공학석사학위논문

Distributed Task Assignment for UAV Air Strike Package Based on CBBA Algorithm

무인기 공격편대군 운용을 위한 CBBA 기반 분산형 임무할당

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이 논문을 공학석사 학위논문으로 제출함

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최슬기의 공학석사 학위논문을 인준함

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Abstract

Distributed Task Assignment for UAV Air Strike Package Based on CBBA Algorithm

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In this thesis, a distributed task assignment algorithm is proposed for the air strike package mission of heterogeneous unmanned areal vehicles(UAVs) based on the consensus-based bundle algorithm(CBBA). Air Strike Package mission can be modeled as a task assignment problem that multiple UAVs perform various actions by their respective roles. The UAVs participating in the operation consist of strike force for the destruction of enemy’s ground targets, SEAD(Suppression of Enemy Air Defense) for the neutralization of enemy's air defense system, and counter-air for the protection of UAV from the enemy’s air-to-air threat. In this study, a distributed task assignment algorithm considering path-planning in presence of SAM(Surface-to-Air Missile) and terrain obstacle is proposed, which is applied to complex air strike package mission based on the characteristics of the ground target and various operational functions of the UAVs. Numerical simulations are performed to demonstrate the effectiveness and applicability of the proposed method.

Key Words : Distributed Task Assignment, Air Strike Package,
Heterogeneous UAV, CBBA(Consensus Based Bundle Algorithm)

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List of Abbreviations

ATO : Air Tasking Order

BDA : Battle Damage Assessment

CTD : Capability of Target Destruction

CBBA : Consensus Based Bundle Algorithm

CBBA-PR : CBBA with Partial Re-planning

CBGA : Consensus Based Group Algorithm

H.V.T : High Value Target

IADS : Integrated Air Defense System

JMEM : Joint Munitions Effectiveness Manual

MILP : Mixed Integer Linear Programming

M.T : Main Target

O.T : Other Target

PSO : Particle Swarm Optimization

RASP : Rapid Air Strike Pairing

R.L : Red Leader

SAM : Surface-to-Air Missile

SEAD : Suppression of Enemy Air Defense

TST : Time-Sensitive Target

UAV : Unmanned Arial Vehicle

WTA : Weapon Target Allocation

Chapter 1

INTRODUCTION

1.1 Background

Recently, air operations have developed into the concept of effectively neutralizing pre-planned enemy targets in response to enemy surface-to-air and air-to-air threats, based on the air strike package. An air strike package is a group of fighter and bomber aircraft that have been combined to provide mutual support against enemy threats while they achieve a common goal of destroying a set of targets. [1] To complete the mission, the fighters in charge of each mission should be systematically coordinated.

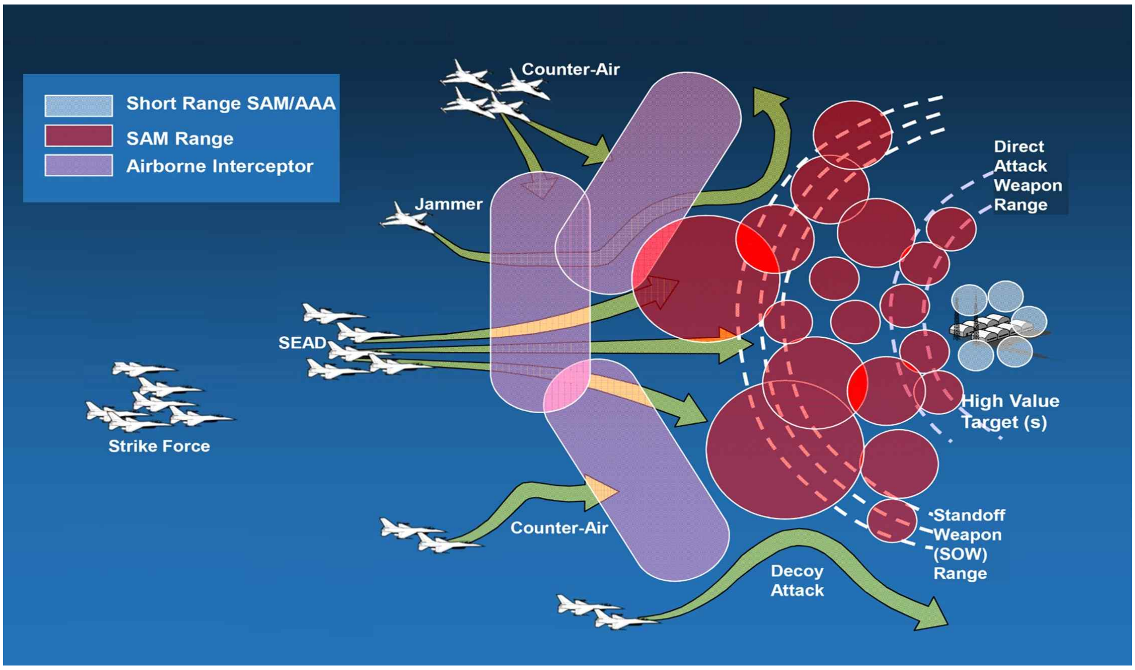


Figure 1.1 Composition and operation overview of the air strike package [2]

The mission of air strike package can be divided into the following steps. First, the mission planner selects the right type and number of aircraft and munitions to efficiently destroy each target. Second, each fighter in the air strike package considers the target's required destruction level and selects the target to hit. Third, the mission planner adds SEAD(Suppression of Enemy Air Defense) and counter-air aircraft to protect the groups of attacker by taking into account enemy threats in the vicinity of pre-planned targets. A group of flights attacking targets in the same vicinity together with strike, SEAD, and counter-air aircraft comprises a typical air strike package. [1] An air strike package works together in an operational environment and conducts its mission to effectively neutralize the enemy as shown in Fig. 1.1. [2]

With the gradual development of UAV(Unmanned Aerial Vehicle) technology, military operations using the UAV have become a reality. In September 2019, two oil refineries in Saudi Arabia were attacked by a teenage drone, and 60% of Saudi Arabia's oil refineries were shut down. [3] In January 2020, US MQ-9 Reeper was launched to eliminate Soleimani, commander of the Iranian Revolutionary Guard Corps, without the danger of manned pilots in local operations. [4] These days, UAV can be used to neutralize high value and high threat targets. The military use of UAV is being actively investigated even in the air operations, where the scope of operations has been expanded beyond local military operations. In particular, this trend has evolved into the cooperative operation of manned and unmanned aerial vehicles. As shown in Fig. 1.2, the US Department of Defense has announced a roadmap for the operation of UAV air strike package integrating strike, SEAD, and counter-air capabilities for the year 2025 to 2030. [5]

On the other hand, many studies on task assignment problems have been performed considering the battlefield scenario regardless of the point of real air operation aspect. However, only a small number of studies have been conducted based on actual military operations. Lee and Tahk considered the unmanned mission using UAVs [6], but the proposed method applying the air strike package concept has not yet been conducted.

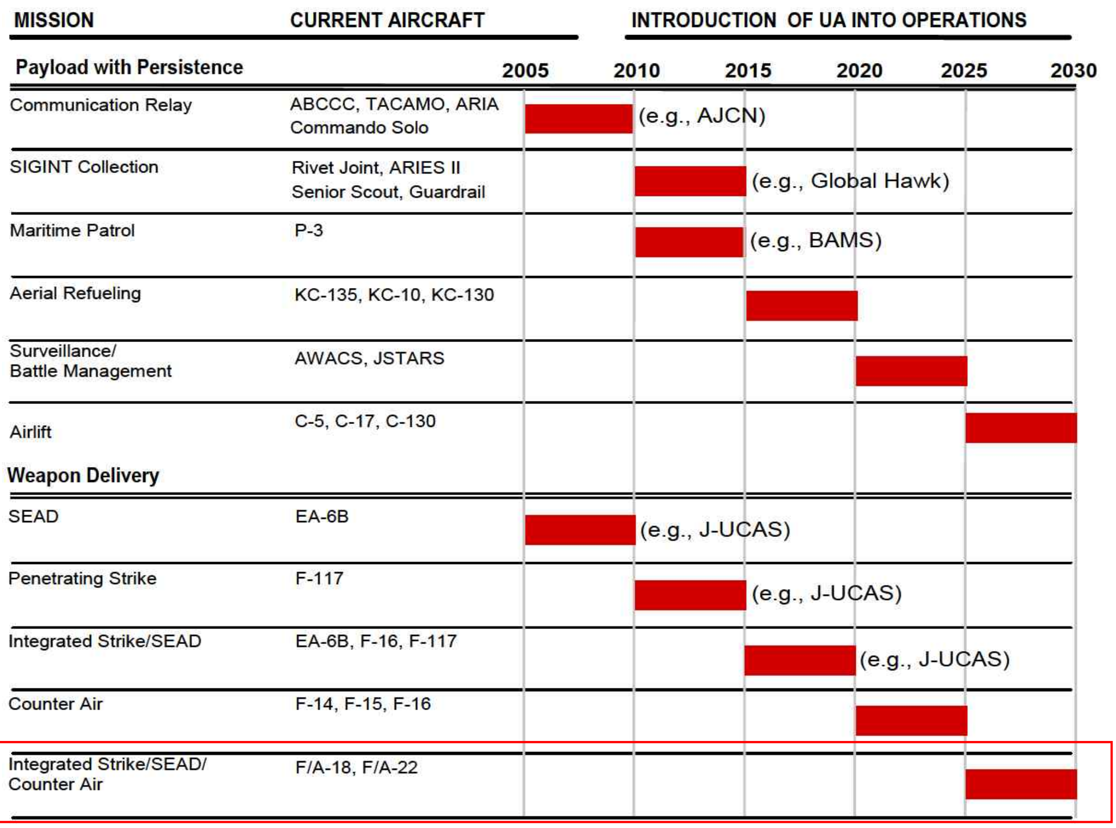


Figure 1.2 U.S. UAV mission roadmap [5]

1.2 Related Research

The problem of efficiently assigning the task to a large number of UAVs has been studied in a great variety of ways. Choi proposed a CBBA [7] that combines the consensus algorithm [8] and the auction algorithm [9]. Because the CBBA composed of task assignment and conflict resolutions, conflict-free sub-optimal solution can be achieved. Many studies complementing the CBBA algorithm in more complex mission environments have been continued. Lee and Tahk proposed a distributed task assignment algorithm for the heterogeneous UAVs, strike and SEAD UAVs, based on CBBA algorithm. [6] Hunt et al. solved the problem using CBGA(Consensus Based Group Algorithm) by assuming a situation where a multiple collaborative attack is required for destroying the targets. [10] Fu et al. extended the CBBA algorithm for selective task assignment using swarm UAVs and introduced the concept of idle time to suggest the possibility of dynamic task assignment in rapidly changing battlefield environments. [11] Buckman et al. proposed CBBA-PR(CBBA with Partial Re-planning) which allocates the new task by only reallocating a subset of task. Through this algorithm, real-time task assignment and optimal results were derived. [12] Zhang et al. improved the CBBA to allocate heterogeneous UAVs that perform the search-attack-evaluation in SEAD missions in a dynamic scenario to minimize computation cost and communication load of UAV. [13]

Other than the CBBA, various task assignment algorithms have also been studied. Choi et al. used mixed integer linear programming(MILP) and genetic algorithm to study the problem of a large number of UAVs, which assigns optimal missions for a problem of large number of missions with obstacles. The efficiency and convergence were also analyzed. [14] Deng et al. applied a genetic algorithm to the problem of task assignment mission using heterogeneous UAVs of different abilities. [15] Oh et al. proposed an effective mission assignment method for targets requiring simultaneous attacks in the mission based on PSO(Particle Swarm Optimization). [16]

On the other hand, to solve the weapon-target allocation problem(WTA), Cho et al. proposed a combinational optimization model of air strike package based on the target group, and they applied the required destruction rate of target and destruction capability of aircraft according to the nature and characteristics of the target via the Joint Munitions Effectiveness Manual (JMEM). [17] They tried to solve the problem from the viewpoint of the operation of the air strike package. For real-time air strike package mission, McLemore proposed a weapon-target allocation method by introducing the concept of Rapid Air Strike Pairing(RASP), and configured the performance index reflecting the operational intention and target distance to be maximized. In addition, the effect and feasibility were analyzed in the scenario of attack against North Korea. [18] Kim et al. solved the problem of minimizing the exposure time of the aircrafts in air strike package to the SAM threats by dividing it into armament-target allocation problem and route planning problem. [19]

1.3 Contribution

Various theories and methods have been applied to the task assignment problem. However, study on practical air strike package mission assignment, that takes into account the characteristics of target group as well as the variety of weapon effects and models of air strike package, has not been performed yet.

The main contribution of this study is to consider the issue of task assignment applied in actual air operations in the task assignment algorithm of UAV air strike package. The capabilities of each UAV constituting the air strike package are different, and the pre-planned targets also differ in the required level of destruction according to their characteristics and importance. In this study, the optimal combination of different offensive and defensive capabilities is determined, which is the main contribution of this study.

Second, only SEAD and strike UAV have been taken into account for the mission in the most previous studies. Note that the complete form of air strike package includes strike, SEAD, and counter-air UAVs. In this study, a full-scale task assignment algorithm based on the real military operation is proposed.

Third, the dynamic applicability of UAV air strike package's kill chain operation[1] is examined against the situation of the enemy's SAM threat and the occurrence of high-value targets whose information has not been confirmed in advance.

1) In preparation for North Korean missile threats, the Korean government's missile defense system is planed to detect and destroy missiles prior to launching them. It is constructed through a chain of detection, identification, determination, and strike. [20]

1.4 Thesis Organization

In this study, a task assignment algorithm is proposed based on target group characteristics using the CBBA algorithm. All the possible paths of the UAVs are generated using a visibility graph [21], and the shortest path is generated using the Dijkstra's algorithm. [22] Then, a reward for each target and SAM(Surface-to-Air Missile) is set based on the path taking into account the level of destruction required to neutralize each target and the different destruction capabilities for each UAV. Finally, the task assignment is conducted using the improved CBBA algorithm.

This thesis is organized as follows. Chapter 1 introduces background, literature survey, and contributions related to this study. Chapter 2 provides an overall air strike package mission that is outlined through problem definition, mission environment, optimization problem, and the improved CBBA algorithm. Chapter 3 deals with the three staged UAV air strike package task assignment model. Chapter 4 provides the results of numerical simulations, and the performance and applicability of the proposed algorithm are analyzed. Finally, concluding remarks and future works are addressed in Chapter 5.

Chapter 2

Problem Statement

2.1 Employment of the Air Strike Package

Victory in modern warfare depends on sharing full-length situational awareness based on an effective network as well as projecting fast and accurate decision-making, command decisions, and strong military power. In today's battlefield, the most powerful and fastest military force can be thought of as an air strike package consisting of multiple fighters and bombers. The air strike package can achieve air superiority and neutralize high-value targets in the enemy's depth. After selecting the enemy's integrated air defense system(IADS) and airfield as the top targets, the air strike package sequentially neutralizes high-value targets including enemy command and strategic facilities. The achievement of air superiority is the most important prerequisite for allowing our forces to strike the enemy freely without interfering and protecting our forces from the enemy.

The early air strike package of the U.S. Air Force operated in World War II consisted of only bombers, which caused a lot of power loss. [23] Tactical and operational doctrine has been developed under the demanding which focused on improving operational concepts for deep strikes against targets heavily defended by sophisticated integrated air defense systems. [24] Based on the lessons learned from the past battlefields, the air strike package has continued to develop, and the SEAD, which neutralizes the enemy's IADS, as well as the counter-air, which responds to enemy's air-to-air force, have added. It has developed in a way that combines the air-to-air defense and strikes the enemy's targets and SAM threats. The air strike package was perfected large force employment by integrating offensive counter-air, precision strike, SEAD, electronic warfare, and command and control. [25] Depending on the configuration, the air strike package includes strike force to attack the target, SEAD to neutralize the enemy's SAM, counter-air(escort or sweep) to respond to air-to-air threats, jammer to perform electronic attacks, and decoys to deceive the enemies.

2.1.1 ATO Cycle

The mission of the air strike package is based on the ATO(Air Tasking Order) cycle. The ATO is an operation plan prepared to meet the strategic objectives of various air combat missions through optimized resource allocation. It goes through the ATO cycle process of strategy development, target development, master air attack plan, ATO production, ATO execution, and assessment as shown in Fig. 2.1. [26] The joint ATO cycle is an analytical, systematic cycle that focuses joint air efforts on accomplishing operational requirements. [27]

Figure 2.1 ATO production cycle [26]

As the first step in the ATO Cycle, the commander provides operational objectives and guidelines that fit the strategic intent. In the second stage target development, the strategic objectives are converted into targets and target groups. Every target is selected according to priority which can achieve the desired effect and goal. The third stage recommends and allocates our forces to each target according to the target's priority and the level of destruction requirements. In the fourth stage, ATO production, the fighters, and bombers in the air strike package are assigned to the targets and detailed air combat plans are made. In the ATO execution, the planned ATO is carried out. The final step consists of evaluating the mission to determine a re-attack or re-establishing the commander's strategic intention in the future. It is widely acknowledged that a given ATO from initial conceptualization to execution takes 72 hours, with a daily ATO release occurring every 24 hours. [28]

2.1.2 Limitations of the pre-planned air strike package

All the air strike packages are operated through the ATO cycle. When the air strike package is composed, the mission commander sets the entry route and time, target hitting time, each mission plans, and finally conducts the mission with package forces. However, even though the ATO is a plan to optimally allocate attack assets to the targets, there exist some limitations. Lee described on several factors as follows, [29]

- The air strike package process is complicated and it takes a lot of time for each step.
- If the plan needs to be changed in the air due to various reasons during the mission, the amount and complexity of information increase the likelihood of errors.
- Due to the lack of flexibility in the pre-planned mission, flexible response to emergency situations is limited.

- When a mission fails, a long delay is inevitable for the next plan.
- It is impossible to quickly operate the mission in a dynamic situation in which an emergency target occurs in a high threat area due to the time for re-planning.

2.1.3 Real-time applicable UAV air strike package

In this study, it is assumed that the mission of the air strike package, which is the core of the air operation, is performed by unmanned aerial vehicles rather than manned pilots such as mission commander. This approach can be a strength of overcoming the existing operational limitations by converting the operation of today's ATO based pre-planned mission into a UAV based real-time mission. If targets are assigned to the UAV air strike package, each UAV calculates in real-time how much armament is required depending on the importance and solidity of each target and strikes through an agreement process. Therefore, it is possible to create an effect of integrating the three steps of the ATO cycle, master air attack plan - ATO production - ATO performance, into one stage, so that air forces can be effectively operated.

Lee and Tahk considered the task assignment problem of heterogeneous UAVs in the SEAD mission environment. [6] In this study, the previous work is expanded to the task assignment problem in the mission of the air strike package. The target destruction capabilities of each UAVs and the required destruction rate of targets are set to be as diverse as the actual operational environment. Figure 2.2 shows an example of the target allocation of air strike packages based on target group. [17] The better fighters and weapons, the more damage can be added to the targets. Therefore, to destroy stronger enemy's main targets, it is necessary to allocate power that can cause more damage than the durability of the targets.

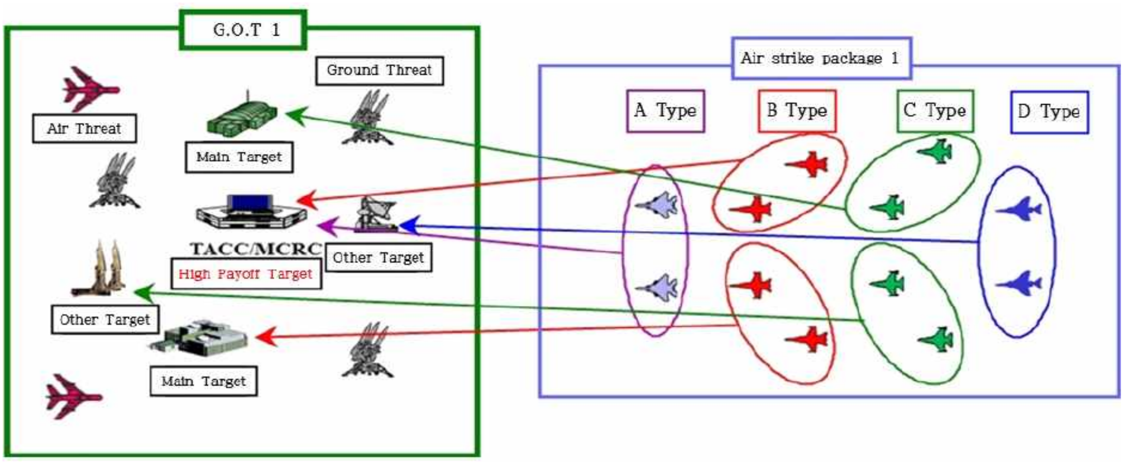


Figure 2.2 Example of the target allocation based on target group [17]

In this study, the model of a UAV air strike package over three stages is considered as sown in Fig. 2.3. First of all, in stage 1, the concept of the air strike package is simplified and a target group-based mission allocation algorithm implementing selective hits according to the target is presented. In the second stage, SEAD and counter-air are added to effectively respond to surface-to-air and air-to-air threats to protect strike forces and deal with mission situations that destroy ground targets. Finally, the third stage implements a full air strike package mission situation that takes into account the strike, counter-air, and SEAD forces. In addition, in this study, a real-time complex mission assignment model is proposed that sequentially performs high-priority missions in consideration of the unplanned pop-up SAM and the occurrence of TST(Time-Sensitive Targets).[2)]

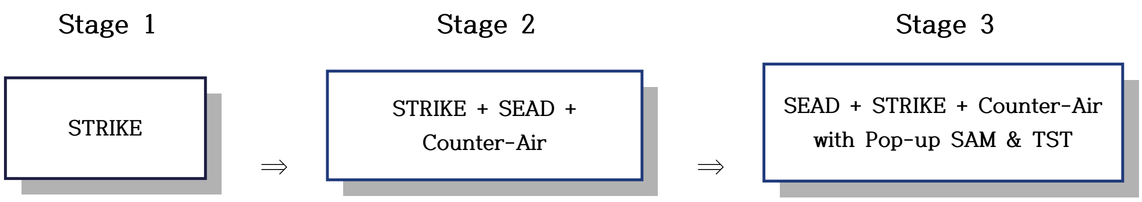
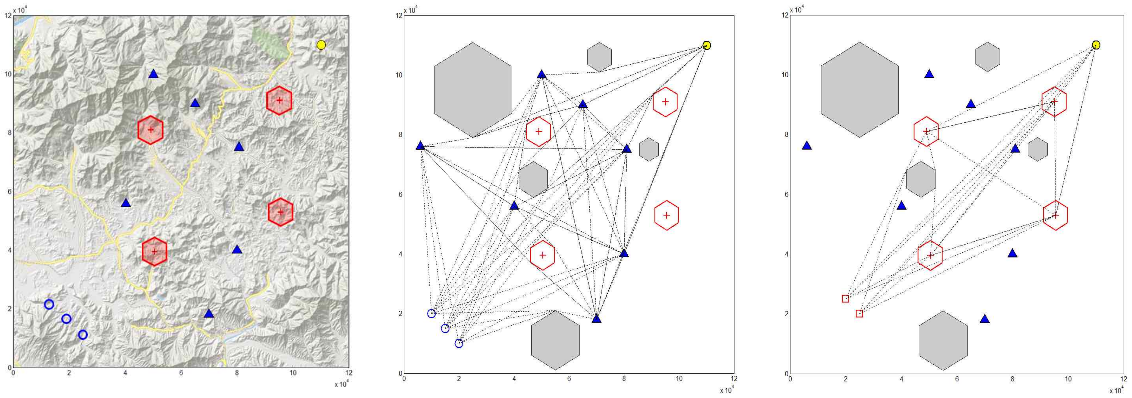


Figure 2.3 Stages of UAV air strike package model

2) It is a target that has high offensive effect and poses an immediate threat to allies if it is not responded promptly. [30]

2.2 Mission Environment of the Air Strike Package

The battlefield environment for the mission of the air strike package is shown in Fig. 2.4. Fig. 2.4-(a) shows the actual battlefield environment, where the SAM bases(hexagons) and various ground targets(triangles) are located on the terrain of 120km in width and length. By abbreviating the battlefield environment, obstacles such as mountain terrain are regarded as fixed obstacles, and the SAM threat area is regarded as a no-fly-zone. Figures 2.4-(b) and (c) summarize the actual battlefield environment and show the battlefield situation recognized by the strike and SEAD forces. The gray hexagons indicate terrain that is not accessible by all UAVs, and red cross marks with hexagons indicate the SAM bases and the threat range of the SAM. The blue triangles represent the enemy's ground targets in the mission area.



(a) Real battlefield (b) Recognition of strike (c) Recognition of SEAD

Figure 2.4 Battlefield environment and recognition of strike and SEAD UAV

In this study, there exist three types of UAVs that make up the air strike package. In Fig. 2.4-(b), strike forces plan the flight path outside the range of terrain obstacles and SAM threats and execute the strikes until they exceeds the level of destruction required for each target. In Fig. 2.4-(c), SEAD forces use armaments that can neutralize the SAM. The SEAD forces aim to destroy the SAM base in the shortest time by avoiding terrain obstacles. After finishing the missions, the strike and SEAD forces move to the yellow point in the upper right of the battlefield, and finally the mission completes. On the other hand, counter-air forces perform the role of protecting the entire UAVs, and therefore they move together with the SEAD forces that first infiltrate the enemy, and perform air escort missions. When the enemy's air-to-air threat appears, the counter-air forces neutralize the enemy's air-to-air threat in the shortest distance and then perform an escort mission again.

2.3 Task Assignment Problem

The mission of the air strike package can be defined as the task assignment problem of heterogeneous UAVs. The strike, SEAD, and counter-air UAVs perform the assigned missions against targets, SAM, and enemy's air forces considering terrain obstacles and SAM threats in a specified operational environment.

The objective of the task assignment problem is to maximize the overall reward function that each UAV can obtain by performing the mission given a total of N_t missions and a total of N_u UAVs. In this study, the total reward function can be expressed as the sum of rewards that can be obtained when each UAV constituting the air strike package completes its assigned mission. This problem can be formulated as the following optimization problem.

$$\max J = \sum_{i=1}^{N_u} \left(\sum_{j=1}^{N_t} c_{ij} \left(t_{ij} \left(p_i \right) \right) x_{ij} \right) \tag{2.1}$$

subject to

$$\sum_{i=1}^{N_t} x_{ij} \leq L_t , \quad i \in 1, \dots , N_u \tag{2.2}$$

$$Energy(j) \leq 0, \tag{2.3}$$

$$Energy(j) = Initial\ Energy(j) - C.T.D.(i), \quad j = 1 \cdots N_t$$

where a decision variable x_{ij} indicates whether or not task j is assigned to UAV i, which has a value of 1 when the UAV i is to perform task j, and 0 when it is not. The reward c_{ij} represents each task value after the UAV performs its mission, which can be expressed as a function of the time t_{ij} meaning the arrival time on task site. The mission arrival time t_{ij} can also be described as a function of the UAV's path p_i. In other words, the starting time for performing the mission varies according to the path of the UAV, and the reward decreases as the mission starts late. In this way, the task assignment problem can be expressed as an optimization problem in the form of interlocking mission assignment and route planning. In Eq. (2.2), L_t denotes the maximum number of missions that can be performed, which is a limiting condition indicating that all UAVs can be assigned only within the limits of their available armaments. Equation (2.3) means that all targets are attacked with a required destruction rate or higher, and the final energy falls below zero and must be destroyed. The initial required degree of destruction can be simplified as the target energy $Initial\,Energy(j)$, where $Energy(j)$ is defined as the value by subtracting the $C.T.D.(i)$ (Capability of Target Destruction) of the UAV i hitting the target from the $Initial\,Energy(j)$ before hitting.

2.4 CBBA Method

For the mission of the air strike package, a task assignment algorithm must reflect the ever-changing operational environment. In addition, real-time applicability, scalability, and flexibility must be guaranteed. One of the representative task assignment algorithms is the CBBA method [7], which is a consensus-based bundling algorithm. The CBBA method is an algorithm in which UAV exchanges information with each other and the algorithm assigns missions to obtain the highest reward. Unlike the centralized algorithm, it is a decentralized algorithm that guarantees reasonable computational load, fast convergence, and excellent scalability in situations where various constraints must be satisfied. Because of this, even if communication between the UAVs is cut off, it is possible to derive a result of non-conflict assignments. Also, it provides a sub-optimal solution[3] and can be applied in real-time, making it very suitable for dynamic mission assignment situations. The CBBA consists of two steps : bundle construction process and conflict resolution process.

Phase 1 is the bundle construction process. The UAV preferentially calculates the rewards that can get when attacking each target from their current position. Then, the target with the highest reward is selected as the first mission. Afterward, the reward when attacking other targets from the first mission is recalculated, and the target with the highest reward is selected in the second order. This calculation is repeated until the limit of armaments, and the missions are sequentially selected in the order of targets that give high rewards.

Through this procedure, each UAV constructs a bundle, which is a list of targets, and completes Phase 1 as shown in Fig. 2.5. A UAV called Agent 1 decides Target 1 as the first mission, which can get 10 points as the first

3) The CBBA algorithm does not provide an optimal solution, but it is proven that it guarantees an efficiency of 50% or more of the optimal solution when the communication environment of all UAVs is guaranteed. [5]

reward. After deciding the first mission, Agent 1 recalculates the rewards for the remaining missions and determines Target 2 as the second target. Then, through the same process, Target 3 is determined as the third target. Finally, Agent 1 completes the bundle, which is the target list, in the order of Target 1 → Target 2 → Target 3.

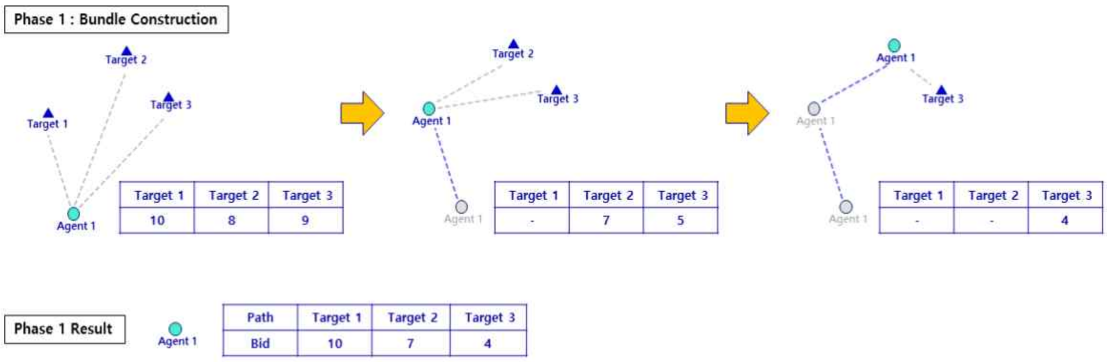


Figure 2.5 Phase 1 : Bundle construction process

In terms of algorithm, to proceed the Phase 1, each UAV must maintain the lists. The first list b_i is a set of targets that the UAV i should attack, and contains information on what the UAV i should perform. The second list p_i contains information on the path order of the mission of the UAV i. The third list z_i is a list of length N_t, and stores index information of which UAV can get the largest reward for each mission. Lastly, the list y_i stores index information of the reward, which is matched in the third list z_i. The target list and reward of Agent 1 in Fig. 2.5 correspond to the third and fourth lists, respectively. This information becomes the basis for agreement on task assignment through information exchange with other UAVs in Phase 2.

Phase 2 is a conflict resolution process. This is the process of comparing the bundle and reward information through communication with other UAVs, which is a consensus phase that the UAVs obtaining possible higher rewards can be assigned missions. Figure 2.6 simplifies this process. Each

UAV is assigned to a task with the highest reward for the mission based on its own bundle. Afterward, if UAV has not been assigned missions, then they create new bundle through the Phase 1 process again. Based on this, it repeats the Phase 2 conflict resolution process iteratively.

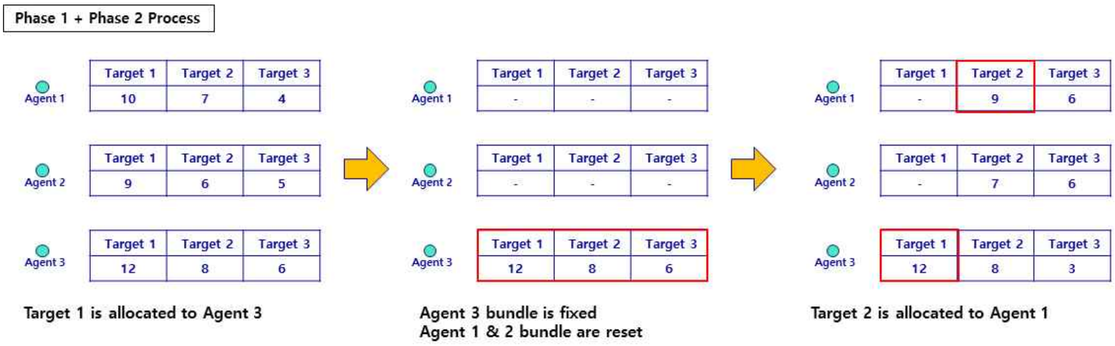


Figure 2.6 Phase 1 and Phase 2 Process

At this time, the sender UAV providing the information transmits the list of z_i and y_i to the receiver UAV. Upon receiving the information, the receiver UAV chooses the action to avoid conflict between UAVs based on the rules set by the CBBA method. All UAVs connected by communication alternately perform the role of a sender and a receiver, each of which provides information. Based on the result of the information agreement, the receiver UAV performs the actions by dividing it into Update(replaces the sender's information), Reset(makes no one perform the mission), and Leave(maintains its existing information).[4] In this way, the Phase 1 bundle construction and Phase 2 conflict resolution are repeated, and all UAVs finalize the mission list.

4) Detailed rules regarding conflict resolution can be found in Ref. [5]. The consequences that the UAV can take through the rules can be expressed as follows,
update : $y_{ij} = y_{ki}$, $z_{ij} = z_{ki}$ / reset : $y_{ij} = 0$, $z_{ij} = 0$ / leave : $y_{ij} = y_{ij}$, $z_{ij} = z_{ij}$

2.5 Distributed Task Assignment Algorithm Considering Selective Strike

In the original CBBA algorithm, the task assignment problem is formulated assuming that there exist no obstacles between all UAVs and tasks, and therefore the UAV path is generated as a line connecting all points and points. However, in the actual battlefield environment, there may exist areas that cannot be entered ; terrain obstacles, and enemy SAM threats depending on the altitude of operations. Therefore, those constraints must be considered in the formulation. To deal with this problem, a visibility graph [31] as shown in Fig. 2.7 is adopted to generate the points based on the UAV's initial starting points, ending points, all outskirts of the terrain obstacles, and the SAM threat. Then, the set of lines connecting these points can be considered as a path through which the UAV can move. After all possible paths for the UAVs are generated, each UAV calculates the shortest path from the starting point to each target and the ending point using Dijkstra's algorithm. [22]

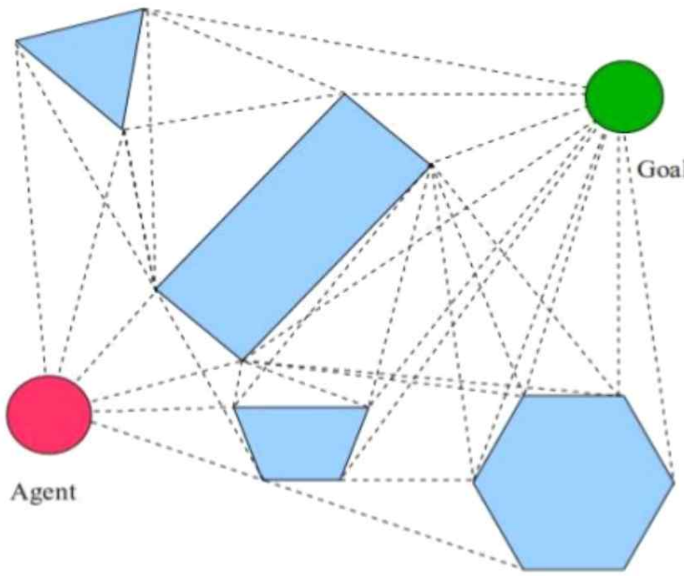


Figure 2.7 Visibility graph [31]

The detailed path can be used to calculate the reward function for implementing the CBBA algorithm. When the assignment is completed using this reward function, the UAV performs the assigned tasks along the shortest path. In this study, to optimize the assignment of missions, a criterion for reward is defined to configure the actual operational environment. The reward c_{ij} obtained by performing the task j by the UAV i is represented as follows,

$$c_{ij} = \lambda^{t_{ij}} s_{ij} w_{ij} \tag{2.4}$$

A variable λ is set with a value of less than 1 to indicate that the value decreases over time, which is to reflect the property that the reward decreases as the target is destroyed later. As the time t_{ij} taking for the UAV i to arrive at the task j increases, the threat of friendly forces in the operational environment increases, while the enemy's ability to protect targets and reject the friendly attacks increases. The variable s_{ij} represents the basic reward of the task j that the UAV i can receive. The greater the importance of the mission itself, the larger the value of s_{ij}. On the other hand, w_{ij} reflects the characteristics of the UAV's platform itself, which can be expressed as the following equation.

$$w_{ij} = \lambda^{t_a} T^{t_a} W \tag{2.5}$$

Equation (2.5) is based on the assumption that simultaneous attacks of the UAV air strike package are limited due to the UAV platform restrictions. When two or more UAVs simultaneously attack a single target, it is more advantageous to get the reward than one UAV re-attack. In other words, it can be considered that λ^{t_a} takes additional time t_a to prepare for a single UAV to re-attack. It also considers the threats T^{t_a}, which is received by exposure to the location when the UAV stands near the target for a period of time t_a to re-attack the same target. The variable W comprehensively reflects the characteristics that the effect of destroying the target when the multiple UAV attacks is even better. In the case of two or more UAVs attacking, the launching points can be diversified and the armament effects will also be increased. Moreover, when the subsequent UAV co-attacks the target after BDA(Battle Damage Assessment), they can more effectively destroy the target. In this study, λ and T are set to a value less than 1, which play a role of reducing the reward as the preparation time for additional firing increases.

As a result, the proposed method in this study ensures that the total reward achieved by the UAVs is maximized. Also, time variable is included in the reward function, and therefore the maximum reward in the shortest time can be obtained. However, operational requirements such as the optimality and rationality of the armament, expense, and fuel are not considered in this study.

The flowchart of the proposed distributed task assignment algorithm is shown in Fig. 2.8. Note that the proposed algorithm can be divided into offline algorithm and online algorithm according to the presence or absence of Environment Update. During the operation, all UAVs should share the information whether the target is destroyed and whether a re-attack is required. In order to assign the tasks, an online algorithm sharing the changed situation at every moment must be applied. In particular, for the real-time application of the counter-air, pop-up SAM, and TST(time-sensitive targets) considered in this study, it is necessary to consider the dynamic operational environment through online conditions, and therefore expansion to the online algorithm must be preceded. In the three stages of the UAV air strike package model considered in this study, the first stage is the most basic step, and the implementation of the mission allocation algorithm based on the target group in the offline environment will be confirmed. In the second and third stages, a task assignment model will be implemented that considers the mission situation changing in dynamic environment.

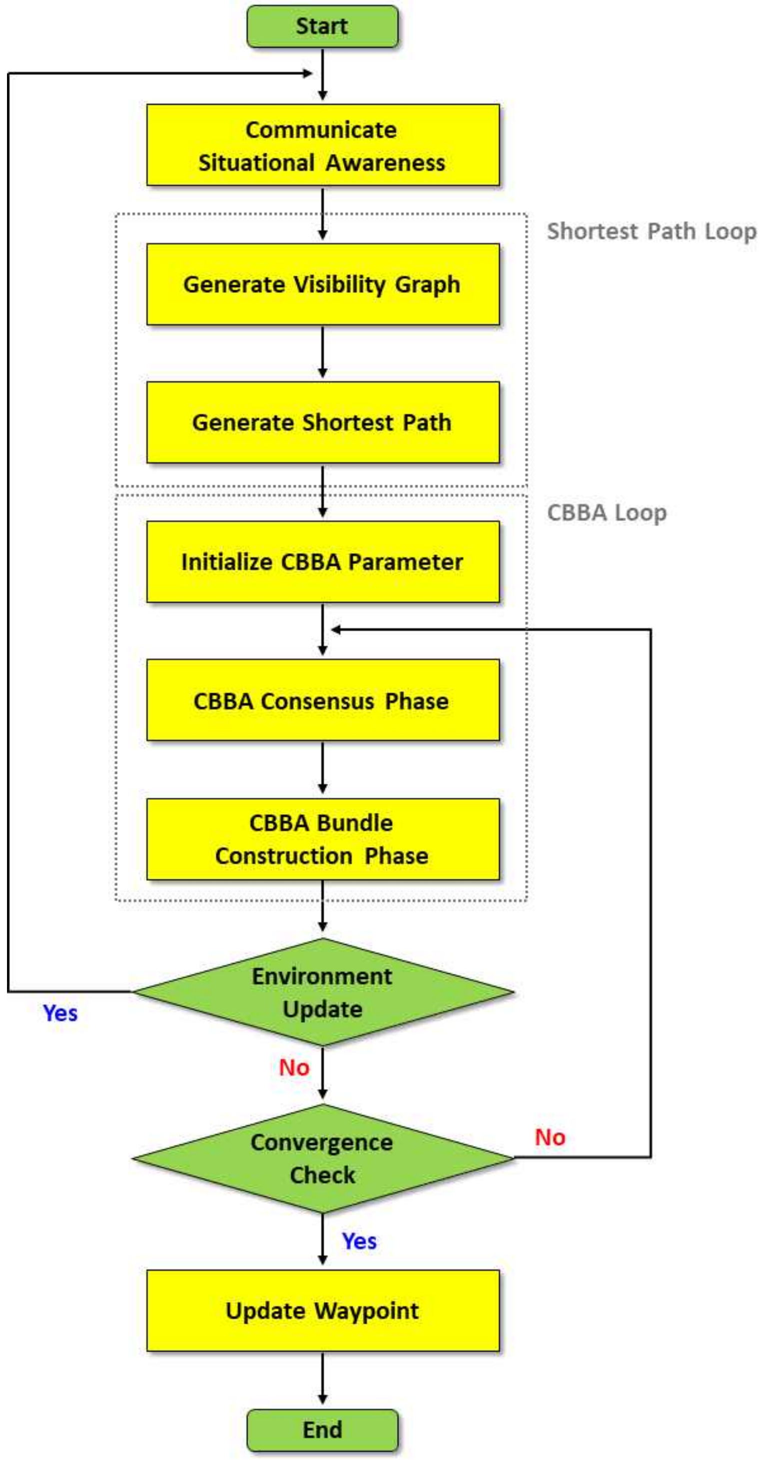


Figure 2.8 Flowchart of task assignment algorithm

Chapter 3

Three Staged UAV Air Strike Package Task Assignment Model

3.1 Model of Target Group-Based Air Strike Package in Offline Environments (Stage 1)

In this section, the first stage of the three-stage UAV air strike package model proposed in Chapter 2 is described. The purpose of this section is to examine whether a target group-based mission can be applied so that the UAV air strike package performs selective strikes based on the characteristics of the targets. This stage is to design the basic algorithm to complete the final (third) stage. In the Stage 1, the air strike package is made up by considering only the strike UAVs that perform the most basic missions, and the situation is limited to an offline operation environment that does not consider real-time dynamic changes in the battlefield.

3.1.1 Assumptions

On the actual battlefield, enemy targets may have different operational importance, according to the terrain and environment, with different levels of required destruction depending on the target group classification. According to the importance of each target, the level of required destruction is differentiated, and therefore the higher the value of the target, the higher the required destruction rate is set. Determining the level of the required destruction of each target is a variable factor, which depends on the operational environment and the commander's warfare guidelines. In this study, simple rules are used to establish a target group, as summarized in Table 3.1. [17] The enemy's ground targets are classified into high-value target, main target, and other target, each with different levels of required destruction, 80%, 50%, and 30%, respectively, which are neutralized if they are attacked by the forces exceeding them.

Type of Target	Required Destruction rate	Remark
High-value target	80 %	Command & Control Post
Main target	50 %	Building, Ground force
Other target	30 %	Supporting facility

Table 3.1 Required destruction rate per types of target

The strike UAVs are classified into two types, depending on their ability to destroy the targets, as summarized in Table 3.2. Following assumptions are considered in this study.

- UAVs have the same speed, armament, mobility, and other performances.
- The strike forces, divided into high-performance UAV and middle-performance UAV, which have different target destruction capabilities, i.e., 60% and 40%, respectively.
- A UAV visiting a target automatically fires an armament.
- There is no limit on the fuel of the UAV.
- The shooting down situation is not considered, and the UAV is set to be equipped with sufficient armament to neutralize all the targets.

Type of UAV	Capability of destruction	Speed	Armament capacity
High-performance UAV	60 %	200m/s	5
Middle-performance UAV	40 %		

Table 3.2 Capability of target destruction by strike UAVs

3.1.2 Target group-based CBBA algorithm

In order to apply the target group-based selective strike, the CBBA algorithm should be modified to reassign the target to the UAV until the target is completely destroyed. Figure 3.1 shows a modified CBBA LOOP of the original task assignment algorithm in Fig. 2.8. In the CBBA consensus phase, a decision step is added i) to allocate the task if the target's energy remains, and ii) not to allocate the task when the energy is below zero. Also, in the bundle construction phase, based on the energy of the mission, if the target is not completely destroyed, a process is introduced to add the target to the bundle until it is destroyed.

The original CBBA algorithm is designed so that a single UAV can obtain the highest reward through one iteration of the bundle construction and consensus phases for destroying one target. On the other hand, the algorithm proposed in this study makes one UAV hit one target through one iteration. The process of updating the status change information of the attacked target for future use in the next iteration is added. As a result, the algorithm is reconstructed to change the criteria of iteration from the destruction of the target to the single strike of the UAV.

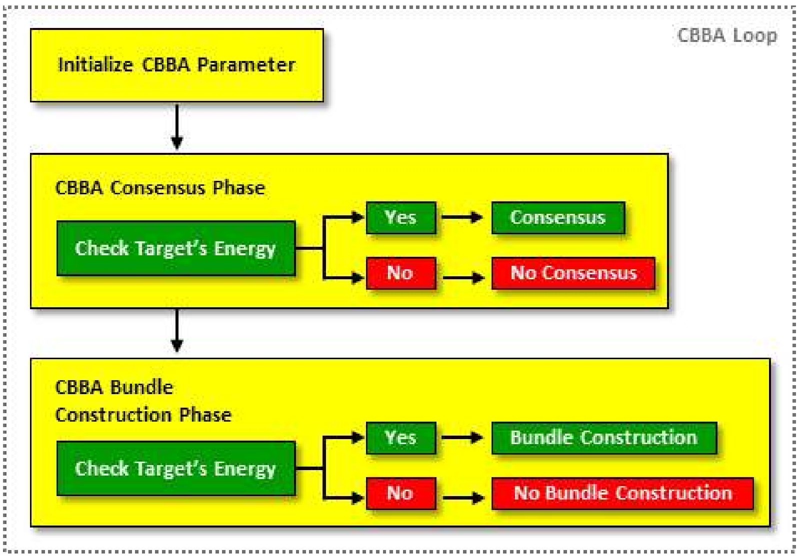


Figure 3.1 Modified CBBA loop

3.2 Model of Air Strike Package with Additional SEAD and Counter-Air in an Online Environment (Stage 2)

This section deals with the task assignment of the UAV air strike package mission, including both SEAD and Counter-Air forces, which are the rest of the squadron through an online environment that updates the situation in real-time. In Ref. [6], to destroy the enemy's SAM, the SEAD and jammer UAVs interfered and struck the enemy's air defense system together, and then the algorithm was applied to neutralize the SAM through the BDA process for the attack. However, while the algorithm neutralizing the enemy's SAM threat was defined in detail, the algorithm did not consider the enemy's air-to-air threat. Therefore, it does not sufficiently match the operational environment of the actual air strike package mission. In order to deal with this problem, it is assumed that the SEAD UAV itself has sufficient ability to strike and neutralize the enemy's SAM site without the help of jammer UAV. And, counter-air UAV is additionally set up to protect friendly UAVs from the enemy's air-to-air threats.

3.2.1 Assumptions

In the usual operational environment, the enemy's ground target is located within the threat range of SAM, so that the incapacitation of the SAM must precede the entry of the fighter to destroy the target. Therefore, SEAD's role is a prerequisite for achieving air superiority, which is one of the most important factors in the entire offensive mission. In this study, the SEAD UAV is set up to infiltrate the enemy's depth first and neutralize the SAM. It is assumed that the SEAD operates a longer range of armament than the threat of enemy SAM and is powerful enough to completely neutralize the SAM site with one armament. The SEAD UAV is not affected by enemy SAM threats and is not destroyed in the mission environment. Therefore, a task is assigned to the SEAD UAV by considering the SAM site through the CBBA algorithm.

The objective of counter-air UAV is to protect the strike and SEAD forces in the air strike package so that they can safely excute their missions. Therefore, in the event of the emergence of an enemy air-to-air threat, the counter-air must first approach and attack the enemy. In the actual operational environment, there may be various cases. For example, there may exist more enemy airs than friendly airs, or the operational capabilities of the enemy are superior to ours. In this study, the capabilities of the counter-air UAV and situations are established as follows.

The counter-air UAVs fly with SEAD UAVs that enter the enemy's depth first, protecting the entire allies. When enemy air threat emerges during the mission, the counter-air UAVs are assigned to neutralize it and intercept it at the top of its list. After all air threats are cleared, the counter-air UAVs change the mission to escort the SEAD UAV again. The counter-air UAVs operate air-to-air missiles with longer range than enemy air threats to preemptively attack and destroy one with a single attack. Table 3.3 summarizes the capability of target destruction by SEAD and counter-air UAVs considered in this study.

Type of UAV	Mission	Capability of destruction	Speed	Armament capacity
SEAD UAV	SAM site	100 %	250 m/s	5
Counter-Air UAV	Enemy Aircraft	100 %		

Table 3.3 Capability of target destruction by SEAD and counter-air UAVs

3.2.2 Online algorithm for a complete-form of air strike package combination

In order to apply the algorithm considering the strike, SEAD, and counter-air at the same time, the offline algorithm should be expanded to an online algorithm. In the case of the strike and SEAD, the enemy's ground targets and the SAM sites are fixed targets, and therefore they do not move or change. In the case of counter-air, however, dynamic environment should be considered, that is, the threat moves in real-time. The enemy airs appears from the enemy's depth and approaches friendly airs during the mission. In other words, unlike Stage 1, the algorithm in Stage 2 must be expanded to an online environment in order to approach the enemy air in consideration of the dynamic environment in real-time and to intercept the enemy's forces before the enemy does.

The key to the problem of task assignment in an online algorithm is that the offline algorithm is performed at every moment. Note that the algorithm for Stage 1 is performed only once for a mission, on the other hand, in this study the algorithm for Stage 2 updates CBBA algorithms every five seconds and allocates the best tasks to UAVs reflecting the changing mission situations. As the mission progresses, UAVs destroy the targets and SAMs and the status of targets and SAMs are updated, and all UAVs of the package can share the information of the changed situation.

On the other hand, in the event of enemy aircraft appearing, one additional condition should be set up for the counter-air forces. The counter-air forces are programmed to attack the enemy air by approaching the shortest distance, but the top priority is to protect all of the package forces. For the top priority, the concept of the RED ALERT situation is introduced as shown in Fig. 3.2. Note that the operating environment of 120 km x 120 km is divided into the lower right and upper left parts of the diagonal. If enemy airs emerge in each part, it is recognized as the situation of RED ALERT 1 and RED ALERT 2, respectively. Depending on each RED ALERT situation, counter-air #1 and #2 respond to the enemy airs. Without these conditions, all counter-air forces attack the same enemy airs, which leads an imbalance in power to defend air-to-air. As a result, there may be a situation where it is not possible to effectively defend the strike and SEAD forces from the enemy airs appearing on the other side.

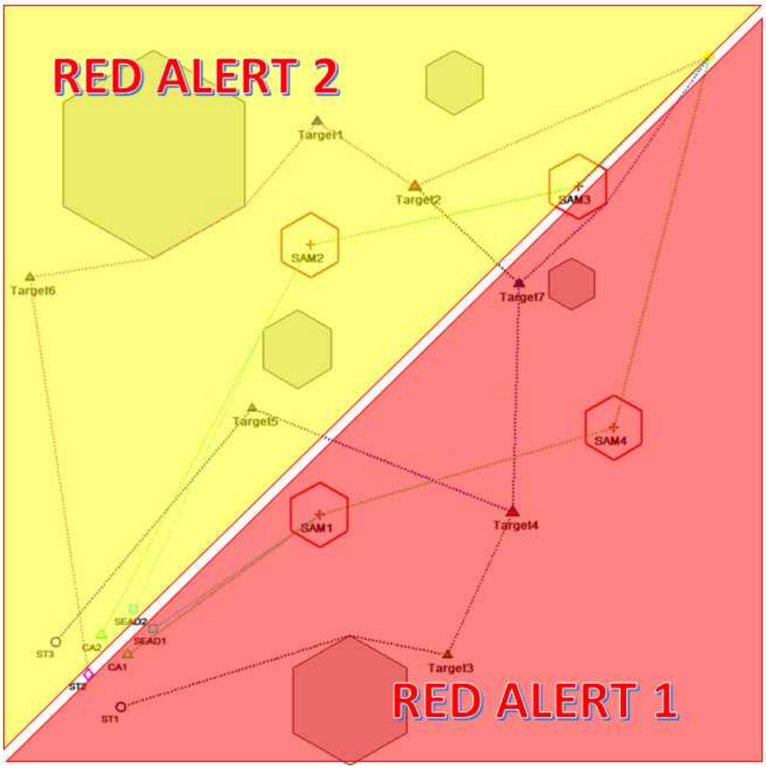


Figure 3.2 RED ALERT situation

3.3 Model of Comprehensive Air Strike Package mission in Complex Threat Situations (Stage 3)

Through the Stage 1 and Stage 2 of the air strike package task assignment models, the target group-based offline algorithm was extended to an online algorithm of complete air strike package combination. Finally, in Stage 3, the unpredictable appearance of pop-up SAM and TST are included while the package UAVs are performing the mission for each role. Considering such a complex scenario, the operational feasibility of the real-time application is verified. At this stage, Pop-up SAM and TST information, which was not previously recognized, is simultaneously transmitted from the ground command center to the UAV squadron in flight. Upon receiving the information, the UAVs are aware of the changing operational environment, initialize the CBBA algorithm, and reassign their missions to treat the changed circumstances. It is possible to verify whether the UAV air strike package conducts the kill-chain operation as shown in Fig. 3.3. The model results combining the Stages 1, 2, and 3 are provided in Chapter 4.

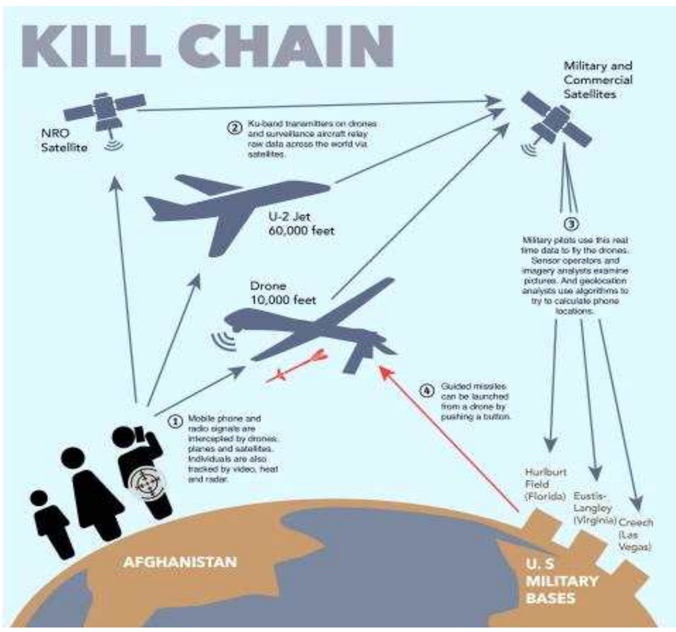


Figure 3.3 Kill chain operation using an UAV [32]

Chapter 4

Numerical Simulation

4.1 Battlefield Environment

In this chapter, numerical simulation is performed to deminstrate the effectiveness of the proposed three-staged UAV air strike package task assignment model. Tables 4.1 - 4.5 indicate the status of the UAV air strike package configuration, enemy targets, SAM, enemy air, pop-up SAM, and TST. After summarizing the simulation legend and situation setting, the process of the Stage 1 going through the Stage 2 to the Stage 3 complex mission simulation will be analyzed.

* C.T.D : Capability of Target Destruction

STRIKE UAV	Mission	Classification	C.T.D	Marking
ST 1	Target	Middle-performance	40%	○
ST 2		High-performance	60%	◇
ST 3		Middle-performance	40%	○

SEAD UAV	Mission	C.T.D	Marking
SEAD 1	SAM site	100%	□
SEAD 2		100%	□

Counter-Air UAV	Mission	Interception Range	C.T.D	Marking
CA 1	Red Air	6 km	100%	△
CA 2		6 km	100%	△

Table 4.1 Status of UAV

Target		Energy (Required Destruction rate)	Name	Marking
1	Main Target	50%	Target 1	▲
2	High-Value Target	80%	Target 2	▲
3	Other Target	30%	Target 3	▲
4	High-Value Target	80%	Target 4	▲
5	Other Target	30%	Target 5	▲
6	Other Target	30%	Target 6	▲
7	Main Target	50%	Target 7	▲

Table 4.2 Status of target

SAM	Threat Shape	Name	Marking
4 sites	Hexagon (Range : 10km)	SAM 1 / 2 / 3 / 4	⬡

Table 4.3 Status of SAM

Enemy Air	Mission	Classification	Interception Range	Marking
RA 1 / RA 2	Blue Air	Red alert 1	4 km	●
RA 3 / RA 4		Red alert 2	4 km	●

Table 4.4 Status of enemy air

SAM	Threat Shape	Name	Marking
1 site	Hexagon (Range : 10km)	Pop-up SAM	⬡

Target	Energy (Required Destruction rate)	Name	Marking
TST	50%	Enemy Leader	★

Table 4.5 Status of pop-up SAM and TST

Depending on the objectives of each stage, the first stage analyzes the task assignment model considering only the strike force and ground targets. In the second stage, SEAD and counter-air power will be added to the package, and SAM and enemy air will be added to the enemy forces. The final third stage deals with simulation in which pop-up SAM and TST situations are added to the enemy forces in the first and second stage composition.

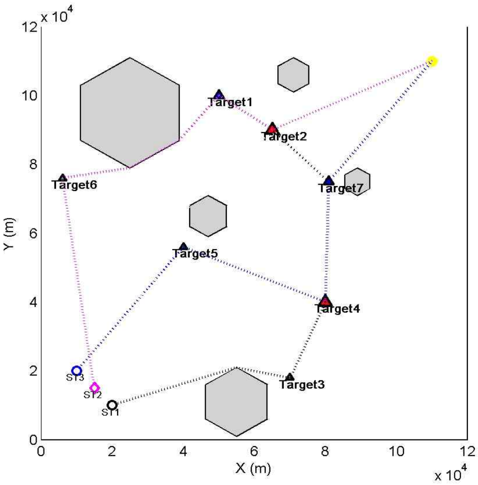
4.2 Simulation Results

4.2.1 Stage I simulation result

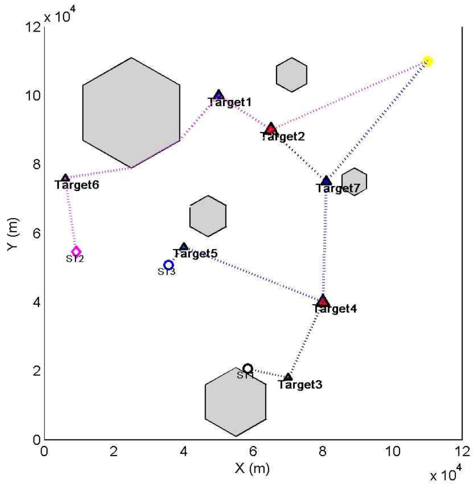
In the first stage of the task assignment model, two middle-performance UAVs and one high-performance UAV participate in the package, which have 40% and 60% of target destruction capability, respectively. Total 7 targets are considered, which consist of 2 high-value targets, 2 main targets, and 3 other targets, each with a required destruction rate of 80%, 50%, and 30%, respectively. The number of armaments available for each strike UAV is applied with five shots.

Simulation results are shown in Fig. 4.1. Figure 4.1-(a) shows the initial results of the UAV task assignment in the offline environment. Each UAV is located at its starting point, which is expressed as dotted lines from the initial point, and then flies along the route to the end of the mission. Among the strike UAVs, the pink ST 2 is a high-performance UAV, and the black ST 1 and the blue ST 3 are middle-performance UAVs. Targets 2 and 4 represented by red triangles are high-value targets, Targets 1 and 7 represented by blue triangles represent the main target, and green triangles represent other target.

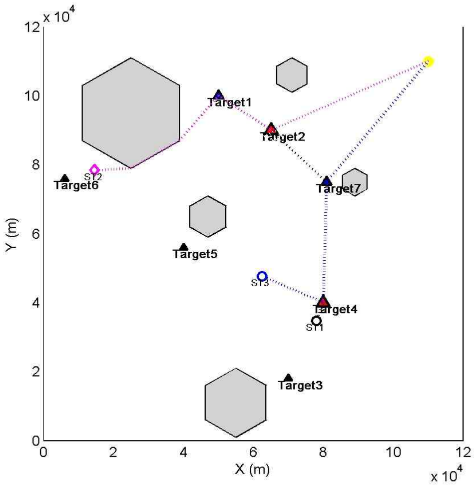
Figure 4.1-(b) shows the simulation result at 210 seconds, ST 1 attacks Target 3, ST 2 attacks Target 6, and ST 3 attacks Target 5 to neutralize them. At this time, all attacked targets are destructed with more damage than the initial energy, thereby all of them are neutralized. Figure 4.1-(c) shows the simulation result after 400 seconds. All of the neutralized Targets, i.e., 3, 5, and 6, are confirmed to be destroyed, and the visual marking changes to black triangle. After that, ST 1 and ST 3 try to attack Target 4 together. At this time, Target 4, high-value target, has initial energy of 80, but the residual energy becomes 0 and it is destroyed due to a joint attack by ST 1 and ST 2. Figure 4.1-(d) shows the result of the engagement at 530 seconds.



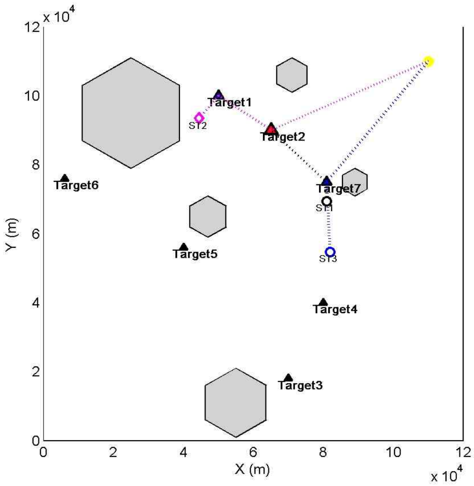
(a) Simulation at 0 seconds



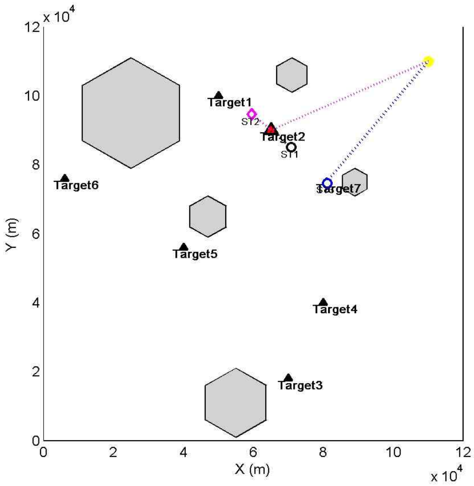
(b) Simulation at 210 seconds



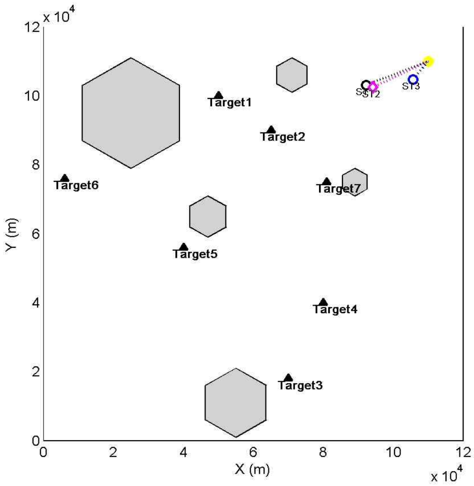
(c) Simulation at 400 seconds



(d) Simulation at 530 seconds



(e) Simulation at 630 seconds



(f) Simulation at 890 seconds

Figure 4.1 Simulation results (Stage 1)

ST 2 attacks Target 1, and ST 1 and ST 3 attack Target 7 together. To destroy the Target 7, main target, it can be confirmed that the middle-performance UAVs employ the multi armaments. In contrast, it can be seen that ST 2, a high-performance UAV, uses 60% target destruction ability, and Target 1 as the main target is destroyed with a single attack. Figure 4.1-(e) shows the result at 630 seconds, and in order to attack the high-value target Target 2, ST 1 and ST 2 are assigned a same task and attack it together. In the meantime, ST 3 performs all of the attack missions assigned to it and moves to the mission end point.

All the targets have been destroyed, and all UAVs are identified as arriving at the end point of the mission as shown in Fig. 4.1-(f) at 890 seconds. Tables 4.6 - 4.7 summarize the target allocation results of each UAV and the final destruction state of the target.

As can be seen from the simulation results in Stage 1, the task allocation of the UAV air strike package based on the target group was successfully done. In addition, it can be seen that, in the operational environment, different types of strike UAVs with different attack capabilities successfully neutralize ground targets with different defense capabilities.

* C.T.D : Capability of Target Destrucion

STRIKE UAV	#1	#2	#3	#4
Mid UAV 1 (C.T.D : 40%)	Target 3	Target 4	Target 7	Target 2
High UAV 2 (C.T.D : 60%)	Target 6	Target 1	Target 2	-
Mid UAV 3 (C.T.D : 40%)	Target 5	Target 4	Target 7	-

Table 4.6 Target allocation results (Stage 1)

* H.V.T : High Value Target / M.T : Main Target / O.T : Other Target

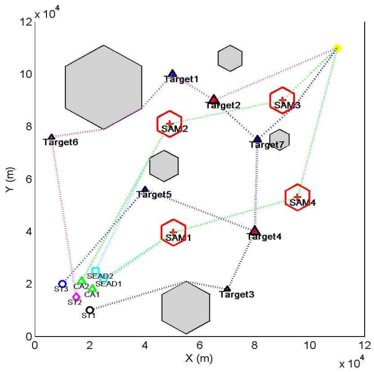
Target #	#1 (M.T)	#2 (H.V.T)	#3 (O.T)	#4 (H.V.T)	#5 (O.T)	#6 (O.T)	#7 (M.T)
Initial Energy	50%	80%	30%	80%	30%	30%	50%
Final Energy	-10%	-20%	-10%	0%	-10%	-30%	-30%

Table 4.7 Task energy status (Stage 1)

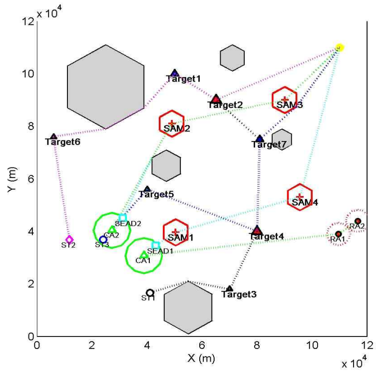
4.2.2 Stage 2 simulation result

Stage 2 is a task assignment model for online algorithm, which adds SEAD and counter-air UAV to the Stage 1 scenario and expand it for real-time application. As a stage with a complete air strike package, a UAV squadron is considered, which consists of 7 units of 4 types in total, strike(2 types, 3 units), SEAD(2 units), and counter-air(2 units). This is a scenario in which the mission is to neutralize all 7 ground targets with different required destruction rates in the battlefield situation where 4 SAMs and 4 enemy air appear. The UAV strike package recognizes the environment to respond to changing threats in real-time, and the UAVs move to the end point after completing the mission. The simulation results are shown in Fig. 4.2.

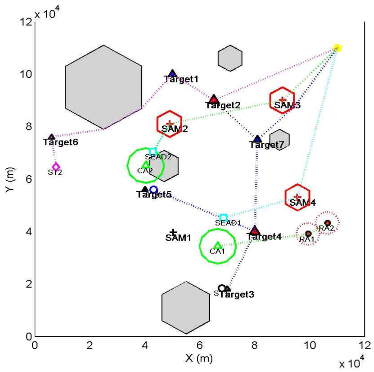
Figure 4.2-(a) shows the initial situation of the mission. In the first offline situation, the mission is carried out according to the route where the assignment has been completed. STs 1, 2 and 3 were allocated to the targets through consensus agreement to effectively neutralize them using the CBBA algorithms. Meanwhile, SEADs 1 and 2 and CAs 1 and 2 are moving together into enemy territory to attack SAM 1 and SAM 2, respectively. Figure 4.2-(b) shows the scenario result at 110 seconds. After the initial task assignment is made, the real-time environment is re-recognized every 5 seconds and the CBBA algorithm is updated. There is a situation where two enemy airs appear in the east of the operational area, and the changing operational environment is recognized for the first time. As a result, the RED ALRET 1 situation is issued, and the CA 1 defending the lower right area of the operational area resets the moving enemy air as a mission objective. The green circle around the CA 1 indicating the possible intercept distance is created. Figure 4.2-(c) shows the result at 300 seconds. ST 1 and ST 3 are moving to Target 4 after destroying Target 3 and Target 5, respectively, and ST 2 is preparing to attack the Target 6. SEADs 1 and 2 also try to destroy the assigned SAMs 2 and 4. All the UAVs are performing their mission properly.



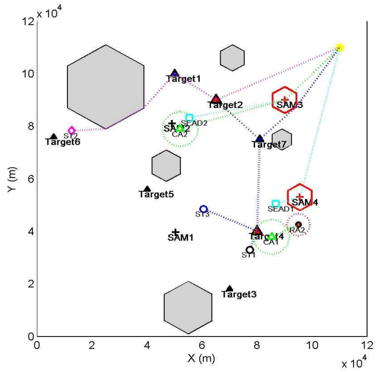
(a) Simulation at 0 seconds



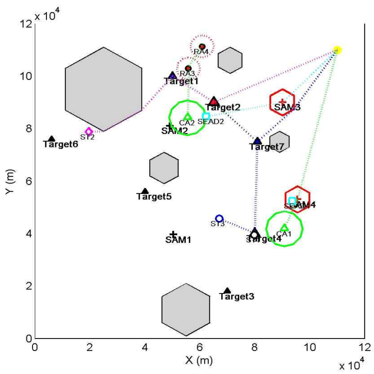
(b) Simulation at 110 seconds



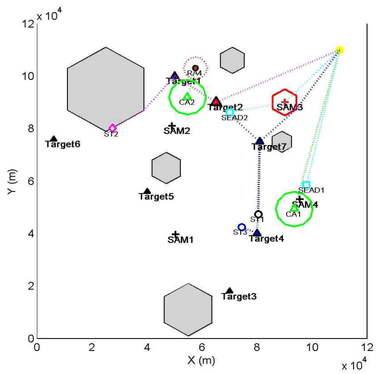
(c) Simulation at 300 seconds



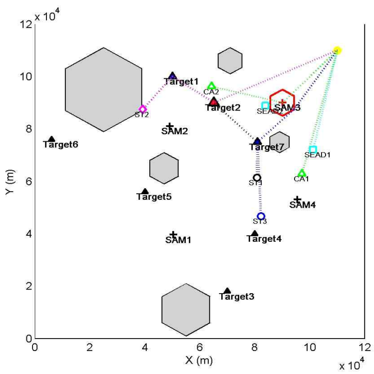
(d) Simulation at 350 seconds



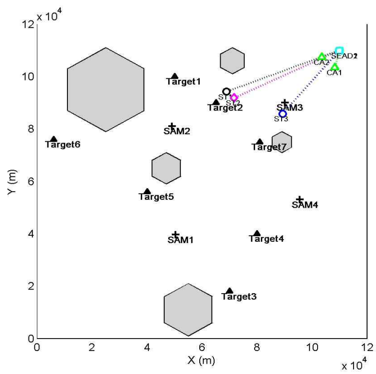
(e) Simulation at 380 seconds



(f) Simulation at 430 seconds



(g) Simulation at 520 seconds



(h) Simulation at 690 seconds

Figure 4.2 Simulation results (Stage 2)

Figure 4.2-(d) shows the result of the engagement at 350 seconds. CA 1, which has a longer intercept range than the enemy, successfully intercepts RA 1 and moves to RA 2 sequentially. It can be seen that CAs 1 and 2 effectively intercept enemy air threat with superior operation capability and flight speed than the RAs 1 and 2. Figure 4.2-(e) is the situation when 380 seconds have passed. CA 1 intercepts all of the RAs 1 and 2, and therefore the RED ALRET 1 situation is terminated. CA 1 switches to the mission to escort SEAD 1 again. Meanwhile, an additional air threat RAs 3 and 4 appear in the north and come down to the south. Accordingly, the RED ALRET 2 situation is issued, and CA 2 switches mission and approaches RA 3 and RA 4 in the shortest distance. CA 2 effectively intercepts in response to RA 3 and RA 4 as shown in Figure 4.2-(f) at 430 seconds. While protecting UAV squadrons from enemy air threat, strike and SEAD UAVs are constantly updating the changed battlefield situation and sequentially hitting the targets and SAM sites. Figure 4.2-(g) shows the result of 520 seconds. CA 2 successfully intercepts the RA, which makes the RED ALRET 2 situation clear. CA 2 switches its mission to cover SEAD 2 again. All the strike and SEAD forces finish their last tasks, and they enter the mission end point sequentially as shown in Fig. 4.2-(h).

The simulation results of Stage 2 are summarized in Table 4.8. Table 4.8 shows the status of targets and SAMs assigned to UAVs including the impact time, and the total number of assigned missions. As a result, it was verified through numerical simulation that the UAV air strike package effectively responds to the surface-to-air and air-to-air threat situations by the appearance of the SAM and enemy aircraft, completely destroying the assigned targets and the SAM sites.

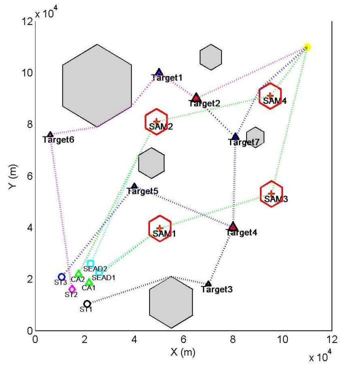
UAV			Marking	Mission (Time, second)				Total Missions
STRIKE	ST 1	Mid UAV	○	TGT 3 (260)	TGT 4 (390)	TGT 7 (565)	TGT 2 (665)	4
	ST 2	High UAV	◇	TGT 6 (310)	TGT 1 (580)	TGT 2 (665)	-	3
	ST 3	Mid UAV	○	TGT 5 (235)	TGT 4 (450)	TGT 7 (630)	-	3
SEAD	SEAD 1		□	SAM 1 (155)	SAM 4 (395)	-	-	2
	SEAD 2		□	SAM 2 (310)	SAM 3 (520)	-	-	2
Counter - Air	CA 1		△	RA 1 (350)	RA 2 (370)	-	-	2
	CA 2		△	RA 3 (420)	RA 4 (450)	-	-	2

Table 4.8 Simulation results (Stage 2)

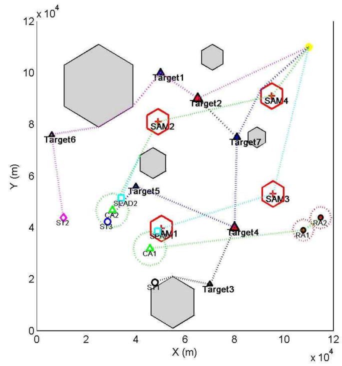
4.2.3 Stage 3 simulation result

Stage 3 is a task assignment model in real-time complex situations in which pop-up SAM and TST situations are added to the mission situations of Stages 1 and 2. The numerical simulation results are shown in Fig. 4.3.

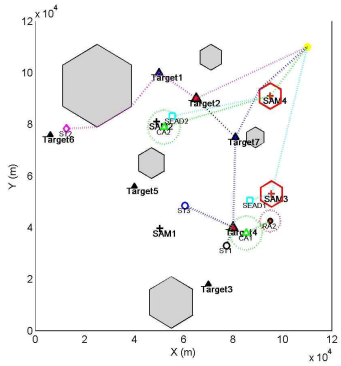
Figure 4.3-(a) shows the initial mission situation. All UAVs that make up the strike package are aware of the changing real-time situation and perform their assigned missions. Figures 4.3-(b) ~ (c) show the same mission result as Stage 2. Figure 4.3-(d) is the result of the engagement at 400 seconds. While each UAV is performing the assigned mission, a pop-up SAM appears in the center of the battlefield. Accordingly, the nearest located SEAD 2 shifts its original plan to attack SAM 4 and changes its target to the pop-up SAM. SEAD 1, which was moving to the end point after completing the mission, is reassigned to the attack mission against SAM 4. Figure 4.3-(e) is the result at 450 seconds. SEAD 2 successfully destroys the pop-up SAM, and SEAD 1 moves to strike the SAM 4.



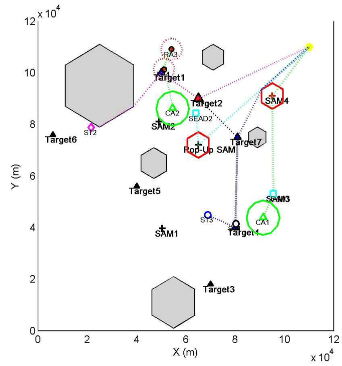
(a) Simulation at 0 seconds



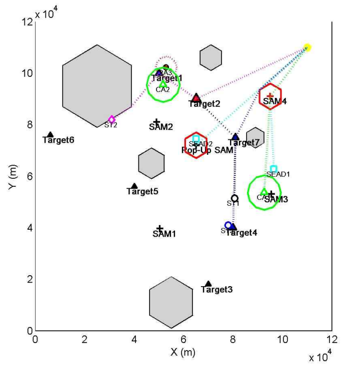
(b) Simulation at 150 seconds



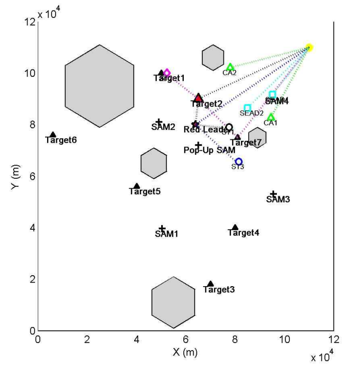
(c) Simulation at 340 seconds



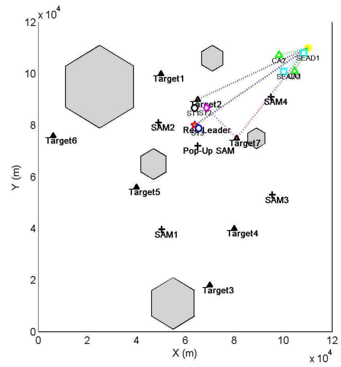
(d) Simulation at 400 seconds



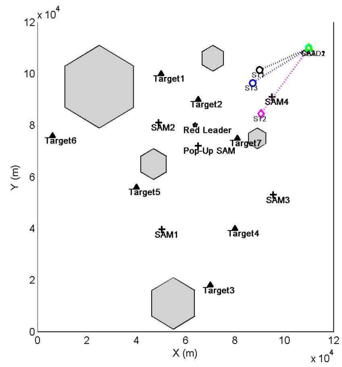
(e) Simulation at 450 seconds



(f) Simulation at 590 seconds



(g) Simulation at 690 seconds



(h) Simulation at 840 seconds

Figure 4.3 Simulation results (Stage 3)

It is confirmed that the UAV strike package effectively responds to the unplanned SAM threats. Figure 4.3-(f) shows the result at 590 seconds. After all SAMs and air threats have been eliminated, the enemy leader attempting to escape from the operation area appears while the strike forces perform their last missions. Accordingly, the ground command center sends the information on TST, which requires an emergency strike, to the package's UAVs in the air. Enemy leader is recognized as a top priority target having higher reward than other pre-planned targets. Through the proposed algorithm, the nearest ST 1 and ST 3 are assigned to carry out the attack together. At this time, ST 2 destroys Target 1 with a single attack and is assigned an additional mission for Target 7 that ST 3 was supposed to hit. Figure 4.3-(g) shows the result of 690 seconds. All the strike UAVs conduct the last mission, ST 1 attacking Target 1, ST 2 attacking Target 7, and ST 3 attacking the enemy leader, and the mission is terminated by destroying the energy of all targets below zero. As shown in Fig. 4.3-(h), all the UAVs in the air strike package arrive at the mission end point after successfully carrying out their missions according to their respective roles.

As shown in the numerical simulation result of Stage 3, the distributed task assignment algorithm proposed in this study ensured effective mission performance even in the dynamic air strike mission environment. This proved that the proposed algorithm can be applied even in a variety of threats, targets, and environmental changes. In particular, it was verified that the algorithm can be applied to the mission of the UAV air strike package, in which heterogeneous UAVs perform their missions collaboratively through mutual cooperation. The above simulation results are summarized in Tables 4.9 and 4.10.

UAV			Marking	Mission (Time, second)					Total Missions
STRIKE	ST 1	Middle performance	○	TGT 3 (260)	TGT 4 (390)	TGT 7 (560)	Red Leader (655)	TGT 2 (710)	5
	ST 2	High performance	◇	TGT 6 (310)	TGT 1 (580)	TGT 2 (665)	TGT 7 (775)		4
	ST 3	Middle performance	○	TGT 5 (235)	TGT 4 (450)	Red Leader (700)	-		3
SEAD	SEAD 1		□	SAM 1 (155)	SAM 3 (395)	SAM 4 (580)	-		3
	SEAD 2		□	SAM 2 (310)	Pop-up SAM (520)	-	-		2
Counter -Air	CA 1		△	RA 1 (345)	RA 2 (370)	-	-		2
	CA 2		△	RA 3 (420)	RA 4 (450)	-	-		2

Table 4.9 Simulation results (Stage 3)

* H.V.T : High Value Target / M.T : Main Target / O.T : Other Target / R.L(Red Leader)

Target #	#1 (M.T)	#2 (H.V.T)	#3 (O.T)	#4 (H.V.T)	#5 (O.T)	#6 (O.T)	#7 (M.T)	R.L (TST)
Initial Energy	50%	80%	30%	80%	30%	30%	50%	50 %
Final Energy	-10%	-20%	-10%	0%	-10%	-30%	-50%	-30 %

Table 4.10 Task energy status (Stage 3)

Chapter 5

Conclusion

5.1 Concluding Remarks

In this thesis, the problem of the target group-based task assignment is solved using the UAV air strike package by applying the CBBA algorithm. Although many previous studies have dealt with the task assignment problem using multiple UAVs, most of them cannot describe and apply the mission environment consistent with the characteristics of air operations from the actual military perspective. Because targets on the battlefield have different levels of required destruction according to their characteristics, effective neutralization can be achieved only when selective armed strikes are applied. In this study, a distributed task assignment algorithm was proposed to redundantly allocate the missions through a combination of the attack capability of the UAV and the defense capability of the target to derive a mission result similar to the actual operational environment. In addition, a complete model of the UAV air strike package responding to both air-to-air threats and ground-to-air threats was presented.

The role of manned aircraft is replaced by UAVs, and the military use of UAVs is gradually expanding. Therefore, the possibility of future development of air operations is raised through the approach of UAVs replacing the strike package as the core of air operations. In particular, it is expected that this will overcome the limitations of the existing air strike package operations consisting of manned aircraft. By increasing the efficiency of the ATO cycle, it is believed that it is possible to implement new air operations that are concise, flexible, fast, and accurate.

5.2 Future Work

There are several issues to consider to apply the algorithm proposed in this study to actual military operations, which include i) considering various performance indices and limited operational circumstances, ii) supplementing algorithm that applies various battle plans of attack squadrons, iii) developing UAV platform that can implement an actual algorithm, and iv) verifying reliability and safety of strike package that is only constituted by UAVs.

Future work needs to consider various mission scenario such as taking into account the armament margin for the dynamic mission, the mission end time, and fuel consumption. Especially, in this study, it is assumed that the friendly forces are advantageous, but the scenario for the unfavorable situation which the enemy's ability is superior to that of the friendly forces should be studied. The additional study on the situations of armament exhaustion, high fuel consumption, and UAV interception may provide more robust results.

In the aspect of algorithm, further study is required to additionally establish combat performance standards that can be applied to various operational situations. For example, detailed combat methods according to air-to-air and air-to-ground combat situations should be considered. And the case that the enemy's air-to-air capability is superior to that of the ally, or case that the enemy’s defense level overwhelms the package’s attack capability should also be contemplated. If the actual combat performance standard is algorithmic for what game plan each UAV will perform on its mission, it would be possible to operate a more effective real-time automated UAV air strike package.

In addition, it is necessary to develop a platform for operating an UAV squadron. Of course, developing UAVs with the same capabilities as manned combat aircraft cannot be done in a short-term approach. Even if such a capable UAV is developed, it is necessary to verify the strategic destructive power and ripple effect of the UAV strike package. It should be based on social and national consensus and trust as well as technical verification of whether it can be operated stably.

The air strike package using UAVs will be a definite end state for air operations. It is not a character invented and introduced by someone at any moment, but a process in which the efforts and achievements of small research are made and overlaid and completed. It is hoped that various approaches and research attempts will continue in the future.

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국문초록

국내､외에서 다양한 임무할당 연구가 진행 중이나 실제 공중작전에 핵심전력인 공격편대군의 작전환경을 고려한 연구는 매우 제한적이다. 무인기 기술이 고도화되어 군사적 운용이 현실화된 오늘날, 세계 최고의 군사 강국인 미국은 2025~30년을 목표로 무인기 공격편대군을 개발하려는 노력을 경주하고 있다.

본 논문에서는 CBBA(Consensus Based Bundle Algorithm)을 기반으로 무인기 공격편대군의 임무수행을 위한 분산형 임무할당 알고리듬을 제시한다. 공격편대군 임무는 이종의 무인기에 각자의 역할에 부합하도록 임무를 부여하는 임무할당 문제로 정의할 수 있다. 작전에 참가하는 무인기는 적의 지상표적을 타격하는 Strike와 대공 방어망인 SAM (Surface-to-Air Missile)을 파괴하는 SEAD(Suppression of Enemy Air Defense), 그리고 적기의 공대공 위협으로부터 아군을 보호하는 Counter-Air 전력으로 구성된다. 본 논문에서는 최단경로생성 알고리듬과 CBBA 알고리듬을 이용하여 SAM 위협과 지형장애물이 존재하는 상황에서 공격해야 할 지상표적의 특성과 아군 무인기의 다양한 작전성능을 고려한 표적군 기반의 분산형 임무할당 기법을 제안한다. 또한, 다양한 위협이 동시에 적용된 복합 상황에서의 공격편대군 임무에 제안한 알고리듬을 적용하고, 수치 시뮬레이션을 통하여 적용된 기법의 성능과 운용 가능성에 대해 검토한다.

본 연구에서는 무인기로 구성된 공격편대군을 가정하여 다양한 복합환경에서의 임무수행 가능성을 알고리듬을 통해 검증하는데 중점을 두었다. 향후 무인기를 활용한 군사작전과 실제적인 전장환경을 고려한 연구가 더욱 확대될 것이다. 이러한 연구들을 통해, 오늘날 국외 기술에 기

반한 전투기·정밀무장 중심의 공중작전이 대한민국의 과학기술과 무인기에 기반한 새로운 무기체계 중심으로 전환하는 계기가 될 것으로 기대된다.

주요어 : 분산형 임무할당, 공격편대군, 이종무인기,
합의기반 묶음 알고리듬

학번 : 2019-20604

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