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Distributed UAV Loss Detection and Auto-replacement Protocol with Guaranteed Properties

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Abstract

Multi-UAV systems are becoming a true reality. They have wide applications in surveillance, search, hazardous rescue and other civil services. Currently, an important challenge is the robust control against UAV failures. In this paper, the distributed UAV loss detection and auto-replacement scheme is discussed. The basic idea is to use the cooperative method to control the multi-UAV system to accomplish the missions. This is achieved by exchanging heartbeats (HBs) and information fusion. We first use the obtained information to detect if one UAV is lost. Subsequently, an auto-replacement logic is used to send a UAV with low priority to occupy the target position or task which was assigned to the lost UAV. Next, a recovery algorithm is proposed when a newly inserted UAV or a lost UAV is recovered from failures. Finally, the proposed scheme is tested by computer simulations and real experiments.

Keywords Cooperative control · Distributed control · Unmanned aerial vehicles

1 Introduction

Unmanned aerial vehicle (UAV) is currently a growing area. This new technology offers many potential civil applications, inspiring scientist to undertake the development of UAV systems. Employing multi-UAVs [1–8] is rapidly becoming possible owing to the development of computer hardware and communication technology. The use of multi-UAVs is advantageous when comparing to a single one. For example, when tasks are very difficult such as to survey multiple places continuously, single UAV will not be able to accomplish them. Furthermore, a team of multi-UAVs inherently provides cooperative control which can collaborate to perform various tasks by exchanging information [9].

Another advantage of employing multi UAVs is that it is robust against failures of single UAV or communication links [11]. This issue can be stated as when one or more UAVs are lost(comm link loss or UAV failure), a group of cooperative UAVs can detect the lost UAVs and take over (or replace) the tasks of the lost UAVs if their tasks are more important.

This paper considers the cooperative control of multiple UAVs performing missions with UAV loss detection and auto-replacement, and other features. The cooperation is implemented through exchanging heartbeat information among UAVs. With heartbeat information, we are able to detect the UAV loss occurrence. We provide an auto-replacement algorithm with contention protocol and are able to guarantee the replacement of the target assigned to the lost UAV even in the presence of communication latencies. If a newly inserted UAV or a lost UAV is recovered from failures, we present a recovery algorithm to ensure that it can find the unassigned target and occupy that target. We evaluate our method by showing computer simulations and a real experiment.

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The paper is structured as follows: in Section 2, the related work is described briefly. In Section 3, the background and our research objectives are briefly described. In Section 4, the solution of the UAV loss detection and auto-replacement scheme is given. The simulation study is given in Section 5, while the experimental study is illustrated in Section 6. Finally, the conclusion is given in Section 7.

2 Related Work

UAVs have become increasingly attractive over the past few years. Research is continuously progressing in various areas such as sensor coverage [4–6], formation [7, 8] and flocking control [10]. Currently, an important challenge is to automatically detect the loss of a UAV and assign another UAV at the lower priority position to take up the vacated target. We shall briefly review a few of the related works in this field.

Reliability of UAVs is particularly critical in the various operating scenarios. It has gained an increasing attention in recent years. For single UAV failure and robust control, various fault detection and fault-tolerant control schemes have been reported [12–14, 16]. However, they are not suitable for implementing multi-UAV missions.

The reliable operation of a swarm system depends on fault detection and fault-tolerant control. The recent reports on detecting fault of swarm systems are listed here. In [17], the authors develop a model-based fault diagnosis technology for formation control of multi-robots. However, modeling behaviors of robots, sensors and actuators are difficult to be implemented in a practical multi-UAV system. In [18], the authors present a fault detection scheme based on signal processing for detecting non-abrupt actuator faults in the formation control problem. In [19], the authors design a bank of distributed unknown observers for fault detection of formation control. In [20], the authors extend the result of [17] to the case where the model states are unknown. In this case, the state observers are designed to estimate the model states and then the fault diagnosis of formation control is achieved based on the state observers. However, these results [17–20] do not consider the auto-replacement when fault occurs to one or more UAVs. For the formation control of swarm systems, when a fault occurs, the normal formation control will not be able to keep the geometrical formation of multiple UAVs. To deal with this case, the work in [21] develops a fault-tolerant control to minimize the effects of fault and recover the geometrical formation; the work in [22] presents a control graph approach to detect a faulty UAV in formation control and reconfigure all healthy UAVs evenly spreading in an elliptic formation; the work in [23] proposes a two-stage fault diagnosis scheme to detect a faulty robot and reconfigure a new formation informed by the leader when fault occurs. However, in our operating scenario, once one UAV is lost, its target becomes unassigned, needing another UAV (we don't have leader) to replace its task. In addition, formation is not required in our mission. Therefore, the work in [21–23] cannot be applied to this situation. The work in [24] uses multi-UAVs to cooperatively detect UAV failures by using differential global positioning system and inertial sensors, but no robustness properties are involved, i.e., there is no UAV taking up the vacated target. One paper in [25] proposes to re-assign tasks among the UAVs when detecting the lost UAV, but UAV loss detection and detailed reallocation are not discussed. According to our knowledge, there is limited literature focused on the robustness issue of multi-UAVs against UAV loss and auto-replacement. This challenging work can be addressed in this paper by increasing the autonomy of UAV team by collaboration with one another.

3 Problem Statement

Consider a mission area D in R^3. In the mission, there is a finite set of targets defined as $T = \{(T_1, P), (T_2, P), ...(T_M, P)\}$ where $P = \{High, Low\}$ represents priority. "*High*" means that its target position is important and should be assigned first, while "*Low*" labeled at its target position should be assigned later. Denote the mobile UAVs by C_i, $i \in \{1, 2, ...N\}$. Our tasks in this paper are

- when one or more UAVs fail, other UAVs should cooperatively detect which UAVs are lost ;
- if the target assigned to the lost UAV is high priority, the nearest UAV with low priority should replace the lost UAV;
- if there is a newly inserted UAV or a lost UAV is recovered from failure (for example, comm link is recovered again), it should find an unoccupied target which is firstly high priority and the nearest to itself.

Our multi-UAV system utilizes wireless communication mode, called the User Datagram Protocol (UDP). In this mode, messages from UAVs are broadcast over one-hop periodically, called Heartbeat (HB). Mesh network as shown in Fig. 1, is applied to the wireless data link communication between UAV and UAV; as well as between UAV and gateway. The use of mesh network offers efficiency and reliability where data can be transmitted from different UAVs simultaneously and the network is still capable of withstanding the high traffic. In the event, where one UAV fails to connect the network, the other UAVs continue to function as desired without causing any performance degradation.

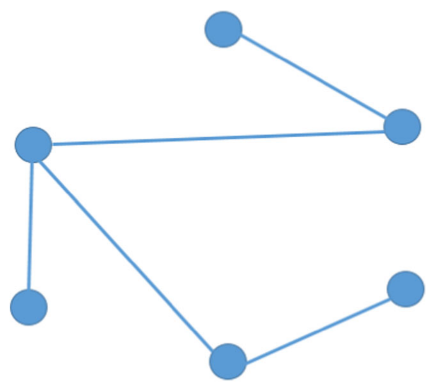


Fig. 1 Mesh network

Although we use the mesh network in this UAV system, we do not use the centralized information processing approach. Alternatively, we use a distributed form for each UAV to make decisions independently.

4 Cooperative UAV Loss Detection and Auto-replacement

In the preceding section, the concepts of UDP and HB have been given. With this in mind, in this section we will discuss how the multi-UAV system does the collaborative work to execute our task. The proposed control structure to each UAV is shown in Fig. 2, which is comprised of cooperation, UAV loss detection, auto-replacement and recovery schemes. The cooperation among UAVs is to share information through heartbeat broadcasting and information fusion. The UAV loss detection always monitors failure occurrence from the obtained information. When the lost UAV is detected, an auto-replacement is activated to determine which UAV should take up the target position assigned to the failure UAV or lost UAV. If a newly inserted UAV or the lost UAV is recovered, the recovery module is triggered to send that UAV to an unassigned target position. In the context below, we will first describe the sharing HB protocol in the multi-UAV system. Next, the UAV loss detection protocol is discussed. After that, the detailed auto-replacement scheme is given. Finally, the recovery algorithm of the lost UAV is given.

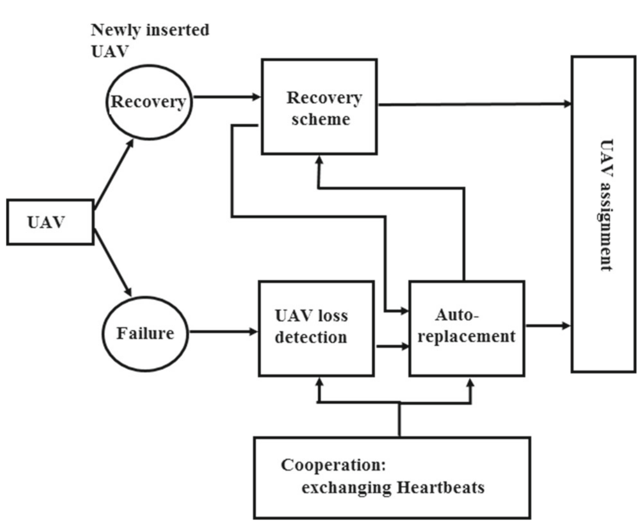


Fig. 2 The control architecture of each UAV

4.1 Cooperation Through Shared Heartbeats

The cooperation task described in this subsection is the sharing UAV information among multi-UAVs and then information fusion developed to extract the useful information. The heartbeat table shown in Table 1 is used.

In a N UAV system, if the communication is working well, each message has N UAV information and broadcasts its message to other UAVs. When receiving the messages from other UAVs, at this moment each UAV has $N-1$ HB messages. In total, it has N HB messages including itself. In the present system, all messages are placed into a MessageBox. Thus, the total messages in each MessageBox includes $N \times N$ information. There exist redundant information in the MessageBox. The question is how to design an information fusion scheme to reduce the information size, thereby generating the size of the HB message of the own UAV. The solution is to check the time of each message. It is known from the HB table that each HB message is attached with a GPS time. Thus, we know the latest message if we compare all GPS time among the messages in the MessageBox. Here, we use a search GPS time algorithm (see Algorithm 1) to find the latest message.

Table 1 UAV (C_i) Heartbeat

UAV ID
UAV adjacent number (UAV valency)
Total UAV number in network
x position
y position
z position
V_x speed
V_y speed
V_z speed
GPS time
UAV mode
Replacement UAV
Target ID
Want to target ID
Cost
UAV status

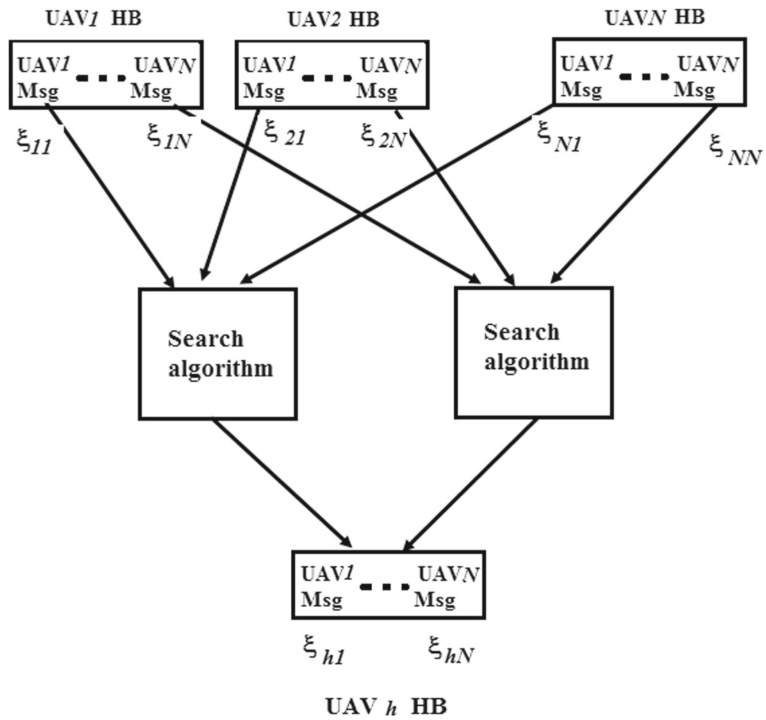


Fig. 3 Information fusion

Using this way, we can guarantee the ith HB formed which is comprised of the latest UAV information received. The information fusion scheme is illustrated in Fig. 3, where for UAV i, we define the message of UAV j as the vector ξ_{ij}. After the fusion, the HB message of each UAV contains only N UAV information.

Algorithm 1 Search algorithm

Input: UAV C_i ID, HB from other UAVs
C_j, $j = 1, 2, ..., N$; $j \neq i$
Output: HB of UAV C_i
for $m = 1$ to Length of total UAVs do
tmp = 0
  for $h = 1$ to Length of total UAVs do
    if GPS T of HB[h*total_UAV_Num+m]
      >= tmp then
      tmp=GPS T of HB[h*total_UAV_Num+m]
      store HB[h*total_UAV_Num+m] information
  end if
 end for
end for
Note:GPS T = GPS Time

The following protocol represents information fusion (Fig. 3) for the hth UAV

$$\xi_{hi}(k+1) = \sum_{j}^{N} \rho_{ji}^{(h)} \xi_{ji}(k) \tag{1}$$

where $\rho_{ji}^{(h)}$ is the weighting of the information fusion. Thus, we have the HB of the hth UAV regarding the ith UAV

$$\xi_i(k+1) = A_i \xi_i(k) \tag{2}$$

where $\xi_i(k) = [\xi_{1i}(k), \xi_{2i}(k), ..., \xi_{Ni}(k)]^T$, and

$$A_i = \begin{bmatrix} \rho_{1i}^{(1)} & \rho_{2i}^{(1)} & \dots & \rho_{Ni}^{(1)} \\ \rho_{1i}^{(2)} & \rho_{2i}^{(2)} & \dots & \rho_{Ni}^{(2)} \\ \vdots & \vdots & \vdots & \vdots \\ \rho_{1i}^{(N)} & \rho_{2i}^{(N)} & \dots & \rho_{Ni}^{(N)} \end{bmatrix} \tag{3}$$

It should be noted that for each row in the matrix A_i, the weighting set of $\{\rho_{1i}^{(h)}, \rho_{2i}^{(h)}, ...\rho_{Ni}^{(h)}\}$ has only one element which is equal to 1 due to the searching result and other elements are zero. Thus, the messages exchanges can reach a consensus.

4.2 UAV Loss Detection Protocol

The main function of the loss detection protocol is to detect UAV failures or crashes in a multi-UAV system. The UAV loss detection protocol is given in Table 2.

The protocol is comprised of two tasks. The aim of task 1 is to find the set of suspected lost UAVs, while task 2 is to record the result of task 1. The other local variable managed by the two tasks is a timer which is used to determine if UAV q is lost.

Periodically, each UAV broadcasts its HB message and other UAVs should receive the message. If UAV p has not received a heartbeat message since time out Δ (according

Table 2 UAV loss detection protocol

Define UAV set π,time interval T,suspected UAV:q, p, r
Initial phase:
suspected = 0;
for all $q \in \pi$
Δ time out where $\Delta = 4T$
begin
Task 1: repeat periodically
For all $q \in \pi$
If $q \notin \pi$ suspected and p did not
receive heartbeat of q during the last time
suspected = suspected $\cup\{q\}$;
send lost UAV q to other processes
Task 2:
When receiving suspected r from a process
Output $\leftarrow$ Output $\cup r$
end

to GPS Time), the suspected set recomputes the values of this set and sends to task 2. When another layer receives the suspected set from task 1, it outputs the right result of the detected lost UAV set.

4.3 UAV Auto-replacement

After receiving a set of lost UAVs, the UAV will decide if it needs to do auto-replacement (UAV goes to that target position and take up the target position of the lost UAV). The criteria for selecting one UAV to implement such task are

– it must currently occupy a target with a lower priority than the lost UAV or it is not assigned to any target position;
– it should have the shortest path to the lost UAV.

According to this principle, the schematic of the auto-replacement protocol is shown in Fig. 4.

Periodically, each UAV runs this process while broadcasting the cost of itself (which is in the HB message) and obtains the costs of other UAVs through the HB messages. Under the contention scheme, each UAV will decide if it takes up the vacated target.

The auto-replacement protocol includes three tasks A, B and C. In order to reach task A, it has to be the lowest priority target point, there is an unassigned target point that is higher priority and the target is the nearest one among all the unassigned higher priority target points. In task A, it compares its distance with all UAVs which have the same target point priority and checks if it is the nearest one to the target point chosen. The way to compute the distance to the other UAV is shown in Fig. 5. In the distance check, Δ_d is defined by the user, which should be selected such that it is

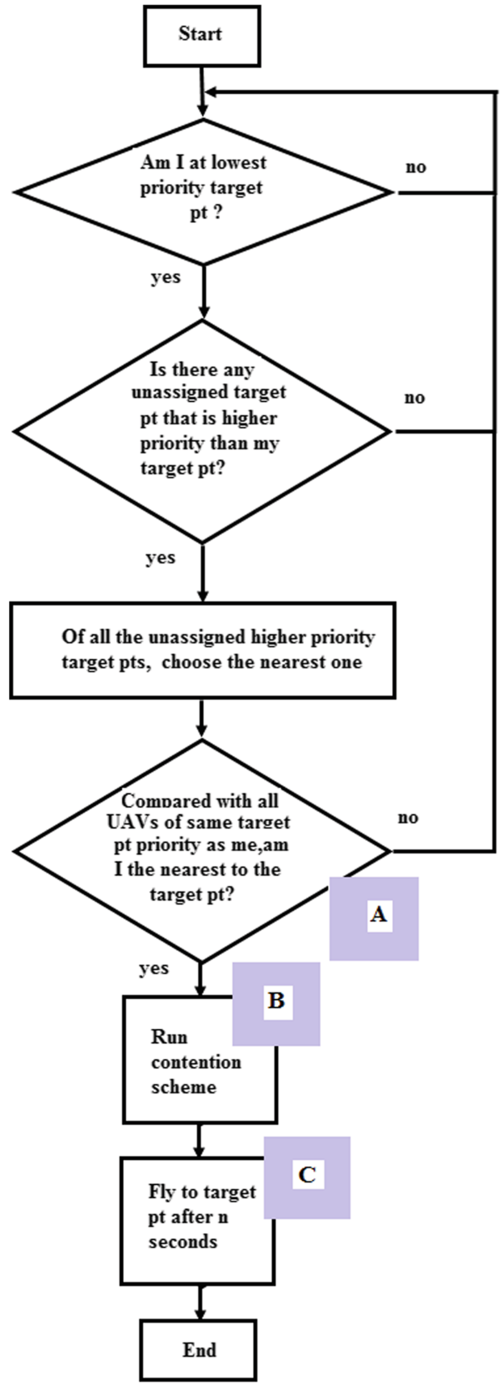


Fig. 4 Auto-replacement protocol (*pt*–point)

greater than that of GPS error and system uncertainty. The following Lemma can be obtained directly.

Lemma 4.3.1 *Assume that there is an unassigned target with higher priority and there exists one or two UAVs having the lowest priority position. By using the distance computation method described above, at least one UAV will be the nearest to the unassigned target.*

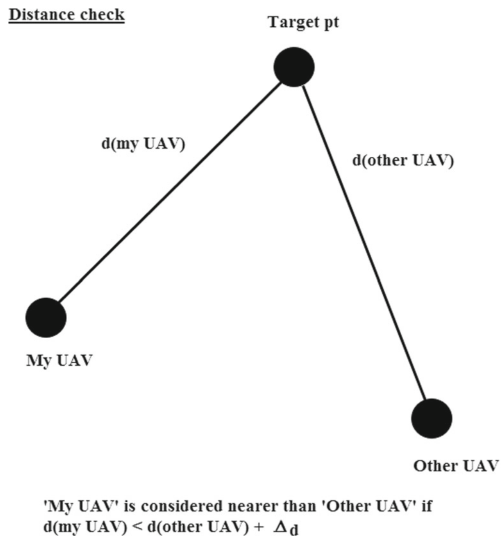


Fig. 5 Distance check: d()= distance of UAV to target *pt* (*pt*–point)

When we have many UAVs having the lowest priority position, applying Lemma 4.2.1 will guarantee that at least one UAV will be the nearest to the unassigned target. When the own UAV finds itself to be the nearest to the unassigned target position, the protocol enters task *B*—the contention scheme. This scheme guarantees that at least one UAV is assigned to the target point whenever there is an unassigned target point or even when there are communication latencies. Figure 6 shows the contention scheme details.

In Fig. 6, the cost function of the ith UAV at time k is denoted as $\text{cost}_i(k)$ which is computed by Table 3.

Table 3 Cost function computation

$d_i(k)$ = distance of the ith UAV to target pt at time k
initialize $\text{cost}_i(0) = d_i(0)$ where $k = 0$ is the time the lost UAV is detected
$\text{cost}_i(k) = \min\{\text{cost}_i(k-1), d_i(k)\}$ at time $k > 0$

Lemma 4.3.2 *Under the contention execution, the cost of each UAV in the multi UAV group*

(i) decreases monotonically;
(ii) has a finite limit as time goes to infinity.

Proof First, we prove that the cost of each UAV decreases monotonically. Assume that UAV i updates its distance to target pt at time k, i.e., that is $d_i(k)$. The cost function of UAV i can be written as

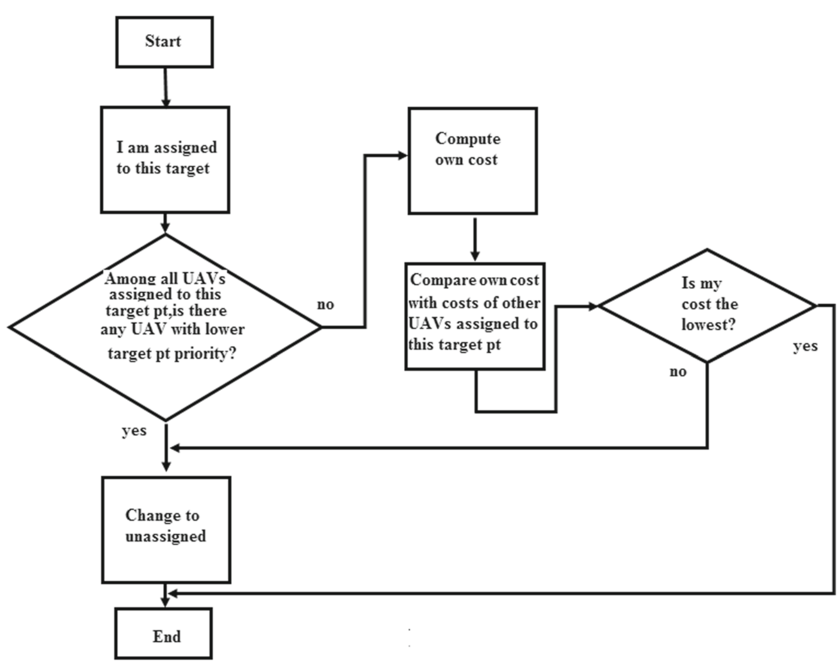
$$\text{cost}_i(k) = \min\{\text{cost}_i(k-1), d_i(k)\} \tag{4}$$

where $\text{cost}_i(k-1)$ is the cost function of the last time. When UAV i updates its distance at time $k+1$, we have the distance $d_i(k+1)$ to the target pt. It has two cases for the distance $d_i(k+1)$.

Case 1 $d_i(k+1) \geq \text{cost}_i(k)$. In this case, the cost of UAV i at time $k+1$ is given by

$$\begin{aligned}\text{cost}_i(k+1) &= \min\{\text{cost}_i(k), d_i(k+1)\}\\ &= \text{cost}_i(k)\end{aligned} \tag{5}$$

Fig. 6 Contention scheme (*pt*–point)



Case 2 $d_i(k+1) \leq \text{cost}_i(k)$. In this case, the cost of UAV i at time $k+1$ is given by

$$\begin{aligned}\text{cost}_i(k+1) &= \min\{\text{cost}_i(k), d_i(k+1)\}\\ &= d_i(k+1)\\ &\leq \text{cost}_i(k)\end{aligned} \tag{6}$$

No matter what cases we have, monotonicity holds

$$\text{cost}_i(k+1) \leq \text{cost}_i(k) \tag{7}$$

Applying the same argument, each UAV leads to monotonic decrease in the UAV group.

Next, we prove that the cost of each UAV in the UAV group has a finite limit.

Since $d_i(k) \geq 0$, this implies that the cost $\text{cost}_i(k)$ is bounded. Thus, the proof of the lemma is easy to see from the fact that a monotonically decreasing function has a finite limit according to the monotone convergence theorem. □

Remark 4.3.1 This lemma is meaningful and it implies that the cost function of each UAV cannot grow unbounded. This also implies that we can compare costs among the UAVs in the UAV group under the contention scheme.

Lemma 4.3.3 *Assume that there is an unassigned target with higher priority and there exists one or two UAVs having the lowest priority position. Under the contention scheme, by using the cost computation method described above, at least one UAV will never unassign itself to a target position even when there are communication latencies.*

Proof We first consider the case where there are no communication latencies. This is an ideal case. Since no latency, all UAVs have the same HB messages and cost assessment formula as given by

$$\min\{\text{cost}_1(k), \text{cost}_2(k), ..., \text{cost}_N(k)\} \tag{8}$$

at time k. In this case, we prove that at least one UAV is assigned to that target. According to the contention scheme, each UAV uses the same cost assessment and there exists the minimum cost among the finite elements. Thus, each UAV always finds the smallest cost. Without loss of generality, UAV i finds that the cost of UAV j is the smallest one (j may be equal to i), while UAV j realizes this fact concurrently (they have the same cost formula). If $j = i$, UAV i is assigned to that target; otherwise, UAV i withdraws and UAV j will be assigned to that target. This guarantees that at least one UAV is assigned to a target position. □

Next, we prove that the above conclusion is also true for the case where there are communication latencies. In this case, the same cost assessment formula for each UAV no longer holds. This is caused by communication latencies. From Lemma 4.3.1, it is known that there is at least one UAV entering the contention scheme. During executing this scheme, it will have two situations.

Situation 1 Only one UAV enters the contention scheme and thus it concludes that this UAV will be assigned to that vacated target according to the scheme.

Situation 2 There is one more UAV entering the contention scheme. Without loss of generality, we assume that both UAVs i and j enter the contention scheme and they have the costs, $\text{cost}_i(k)$ and $\text{cost}_j(k)$ at time k respectively. Assume that the following condition holds

$$\text{cost}_i(k) > \text{cost}_j(k) \tag{9}$$

at time k (later we will consider another condition $\text{cost}_i(k) \leq \text{cost}_j(k)$). Since communication latencies, $\min\{\text{cost}_i(k), \text{cost}_j(k)\}$ is not available for each UAV at time k, as stated above. Both UAVs i and j use the HB information which contains the costs from other UAVs, to do the cost assessment. In fact, for UAV i, it uses the cost assessment

$$\min\{\text{cost}_i(k), \text{cost}_j(k - t_L)\} \tag{10}$$

where t_L is the communication latency, while UAV j uses the cost assessment

$$\min\{\text{cost}_j(k), \text{cost}_i(k - t_L)\}. \tag{11}$$

Now, we consider all the possibilities for the cost assessment of UAV i.

i) If UAV i finds that

$$\text{cost}_i(k) > \text{cost}_j(k - t_L), \tag{12}$$

UAV i withdraws under this condition. Concurrently, UAV j finds that

$$\text{cost}_j(k) \leq \text{cost}_i(k - t_L). \tag{13}$$

Because if $\text{cost}_j(k) > \text{cost}_i(k - t_L)$, this implies that $\text{cost}_j(k) > \text{cost}_i(k)$ since $\text{cost}_i(k - t_L) \geq \text{cost}_i(k)$ due to the conclusion (i) of Lemma 4.2.2. This contradicts the condition (9). Therefore, UAV j will be assigned to that vacated target.

ii) if UAV i finds that

$$\text{cost}_i(k) \leq \text{cost}_j(k - t_L), \tag{14}$$

UAV i will be assigned. At the same time, UAV j finds that

$$\text{cost}_j(k) \leq \text{cost}_i(k - t_L). \tag{15}$$

This is because it is not possible to have $\text{cost}_j(k) > \text{cost}_i(k - t_L)$ as proved in the process i). Thus, UAV j will also be assigned.

We consider another case for both UAVs i and j, that is

$$\text{cost}_i(k) \leq \text{cost}_j(k) \tag{16}$$

at time k. Taking a similar procedure as above, we can prove that at least one UAV will be assigned under this case. In the conclusion, no matter what situations both UAVs have, at least one UAV will be assigned to that vacated target. This completes the proof.

Remark 4.3.2 When we have many UAVs having the lowest priority position, taking a similar proof procedure as in Lemma 4.3.3 we will guarantee that at least one UAV will be assigned to that vacated target.

It is possible that we have several UAVs satisfying the condition of the contention scheme, thereby flying to the unassigned target point at the same time. For example, both UAVs hover over their target positions respectively and have the same path to the unassigned target pt at time $k = 0, 1, 2, ...$ In this situation, in order to minimize it from happening, we introduce another mechanism. This is called the conflict prevention mechanism. The core of this mechanism is to assign n seconds delay in ascending order of UAV ID to those UAVs before flying to the unassigned target. The detailed mechanism is given by

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Conflict prevention mechanism:
Consider all UAVs that are assigned to
this target pt
Select those with same cost and
same previous target priority
Arrange them in ascending order of ID.
Consider m UAVs. Without loss of generality,
they are in ascending order of ID
UAV ID 1, $n = time\_interval \times (0)$
UAV ID 2, $n = time\_interval \times (1)$
......
UAV ID m, $n = time\_interval \times (m - 1)$

The parameter $time\_interval$ should be chosen as a positive number of times to the iteration time of the contention scheme loop. This parameter also depends on the communication latencies. The longer the latency, the longer the $time\_interval$ we should choose.

Lemma 4.3.4 *Consider two UAVs i and j having the same cost and distance to the unassigned target pt at time k. Assume that ID of UAV i is less than that of UAV j, and both UAVs are intended to fly to the unassigned target at the same speed v. According to the conflict prevention mechanism, reset the costs of UAVs i and j as $d_i(k)$ and $d_j(k)$ at time k respectively, the cost of UAV i is less than that of UAV j in a finite time.*

Proof According to the conflict prevention mechanism, we have n seconds delay for UAV i and j □

UAV ID i, $n = 0$
UAV ID j, $n = time\_interval$.

Consider the both UAVs at current time k. This implies that UAV i goes to the unassigned target immediately at time k, while UAV j stops at its current position until time $=k + time\_interval$. The cost of UAV i at time k is reset by

$$\text{cost}_i(k) = d_i(k) \tag{17}$$

After an iteration time updates, the distance of UAV i at time $k + 1$ is given by

$$d_i(k+1) = d_i(k) - v \times iteration\_time \tag{18}$$

Since $v > 0$, this implies that

$$d_i(k+1) < d_i(k). \tag{19}$$

This also implies that

$$\begin{aligned} \text{cost}_i(k+1) &= \min\{\text{cost}_i(k), d_i(k+1)\} \\ &= d_i(k+1) \\ &< d_i(k) \\ &= \text{cost}_i(k) \end{aligned} \tag{20}$$

However, at time $k+1$, UAV j stops at its location as at time k, due to the conflict prevention mechanism. This implies that

$$d_j(k+1) = d_j(k) \tag{21}$$

Resetting the cost of UAV j, this also implies that

$$\begin{aligned} \text{cost}_j(k+1) &= \min\{\text{cost}_j(k), d_j(k+1)\} \\ &= \text{cost}_j(k) \end{aligned} \tag{22}$$

Since $\text{cost}_j(k) = \text{cost}_i(k)$ at time k, this implies that at time $k + 1$, we have

$$\text{cost}_i(k+1) < \text{cost}_j(k+1) \tag{23}$$

where we have used the equations (17) and (20).

Remark 4.3.3 Taking a similar proof procedure as in the Lemma 4.3.4, even when many UAVs have the same path to the target pt, only the cost of one UAV which is smallest ID among other UAVs, is less than those of other UAVs. This will guarantee only one UAV going to do auto-replacement to the unassigned target pt in a finite time. Thus, we have the following theorem.

Theorem 4.3.1 *Assume that there is an unassigned target with higher priority and there exists at least one UAV having the lowest priority position. By applying the auto-replacement protocol to each UAV, we guarantee that only one UAV in the multi-UAVs system willtake up the vacated target.*

Table 4 Target and control mode of ten UAVs

UAV ID	Target	Way points	Control mode
UAV 0	$(T0, 3)$	$T0 = \{(150, 0)\}$	Hover
UAV 1	$(T1, 1)$	$T1 = \{(110, 1)\}$	Hover
UAV 2	$(T2, 3)$	$T2 = \{(-100,50)\}$	Hover
UAV 3	$(T3, 3)$	$T3 = \{(-50, -50)\}$	Hover
UAV 4	$(T4, 3)$	$T4 = \{(-150,-50), (-150,100)\}$	Patrol
UAV 5	$(T5, 3)$	$T5 = \{(-120,-150), (70,-150)\}$	Patrol
UAV 6	$(T6, 3)$	$T6 = \{(50,120), (-100,120)\}$	Patrol
UAV 7	$(T7, 1)$	$T7 = \{(150,-150)\}$	Hover
UAV 8	$(T8, 3)$	$T8 = \{(200, -200),(210,0),$ $(180,70),(200,80),(210,110),(230,130)\}$	Patrol
UAV 9	$(T9, 1)$	$T9 = \{(100, -80)\}$	Hover

$(Ti,3)$ where 3 is low priority point; $(Ti,1)$ where 1 is high priority point

Recovery Algorithm of UAV C_i.

Initial State: UAV C_i is set to unassigned state
UAV C_i does information fusion and
gets its HB
UAV C_i broadcasts its HB to other UAVs
while unassigned targets are not assigned to
any UAV **do**
Call Auto-Replacement Logic
UAV C_i gets its target, flying to the target
end while
End State: UAV C_i reaches its target

Remark 4.3.4 The report [25] proposes a re-planning method for the UAV group if one UAV is lost. However, it does not give any logic and design details; only the mathematical equation for the cost optimization. Since each target has priority in our control task, the auto-replacement strategy becomes more complex involving target priority, shortest path to the target, cost function and conflict prevention mechanism, and therefore the method of [25] is not suitable for our problem. In addition, it should be noted that the proposed auto-replacement method is a dynamical process and it does auto-replacement continuously until the replacement UAV reaches to the unassigned target.

4.4 Recovery of the Lost UAV

It is possible to recover a lost UAV. For example, the lost UAV may re-connect to the network again and become a normal UAV. In this situation, it will set itself to unassigned status, even it knows its last target position, and it has to use the auto-replacement logic to find an unassigned target at this moment. The detailed algorithm is shown in the Recovery Algorithm.

5 Simulation

To evaluate the proposed UAV loss detection, auto-replacement and recovery scheme, simulation test is conducted. The simulation involves multiple UAVs assuming each UAV is embedded with the proposed algorithm. In addition, collision avoidance is also a requirement in designing a multi UAV system. To perform our task, it is necessary to ensure each UAV can reach its target without colliding with any moving or static obstacles. In this paper, the velocity obstacle (VO) method [26] is used for collision avoidance.

Table 4 shows the target and control mode of ten of the UAVs. Ten UAVs fly to the waypoints assigned by the ground control station. Some UAVs are in the hover mode, while others are in the patrol mode. For each UAV, the safety radius required is 15 m, while the flight altitude is 60 m.

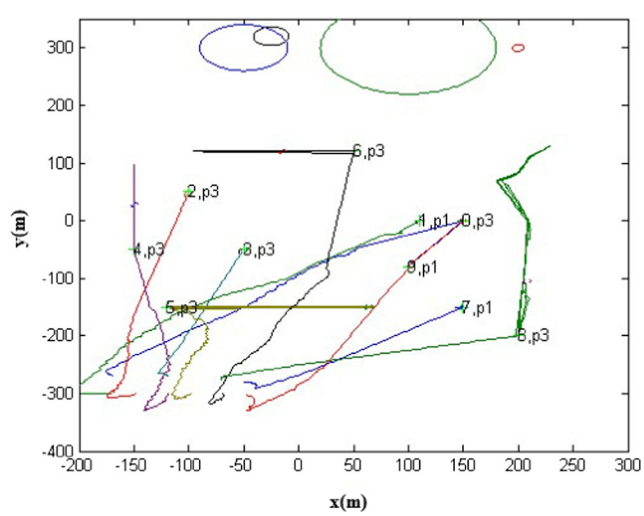


Fig. 7 Case 1– Ten UAVs performed the missions (2-D): circle represents static obstacles

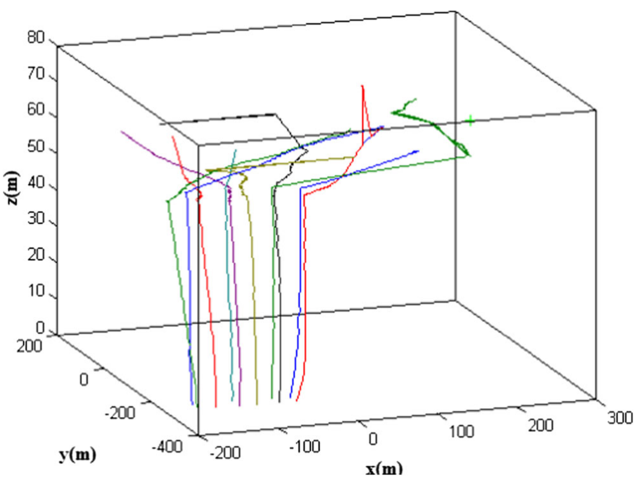


Fig. 8 Case 1– Ten UAVs performed the missions (3-D)

Case 1 It is assumed that UAV 9 with high priority target ($p1$) lost connection with the other UAVs at time = 320 s and climbed up to a height of about 75 m for safety reason. Thus, the target position $T9$ was empty. Those UAVs with low priority target used HB information to run the auto-replacement logic to decide which UAV to take up the target position. UAV 0 at low priority target (p3) found it was the closest to the target position of the lost UAV 9 and decided to take up the vacated target. Later, at time = 450 s, UAV 9 re-connected to the other UAVs and joined the network again. It used the recovery algorithm to occupy an empty target position. Figure 7 shows all flight paths of ten UAVs over the x and y-axes, while Fig. 8 shows all flight paths of ten UAVs in 3D space. Figure 9 shows the profile of the separation distance from UAV to UAV along the horizontal direction. It is observed that all the separation distances are above safe distance 30 m, except that one curve of the separation distance is almost zero during the time interval 320–450 s.

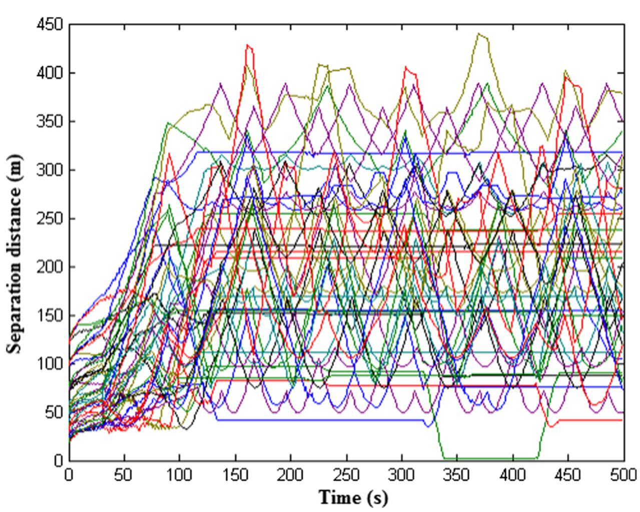


Fig. 9 Case 1–Profile of the separation distance of ten UAVs (2-D)

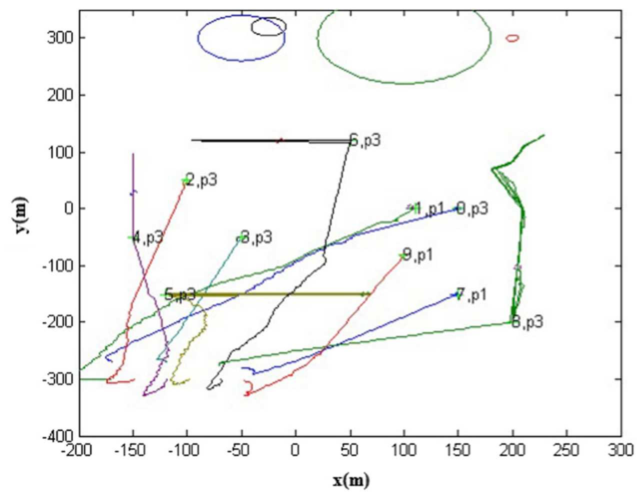


Fig. 10 Case 2–Ten UAVs performed the missions (2-D): circle represents static obstacles

This is because UAV 0 took up the target position of UAV 9, thereby resulting in UAV 0 and UAV 9 having the same position in the horizontal direction but staying at different altitudes safely. Thus, all UAVs have implemented their missions without colliding with any moving UAVs.

Case 2 It is assumed that UAV 0 with low priority target ($p3$) lost connection with the other UAVs at time = 320 s and climbed up to a height of about 75 m for safety purposes. Thus, the target position $T0$ was empty. Those UAVs at low priority target used the auto-replacement algorithm to decide which UAV to take up the target position assigned to UAV 0. Since target $T0$ is low priority, there are no UAVs replacing the target $T0$ according to the auto-replacement algorithm. Later, at time = 450 s, UAV 0 re-connected to the other UAVs. It found that the target $T0$ was unassigned and decided to occupy $T0$ again according to the recovery algorithm. Figure 10 shows all flight paths

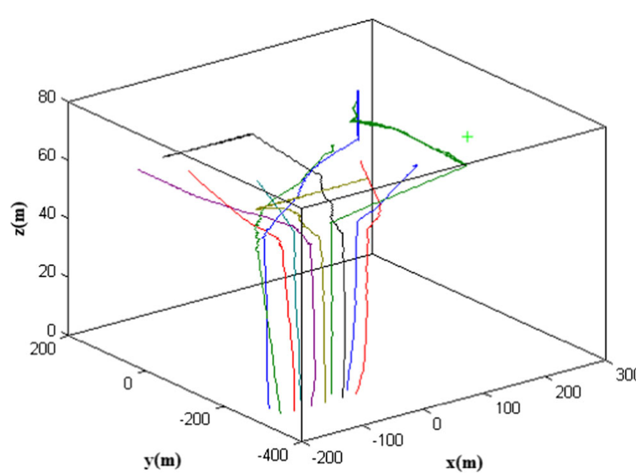


Fig. 11 Case 2–Ten UAVs performed the missions (3-D)

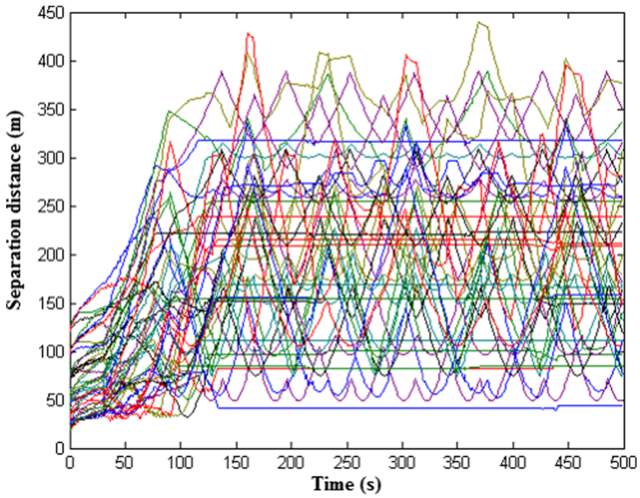


Fig. 12 Case 2–Profile of the separation distance of ten UAVs (2-D)

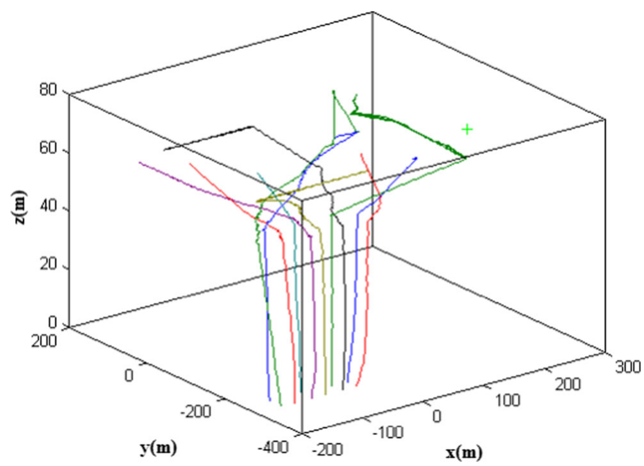


Fig. 14 Case 3– Ten UAVs performed the missions (3-D)

of ten UAVs over the x and y-axes, while Fig. 11 shows all flight paths of ten UAVs in 3D space. Figure 12 shows the profile of the separation distance from UAV to UAV along the horizontal direction. It is observed that all the separation distances are above safe distance 30 m. This has verified that all UAVs have implemented their missions without colliding with any moving UAVs.

Case 3 It is assumed that UAV 1 with high priority target ($p1$) lost connection with the other UAVs at time = 320 s and climbed up to a height of about 75 m for safety purposes. Thus, the target position $T1$ was empty. Those UAVs with low priority target used the auto-replacement algorithm to decide which UAV to take up the target position assigned to UAV 1. UAV 0 with low priority target (p3) found it was the closest to the target position of the lost UAV 1 and decided to take up the vacated target. Later, at time = 450 s, UAV 1 re-connected to the other UAVs and joined the network again. It used the recovery algorithm to occupy an empty target position. Figure 13 shows all flight paths of ten UAVs over the x and y-axes, while Fig. 14 shows all flight paths of ten UAVs in 3D space. Figure 15 shows the profile of the separation distance from UAV to UAV along the horizontal direction. It is observed that all the separation distances are above safe distance 30 m, except that one curve of the separation distance is almost zero during the time interval 320–450 s. Similar to Case 1, we have the same explanation to this situation. This is because UAV 0 took up the target position of UAV 1, thereby resulting UAV 0 and UAV 1 having the same position in the horizontal direction but staying different altitudes safely. Thus, all UAVs have implemented their missions without colliding with any moving UAVs.

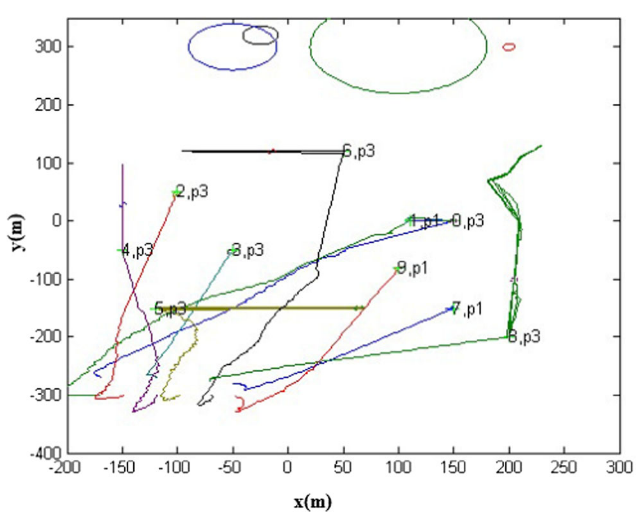


Fig. 13 Case 3– Ten UAVs performed the missions (2-D): circle represents static obstacles

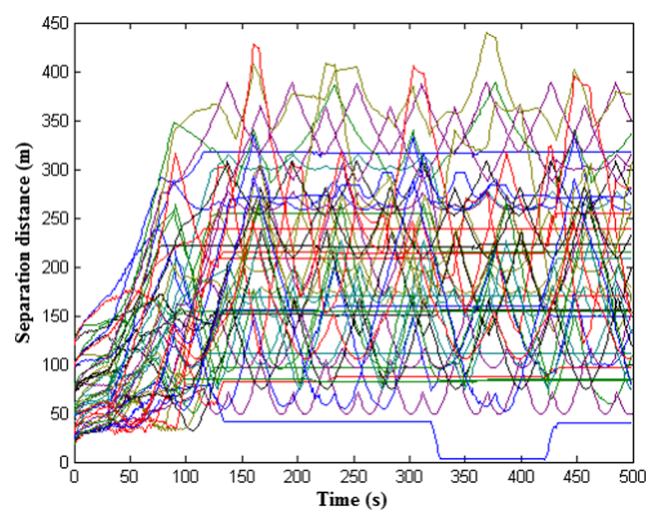


Fig. 15 Case 3–Profile of the separation distance of ten UAVs (2-D)

6 Experiment

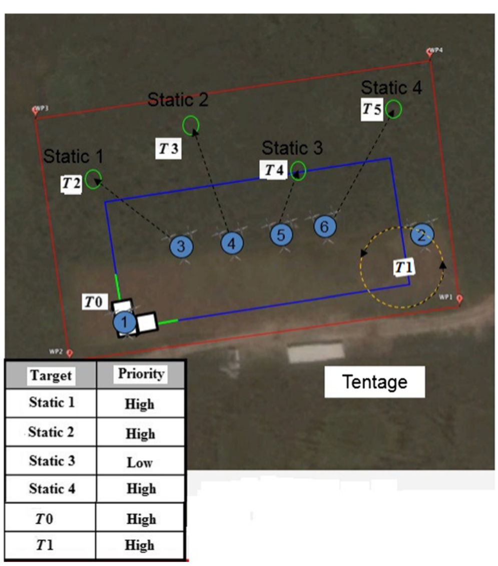
In this section, the proposed method is illustrated by experimental tests. We have the following test objectives:

- To verify one UAV will perform primary link loss logic profile
- To verify UAV auto-replacement logic when low priority static UAV will replace the failure UAV
- To verify UAV recovery logic when the lost UAV will connect to the network

Six UAVs performed their missions. Figure 16 shows the test scenario. One UAV is required to go to the target $T0$ which is in the patrol mode, while another UAV goes to the target $T1$ which is in the orbit mode. The other UAVs are required to go to stationary targets 1–4. At a certain time, one UAV will perform link loss. After detecting the lost UAV, the remaining UAVs use the auto-replacement algorithm to take up the vacated target. Later, the lost UAV re-connects to other UAVs and finds the unassigned target using the recovery algorithm. Finally, all UAVs are required to recover to the recovery points.

Figure 17 shows the flight paths of six UAVs, where

UAV 514 $\longrightarrow T0$
UAV 515 $\longrightarrow T1$
UAV 516 $\longrightarrow T3$
UAV 517 $\longrightarrow T2$
UAV 520 $\longrightarrow T5$
UAV 521 $\longrightarrow T4$



Target	Priority
Static 1	High
Static 2	High
Static 3	Low
Static 4	High
$T0$	High
$T1$	High

Fig. 16 Test scenario

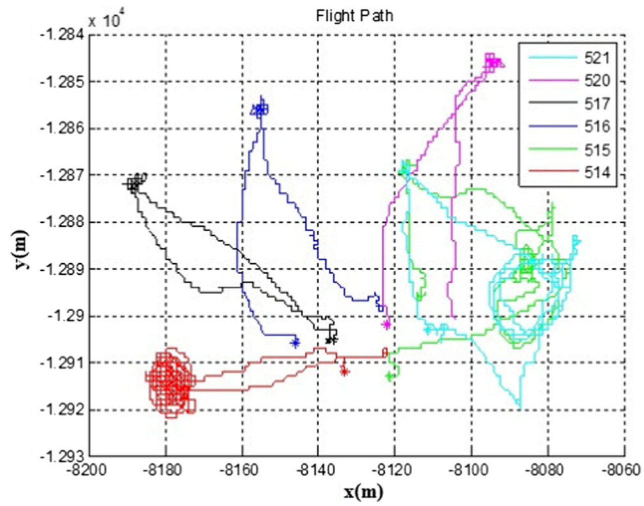


Fig. 17 Flight paths of Six UAVs (horizontal plane)

The target $T1$ represents an orbit motion with 10 m radius, where we use four points to approximate orbit trajectory. In the experiment, UAV 515 was simulated to do link loss and it climbed up to a 25 m for safety purposes. After UAV 515 performed link loss logic, the remaining UAVs 514,516,517,520,521 used the heartbeat information to perform the auto-replacement logic. UAV 521 staying at the target $T4$, found it was the shortest distance to $T1$ and decided to take up the vacated $T1$ according to the auto-replacement algorithm. Figure 18 shows the flight path of UAV 521 when performing its mission. Later, UAV 515 re-connected to the other UAVs and found the unassigned $T4$. Thus, it went to Static 3 ($T4$). The flight path of UAV 515 during the test is shown in Fig. 19. All the test objectives have been achieved.

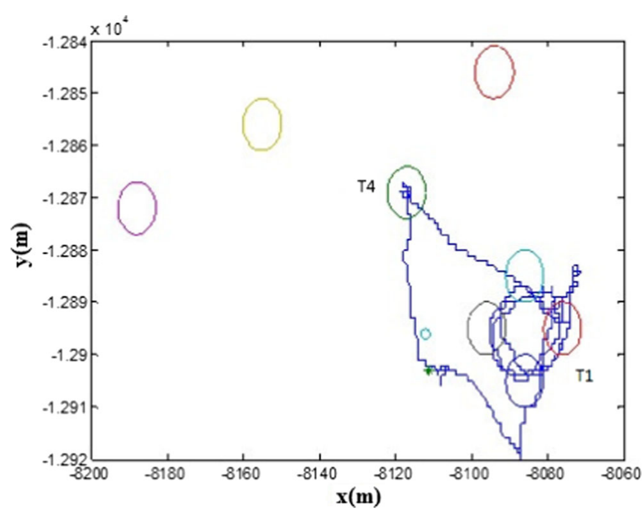


Fig. 18 Flight path of UAV 521(horizontal direction): it was launched first and going for static hover target $T4$. After that, it found one UAV (UAV 515) is lost and did do an auto-replacement to the target $T1$. Finally, it executed the command to recover to home (star represents home)

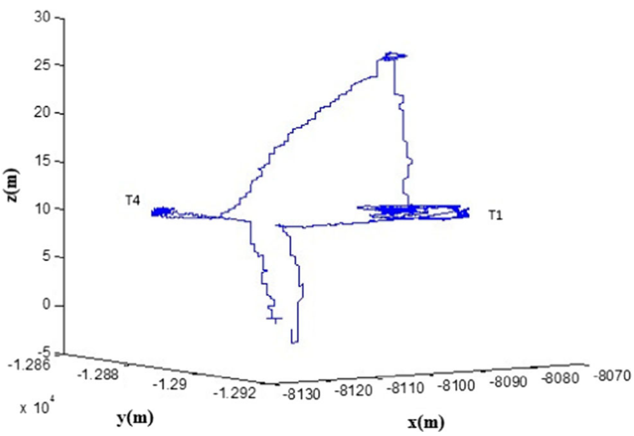


Fig. 19 Flight path of UAV 515: it was launched first and going for orbit motion $T1$. At a certain time, it was lost. Later, it was re-activated to be a normal UAV again and occupied an empty target $T4$. Finally, it recovered to home

7 Conclusions

This paper has presented a solution for the cooperative control of the multi UAV system when UAVs have failures. The simulation and experimental tests have verified that the multi-UAVs system can implement UAV loss detection and auto-replacement mission by collaboration with one another. In future research, we will incorporate the proposed method into the coverage control problem of swarm systems.

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