Unmanned Aerial Vehicle cooperative search model for sea based on OODA

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Abstract. UAV reconnaissance has the advantages of strong mobility and high positioning accuracy, and efficient multi-UAV cooperative operation can greatly improve the search and reconnaissance capability, which is of great significance to the collaborative perception of sea situation. The purpose of this paper is to study the problem of optimal route planning for multi-UAV collaborative search of maritime targets. The core method is to use the distributed model predictive control method integrating OODA theory to optimize the cooperative maritime reconnaissance model of multiple UAVs in the planning period, and then use distributed MPC to solve the cooperative maritime search problem of multiple UAVs. This paper innovatively uses the idea of OODA model, fits in with the modern battlefield environment, and greatly improves the efficiency of actual combat UAV search.

Keywords: Multi-UAV Collaboration, Sea Target Search, OODA Theory, Distributed Model Predictive Control.

1. Introduction

The background of this paper assumes that the red side(Our unit) is conducting an act in a certain sea area. In order to locate the blue side(Enemy or Target unit) electronic reconnaissance ship(a naval service ship used for electronic reconnaissance in case the enemy interferes with our communications), The Red side sent four drones from the A1 and A2 airports to search the the sea area. To determine the optimal search route, an innovative OODA-based UAV-based collaborative sea search model is proposed in this paper, which greatly improves the detection efficiency and the Sea-based collaborative awareness with UAVs. Previous studies mainly focused on multi-UAV distributed collaborative target search with pheromone return mechanism [1-4] and rolling time-domain search [5-8]. Therefore, there is no practical application of OODA theory to UAV system programming. So the OODA unmanned aerial system search model [9] established in this paper has a more clear and complete description of maritime cooperative search, and the MPC-based distributed prediction algorithm offers a simple solution to reduce the time required to search for the optimal route. To sum up, the core idea of this paper is to apply Constraints of UAV dynamics model and the distributed model predictive control method integrating OODA theory to optimize the UAV-sea cooperative search model, and finally obtain the optimal UAV-sea cooperative search trajectory through MPC prediction.

2. The basic fundamental of OODA model

2.1. UAV dynamics modeling

In this paper, the studied sea area map is rasterized, and each grid is denoted as， The drone can only move one grid at a time within the map grid, Set as the maximum heading turning Angle of the UAV, which is 45°, and set as the minimum direct flying distance constraint of the UAV, which is 1km, as shown in Figure 1.

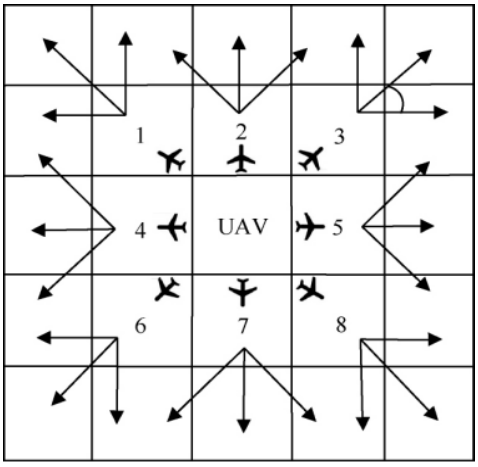

Figure 1. The drone steps through the grid

2.2. The model building of infographic

2.2.1 Target probability graph

Assuming that a heat map of 1000 km *1000 km sea area is randomly generated and globally normalized according to the formula, the initial probability of the target appearing at any location in this sea area can be obtained.

$$p_{\mathrm{ij}} = p(x_i, y_j) = \frac{h_{ij}}{\sum_{i=1}^{1001}\sum_{j=1}^{1001} h_{ij}} \tag{1}$$

In the process of carrying out the search task, the UAV uses the Bayesian criterion to update the target existence probability according to the detection probability of its own sensor. The updating formula is as follows:

$$p(x,y,t_{n+1}) = \begin{cases} 1 & b=1 \\ \frac{p_d(x,y,t_n)\times[1-p(x,y,t_n)]\times p(x,y,t_n)}{[1-p_d(x,y,t_n)]\times p(x,y,t_n)+[1-p(x,y,t_n)]}+p(x,y,t_n) & b=0 \end{cases} \tag{2}$$

$p_d(x,y,t_n)$ is the radar detection probability at time t_n at the sea position G(x,y), b=1 means radar picked up the target,b=0 means radar's not picking up the target.

2.2.2 Radar detection probability graph

Radar detection probability The figure shows the detection probability of the sea position G(x,y) found by the sensor radar. The probability of a Type U_k UAV detecting a target in the imaging influence is:

$$q_k(d) = \begin{cases} \exp(-d/\alpha_k), & d\in[0,R_k] \\ 0, & else \end{cases} \tag{3}$$

After several detections, the probability of finding the target $p_{dk}(x,y,t)$ is:

$$p_{dk}(x,y,t) = 1-\prod_{i=1}^{N}[1-q_k(d_i)] \tag{4}$$

The distance between the drone and the target is d, α_k is the detection index.

2.2.3 Environmental uncertainty diagram

The initial uncertainty of the environment can be regarded as the information entropy of the probability of the existence of the grid target:

$$\chi(x,y,t)=H[p(x,y,t)]=-p(x,y,t_n)\log_2 p(x,y,t)-(1-p(x,y,t))\log_2(1-p(x,y,t)) \tag{5}$$

When the UAV flies over the map grid, the UAV will increase its understanding of the information and situation in the grid, Therefore, the uncertainty χ is constantly updated, and the updating formula is as follows:

$$\chi\,(x,y,t_{n+1})=\begin{cases}\mu^m\chi(x,y,t_n)\\ \chi(x,y,t_n)\end{cases} \tag{6}$$

$\mu\in[0,1]$ is an environmental uncertainty attenuation factor, m is the number of drones searching the current grid simultaneously.

2.2.4 Environment search status graph

In the process of UAV search, update the environment search status graph according to the detection of each grid by UAV:

$$\mathrm{o}(x,y,t)=\begin{cases}1\\0\end{cases} \tag{7}$$

2.3. Establishment of performance index

2.3.1 Environmental search revenue

The environmental search income is mainly used to describe how to reduce the degree of environmental uncertainty as soon as possible in the search process of drones.

$$J_e(x,y,t_n)=\sum_{k=1}^{N_u}\sum_{(x,y)\in R_k^n}\chi(x,y,t_n)-\chi(x,y,t_{n+1}) \tag{8}$$

$\chi(x,y,t_n)$ is environmental uncertainty in G(x,y) at t_n.

2.3.2 Target discovery yield

Target discovery yield J_t refers to the possibility of the UAV to capture the target during flight, that is the sum of the probability of the target that can be detected during the UAV search process, so it is defined as:

$$J_t(x,y,t)=\sum_{k=1}^{N_u}\sum_{(x,y)\in R_k^n}p(x,y,t) \tag{9}$$

2.3.3 Inter-machine synergy benefits

The collaborative benefit is defined as a function of the UAV environment search state graph $o(x,y,t)$, which is specifically described as:

$$J_c(x,y,t)=\sum_{k=1}^{N_u}\sum_{(x,y)\in R_k^n}[1-o(x,y,t)] \tag{10}$$

2.3.4 Supplementary energy income

Supplementary energy income is described as related to the endurance capacity of the UAV, the location of the airport, and the current location of the UAV:

$$J_r(x,y,t)=\sum_{k=1}^{N_u}\frac{k_1\times(k_2T_{OK}-t)}{(P(x,y)-P_A(x,y)+u)^2} \tag{11}$$

$P(x,y)$ is the coordinates of the UAV at the t moment, $P_A(x,y)$ is the airport position, u is 0.1, T_{OK} is the endurance of the UAV, k1, k2 is the coefficient, k1 is 100, k2 is 0.5.

2.4. UAV restatement of maritime cooperative search problem based on OODA theory

2.4.1 restatement of the problem

The problem can be reformulated as optimizing the solution of multi-objective performance indicators under the constraints of UAV dynamics:

$$\max\sum_{t=0}^{T}J(t)=w_1J_e+w_2J_t+w_3J_c+w_4J_r \tag{12}$$

2.4.2Weight determination based on AHP analytic hierarchy process

The performance index is weighted by four sub-objectives, but its weight value w_i needs to be established. Since the four variables are not of the same magnitude, the correction coefficient μ_i is set in this paper, and the weight ratio between the four variables is set to w_i.

$$w_i=\mu_i\times w_i \tag{13}$$

Combined with the income model established in section 2.3 above, the weight of each criterion for the target is determined by mutual comparison, that is the judgment matrix is constructed as is shown in the Table 1.

Table 1. judgment matrix

Z	P_1	P_2	P_3	P_4
P_1	1	2	2	3
P_2	1/2	1	3	5
P_3	1/2	1/3	1	2
P_4	1/3	1/5	1/2	1

Therefore, the weights of each variable obtained are:

$$w_i=[0.2823,0.1053,0.2124,0.02413] \tag{14}$$

2.4.3 Basic principles of OODA model

OODA means that in modern military intelligent, automated and systematic operations, a complete military decision-making process needs to be composed of four parts: "observation - judgment - decision - action", and it is a dynamic cycle system.

2.5. UAV cooperative search model for sea based on model predictive control method

2.5.1 Fundamentals of distributed model predictive values

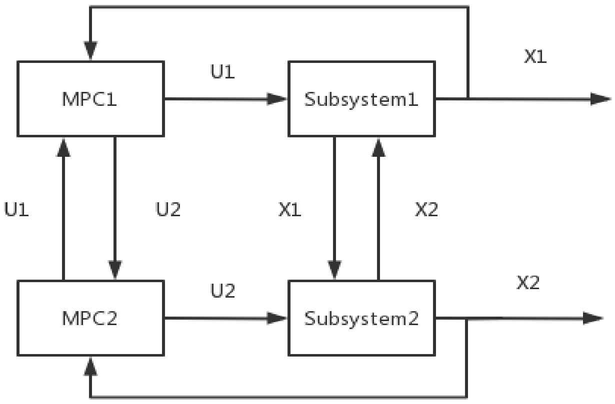

Figure 2. Model predictive control classification

According to the Figure 2, Synchronous distributed model predictive control is adopted, that is, in each control cycle, each sub-controller solves its own optimization model at the same time, obtains its own control sequence, and sends control information and state information to other UAVs through the communication system.

2.5.2 Model predictive control method based on fusion OODA theory

The multi-UAV cooperative rolling search problem in the planning period T_p can be described as: solving the multi-UAV cooperative search track with the maximum performance index benefit J_t under the dynamic constraints of the UAV turning Angle and the minimum direct flight distance within the planning period T_p . $t \in [t_p, t_p + T_p], k = 1,2,\cdots, N_U$, t_p is Rolling planning time.

$$\max \sum_{t=t_p}^{t_p+T_p} J(t) = w_1 J_e + w_2 J_t + w_3 J_c + w_4 J_t \tag{15}$$

Combined with the basic principle of OODA cycle, the distributed MPC model and OODA are integrated. The logical architecture of OODA's distributed MPC based cooperative search model for multiple UAVs on the sea is shown in Figure 3:

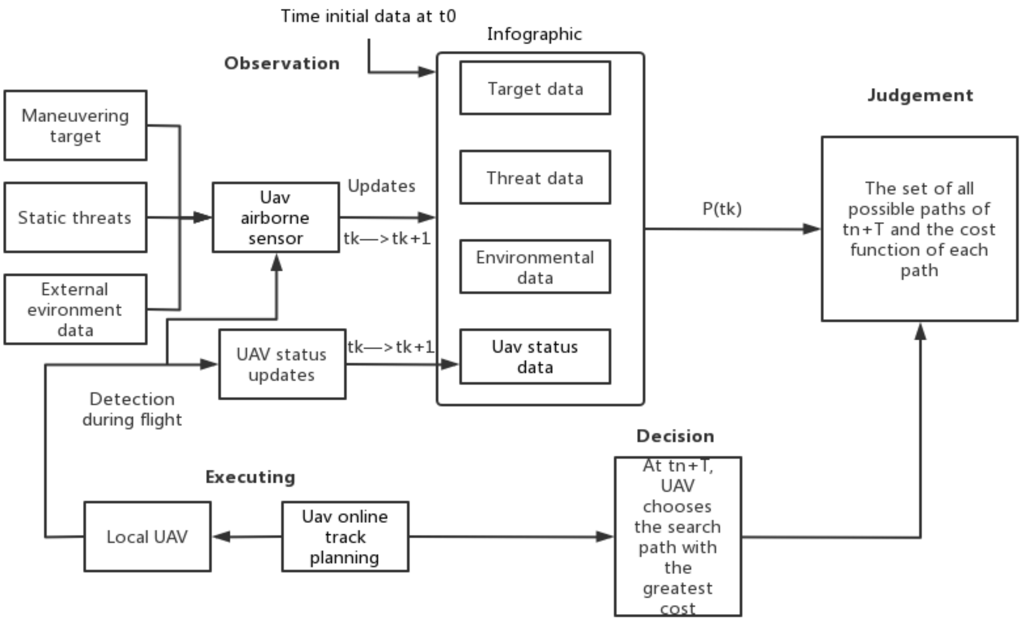

Figure 3. OODA and model predictive control fusion architecture

The corresponding OODA processes are as follows:

Observation: creation and updating of infographics, as well as information on UAV status Judgment: There are all possible paths for searching UAV during the planning cycle T_p

Decision: Choose the path with the highest UAV revenue within the planning cycle T_p

Execution: Execute the UAV during the execution cycle T_e and perform status updates.

3. Results

Table 2. UAV related parameters (Random Generation)

Type	Cruising ability	Cruising speed	Replenishment time	Maximum detection distance	Detection index
U_1	8h	320km/h	1.5h	60km	9km
U_2	4h	640km/h	1h	80km	13km

In order to reduce the search time as much as possible, the sea area map was processed, and the peripheral effective points of the target probability graph were determined by SECP [10], thus simplifying the search scope is shown in Figure 4.

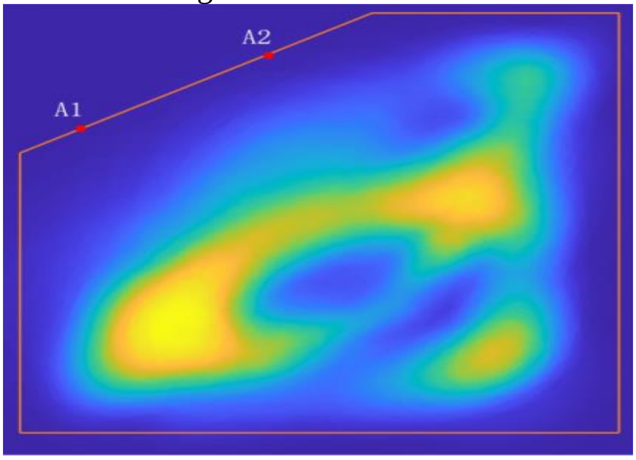

Figure 4. Search range reduction

Set the execution periodof distributed MPC to 20s, the planning periodto 1350s and other parameters as Table 2(The data were randomly generated), The simulation results are shown in the Figure 5 and Figure 6:

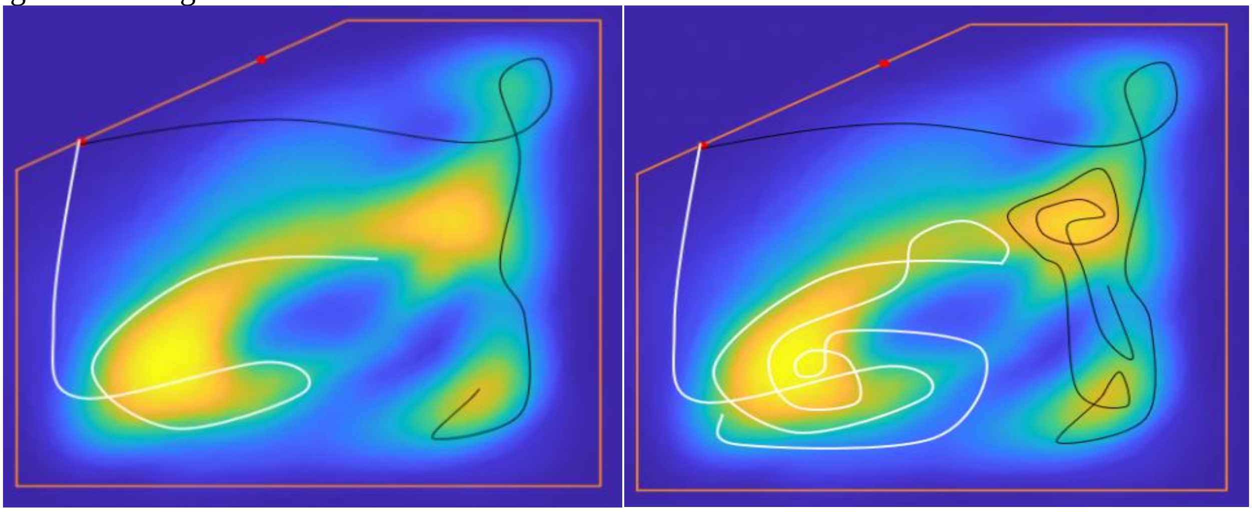

Figure 5. U1:2 UAVs on t=1h and t=2.21h trajectories

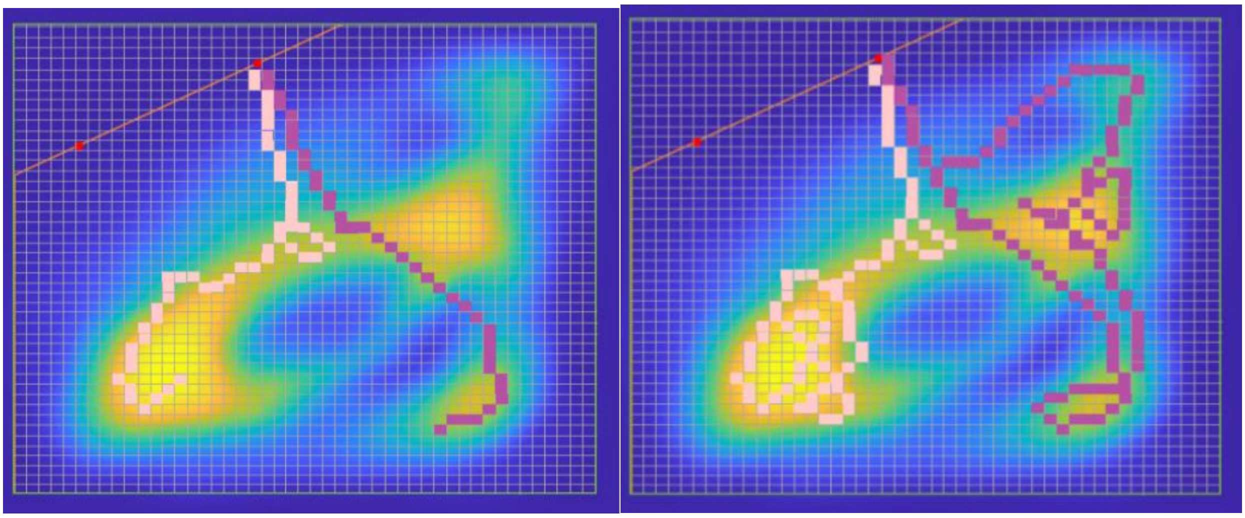

Figure 6. U2:2 UAVs on t=1h and t=2.21h trajectories

4. Conclusions

Based on the application of OODA theory, and distributed prediction model (MPC), this paper mainly optimizes the sea search strategy of UAVs to a large extent, simplifies the search scope, and fully improves the route of multi-UAVs' collaborative search of sea targets. Moreover, the algorithm based on the fusion of OODA and MPC can make the large-scale and long-term search prediction change from incalculable and difficult to calculate to fast and accurate calculation.

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