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Multiple UCAVs Mission Assignment Based on Modified Gravitational Search*

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Abstract—**With further developments of Uninhabited Combat Aerial Vehicles (UCAVs), the problem of multiple UCAVs mission assignment is a hot point, and many solutions aimed at multiple UCAVs mission assignment are proposed in the past years. However, it's still difficult to satisfy the actual need of complicated battlefield owing to the larger scale of problems and the limit of operation speed. In this paper, we proposed a novel solution for UCAVs mission assignment based on a modified Gravitational Search Algorithm (GSA). The basic GSA is modified by improving the initialization, the mass weighing value and natural selection rules are also adopted. Comparative experimental results verified that the three parts of the GSA can be improved: algorithmic reconnaissance ability, speed and optimization of finding the solution. The results show that our proposed GSA can solve the multiple UCAVs mission assignment effectively.**

I. Introduction

Over the past decades, the uninhabited combat aerial vehicles (UCAVs), which is a kind of powerful armament, has attracted more and more attention all over the world [1]. Under the support of information nets in the air-space-ground, it can accomplish the tasks efficiently and effectively with bearing missiles or bombs, such as the task of combat, monitor and so on [2]. The one of main fighting modes of UCAVs is the multiple UCAVs cooperative combat, while the critical research issues of cooperative combat are multiple UCAVs mission assignment. Generally, multiple UCAVs mission assignment is a type of resource allocation problem, considering the performance of UCAVs and the advantages between two sides. The goal of mission assignment is to promote the effect of UCAVs with the minimum price [3]. Recently, many researchers focus on many methods of automatic finding optimal solutions to the problem of multiple UCAVs mission assignment, such as differential evolutionary (DE) algorithm, genetic algorithms (GA), particle swarm optimization (PSO) and so forth [4]. For example, PSO can solve many problems about the UCAV [5-7]. However, the algorithms can easily fall into premature convergence and are lack of effective acceleration mechanism. Especially when solving different problems, different algorithms have their own limitations, such as slow speed of calculation especially in solving large-scale problems.

Gravitational Search Algorithm (GSA) was originally presented as a new optimization search technology which simulates the function of gravitation, proposed by the professor of Iranian University Esmat Rashedi Blackman in 2009, which is under the inspiration of the Newtonian gravity [8]. It is a kind of global stochastic optimization technique and can find the optimum area actually by interactions between particles in a complex search space. The system initializes automatically a set of random solutions at the beginning and then, solution approaches the optimal one through continuous iteration. Compared with DE and GA, GSA runs without the complex operator, like "crossover", "mutation". Therefore, it can achieve optimization purposes more quickly, just simply by optimizing the particle mechanisms within groups. Compared to PSO [9], GSA not only considers the position information of each particle to update its own solution, but also forms a gravity model to simulate the forces of nature by adjusting the adaptation value in the search space of the individual particles to give them a precise analog inertial mass. By this way, it can expand the search space to some extent.

Through theoretical analysis, GSA retains the PSO's advantages and it has been proved to possess the better performance. However, it still exist premature convergence, local convergence and other problems in solving multiple UCAVs mission assignment. This paper focuses on multiple UCAVs mission assignment and attempts to apply the GSA to discrete problem, while GSA is generally used to solve continuous problems. To make the algorithm more adaptable, we concentrate on the improvement of the GSA. In dealing with discrete problems, the paper sorts search results and improves bounds overflow. And it is promoted from several aspects. First, by using the properties of chaos (randomicity, regularity and ergodicity), we improve the initialization of algorithm to make initial solution more reasonable. Second, considering the nature of gravity, the mass weighing value was led into the process to acceleration the speed of convergence. Besides, we also introduce some useful properties of PSO and DE to improve bad solution and expand searching range. In this paper, we also call this kind of selection mechanism as natural selection rule, which can solve local convergence, but not give up the advantages of GSA.

The remainder of the paper is organized as follows. The next section introduces mathematic model of mission assignment for multiple UCAVs. In section III, we describe the principle of gravitational search algorithm in detail. Section IV explains how to improve the basic GSA to apply for a mission assignment. The procedure of multiple UCAVs

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mission assignment using modified GSA is proposed in Section V, and Section VI gives the comparative simulation results. Finally, our concluding remarks are contained in Section VII.

II. THE MODELING OF MULTIPLE UCAVS MISSION ASSIGNMENT

GSA are used to solve the problem of multiple UCAVs mission assignment, by constructing multiple UCAVs air combat superiority matrix based on the establishment of a comprehensive situation assessment function. Taking the fact that GSA can't deal with the discrete problem directly into consideration, we adopt collation to transform the continuous problem into a discrete problem [10].

A. *Modeling for Multiple UCAV Mission Assignment*

Air combat situation assessment is the basis of UCAV task assignment [11]. We should maintain a high level of air combat situation assessment, in order to get a reasonable and accurate assignment results.

UCAV combat situation assessment mainly considers the following factors [12]:

(1) The type of target;

(2) The relative positional relationship between two sides, including angle, height and distance;

(3) The relative motion parameter, mainly considering speed;

(4) The weapon performance.

Assumption the UCAVs of each side have the roughly same performance. Superiority matrix is established by considering the motion parameters, relative positional relationship and the range of missiles, which gives a quantitative description of the relative situation of two sides.

B. *Establishing the Superiority Matrix*

The model of multiple UCAV mission assignment is illustrated as follows [13]:

1) The advantage of angle

The two sides have an angle at the velocity direction and according to this angle and we can ensure the advantage of point. The edge angle can be expressed as the following function:

$$S_{ij}^{a} = (a_j - a_i)/180^{\circ} \tag{1}$$

where a_j is the angle between our UCAVs' velocity vector and the line sight to the target, and a_i is as the angle between enemy's UCAV's velocity vector and their line sight to their target and $0° \leqslant a_i, a_j \geqslant 180°$. If S_{ij}^{a} is positive, it means that our UCAVs are dominant, otherwise the enemy is dominant.

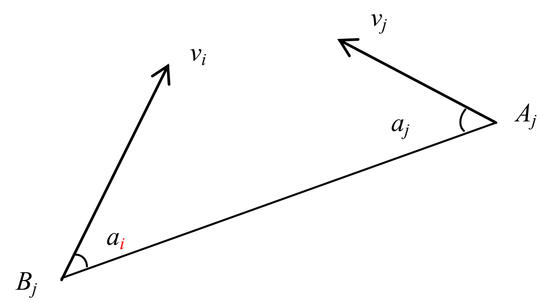

Figure 1 Angle

2) The advantage of velocity

At the same time, the speed of two sides may be different. We can determine the advantage of velocity by establish the matrix of the speed advantage function:

$$S_{ij}^{v} = \begin{cases} 1, V_i - V_j > 1km/s \\ V_i - V_j, \left|V_i - V_j\right| \le 1km/s \\ -1, V_i - V_i < -1km/s \end{cases} \tag{2}$$

where V_i is the speed of our *i*-th UCAV and V_j is the speed of enemy's *j*-th UCAV. If S_{ij}^{v} is positive, it means that we are dominant; otherwise, the enemy is dominant.

3) The advantage of weapon performance

The advantage of weapon performance is related to the distance of two sides. Therefore, we can combine the distance with weapon performance to establish the following function:

$$S_{ij}^{w} = \begin{cases} 1, D_{mi} - D_{mj} > 10km \\ (D_{mi} - D_{mj})/10, \left|D_{mi} - D_{mj}\right| \le 10km \\ -1, D_{mi} - D_{mi} < -10km \end{cases} \tag{3}$$

where D_{mi} is the maximum transmission range of our UCAV and D_{mj} is the maximum transmission range of enemy's UCAV. If S_{ij}^{w} is positive, it means that we are dominant; otherwise, the enemy is dominant.

To sum up, we can get comprehensive situation assessment function:

$$S_{ij} = k_v S_v + k_a S_a + k_w S_w \tag{4}$$

where *Sij* is the comprehensive situational advantage values and k_v, k_a, k_w are the weighs of the speed advantage, angle advantage and weapon performance advantage and $k_v+k_a+k_w=1$. The size of weight is based on experience and mathematical simulation analysis.

III. PRINCIPLE OF GRAVITATIONAL SEARCH ALGORITHM

Gravity is one of the four fundamental interactions in nature and the gravitational force between two particles is directly proportional to masses and inversely proportional to the square of the distance [14]. GSA, a newly developed stochastic reach algorithm based on the law of gravity and mass interaction, is proposed by the professor of Iranian

University Esmat Rashedi Blackman in 2009. According to the GSA, agents are looked on as objects and their performance are determined by their masses and the position of each agent is a probable answer to the problem.

To describe the GSA, we can define the position of dimension *d* from agent *i* as x_i^d .

$$X_i = \left(x_i^1, x_i^2, \ldots, x_i^M\right) \tag{5}$$

At a specific time *t*, we can define the gravitational force exerted on particle *i* from particle j as F_{ij}^d [5].

$$F_{ij}^d(t) = G(t)\frac{M_{pi}(t)M_{aj}(t)}{R_{ij}(t)+\varepsilon}\left(X_j^d(t)-X_i^d(t)\right) \tag{6}$$

$$R_{ij}(t) = \left\|X_i(t), X_j(t)\right\|_2 \tag{7}$$

$$G(t) = G_0 \exp(-\alpha \times \frac{t}{T}) \tag{8}$$

where $M_{pi}(t)$ is the passive gravitational mass related to particle *i*, $M_{aj}(t)$ is the active gravitational mass related to particle *j*, *G(t)* is gravitational constant at time *t*, ε is a small constant, $R_{ij}(t)$ is the Euclidian distance between two particle *i* and *j* at time *t*, *G*(*t*) is gravitational constant at time *t*. Where is the initial value of gravitational constant and we define G_0 as 100 and *T* represent the maximum iteration number.

The force exerted on a particle at time *t* is equal to the sum of all forces exerted on it from others.

$$F_i^d(t) = \sum_{j=1, j\neq i} rand_i \times F_{ij}^d(t) \tag{9}$$

where *rand* is a random number in the interval [0, 1].

According to the law of motion, the acceleration of particle *i* is defined

$$a_i^d(t) = F_i^d(t) / M_i(t) \tag{10}$$

where $M_i(t)$ presents the mass of the *i*-th particle.

In the GSA, for each iteration, particles will update their position based on Eq. (11) and Eq. (12).

$$v_i^d(t+1) = rand_j \times v_i^d(t) + a_i^d(t) \tag{11}$$

$$x_i^d(t+1) = x_i^d(t) + v_i^d(t+1) \tag{12}$$

where $rand_j$ presents a random number in the interval [0, 1].

The mass is calculated and renewed by the performance evaluation function. We update the gravitational and inertial masses by the following formula:

$$M_{aj} = M_{pi} = M_{ii} = M_i, i = 1,2,3 \ldots N \tag{13}$$

$$m_i(t) = \frac{advantage_i(t) - worst(t)}{best(t) - worst(t)} \tag{14}$$

$$M_i(t) = \frac{m_i(t)}{\sum_{j=1}^{N} m_i(t)} \tag{15}$$

where $advantage_i(t)$ denotes the performance of the *i*-th particle at time *t*.

For the problem of multiple UCAVs mission assignment, $worst(t)$ and $best(t)$ can define as

$$\begin{aligned} best(t) &= \min_{j\in\{1,2,\ldots N\}} advantage_j(t) \\ worst(t) &= \max_{j\in\{1,2,\ldots N\}} advantage_j(t) \end{aligned} \tag{16}$$

IV. MODIFIED GRAVITATIONAL SEARCH ALGORITHM

Because gravity search algorithm is a continuous intelligent algorithm, the traditional method can't solve the multiple UCAVs mission assignment. Therefore, we use the size sorting rules to resolve this problem. Besides, in order to solve the problem which is easy to fall into local convergence, we improve the performance of GSA by improving the initial condition, leading into the mass weighing value and natural selection rule.

A. Collation

To maximize the use of per UCAVs, we stipulates that every enemy' UCAV can be only a target for us. Thus, we turn the situation of multiple UCAVs into N-dimensional function optimization problems.

We rule that abscissa is discrete positive integer that represents the number of our UCAVs and the ordinate represents the number of enemy's UCAVs. Considering the numbers of vertical axis is positive real number, we transform them into positive integer based on the collation when we are calculating the superior matrix. The function of collation is that we rule the greatest value on behalf of first enemy's UCAVs and the smaller real number is chosen as second enemy's UCAVs. So, all position of all the particles will be transformed into a sort by this method, which can be determined the targets of every our UCAV [10].

B. The Rules of Boundary Overflow

In the GSA, a feasible region is provided in the search process. When the object is moving out this feasible region, we can take a certain process so that the position of object is on the boundary. But in the discrete problem, because we use collation to determine the target of our UCAVs, it should require a certain process which not only the position can basically in the feasible region range, but also don't produce the sort of disorder. The specific methods of operation are as follows.

If ($x_i > x_{max}$) then

$$x_i = x_{max} + c \cdot x_{t_i}$$

End

$$\text{If } (x_i < x_{min}) \text{ then}$$

$$x_i = x_{min} - c \cdot x_{t_i}$$

$$\text{End}$$

where c is a very small value which can be 0.0001. x_{t_i} is the converted value which sorted.

C. Initial condition improvement

A good initial result can help improve the quality solution and accelerate the speed of operation. There are two standards determining a good initial result. On one thing, they should be throughout the solution space. On another, the initial results should contain a better solution. Obviously, if there is no good initialization mechanism, but rather rely on random generation, it difficult to ensure two conditions are met. Our solution in this paper is to use the property of chaotic search to improve it.

Generally speaking, the definition of chaotic motion refers to the random motions acted by deterministic equations. Logistic map is a typical chaotic systems and the iterative formula is given by Eq. (17) [15]:

$$t_{i+1} = \mu t_i(1 - t_i), i = 0,1,2..., \mu \in (2,4] \tag{17}$$

where μ presents control parameters and when $\mu = 4$, $0 \le t \le 1$, Logistic is completely on chaotic state.

Therefore, according to the feature of chaotic motion which in a certain range cannot repeatedly traverse the same states under their own laws, the basic improvement idea is: generating a large number of initial solutions and choose the better one with the ergodicity of chaotic motion.

D. The Principle of Mass Weight

The GSA renews the mass of particle based on the advantage value which calculated by mathematical model we establish. The formula of gravity shows that the larger mass a particle has, the more attractive for other particle it will be. The result is that particles tend to the position of the best particles. Therefore, to have a faster convergence, we modified the principle of updating the inertial masses. With the principle of inertial mass weight, particles which has heavy inertial mass will become heavier and particles which has small inertial mass will become smaller. In this way, it can improve the convergence speed and convergence result.

In every process of iteration, according to the amount comes from the inertial mass, we account every $m_i(t)$ power by K.

The weight value K is defined as a constant.

By the derivation off mathematical, when K is greater than or equal to 1, the greater $m_i(t)^k$ is, the larger proportion $m_i(t)^k$ in $\sum_{j=1}^{N} m_i(t)^k$ has, and the inertial mass will become greater.

E. The Strategy of Natural Selection

As we know, Adaptable organisms are likely to survive in the competition and inadaptable one will be eliminated, which is one of the Darwin's basic ideas. Meanwhile, when an individual has to change its living condition, the decision of new place must be affected by its prior experience. These two points are what we called the strategy of natural selection. Similar to the natural evolution strategy, we refer to the characteristics of DE and PSO algorithms to improve the GSA.

Given that the individual's own experience can play a guiding role in the process, we attempt to introduce the smart communication strategy into GSA. We propose a new velocity formula given as:

$$v_i^d(t+1) = wv \cdot v_i^d(t) + c \cdot rand_j\left(p_{best}^d - x_i^d(t)\right) \tag{18}$$

where $rand_j$ is a random variable in the range [0, 1], c is constant in the range [0, 1] and wv is the weight of current speed, whose range is [0, 1]. We can balance the effectiveness of "law of gravity" and effectiveness of "memory information" through c and wv.

Besides, we want to eliminate some bad results to improve the algorithm's search capabilities. We introduce the cross operator and alternative operator to improve some bad results. Meanwhile, we also give those variation particles a small perturbation $r(t)$ and generate a new one to ensure the possibility of global search.

$$r(t) = rand \times r_0 \times \exp(-\alpha \times t / T) \tag{19}$$

where r_0 and α are constant. T presents the mount of iteration. With the increasing in the number of iterations, the effect of perturbation is waning.

If the particles have less or equal objective function value than the new individuals, the new one will replace this particle and enter the population of next generation. Otherwise, the position of this particle will remain in the population for the next generation. The selection procedure can be expressed by the following equation [10]:

$$plan_i^{t+1} = \begin{cases} new_i^t, & if\ f(new) < f(current) \\ current_i^t, & otherwise \end{cases} \tag{20}$$

V. Procedure of Multiple UCAVs Mission Assignment Using Modified GSA

The procedure of multiple UCAVs mission assignment using our modified GSA is described in detail as follows:

Step 1: Established the coordinate system. The abscissa is a series of positive integer which represents the number of our UCAV. Every feasible solution is number column made up of D coordinates expressed by floating-point number. It is denoted as $P=\{p_1, p_2, \cdots, p_D\}$;

Step 2: In the range of feasible region, choose $\mu = 4$ in Eq. (17) and randomly generate $3N$ initial solution according to chaotic motion rule. We calculate the value of each solution's advantages and select the first *N* best solution as the initial solution.

Step 3: According to rules of collation and boundary overflow, we get the initial allocation, that is, the target of each UCAV;

Step 4: According to the situation between two sides in the battlefield, we can calculated the total advantage of each allocation, update the gravitational constant $G(t)$, the best value $best(t)$, the worst value $worst(t)$ and inertia mass $M_i(t)$ in accordance with the weight-based rule.

Step 5: Calculate the sum of the acceleration of each particle in each direction;

Step 6: Update the velocity of particles by Eq. (18) and the position of them by Eq. (12);

Step 7: According to the rule of natural selection, choose the better particle instead of poor solution enter the population of next generation;

Step 8: If the current number of iterations *Nc* is less than *Ncmax*, go back to step 3. Otherwise, the algorithm is terminated, and the best solution is output.

VI. Simulation Result

In order to verify the feasibility and effectiveness of the basic GSA and our modified GSA, some simulation experiments are carried out. We set the parameter values as follows.

TABLE I PARAMETER OF GSA

N	*Ncmax*	k_v	k_a	k_w
30	200	0.5	0.4	0.1

TABLE II PARAMETER OF MODIFIED GSA

N	*Ncmax*	*w*	*CR*	*F*	*wv*	*c*	k_v	k_a	k_w
30	200	3	0.8	0.5	0.8	0.2	0.5	0.4	0.1

The data in Table I are the parameters of basic GSA, and the data in Table II are the parameters of modified GSA.

Among them, the parameter *N* denotes the number of particles initially. Parameter *Ncmax* denotes the maximum number of algorithm iterations. The parameter k_v, k_a, k_w respectively is the weight of the speed advantage, angle advantage and weapon performance benefit. In Table 2, the parameter *w* denotes mass weight. The parameter *F* and *CR* respectively denotes the value of mutation operator and crossover operator. *c* is variable in the range [0, 1] and *wv* is the weight of current speed, whose range is [0, 1]

TABLE III PARAMETER OF UCAVS

	Position X	*Position Y*	*Velocity X*	*Velocity Y*	*Range of fire*
R UCAV1	-15	0	0	0.3	120
R UCAV2	-5	0	0	0.3	120
R UCAV3	5	0	0	0.3	120
R UCAV4	15	0	0	0.3	120
B UCAV1	-20	60	0.1	-0.2	110
B UCAV2	-10	60	0.1	-0.19	110
B UCAV3	0	80	-0.1	-0.21	110
B UCAV4	0	70	-0.8	-0.21	110
B UCAV5	0	50	0.9	-0.2	110
B UCAV6	0	40	0.9	-0.22	110
B UCAV7	10	60	-0.9	-0.22	110
B UCAV8	20	60	-0.2	-0.17	110

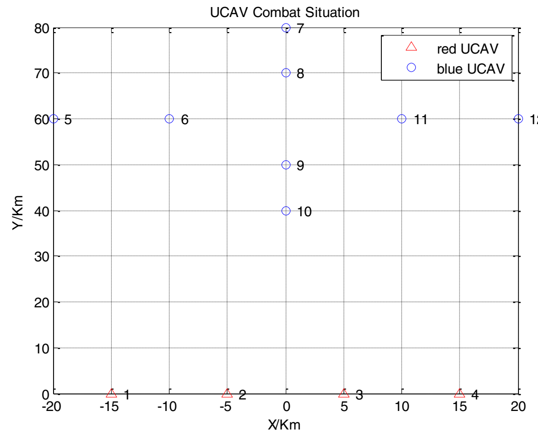

Figure 2 Multiple UCAVs combat situation

We use the basic GSA, PSO, DE and modified GSA to solve the problem of multiple UCAVs mission assignment respectively. In order to make conclusion more objective and scientific, each algorithm are used to process the same mission assignment with reasonable parameters and the simulation is carried out at least 20 times. The conclusion in this paper was the most typical one selected from about 20 simulations.

The assignment results of GSA are given in Table IV.

TABLE IV ASSIGNMENT RESULT OF GSA

Red UCAV	1		2		3		4	
Blue UCAV	4	2	8	6	1	5	3	7
Advantage	7.70676							

The assignment results of DE is given in Table V.

TABLE V ASSIGNMENT RESULT OF DE

Red UCAV	1		2		3		4	
Blue UCAV	4	2	3	6	1	5	8	7
Advantage	7.70676							

The assignment results of PSO are given in Table VI.

TABLE VI ASSIGNMENT RESULT OF PSO

Red UCAV	1		2		3		4	
Blue UCAV	4	3	2	6	1	5	8	7
Advantage	7.70374							

The assignment result of modified GSA is given in Table VII.

TABLE VII ASSIGNMENT RESULT OF MODIFIED GSA

Red UCAV	1		2		3		4	
Blue UCAV	4	5	8	6	1	2	3	7
Advantage	7.70676							

The comparative convergence curves are given in Fig. 3.

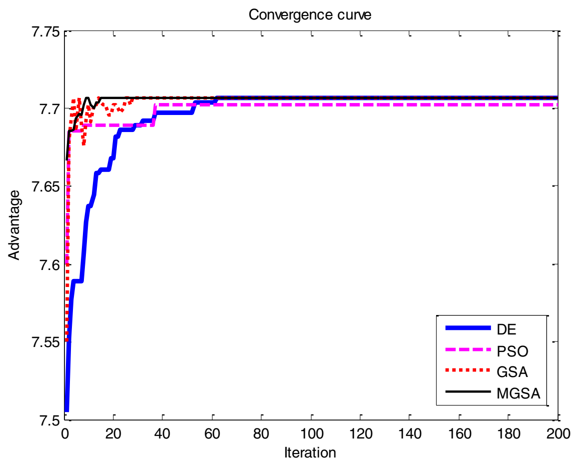

Figure 3 Comparison among convergence curves

From the simulation results, we can determine the quality of different algorithms in handling multiple UCAVs mission assignment. Through several rounds of comparative simulations, we found that the basic DE, basic PSO, basic GSA and our modified GSA can all find the best global solution. However, for DE, its convergence speed is not fast comparing to other algorithms. If solving problem of larger scale, it's difficult to meet real-time requirement. As for PSO, the results show that it coverge to the global best with more iterations. As for basic GSA, it sometimes falls into local convergence, even it has fast convergence speed. From Fig. 3, it is obvious that the modified GSA can successfully solve the problem of multiple UCAVs mission assignment. It can converge more quickly with a better solution. More importantly, the phenomena of local convergence and divergence is not existing.

VII. CONCLUSIONS

In this paper, a modified GSA is proposed for solving the problem of multiple UCAVs mission assignment. Comparative simulation results show that the modified GSA is superior to other algorithms (DE, PSO, and basic GSA) in all aspects.

Our future work also will apply a new type of swarm intelligence optimizer, namely Pigeon-inspired Optimization (PIO) [16], for solving multiple UCAVs mission assignment problems in more complicated combat battlefields.

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