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TASK ALLOCATION METHOD FOR COMPLEX RECONNAISSANCE AREA BY MULTIPLE UAVS

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Abstract

It is the primary application for UAV swarms to accomplish reconnaissance tasks in a complex environment. Firstly, according to UAVs' maneuverability and anti-interference ability, the flight strategy of UAVs in a complex environment is established, respectively. Secondly, according to its flight strategy, the range cost of UAV swarms is calculated. Then, learning from the mechanism of the influence of parents and partners on children's behavior in the process of learning, the children’s behavior optimization (CBO) algorithm is established. Finally, the allocation examples of 5 UAVs cooperating in 5 target areas are given, and the UAV swarms under different parameters are analyzed. The CBO algorithm is more efficient than the traditional algorithm. Furthermore, the excellent usability and broad applicability of the model are proved.

Keywords: UAV swarm; reconnaissance task; children’s behavior optimization algorithm; task allocation; range cost

1. Introduction

With the development of aviation technology and the promotion of military needs, the UAV(Unmanned Aerial Vehicle) swarms have been used on battlefields to perform major combat tasks such as Search Reconnaissance, Suppression of Enemy Air Defenses, Close Air Support, and other significant combat tasks [1-4]. Subject to cost and load capacity, the ability of a single UAV to complete its mission is weak. However, the completion of the task can be improved by the cooperation of UAV swarms. Therefore, the multi-UAV cooperative operation will be the main operational mode of UAVs in the future.

Obtaining battlefield information is the primary issue in conducting UAV swarms operations. Existing literature has conducted in-depth research on continuously distributed combat areas [5-9]. However, the combat areas where UAV swarms operations are located are often scattered. At the same time, literature [10-13] only considers the geographical obstacles to the operational environment, and literature [14-16] only considers the electromagnetic interference in the operational environment. However, in the actual combat environment, geographical obstacles and electromagnetic interference exist simultaneously.

In this paper, a complex environment model is established to solve the problem of UAV swarms cooperating with multiple distributed areas in a complex environment. At the same time, considering UAVs' reconnaissance ability, obstacle avoidance ability, and anti-jamming ability, the allocation model of multi-UAVs reconnaissance in the multi decentralized area is established. Finally, the model is solved by the children’s behavior optimization (CBO) algorithm, and a better allocation scheme is obtained.

2. Multi-UAVs Collaborative Reconnaissance Distribution Model

2.1 Problem Description

There are M UAVs in the multi-UAV swarms. It is assumed that $U = \{ U_1, U_2, \ldots, U_M \}$. There are N target areas. It is assumed that $T = \{ T_1, T_2, \ldots, T_N \}$. The environment of target areas is often complex. Two main factors affect the UAV swarms to complete the task in the target areas: 1). The Complex geographical environment; 2). The Complex electromagnetic environment. Accordingly, the following preconditions are established for the model.

1). The reconnaissance area considered in this model is discrete;

2). When the UAV carried out reconnaissance operation, the weather condition was good and did not affect the CCD camera imaging;

3). The interference in ground clutter to UAV could be ignored;

4). When conducting reconnaissance operations, the UAV was moving at a constant speed;

5). The UAV's fuel could meet the needs of a reconnaissance mission.

2.2 The Influence of Complex Geographical Environment Factors

The complex geographical environment mainly refers to the existence of obstacles such as high mountains and high-rise buildings that block the cruise route of UAV, as shown in Figure 1 in this reconnaissance area. There are two strategies for UAVs to choose when encountering obstacles in reconnaissance areas.

1. If the climbing performance of the UAV is enough to climb obstacles, then the UAV will ascend directly and leap over obstacles;
2. If the climbing performance of the UAV is not enough to climb over the obstacle, the UAV can bypass the obstacle.

When the UAV can climb and fly around simultaneously, the shortest path is chosen.

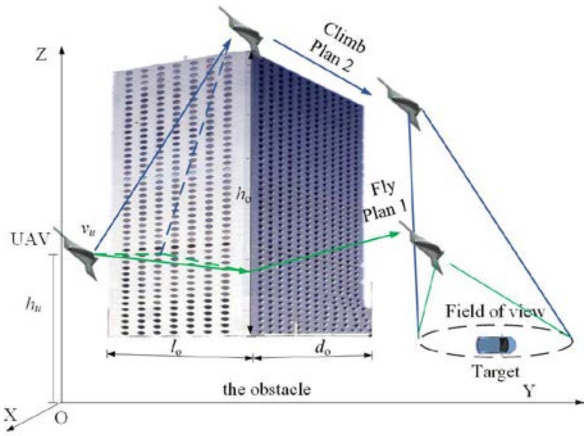

Figure 1 – The complex Geographical Environment Modeling

Plan1: If $\gamma_u < \theta_o$, the UAV travels through the path L1 as:

$$L_1 = d_o + \sqrt{v_u^2 + (\frac{l_o}{2})^2} \tag{1}$$

Plan2: If $\gamma_u > \theta_o$, the UAV travels through the path L2 as:

$$L_2 = d_o + \sqrt{v_u^2 + (h_o - h_u)^2} \tag{2}$$

Where: γ_u is the maximum climb angle of the UAV; θ_o is the angle between the UAV and the top of the obstacle, its value is calculated by Formula (3); l_o denotes the obstacle length; d_o denotes the obstacle width; h_o denotes the obstacle height respectively; h_u denotes the cruise altitude of UAV; v_u represents the speed of the UAV.

$$\theta_o = \arctan(\frac{h_o - h_u}{v_u}) \tag{3}$$

2.3 The Influence of Complex Electromagnetic Environment Factors

As shown in Figure 2, the complex electromagnetic environment mainly refers to the electromagnetic interference in UAV data transmission in the reconnaissance area.

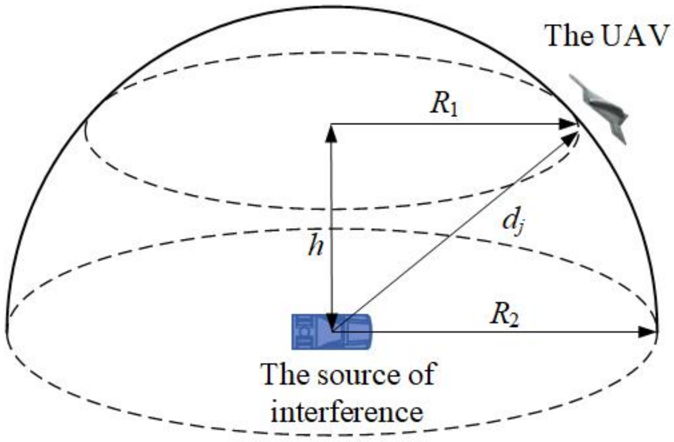

Figure 2 – Complex Electromagnetic Environment Modeling

When encountering electromagnetic interference in the reconnaissance area, the normal reconnaissance behavior depends on the signal to interference ratio (SIR) of the UAV[17].

$$SIR = \frac{P_t G_{tr} G_{rt} G_s}{P_j G_{jr} G_{jt} G_j} \bullet (\frac{d_j}{d_c})^2 \tag{4}$$

Where: *SIR* characterized the ability of the UAV to overcome electromagnetic interference. P_t represents the output power of the communication transmitter; P_j represents the output power of the interference transmitter; G_{tr} represents the antenna gain of the communication transmitting antenna in the transmitting direction; G_{jr} represents the antenna gain of the interference transmitting antenna in the transmitting direction; G_{rt} represents the antenna gain of the communication receiving antenna in the direction of the communication transmitting antenna; G_{jt} represents the antenna gain of a communication receiving antenna over an interference antenna; G_s represents the processing gain for communication; G_j represents the interference processing gain; d_c represents the communication distance; d_j represents the interference distance.

According to the power criterion of effective interference, when the SIR of the UAV in a particular area is more significant than a specific value, it is considered that the drone has not interfered. On the contrary, it was disturbed. UAVs have two strategies to choose from when encountering obstacles in reconnaissance areas.

1. If $SIR > SIR_{th}$, the UAV is not disturbed, it can fly directly over the area.

$$L_3 = 2\sqrt{d_j^2 - h_u^2} \tag{5}$$

2. If $SIR < SIR_{th}$, the UAV is disturbed, the UAV needs to fly outside the jamming range.

$$L_4 = \pi\sqrt{d_j^2 - h_u^2} \tag{6}$$

Where: SIR_{th} represents the threshold of signal to interference ratio of UAV.

2.4 Range cost Model

According to the UAV field of view model which was considered a rectangle shown in Figure 3, W_u represents the width of view of the UAV. γ_s represents the angle of view of the UAV, α_s represents the angle of installation of the UAV sensor.

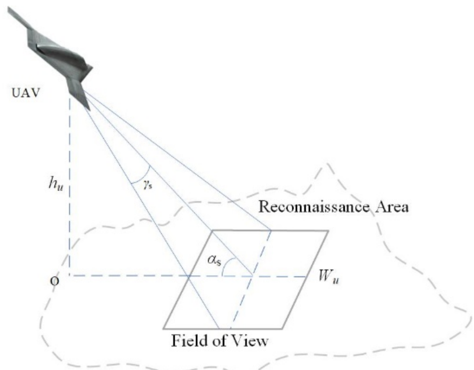

Figure 3 – UAV Reconnaissance Field of View Model

$$W_u = 2h_u \frac{\tan \gamma_s}{\tan \alpha_s} \tag{7}$$

Matrix C_1 as shown in figure 4 is defined as the length of the route for a single UAV to scout a single target area, which can be calculated using the following formula:

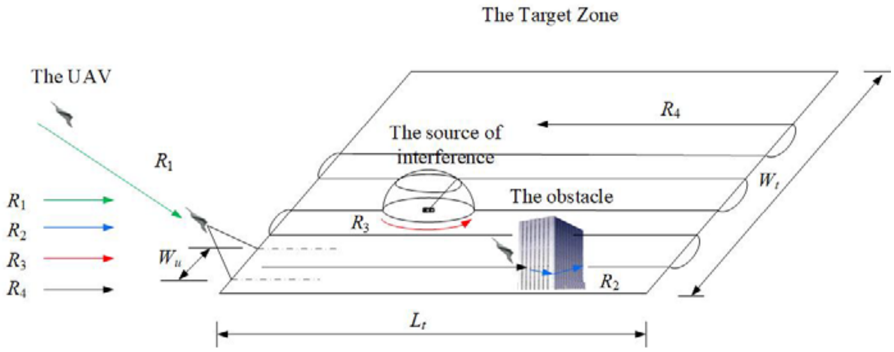

Figure 4 – Schematic diagram of UAV path in the reconnaissance mission

$$C_1 = R_1 + R_2 + R_3 + R_4 \tag{8}$$

$$R_1 = \sqrt{(x_t - x_u)^2 + (y_t - y_u)^2} - \frac{L_t}{2} \tag{9}$$

$$R_2 = \begin{cases} L_1; \gamma_u < \theta_o \\ L_2; \gamma_u > \theta_o \end{cases} \tag{10}$$

$$R_3 = \begin{cases} L_3; SIR > SIR_{th} \\ L_4; SIR < SIR_{th} \end{cases} \tag{11}$$

$$R_4 = L_t \frac{W_t}{W_u} - d_o - 2\sqrt{d_j{}^2 - h_u^2} + \pi r_u (\frac{W_t}{W_u} - 1) \tag{12}$$

Where: R_1 is the distance from the UAV to the edge of the target area; R_2 is the route length of the UAV over the geographic obstacle area; R_3 is the route length of the UAV over the electromagnetic interference area; R_4 is the route length of the UAV in the reconnaissance area; L_t is the lentgh of view of the target zone; W_t is the width of view of the target zone. r_u is the turning radius of the UAV.

2.5 Reconnaissance advantage Model

The essence of targeting allocation is to make the resource allocation as optimal as possible based on the existing resources. Therefore, task allocation should be found on the relative advantages of different UAVs. For example, in terms of reconnaissance tasks, the distributed UAV cooperation system needed to consider the excellent performance of the charge-coupled device camera carried by the UAV. Therefore, the reconnaissance advantages of the UAV relative to the target area were considered based on the view of the UAV.

$$S_u = W_u \bullet v_u \tag{13}$$

Where: S_u represents the area of field of view detected by the UAV in unit time. When the UAV is investigating, the wider the radar detection range per unit timed, the stronger the UAV's ability to detect the target area. Therefore, the reconnaissance advantage function R_{cn} is characterized by the detection area ratio, and the function should be:

$$R_{cn} = \frac{S_u}{S_t} \tag{14}$$

Where: S_t represents the area of field of reconnaissance.

The definition matrix C_2 is the revenue matrix of the multi-UAVs collaborative reconnaissance process.

$$C_2 = R_{cn} V \tag{15}$$

2.6 Objective Function

The allocation of reconnaissance areas by UAV swarms can be modeled as follows:

$$J = \max \sum_{i=1}^{m} \sum_{j=1}^{n} (-\omega_1 C_1 + \omega_2 C_2) X_{ij} \tag{16}$$

$$s.t. \omega_1 + \omega_2 = 1; \tag{17}$$

$$x_{ij} \in \{0,1\}, i \in \{1,2,\ldots,m\}, j \in \{1,2,\ldots,n\} \tag{18}$$

$$\sum_{j=1}^{n} x_{ij} \in \{0,1\} \tag{19}$$

$$\sum_{i=1}^{m} \sum_{j=1}^{n} x_{ij} = n \tag{20}$$

As shown in Equation (16), the objective function is composed of the cost of the track length and the benefit of reconnaissance. Equation (17)~(20) reflect the constraints in task assignment. Equation (17) means that the sum of these weights is 1. Equation (18) means the value range of x_{ij}: when the UAV *i* is assigned for target *j*, x_{ij} =1. Otherwise, x_{ij} =0. Equation (19) means the UAV *i* is assigned at most one target. Equation (20) describes all *n* targets that should be assigned to the UAV.

3. Solving algorithm

3.1 Decimal Based Coding

To solve this problem, children's behavior optimization (CBO) is described in this section. The encoding method based on decimal reflects the corresponding relationship between particles and allocation schemes. The particles will be 2□ N-dimensional matrices. As table 1 shown, an example of the coding shows the allocation of 5 UAVs and 5 targets.

Table1 the coding schematic

Target	1	2	3	4	5
UAV	5	4	2	1	3

3.2 Children's behavior optimization algorithm

In order to study the group behavior of agents, this paper establishes a children's behavior optimization (CBO) algorithm based on children's learning behavior. Refer to children's behavior in learning to develop an intelligent algorithm. Children are influenced by their partners and parents in the process of learning. A particle in the algorithm is equivalent to a learning child. The following formula can be obtained:

$$v_{t+1} = \begin{cases} c_1 v_t, rand \le c_1 \\ c_1 v_t \oplus (p_{ig,t} \ominus x_t), rand > c_1 \end{cases} \tag{21}$$

$$x_{t+1} = x_t + v_{t+1} \tag{22}$$

Where c_1 is the coefficient between 0 and 1; v_t refers to the self-learning speed of the particle *i* in the *j* dimension at time *t*; the particles which are defined as children have a certain probability of following their own learning speed but also have a certain probability of being affected by partner particles or parent particles; x_t is the position of the child *i* in the *j* dimension at time *t*; $p_{ig,t} \ominus x_t$ means the influence of the outside world on children's learning process, which is obtained by formula (21).

$$p_{ig,t} = \begin{cases} c_2 p_{i,t} \oplus \xi (p_{g,t} \ominus p_{i,t}), rand \le c_2 \\ c_2 p_{g,t} \oplus \xi (p_{i,t} \ominus p_{g,t}), rand > c_2 \end{cases} \tag{23}$$

Where $p_{g,t}$ is the position which is the influence of the parents, which is considered as random particles with the same dimension; $P_{i,t}$ is the position which is the influence of the partners, which is regarded as the optimal value of one calculation in particle population, ξ is coefficient which is obtained by formula（24）.

$$\xi = \frac{1}{1+e^{-\frac{0.5t_{max}-t}{t_{max}}}} \tag{24}$$

To illustrate the update mechanism, first define the following operating rules, as shown in Figure 5.

A⊝B: Shift operation, select some values in vector B, insert them into the front of vector A, and delete the same values in vector A.

A⊕B: Cross operation, the vectors A and B exchange the values of the selected position.

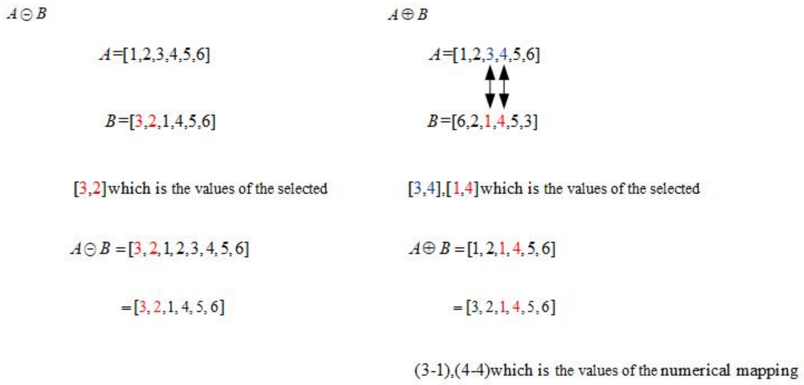

Figure 5 – The Operating Rules

In summary, the algorithm flow is shown in figure 6:

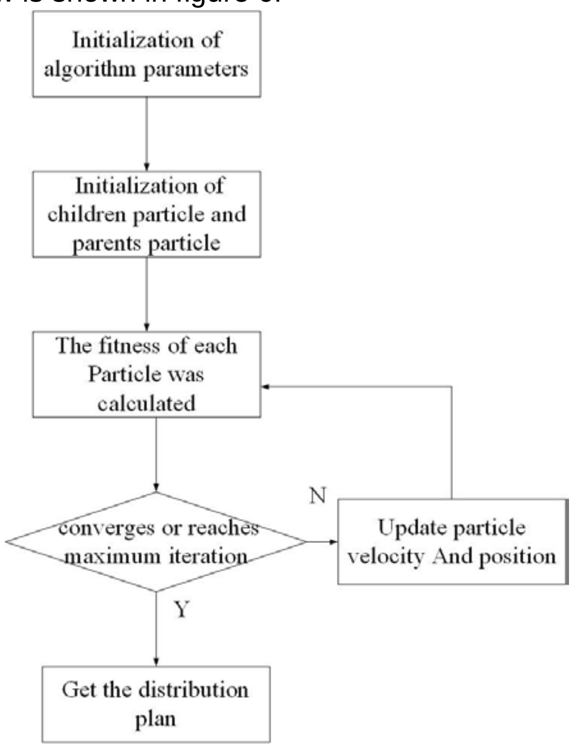

Figure 6 – The flow Chart of algorithm

4. Example Analysis

It is a crucial combat style that uses multi-UAV systems and carries out a reconnaissance mission. Moreover, the survey proposed CBO algorithm can efficiently solve the task allocation problem of heterogeneous UAVs. The simulation environment is an Intel (R) Core i5-7600K CPU with 8 GB RAM.

4.1 Experimental Design

4.1.1 Multi-UAVs and Target distribution simulation

Suppose a group of terrorists are hiding in area A, there are 5 areas where they may be hiding. 5

UAVs are now dispatched to scout these areas. In order to conform to the actual situation, the total coverage of the operation area is 16000 km^2, represented by the coordinate (0, 400) on the x-axis and (0, 400) on the y-axis, respectively. Table 2~3 lists the details of UAVs and targets.

Table 2 Parameters of the area to be detected

TARGET	T1	T2	T3	T4	T5
Area/(km^2)	40	50	60	70	80
L_t/(km)	4	5	6	7	8
W_t/(km)	10	10	10	10	10
Position/(km)	(300,300)	(250,150)	(270,50)	(125,500)	(200,200)
Value	0.7	0.8	0.75	0.6	0.6
L_o/(km)	0.5	0.4	0.8	0.7	0.3
W_o/(km)	1.5	2	1.6	0.9	1
h_o/(km)	1.2	1.5	1.4	1	1.2
P_j (w)	15	10	15	25	12
G_{jr} (dB)	6	10	7	8	6
G_{rj} (dB)	6	8	10	12	15
G_j (dB)	8	6	5	4	4
d_j (km)	4	5	6	7	8

Table 3 Parameters of UAV

UAV	U1	U2	U3	U4	U5
v_u/(m/s)	70	80	100	90	100
Position/(km)	(125,200)	(370,180)	(200,160)	(350,100)	(300,380)
h_u/(m)	400	500	600	700	800
γ_s(°)	30	45	50	45	35
α_s(°)	30	35	45	50	55
P_j (w)	20	30	60	40	60
G_{tr} (dB)	6	7	8	5	6
G_{rt} (dB)	2	2	3	4	3
G_s (dB)	4	6	8	6	5
d_c (km)	80	100	120	150	160
r_u(km)	0.04	0.05	0.06	0.07	0.08
SIR_{th}	15	15	18	18	20
γ_U(°)	45	50	55	60	65

Figure7 shows the initial positions of the UAVs and targets. The five targets are marked by the blue triangles, and the take-off positions of UAVs are marked by the blue diamonds.

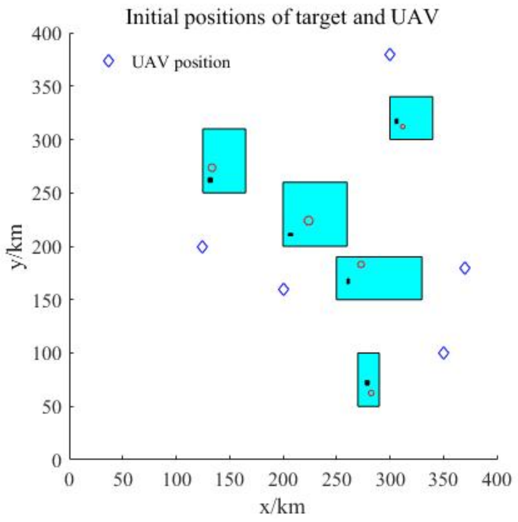

Figure 7 the initial positions of target and UAV

4.2 Result

4.2.1 Environmental Parameter Impact Analysis

There are two kinds of decisions for UAV in the face of the obstacle. According to these two decisions, the range length is calculated respectively, as shown in Table 4 and Table 5. As shown in the table, when the UAV has good vertical maneuverability, its range is short.

Table 4 The range of the UAV in case of the obstacle

R_{2_1}(km)	T1	T2	T3	T4	T5
U1	2.71	3.21	2.72	1.84	1.94
U2	3.14	3.22	2.74	1.76	1.99
U3	2.58	3.27	2.80	1.88	2.08
U4	1.61	2.94	2.46	1.48	1.71
U5	1.94	2.86	2.38	1.44	1.64

Table 5 The range of the UAV without the obstacle

R_{2_2}(km)	T1	T2	T3	T4	T5
U1	2.06	2.54	2.24	1.51	1.52
U2	2.73	2.73	2.41	1.68	1.72
U3	2.58	2.92	2.58	1.87	1.91
U4	1.51	2.54	2.24	1.51	1.52
U5	1.52	2.54	2.24	1.51	1.52

There are two kinds of decisions for UAVs in the face of electromagnetic interference. According to these two decisions, the range length is calculated respectively, as shown in Table 6 and Table 7. As shown in the table, when a UAV has a strong jamming capability, its range is short.

Table 6 the range of the UAV in case of the interference

R_{3_1}(km)	T1	T2	T3	T4	T5
U1	12.50	15.65	18.80	21.94	25.09
U2	12.46	15.62	18.77	21.92	25.07
U3	12.42	15.59	18.75	21.90	25.05
U4	12.37	15.55	18.71	21.87	25.02
U5	12.31	15.50	18.67	21.84	24.99

Table 7 the range of the UAV without the interference

R_{3_2}(km)	T1	T2	T3	T4	T5
U1	7.96	9.97	11.97	13.98	15.98
U2	7.94	9.95	11.96	13.96	15.97
U3	7.91	9.93	11.94	13.95	15.95
U4	7.88	9.90	11.92	13.93	15.94
U5	7.84	9.87	11.89	13.91	15.92

4.2.2 Reconnaissance Area Assignment Results

In order to verify the effectiveness of the CBO algorithm, the particle swarm optimization (PSO) algorithm and genetic algorithm (GA) were selected for comparison. These algorithms have the same size of population and repository with a population of 50, and a maximum iteration number of 200. The parameter settings of the above algorithm were shown in Table 8.

Table 8 Algorithm parameter table

Algorithm	Parameter1	Parameter2	Parameter3
CBO	c_1=0.5	c_2=0.5	-
PSO	c_1=1.49	c_2=1.49	ω=0.9
GA	P_c=0.5	P_m=0.3	β=0.3

As shown in figure 8, through 200 steps of iteration, the fitness value of the CBO algorithm is 0.636. The distribution results are shown in Table 8. The above algorithms all found the same allocation result. However, the CBO algorithm found the best allocation result after 20 iterations. PSO algorithm and GA algorithm found the best result after 82 and 190 iterations respectively.

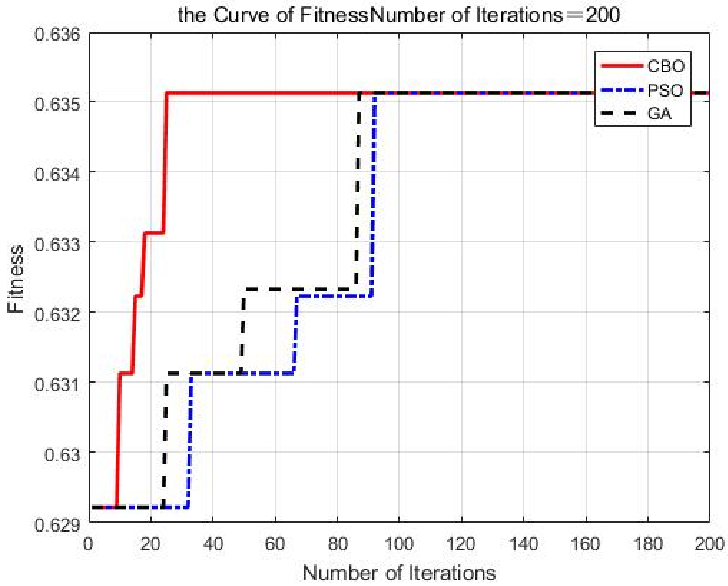

Figure 8 Evolution curve of the optimal value of task assignment objective function

Table 8 Task assignment result

UAV	5	4	1	3	2
TARGET	1	2	3	4	5

5. Conclusion

Mission planning of a UAV swarm based on environmental characteristics is the critical technology for multiple UAVs to perform reconnaissance missions. The main work of this paper is as follows:

- According to the climbing ability of UAVs, the flight strategy of UAVs facing geographical obstacles is established.
- According to the anti-jamming ability of UAVs, the flight strategy of UAVs facing electromagnetic obstacles is established.
- The CBO algorithm is used to solve the allocation problem of 5 UAVs to 5 regions. Compared with the PSO and GA algorithm, this algorithm has excellent advantages in iterative speed.

This paper is only the preface to the UAV cluster reconnaissance mission, which aims to provide the basis for subsequent dynamic reconnaissance missions.

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7. Copyright Statement

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