

Research on the Kill Chain of UAV Swarm Coordinated Attack on Time-sensitive Targets based on Behavior Tree

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Abstract

Fire strike is a crucial part of the current UAV-assisted landing operations and seizing control, which directly affects the final success or failure of the landing operations. In view of the current problems that a single reconnaissance/strike UAV cannot cover the entire combat area in a short time and repeated low-altitude reconnaissance is easy to be detected and attacked, this paper models the UAV behavior based on behavior tree and finite state machine, constructs a kill chain for the coordinated attack of time-sensitive targets by a double-layer UAVs of reconnaissance and reconnaissance/strike, conducts simulated attacks on random time-sensitive targets at different altitudes, and counts their survival time. The experimental results show that the reconnaissance/strike UAVs swarm can conduct patrol, reconnaissance and coordinated strike operations at an altitude of 4km~4.75km, covering the entire combat area in a short time, shortening the kill chain closing time to within 290s, and controlling the survival time of time-sensitive targets within 345s, effectively reducing the threat of defensive weapons and improving the safety of troop landing operations, which is of great significance to the research on troop landing operations.

Keywords

UAVs Swarm; Time-sensitive Targets; Kill Chain; Behavior Tree.

1. Introduction

This paper takes a typical scenario of army landing on a certain coast as the research object. Usually, the defender will deploy highly mobile and destructive equipment (time-sensitive targets) in high-value flat areas such as beaches and ports to prevent the landing of soldiers from the attacker[1]. Therefore, soldiers landing need to prioritize suppressing time-sensitive targets and seizing control of beaches, ports, etc. With the widespread application of UAV in military operations[2,3], the use of UAVs that are small in size, low in cost, and easy to evade radar[4,5] to carry out fire strikes has extraordinary significance for seizing control of beaches, ports, etc. and thus achieving landings.

Fire strike is one of the main means for UAVs to seize control. Its operation belongs to the E stage of F2T2EA[6-9] and is a crucial link in the kill chain, which directly affects the accuracy of the kill chain and the speed of the kill chain closing time. In previous landing operations,

when troops were trying to seize control of occupied areas, they often used a single reconnaissance/strike UAV to conduct reconnaissance and fire strikes on time-sensitive targets. However, its range was limited and it was impossible to cover the entire combat area in a short period of time. In addition, some anti-UAV equipment is usually deployed in areas such as beaches and ports, such as the KCE-ABM machine gun with an effective range of 3,000 meters and a maximum range of 4,000 meters[10], and laser weapons with a strike range of 200 to 4,000 meters[11]. Reconnaissance/strike UAVs swarm are large targets, and repeated low-altitude operations can easily lead to detection, identification and attack by the opponent's anti-UAV equipment, resulting in high deployment costs.

In response to the above problems, this paper proposes a solution for UAVs to coordinate strikes against time-sensitive targets. Small reconnaissance UAVs swarm with lower costs and lower detection potential are deployed in advance at long distances to conduct regional coverage and reconnaissance searches in the occupied areas. At the same time, multiple reconnaissance/strike UAVs swarm are deployed at high altitudes to patrol and cooperate with the reconnaissance UAV to ensure that time-sensitive targets can be discovered within a short period of time after they appear, and then destroyed and struck [12–14]. In order to save the consumption of UAVs operation resources, shorten the kill chain closing time, realize the long-distance collaborative operation of UAVs to seize control of beaches, ports, etc., and improve the landing safety of soldiers. This paper constructs the F2T2EA dynamic kill chain [15–18] for the landing scenario and simulates the coordinated operation of UAVs through behavior trees, finite state machines and greedy algorithms [19] to study the impact of the patrol altitude of the reconnaissance/strike UAVs swarm on the kill chain closing time and target survival time. It determines the patrolling and striking operation plan suitable for the reconnaissance/strike UAVs swarm, improves the accuracy of the kill chain and shortens the kill chain closing time.

2. Research on the Kill Chain of UAVs Collaborative Operation

2.1. Construction of the UAV Kill Chain

Combined with the landing combat scenario, the six-stage nodes of the F2T2EA dynamic kill chain are constructed, see **Figure 1** and **Table 1**.

Among them,

- Kill chain closing time: the time from the target being discovered to the target being killed,
- Target survival time: the time from the target's appearance to the target's death,
- Approach time: The time it takes for a reconnaissance/strike UAV to approach a target after receiving a strike mission until conditions permitting firing,
- Firing time: The time from when the reconnaissance/strike UAV starts firing to when the target dies,
- Strike time: The time from when the reconnaissance/strike UAV receives the strike mission to when the target dies.

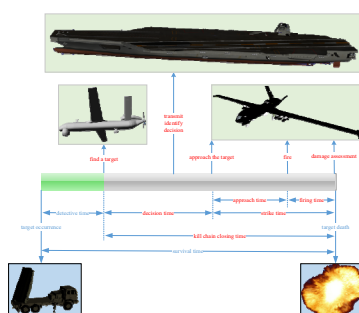


Figure 1. Design of UAV kill chain node for this landing operation scenario

Table 1. Description of the stages of UAVs kill chain for this landing operation scenario

F2T2EA	behavior			time		
	reconnaissance UAV	command center	reconnaissance/strike UAV			
Find	gather data, simple identification	-	-	detective time	-	target survival time
Fix	upload suspect target location	precise identification, value ranking	-	decision time	kill chain closing time	
Track	constantly update the target's location	intelligent decision, assigning task	approach target	approach time		
Target	stop tracking target	-	adjust posture to aim at target			
Engage	-	-	fire	firing time		
Assess	-	-	assess whether the target is dead	evaluate time		

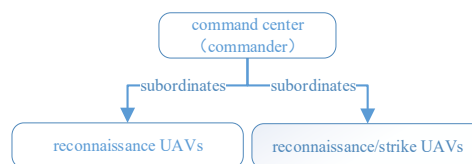
2.2. Kill Chain Performance Evaluation Method

There are many ways to evaluate kill chain performance, such as high accuracy (strong strike capability), short closure time, and large number of kill chains (many optional combat units). In order to improve the combat capability, this paper optimizes the collaborative operation plan of the reconnaissance/strike UAVs swarm based on the behavior tree to ensure that the command center will not lose the target before confirming that the target is not dead, and there is always a reconnaissance/strike UAV operating on it. Therefore, this paper adopts the Monte Carlo Algorithm to record the time of each randomly appearing time-sensitive target in each stage of the kill chain in the scenarios of reconnaissance/strike UAVs swarm at different altitudes, and studies the relationship between the altitude of the reconnaissance/strike UAVs swarm and the target survival time and the average kill chain closing time through multiple rounds of simulation experiments.

2.3. Construction of UAV Swarm Collaborative Operation Scenario Model

2.3.1. Building an Information Chain

The information link is the basis for the UAVs to achieve long-distance communication and collaborative operations, see **Figure 3**. The Red Army has two command links: command center and reconnaissance UAVs, command center and reconnaissance/strike UAVs swarm, see **Figure 2**. The network segments between the command center and the reconnaissance UAVs and the reconnaissance/strike UAVs swarm are set up accordingly.

**Figure 2.** Red side command link structure

After the reconnaissance UAV finds a preliminary suspicious target, it uploads the picture, the coordinates, speed, direction of movement and other information of the suspicious target to the command center; the command center identifies the picture and confirms that it is a high-value time-sensitive target, then assigns the task based on the current situation of the reconnaissance/strike UAVs swarm, and sends the operation task and the coordinates and characteristics of the target to one of the reconnaissance/strike UAVs swarm; the

reconnaissance/strike UAV that receives the operation task leaves the patrol state, searches for the target at the fastest speed, adjusts its posture and enters the firing state after locking the target, evaluates the target after the weapon explodes, and returns to the patrol path after determining that the target is unable to operate.

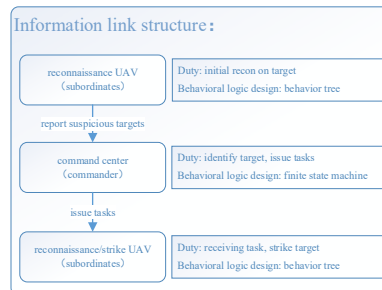


Figure 3. Red side information link structure

2.3.2. UAVs Collaborative Operation Model based on Finite State Machine and Behavior Tree

The behavior tree structure of a single UAV operation is simple. If it is directly applied to UAVs operations, it is easy to cause resource redundancy and there is a lot of room for optimization. Therefore, this paper constructs an entity behavior model based on finite state machine and behavior tree. By adjusting and optimizing the behavior tree of the UAVs, the automatic collaborative operation of the UAVs in different situations can be achieved, thereby maximizing the use of its own resources.

Finite state machine is a mathematical model that describes the transition between a finite number of states. It controls the behavior of entities by designing the conditions for state transitions, thereby enabling entities to intelligently process events.

The behavior tree is a tree-like structure composed of root node, action nodes and control nodes (sequence, parallel, selector, priority selector, weighted random). The intelligent control of complex behavior is realized by combining conditional statements.

(1) Command Center

The command center is the core of realizing the automated collaborative operation of UAVs. The following three points are achieved through the finite state machine:

1) Intelligence coordination: The command center needs to integrate multiple pieces of dynamic reconnaissance information on the same target. For one target, only one operation task needs to be issued to the reconnaissance/attack UAVs swarm.

2) Operational coordination: For a target, the commander must designate a reconnaissance/strike UAV from the dynamic reconnaissance/strike UAVs swarm. If the weapons of the reconnaissance/strike UAV have been used up and the mission target can still be operated, the mission of the reconnaissance/strike UAV is changed to tracking the target. The commander then issues the operation task from the reconnaissance/strike UAVs swarm. The previous reconnaissance/strike UAV will return to replenish weapons and power after the new reconnaissance/strike UAV captures the target.

3) Automated operation: A dynamic target has multiple dynamic kill chains throughout its life cycle. As shown in the **Figure 4**, if it is discovered by two reconnaissance UAVs in succession, the target will have 10 kill chains. When the kill chain of the target changes, the command center calculates the local optimal solution at this time through the greedy algorithm coupled to the finite state machine, greatly shortening the time for decision-making and approaching the target, thereby achieving the purpose of shortening the kill chain closing time.

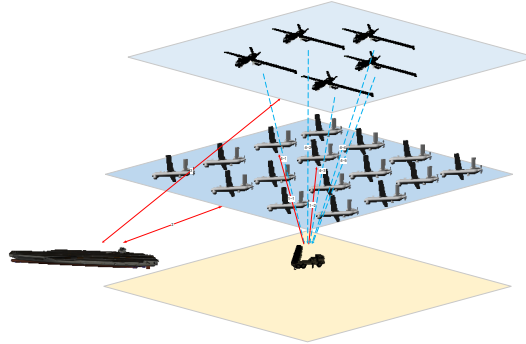


Figure 4. The UAVs kill network

Its finite state machine design is shown in the **Figure 5**. When the command center is in the acquire state, it shields the problem of multiple information sources for the same target through information fusion to avoid repeated assignment of tasks. In the assign state, it uses a greedy algorithm to obtain the local optimal solution for the intersection of an operational, dynamic reconnaissance/strike UAVs swarm and a moving target. In the cancel state, the coordination between reconnaissance/strike UAVs swarm are achieved by setting the conditions for canceling the reconnaissance/strike UAV mission, and the coordination between the reconnaissance/strike UAVs swarm are achieved by canceling the tracking mission of the reconnaissance UAV.

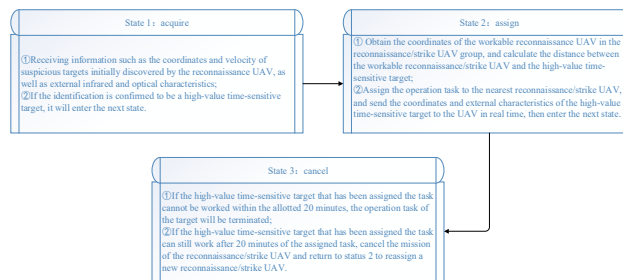


Figure 5. The finite state machine architecture of the command center

(2) Reconnaissance UAVs swarm

The reconnaissance UAVs swarm use a parallel + sequential behavior tree structure to achieve collaborative tracking, ensuring that the target continues to provide target information to the command center before the reconnaissance/strike UAV locks on. The behavior tree node design is shown in the **Figure 6**. The report node is used to control the reconnaissance UAV to report the target location and appearance characteristics when it finds a suspicious target. At the same time, it enters the tracking node, turns on the tracking radar to stare at the target, and continuously reports the target location and appearance characteristics to the command center, and then enters the stop tracking node. If the command center issues an order to turn off the tracking radar or it exceeds the range of the tracking radar, the tracking radar will be turned off.

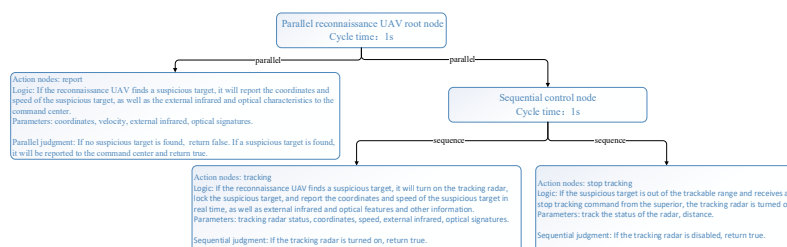


Figure 6. Behavior tree structure of reconnaissance UAVs swarm

(3) Reconnaissance/strike UAVs swarm

The reconnaissance/strike UAVs swarm use a sequential + selective behavior tree structure to achieve coordinated strikes and damage assessment, ensuring that the discovered high-value time-sensitive targets cannot be operated. The behavior tree node design is shown in the **Figure 7**. Approach node, the reconnaissance/strike UAV plans a path based on the coordinates and appearance features issued by the command center, approaches the target at the fastest speed, and enters the fire node after locking the target. Fire node, the reconnaissance/strike UAV switches to combat state, adjusts its posture, and fires when the firing conditions are met. After the weapon explodes, it enters the damage assessment state. The damage assessment state uses the priority selector structure. If the reconnaissance/strike UAV has no weapons or is low on power, it will enter the go home node first. If the target is not dead, it will enter the fire again node first. If the target is dead, it will enter the back patrol route node.

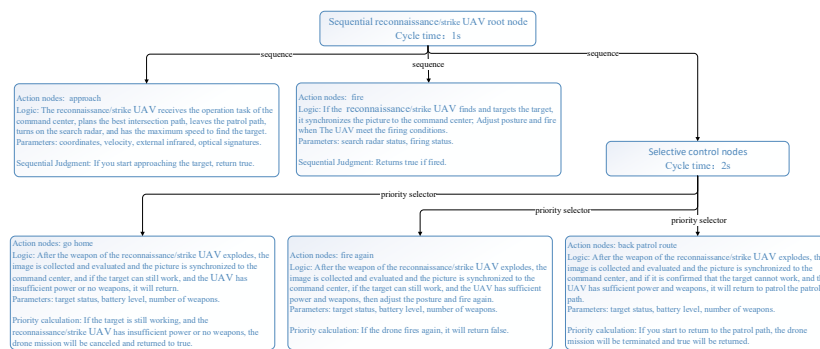


Figure 7. Behavior tree structure of reconnaissance/strike UAVs swarm

3. Construction of the Kill Chain Scenario for UAVs Collaborative Operation

3.1. Blue Force Deployment

A high-value time-sensitive target is hidden in a flat area on a beach. It randomly emerges every 10 minutes to start operation. After 8 minutes of operation, it randomly selects a direction in this area and maneuvers at a speed of $v_{T\ max}$ km/h. If it hits the boundary of the area, it deflects 170 degrees until the end of the simulation, as shown in the **Figure 8**.



Figure 8. The time-sensitive target maneuvers in the plane area after the stationary work

3.2. Red Force Deployment

3.2.1. Command Center

The Red Force's command center is deployed on a distant ship, setting up a wireless network to communicate with the UAVs.

3.2.2. Reconnaissance UAVs

A UAV is dropped from a distant ship to monitor the beach in advance. The reconnaissance UAV patrols at a speed of v_D km/h at an altitude of 1,000 m above the ground. After discovering a suspicious target, it turns on the tracking mode and tracks the target until the target is locked by the reconnaissance UAV, as shown in the **Figure 9**.

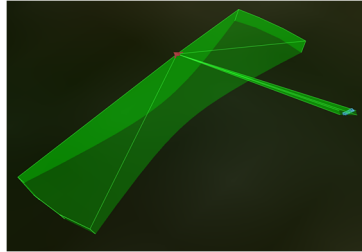


Figure 9. The reconnaissance UAV turn on tracking radar when it spots the target

In order to detect time-sensitive targets within t minutes, the distance between each pair is $v_D \times t/60$ km, as shown in the **Figure 10**.

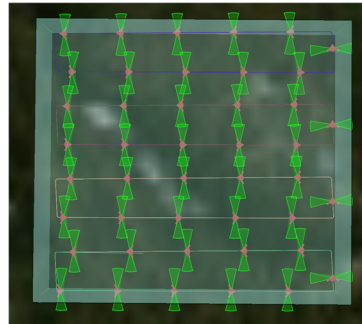


Figure 10. The reconnaissance UAVs deployment

3.2.3. Reconnaissance/Strike UAVs Swarm

The reconnaissance/strike UAVs swarm patrols over the center of the area at a speed of v_A km/h, as shown in the **Figure 11**.



Figure 11. The reconnaissance/strike UAVs swarm deployment

When the target is discovered by the reconnaissance UAV, the commander designates a reconnaissance/strike UAV (A_j) to leave the patrol state and approach the target at a speed of $v_{A_{max}}$ km/h. A_j fires after the firing conditions are met until the target dies, and then returns to patrol on the patrol route. By setting the patrol altitude of the reconnaissance/strike UAVs swarm multiple times, the changes in the kill chain closing time and the target survival time are observed.

4. Experimental Verification of the Kill Chain of Drone Swarm Collaborative Operation

4.1. Experimental Simulation Platform

This paper uses the AIFSIM (Artificial Intelligence Frame for Simulation Integration and Modeling) simulation platform to model the UAVs collaborative operation scheme. The simulation duration is set to 300 minutes. The simulation test environment is shown in **Table 2**, and the entity initialization parameters are shown in **Table 3**.

Table 2. Computer test environment

Computer environment category	parameter
CPU	11th Gen Intel(R) Core (TM) i5-1130G7 @ 1.10GHz 1.80 GHz
RAM	16.0 GB
System Type	64-bit operating system
Windows version	Windows 11 family Chinese version (21H2)

Table 3. Entity initial parameters

entity	Behavioral Modeling	Initial Parameters	Process Description
time-sensitive target	behavior tree	maximum speed 85km/h	After 40 minutes of simulation time, random objects are created in the area every 10 minutes, and they stay for 8 minutes before moving randomly in the area.
command center	finite state machine	deployed on a ship 80km from the coast	maintaining communication with the UAVs
reconnaissance UAV	behavior tree	maximum speed 150km/h, power 5h	fly from the command center to the occupied area for patrol at 150km/h.
reconnaissance/strike UAV	behavior tree	maximum speed 200km/h, ammunition load 4, power 5h	fly from the command center to the occupied area for patrol at 200km/h.

4.2. Simulation Data Collection

This experiment uses the Monte Carlo Algorithm to ensure that each target appears randomly and each round of simulation tests is independent.

(1) Reconnaissance/strike UAVs swarm patrolling at an altitude of 3,000 m

At the end of the i -th round of simulation, we can obtain the total number of N_i time-sensitive targets destroyed in the i -th round, as well as the kill chain closing time (Tk_{ij}) and target survival time (Ts_{ij}) of the j -th time-sensitive target (N_{ij}). Then we have the average kill chain closing time (Tk_i) and target survival time (Ts_i) of the i -th round:

$$Tk_i = \sum_{j=1}^{N_i} Tk_{ij} / N_i, \quad Ts_i = \sum_{j=1}^{N_i} Ts_{ij} / N_i \quad (j=1,2,3 \dots N_i)$$

At the end of the n -th round of simulation, the average kill chain closing time and target survival time of the n -th round when the reconnaissance/ strike UAVs swarm cruises at an altitude of 3000m are:

$$Tk = (\sum_{i=1}^n Tk_i) / n, \quad Ts = (\sum_{i=1}^n Ts_i) / n \quad (i=1,2,3 \dots n)$$

(2) Reconnaissance/strike UAVs swarm cruises at an altitude of 3,500m

Set the cruise altitude of the reconnaissance/strike UAV to 3500m, run the simulation system, and obtain the average kill chain closing time and target survival time when the reconnaissance/strike UAVs swarm cruises at an altitude of 3500m in the same way as (1).

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(12) Reconnaissance/strike UAVs swarm cruises at an altitude of 6,000m

Set the cruise altitude of the reconnaissance/strike UAV to 6,000m, run the simulation system, and obtain the average kill chain closing time and target survival time when the reconnaissance/strike UAVs swarm cruises at an altitude of 6,000m in the same way as (1).

4.3. Results and Analysis

After multiple rounds of experiments at each altitude, the average kill chain closing time and target survival time are shown in the **Table 4**.

Table 4. The average kill chain closing time and average target survival time of reconnaissance/strike UAVs swarm patrol altitude

num	Altitude(m)	average kill chain closing time(s)	average target survival time(s)
1	6000	306.3606	359.2101
2	5750	301.9444	359.1611
3	5500	300.7523	354.6023
4	5250	299.5359	350.7346
5	5000	293.2856	347.7964
6	4750	287.7617	343.093
7	4500	282.3088	341.8263
8	4250	280.3067	341.6963
9	4000	280.8838	338.7287
10	3750	279.694	335.2395
11	3500	268.3745	330.4258
12	3000	260.9533	323.1137

4.3.1. Relationship between Altitude and Kill Chain Closure Time

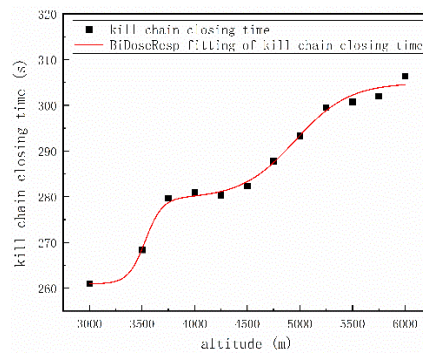


Figure 12. Relationship between kill chain closing time and altitude for this landing operation scenario

The reconnaissance/strike UAVs swarm patrol altitude and kill chain closing time complex BiDoseResp function relationship.

BiDoseResp function :

$$y = A_1 + (A_2 - A_1) \left[\frac{p}{1 + 10^{(\text{LOG}x01 - x)h_1}} + \frac{1 - p}{1 + 10^{(\text{LOG}x02 - x)h_2}} \right]$$

The test results show that in this area, when the patrol altitude of this reconnaissance/strike UAVs swarm are between 3km and 6km, the kill chain closure time of time-sensitive targets is less than 310s. When the patrol altitude is between 3km~3.75km and 4.5km~5.25km, the kill chain closure time increases very quickly; when the patrol altitude is between 3.75km~4.5km and 5.25km~6km, the kill chain closure time increases slowly.

Table 5. BiDoseResp function parameters of reconnaissance/strike UAVs swarm patrol altitude and kill chain closing time

kill chain closing time	value	standard error	t value	probability t	correlation
A1	260.91344	1.62933	160.13509	1.80173E-10	0.68769
A2	304.92549	1.59861	190.74369	7.51493E-11	0.80878
LOGx01	4955.44859	68.89951	71.92284	9.84171E-9	0.6707
LOGx02	3531.02993	41.48474	85.11635	4.24226E-9	0.54371
h1	0.00169	4.64847E-4	3.64357	0.01485	0.75385
h2	0.00538	0.00358	1.50543	0.19256	0.5057
p	0.57465	0.0567	10.13564	1.60246E-4	0.90389
A2-A1	44.01205	2.27719			
adjusted R-squared (COD)	0.98681	-			

4.3.2. Relationship between Altitude and Target Survival Time

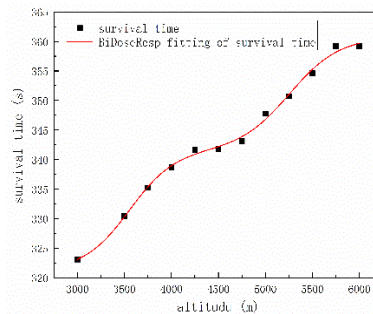


Figure 13. Relationship between survival time and altitude for this landing operation scenario
The reconnaissance/strike UAVs swarm patrol altitude and target survival time complex BiDoseResp function relationship.

Tabel 6. BiDoseResp function parameters of reconnaissance/strike UAVs swarm patrol altitude and target survival time

target survival time	value	standard error	t value	probability t	correlation
A1	321.28208	2.47531	129.79454	5.14927E-10	0.95549
A2	360.79043	1.7174	210.0792	4.63749E-11	0.94009
LOGx01	5257.54784	70.39971	74.68139	8.1547E-9	0.81603
LOGx02	3553.51751	71.38157	49.782	6.18111E-8	0.81909
h1	0.00163	4.8867E-4	3.33485	0.02067	0.88479
h2	0.0018	6.74017E-4	2.67259	0.04421	0.89818
p	0.4876	0.08725	5.58884	0.00253	0.98506
A2-A1	39.50835	2.60794			
adjusted R-squared (COD)	0.99322	-			

The test results show that in this area, when the patrol altitude of this reconnaissance/strike UAVs swarm are between 3km and 6km, the survival time of time-sensitive targets is less than 360s. When the patrol altitude is between 3km~4.25km and 4.75km~5.75km, the survival time of time-sensitive targets increases rapidly; when the patrol altitude is between 4.25km~4.75km and 5.75km~6km, the survival time of time-sensitive targets increases slowly.

5. Conclusion

This paper models the UAVs collaborative operation scenario based on finite state machines and behavior trees. At the same time, it constructs kill chain nodes for the reconnaissance and reconnaissance/strike double-layer UAVs operation scenarios, and adjusts and optimizes the

behavior tree of the reconnaissance/strike UAVs swarm in combination with the performance of anti-unmanned weapons to shorten the strike time of the overall kill chain. And, the greedy algorithm is used to implement the collaborative combat strategy of "one target, one UAV locking, one UAV attacking, and one UAV damage assessment", which saves the operating resources of the UAVs to the maximum extent, and by selecting the shortest kill chain among multiple dynamic kill chains, the target's kill chain closing time can be shortened.

Through multiple Monte Carlo Algorithm simulation experiments, the altitude of the patrol of the reconnaissance/strike UAVs swarm were adjusted, and the kill chain closing time and target survival time were calculated. It was finally determined that the appropriate strike plan and optimal patrol altitude for this reconnaissance/strike UAVs swarm were between 4km and 4.75km. The reconnaissance/strike UAVs swarm patrolling within this altitude range can control the kill chain closing time of time-sensitive targets within 290 seconds and the survival time within 345 seconds (the initial target dwell time is 480 seconds). This shows that this UAVs operation plan can save UAVs operation resources while ensuring the safety of the reconnaissance/strike UAVs swarm, and to a great extent reduce the threat of the defender's weapons and improve the safety of the troops' landing operations.

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