simulation mainly includes four modules: parameter initialization, state display, multicopter control and plotting. The size of area $\mathcal{A}$, the number of multicopters, the radius and position of each obstacle, the control gain, the maximum speed and safety radius of the multicopter and a series of waypoints are all entered by the user through the parameter initialization module. The initial state of each multicopter is *Standby State* by default. The state display module is implemented in Stateflow with the same principle as shown in Fig. 4. It can judge and display the current status of each multicopter so that multicopters can fly according to the control laws (8)-(12) through the multicopter control module.

According to the horizontal airspace shown in Fig. 1, let $M = 20$, $N_i = 6$, $l_i = 5$, $\varepsilon = 1$, $r_{\text{a}} = 12$ m, $v_{\text{m},i} = 10$ m/s, $y_1 = y_2 = y_3 = 500$ m, $x_1 = 800$ m, $\mathbf{p}_{\text{o},1} = [200\ \ 250]^{\text{T}}$ m, $\mathbf{p}_{\text{o},2} = [600\ \ 250]^{\text{T}}$ m, $r_{\text{o},1} = r_{\text{o},2} = 80$ m, $r_{\text{h}} = 50$ m, $\mathbf{p}_{\text{h},1} = [100\ \ 1000]^{\text{T}}$ m, $\mathbf{p}_{\text{h},2} = [100\ \ 500]^{\text{T}}$ m, $\mathbf{p}_{\text{h},3} = [700\ \ 500]^{\text{T}}$ m, $\mathbf{p}_{\text{h},4} = [700\ \ 1000]^{\text{T}}$ m.

Each multicopter is required to fly from home on Free Flight Area 1 and then enter into Airway 1. After passing Airway 1, multicopters have to arrive at corresponding waypoints located on Free Flight Area 2. After that, they have to return home through Airway 2. For each multicopter, six waypoints are used to describe the task. In the process of mission completion, the position of each multicopter is collected from 0 to 480 seconds. Two types of simulations are carried out. One is to complete the mission with the designed local decentralized air traffic protocol, and the position of each multicopter is plotted every 60 seconds in Fig. 5. The other is to achieve the same mission by using a traditional APF method, and the position of each multicopter is plotted every 60 seconds in Fig. 6.

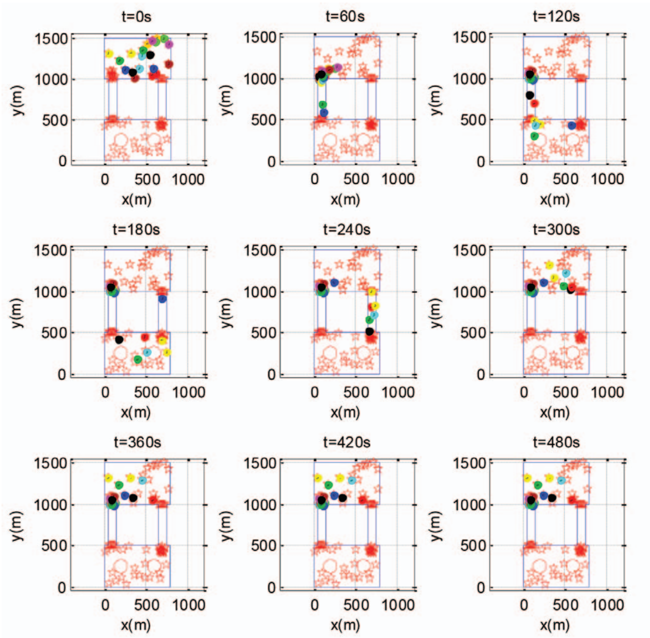

Fig. 5. The position of each multicopter in the air traffic mission by using a traditional APF method.

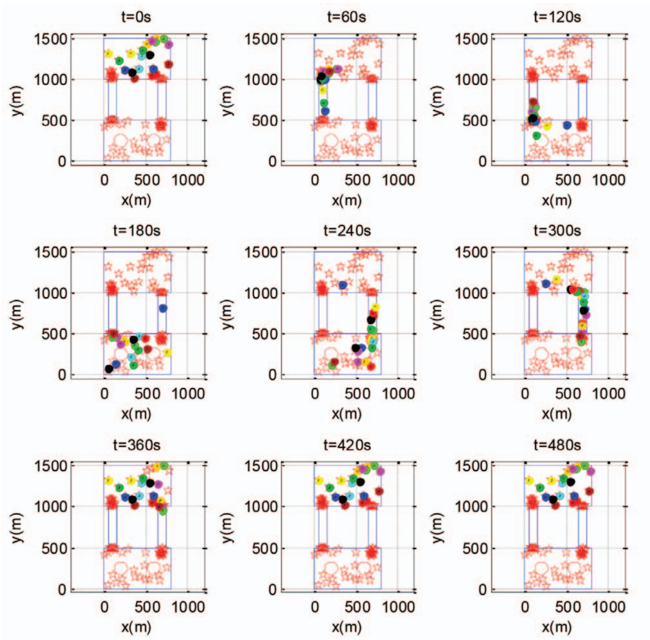

Fig. 6. The position of each multicopter in the same mission by using the designed protocol.

B. Results Analysis

Similar to the horizontal airspace shown in Fig. 1, those blue lines, red circles, and red pentagrams shown in Fig. 5

are representative of the edge of area $\mathcal{A}$, the static obstacles and randomly generated waypoints, respectively. There are 20 multicopters in 10 colors. Getting the results from the subplot 9, only 7 multicopters complete their tasks and return home. By comparing with the subplots 2-9, the other 13 multicopters get trapped at the entrance into Airway 1. Thus, the mission may never be finished.

By comparing with the simulation results above, the effect of the protocol is demonstrated. In Fig. 6, even though there is a great jam at the entrance into Airway 1 at 60 seconds, the phenomenon disappears at 120 seconds shown in subplots 3. Finally, all the multicopters escape out of the trap, complete the mission and return their home within 480 seconds. To make the simulation results more persuasive, some dangerous distances are shown in Fig. 7.

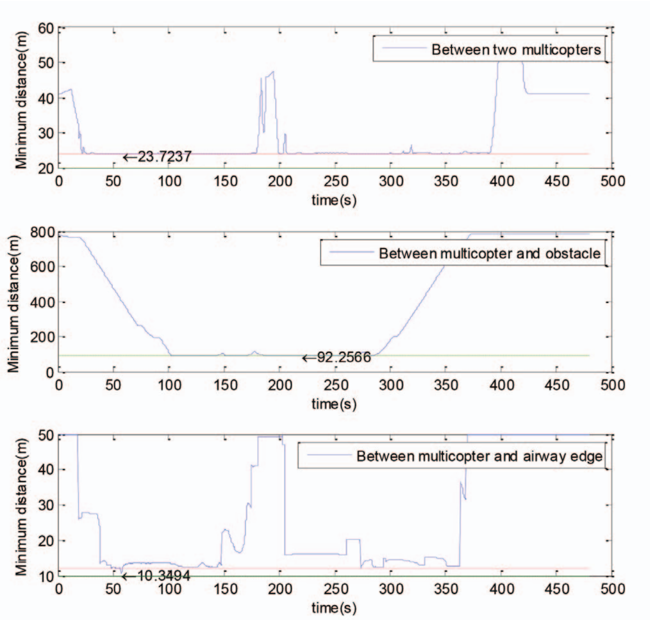

Fig. 7. Three kinds of minimum distance in the air traffic task by using the designed protocol.

As shown in Fig. 7, the green lines and red lines are representative of the safety distance and avoidance distance, respectively. In the whole process, each multicopter can always keep the avoidance distance from other multicopters and obstacles, namely $2r_{\mathrm{a}} = 24$ m from other multicopters and $r_{\mathrm{a}} + r_{\mathrm{o},k} = 92$ m from obstacles. The distance between two multicopters and the distance between a multicopter and an obstacle are satisfied (4) and (6), respectively. Although the minimum distance between multicopter and airway edge is lesser than r_{a} at 50 seconds and 300 seconds, each multicopter can always keep the safety distance $r_{\mathrm{m}} = 10$ m.

V. Conclusion

In this paper, a local decentralized air traffic protocol for multiple multicopters in a low altitude airspace is proposed. Based on the APF method, the protocol is proposed in the form of a state machine to coordinate the motions of multiple multicopters including solving the trap problem, keeping within airways, converging to spatial destinations, avoiding collision with any obstacle and other multicopters. A series of simulations are carried out to show the effectiveness of the designed protocol in a case study.

Although this protocol has some ideal simulation results, there are still some parts to be improved. First, there are some ignored states such as the damaged state and the fault state. Second, we discuss the horizontal airspace so that the situation about flying over the obstacle is not considered. Thus, this local decentralized air traffic protocol should also consider more in future research.

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