Reconnaissance Target Grouping and Assignment Considering Fault Severity for UAV Swarm

Taegyun Kim[1], Jingu Kim[2], Ilwon Seo[2] and Seungkeun Kim[1] *
[1] Chungnam National University, Republic of Korea
[2] Poongsan R&D Institute, Republic of Korea

Abstract

This study proposes an optimal task assignment algorithm by using the Hungarian algorithm considering the fault severity and the number of targets. In order to ensure that the efficiency of the swarm reconnaissance mission does not decrease even under the UAV fault, the distance to the targets and the reconnaissance target maximum number are considered as costs. First, we construct the cost calculation formula according to the degree of fault by defining the fault severity. Second, target grouping is performed using the k-means algorithm. Then, to analyze the performance of the proposed algorithm, the simulations are done according to the target number and the ratio of faulty UAVs in the swarm.

1 Introduction

1.1 Background

Unmanned aerial vehicles (UAVs) are employed in various real-life applications, such as surveillance and reconnaissance. Because of their ability to reduce the risk to humans and provide cost-effective options that can be used in several conditions where the operating system cannot be used. With the development of communication technology, multiple UAVs, the swarm flight, can simultaneously perform missions. A group of UAVs can acquire more data and occupy a wider area during surveillance and reconnaissance missions than a single UAV [1]. In addition, the survival rate is higher than when a single UAV is operated on the battlefield. However, even if rotary UAVs have been studied and operated due to their vertical flight capability, they sometimes experience accidents and get a fault. In order to overcome the problem of fault during flight operation, it is important to diagnose the fault and assign and proceed with the mission thereafter.

1.2 Related work

Recently, various studies have been conducted to optimize swarm task assignments by using the Hungarian algorithm [2]–[3]. Amir *et al.* propose a matching algorithm; it matches the UAV to the best nesting station considering UAV's energy and distance to the station [4]. Arezoo *et al.* proposed an algorithm, namely, the Duplicate Agent Hungarian Based Algorithm, for task allocation for UAV package delivery [5]. Moon *et al.* studied and developed an approach to reduce the maximum UAV movement distance to increase the operating time using the Fair Hungarian Algorithm [6]. From the above research cases, it can be seen that the Hungarian Algorithm is widely used for task assignments during swarm missions.

*Email address: skim78@cnu.ac.kr

1.3 Main contribution

In this study, the cost calculation is different according to the fault condition by giving the classification of fault severity. Through this, it is possible to perform the optimal task assignment of the swarm. The main contribution in this study are summarized as follows.

The first contribution is the swarm task assignment algorithm considering the fault severity, which can increase the efficiency of mission performance even if the fault occurs during swarm operation.

The second contribution is to minimize each UAV's movement distance and maximize the number of reconnaissance targets to improve swarm operation performance.

Lastly, since the proposed algorithm can calculate only the fault diagnosis result, it can be linked with various fault diagnosis modules.

This paper is organized as follows: Section 2 defines the fault severity and shows the target clustering by the k-means algorithm. Afterwards, the task assignment algorithm constructed based on the Hungarian algorithm will be described. Section 3 compares the performance of the minimization distance algorithm and the proposed algorithm by simulating them in the same environment. Section 4 offers conclusions of the paper with future work.

2 Considering Fault Severity for UAV Swarm

2.1 Fault severity definition

In performing a flight mission, fault situations occur due to various factors. In this process, there may be cases in which missions can be performed limitedly due to prop damage, etc., or mission continuation is impossible due to a fault of the actuator. Therefore, in order to increase mission efficiency and success rate, it is necessary to assign different missions according to the fault severity. The more severe the fault of the UAV, the lower its mission capability can be. Therefore, by defining the severity of such fault, it is

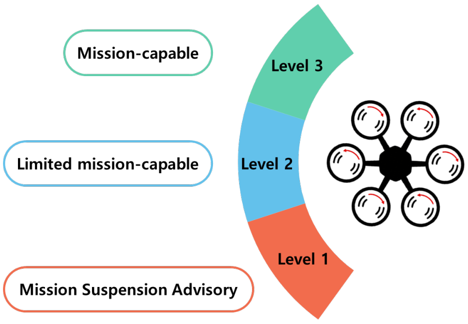


Figure 1: Definition of the fault severity

necessary to classify the task performance. Figure 1 is a definition of the severity levels according to the fault.
In this paper, the UAV severity of the fault is classified into three levels. Level 3 is a mission-capable state, which is non-faulty or close to a healthy state that can carry out the mission. Level 2 is a limited mission-capable state, where failures have occurred but are not fatal to continue missions. Level 1 is a mission suspension advisory state, and a fatal fault occurs, and the UAV must be returned home.

2.2 *Target grouping*

In order to allocate multi targets to available UAVs, clustering is performed according to the number of UAVs. So, the k-means algorithm is used for target clustering. K-means clustering [7] is an iterative, data-partitioning algorithm that assigns n observations to precisely one of the k clusters defined by centroids, where k is chosen before the algorithm starts. In this study, n is the total number of targets, and k is the number of UAVs capable of reconnaissance missions. Fiugre 2 shows a flow chart of the target grouping algorithm.

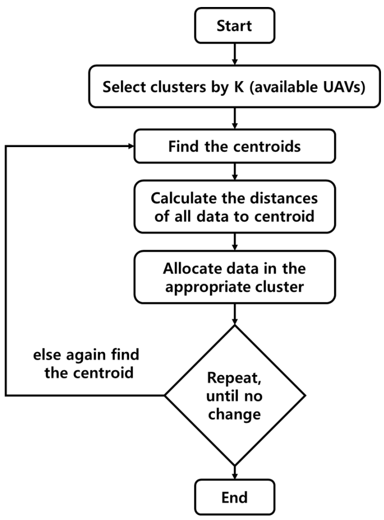


Figure 2: A flow chart of the target grouping algorithm

The center of the target cluster is calculated using the k-means++ algorithm. For $m = 1, ..., n$ and $p = 1, ..., j–1$, select centroid j at random from X with probability k-means++ algorithm is as follows:[8].

$$\frac{d^2(x_m, c_p)}{\sum_{h;x_h \in C_p} d^2(x_m, c_p)} \tag{1}$$

where $d(x_m, c_j)$ denote the distance between c_j and observation m, c_p is the set of all observations closest to centroid c_p and x_m.

2.3 *Task assignment algorithm*

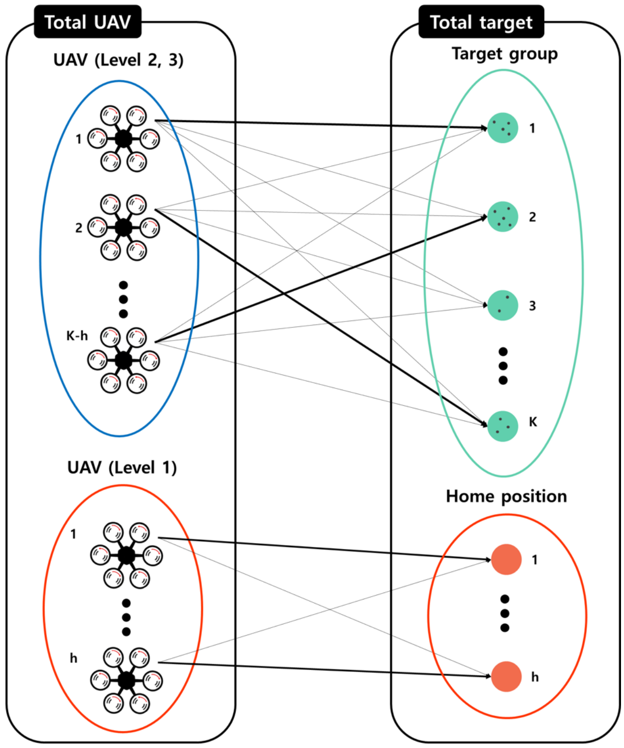


Figure 3: Bipartite graph (Task assignment)

In this paper, we decouple the problem into two sequential optimization subproblems. The first subproblem allocates reconnaissance locations where the center of the target cluster. The second subproblem is to find the optimal task assignment for each UAV using the fault severity level. The assumptions of this paper are as follows:

1) Throughout the allocation process, the attributes of all UAVs and tasks are unchanged.
2) Each UAV knows its own and other UAVs' datas and the number of tasks.
3) All UAVs at each level is controlled through fault tolerance control. However, in the case of level 1, it is assumed that the mission continuation is impossible, and a return to home is necessary.

Figure 3 illustrate the proposed algorithm for task assignment by a bipartite graph. k is the number of total UAVs and h is the number of level 1 UAVs. The proposed task assignment algorithm is based on a Hungarian algorithm. The Hungarian algorithm is an optimization method for solving assignment problems to maximize or minimize a cost [9]. In this problem, the main goal is to minimize the distance and maximize the target number under successful reconnaissance. The assignment problem is summarized in Algorithm 1.

C is a $k \times k$ cost matrix that can be computed using the attributes of agents and tasks. X is the assignment matrix. $cost$ is the overall cost. w_{i1} is a weight of each level i. $dist$ is the distance between the UAV and the target cluster center, and $dist_{max}$ is the maximum distance from the target cluster center that the UAV can reconnaissance. $dist_h$ means distance from the UAV to home position. $target_n$ is the number of targets in the cluster. The cost calculation is different according to the determined fault diagnosis severity in the proposed algorithm. Level 3 UAVs put more weight on reconnaissance over many targets rather than minimum distances, and Level 2 UAVs put more weight on going minimum distances.

Algorithm 1 Task Assignment by Hungarian Algorithm

procedure $(X, cost)$ = Hungarian(C)
  $0 \leq w_{31} < w_{21} \leq 1$
  if Level 3 **then**
    $C = w_{31}\frac{dist}{dist_{max}} + (1 - w_{31})\frac{1}{target_n}$
  end if
  if Level 2 **then**
    $C = w_{21}\frac{dist}{dist_{max}} + (1 - w_{21})\frac{1}{target_n}$
  end if
  if Level 1 **then**
    $C = dist_h$
  end if
Step 1 : Subtract the smallest cost in each row from all the costs of its row.
Step 2 : Subtract the smallest cost in each column from all the costs of its column.
Step 3 : Draw lines through appropriate rows and columns so that all the zero costs of C are covered and the minimum number of such lines is used.
Step 4 :
  procedure Test for optimality :
    if the minimum number of covering lines is k, an optimal assignment of zeros is possible and the assignment is finished. **then**
    end if
    if the minimum number of covering lines is less than k, an optimal assignment is not yet possible. Proceed to Step 5. **then**
    end if
Step 5: Determine the smallest cost not coverd by any line. Subtract this cost from each uncovered row, and then add it to each covered column. Return to Step 3.
  end procedure
Return X and $cost$
end procedure

3 NUMERICAL RESULT AND DISCUSSION

3.1 Simulation setup

In this scenario, we operate k UAVs and reconnaissance as many as possible out of n targets in clusters. In addition, it aims to efficiently operate the reconnaissance range by adjusting the reconnaissance distance according to the severity of the UAV fault. To have a better result in the target amount and distance of the reconnaissance task assignment problem, Figure 4 shows a mission problem example where several UAVs are in the swarm considering fault severity. The simulation compares the performance of the proposed algorithm with the algorithm that minimizes only the movement distance. The variables used for the simulation are the total number of targets and the rate of faulty UAVs within the swarm. The performance criterion compares the number of targets under successful reconnaissance to the distance each UAV has moved.

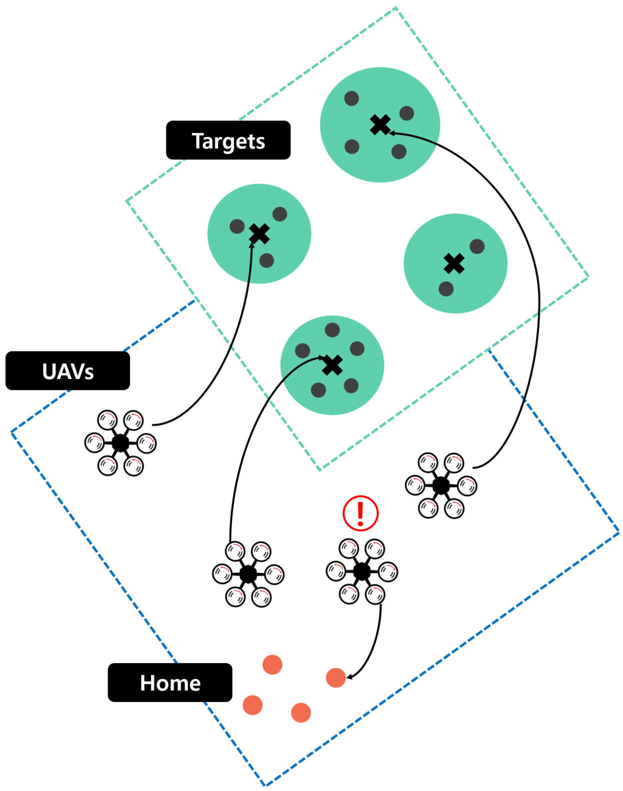
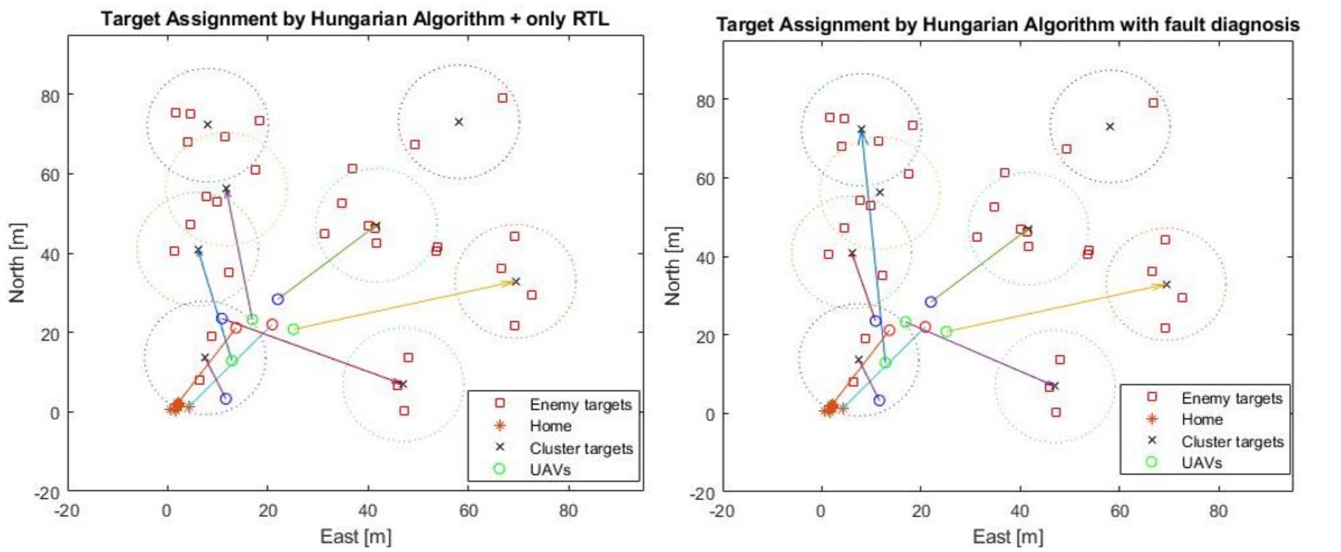


Figure 4: Mission problem description



(a) The case that minimizes only the movement distance

(b) Proposed algorithm

Figure 5: Case 1 simulation

Target number	20		30		50		70	
	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm
Search target	14	15	23	25	31	37	48	58
Level 3 UAVs average distance	27.27 m	40.39 m	36.01 m	46.56 m	26.11 m	54.51 m	42.01 m	57.81 m
Level 2 UAVs average distance	31.35 m	21.73 m	26.03 m	18.78 m	24.75 m	17.04 m	30.18 m	22.83 m

Table 1: Comparison of the algorithm performances (case 1)

3.2 Simulation results

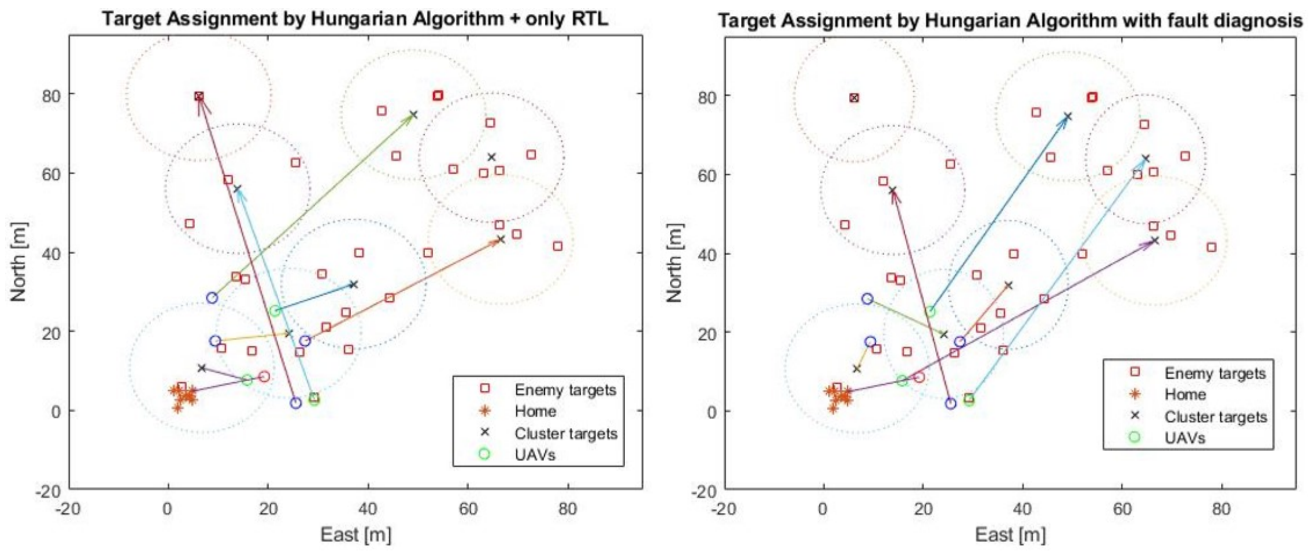
3.2.1 Case 1 Simulation : Total target number

In this scenario, we operate 8 UAVs assuming that the swarm is operated with 3 units of 'Level 3', 3 units of 'Level 2', and 2 units of 'Level 1' to compare the performance of the allocation algorithm while changing the total number of targets. In this simulation, it is assumed that the maximum range that the UAV can reconnaissance is fixed. The simulation is performed when the number of targets is 20, 30, 50, and 70 to compare the performances. Figure 5 (a), (b) shows simulation results when the number of targets is 30 using by minimizing only the movement distance algorithm(a) and proposed algorithm(b), respectively. The green, blue, and red circles are Level 3, Level 2, and Level 1 UAVs.

Referring to Figure 5(a), only the minimum distance between each UAV and cluster target is considered and assigned to the nearest cluster target location. Because the fault severity is not considered, the UAV with the fault is assigned to a distant location. On the other hand, when using the proposed algorithm, as shown in Figure 5(b), the Level 3 UAV goes to a distant place. The Level 2 UAV is assigned to a relatively nearby location. Table 1 compares the average performances of 30 simulations of two cases according to the number of targets. The proposed algorithm assigns the Level 3 UAV to a more distant location on average, and the Level 2 UAV to a nearer location in all simulation cases. Also, more targets could be under successful reconnaissance by considering the number of targets in the cost.

3.2.2 Case 2 Simulation : Rate of fault UAVs

Case 2 simulation compares and analyzes the performance according to the rate of faulty UAVs. We operate 8 UAVs, and the performance in the same environment is compared while changing the ratio of Level 3 and Level 2 UAVs. In Figure 6(a), (b) a simulation results are given when the number of targets is 30. The swarm is operated with 3 units of 'Level 3', 4 units of 'Level 2', and 1 unit of 'Level 1'. When the proposed algorithm is used, the movement distance of the Level 3 UAV increases, but the movement distance of the Level 2 UAV decreases compared to the minimized distance



(a) The case that minimizes only the movement distance (Level 2: 4)

(b) Proposed algorithm (Level 2: 4)

Figure 6: Case 2 simulation

Faulty UAV number	Level 3 : 5 Level 2 : 2 Level 1 : 1		Level 3 : 4 Level 2 : 3 Level 1 : 1		Level 3 : 3 Level 2 : 4 Level 1 : 1		Level 3 : 2 Level 2 : 5 Level 1 : 1	
	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm
Search target	27	27	26	28	26	29	26	26
Level 3 UAVs average distance	42.31 m	52.30 m	32.78 m	57.24 m	35.33 m	59.65 m	36.62 m	80.18 m
Level 2 UAVs average distance	43.81 m	13.75 m	29.33 m	24.15 m	49.17 m	30.12 m	40.15 m	30.21 m

Table 2: Comparison of the algorithm performances (case 2)

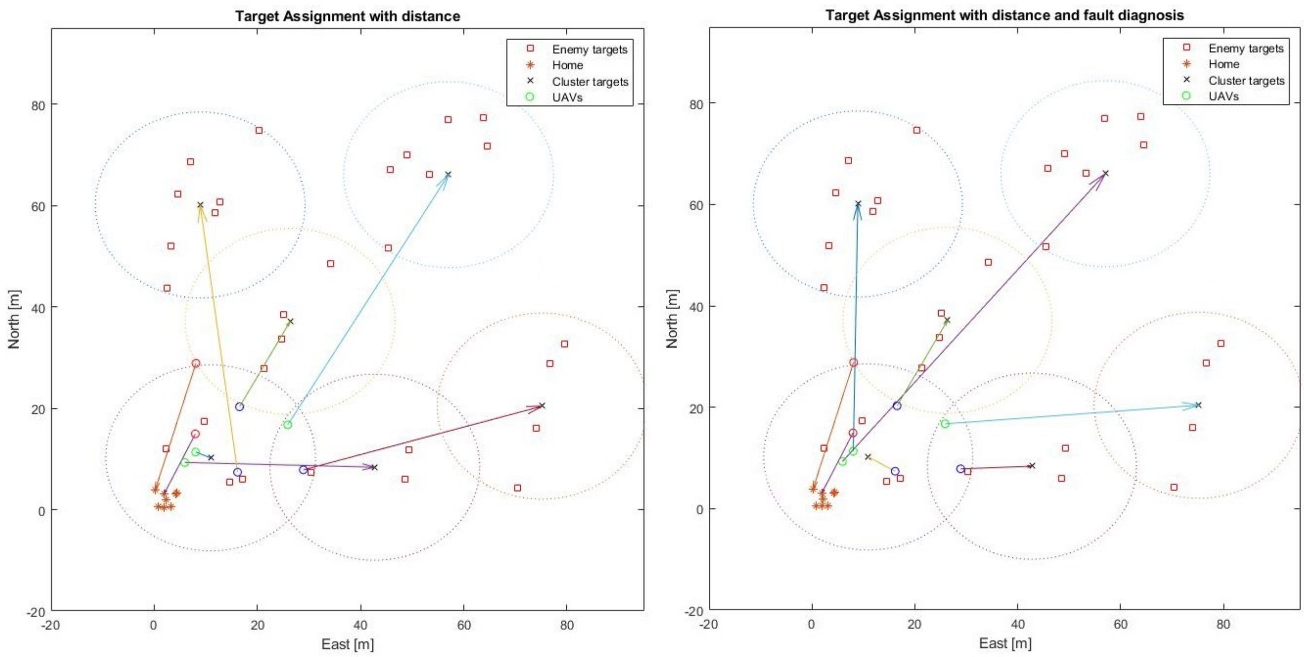
algorithm in the same way as in the case 1 simulation. Table 2 compares the average performances of 30 simulations of the distance minimizing algorithm and the proposed algorithm according to the rate of fault UAVs.

In most cases, the proposed algorithm monitered more targets than distance minimizing algorithm. However, if there are much more Level 3 UAVs or even more Level 2 UAVs, they all have the same number of targets found. It is judged that similar results were obtained because the effect was reduced by giving weight according to the level while being driven to one side. Nevertheless, the movement distance of the Level 2 UAV was reduced in all cases. In some cases, the distance minimizing only algorithm can be seen that Level 2 moves more than Level 3. These results mean that the proposed algorithm can operate the faulty UAVs more efficiently.

3.2.3 Case 3 Simulation : All target assignments

In Case 3, simulation compares the performance when the clustering algorithm is performed only with Level 2 and 3 aircraft that can participate. We operate 8 UAVs assuming that the swarm is operated same condition with case 1 scenario. In Figure 7 (a), (b) a simulation results are given when the number of targets is 30. In Figure 7 (a), (b), each UAV is assigned to a close target cluster before considering the severity of faults. However, using the proposed algorithm, it can be confirmed that the Level 3 UAV is a little further away and is assigned to a swarm with many targets.

Table 3 shows the performance comparison of Level 3 UAV and Level 2 UAV according to the total number of targets. 50 simulations were performed with the same scenario, and the average values are summarized in Table 3. Level 3 target means the sum of the number of targets assigned to Level 3 UAV, and Level 2 target means the sum of the number of targets assigned to Level 2 UAV. When the proposed algorithm is applied, fewer targets are assigned to the Level 2 UAV than



(a) The case that minimizes only the movement distance

(b) Proposed algorithm

Figure 7: Case 3 simulation

Target number	20		30		50		70	
	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm	Distance minimizing	Proposed algorithm
Level 3 target	10	10	15	19	26	31	37	47
Level 2 target	10	10	15	11	24	19	33	23
Level 3 UAVs average distance	49.24 m	65.16 m	32.78 m	58.19 m	17.30 m	52.14 m	37.04 m	54.29 m
Level 2 UAVs average distance	32.70 m	17.32 m	40.22 m	13.11 m	56.46 m	24.66 m	31.32 m	19.16 m

Table 3: Comparison of the algorithm performances (case 3)

when only the distance is considered, and the Level 2 UAV moving distances are shorter than only distance considered cases.

4 CONCLUSION

This paper proposes a task assignment algorithm for optimal target reconnaissance considering the severity of faults for swarm UAV operations. The fault severity was defined in three levels according to the degree of fault, and the cost calculation was summarized accordingly. The calculated cost was optimized based on the Hungarian algorithm, and the target reconnaissance mission assignment was performed based on this result. Targets were clustered based on the k-means clustering algorithm to maximize reconnaissance targets.
To verify the performance of the proposed algorithm, simulations were performed in the same environment as the algorithm considering only the distance minimization. When using the proposed algorithm, the movement distance of the Level 2 UAV was reduced, and at the same time, more targets could be monitored. As future research, it is planned to perform a swarm flight test after assigning a mission in conjunction with a real-time fault diagnosis module.

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