Collaborative Strategy of Multi-UAV for Searching Sea Area

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Abstract. This paper proposed a collaborative strategy of multi-UAV for searching sea area based on ‘Z’ route, and an improved ‘Z’ route is designed. Firstly, UAV model and target model are built. Secondly, collaborative searching strategy based on ‘Z’ route is proposed, and navigation points are selected. Finally, three searching models are built and simulation study verifies the effectiveness of the proposed method.

Introduction

Implementation of intelligence, reconnaissance and surveillance tasks is the basic mission of the current unmanned system [1]. The US Department of Defense released the "Development of unmanned system", said "reconnaissance and surveillance" would be the primary task of current unmanned system [2].

For still targets, there are ‘Z’ route [3] and spiral path [4] to solve the search problem. As the battlefield environment becomes more and more complex, obstacle and danger zone appears, real-time detection method such as probability diagram [5], pheromone [6], response rate [7] and uncertain chart [8] are proposed to solve the dynamic target problem. They solve the UAV search tracks online, and have better effect on the dynamic environment. Hu [9, 10] solve the searching problem of multiple-UAVs with multi-static targets base on distributed iterative probability diagram updating model. Meng considers the dynamic characteristics of UAV and the anti-collision of multiple UAVs, and proposes multi-UAV take-off, target searching, task assignment and target tracking method. Ryan[11] solve the cluster control problem of multi-UAV dynamic cooperative cleaning based on agent simulation using dynamic data-driven application system. Farid [12] use cooperate method containing search and monitor, and solve the distributed collaborative searching problem considering multi-UAVs.

The paper proposes a new collaborative searching method based on ‘Z’ route. Target model and sensor model are built. The proposed collaborative strategy is economic and effective.

UAV Model

We assume that UAV has a constant flying height, and do not consider the influence of the wind. Its dynamic model can be described as:

\[
\begin{align*}
\dot{x}_i &= v_i \cos \varphi_i \\
\dot{y}_i &= v_i \sin \varphi_i \\
\dot{z}_i &= 0 \\
\dot{\varphi}_i &= w_i \eta_{\text{max}}
\end{align*}
\]

(1)

where \((x_i, y_i, z_i)\) is UAV’s coordinate, \(\varphi_i\) is heading angle, \(v_i\) is velocity, \(\eta_{\text{max}}\) is maximum turning angular velocity, \(w_i\) is angular acceleration, \(w_i \in [-1, 1]\).
Sensors on UAV include Infrared, electro-optical, synthetic aperture radar. Observation equation can be described as:

\[ z_i[k] = h(x_i[k], k) + v_i[k] \]  

(2)  

where \( v_i[k] \sim N(0, R_i[k]) \).

\[
h(x_k, k) = \begin{bmatrix} \rho_k \\ \phi_k \\ \theta_k \end{bmatrix} = \begin{bmatrix} \sqrt{(R_{sk})^2+(R_{sk})^2+(R_{sk})^2} \\ \tan^{-1} \left( \frac{R_{sk}}{R_{sk}} \right) \\ \tan^{-1} \left( \frac{R_{sk}}{\sqrt{(R_{sk})^2+(R_{sk})^2}} \right) \end{bmatrix}
\]

(3)

\[
\begin{align*}
R_{sk} &= \sqrt{\left(\rho_k\right)^2 - (R_{sk})^2} \\
R_{sk} &= \tan \phi \sqrt{\left(\rho_k\right)^2 - (R_{sk})^2} \over 1 + \tan^2 \phi_k
\end{align*}
\]

(4)

**Target Model**

State equations of targets can be described as:

\[ X(n) = FX(n-1) + W(n-1) \]  

(5)

where \( F \) is state transition matrix, \( W \) is position and speed noise, \( W = [p_{n-1}, p_{n-1}, q_{n-1}, q_{n-1}] \), \( X(n) = [x(n) \ x(n) \ x(n) \ y(n) \ y(n)] \), \( x(n) \) and \( y(n) \) are target displacement, \( x(n) \) and \( y(n) \) are corresponding speed components, \( T \) is sampling time.

\[
F = \begin{bmatrix}
1 & T & T^2/2 & 0 & 0 & 0 \\
0 & 1 & T & 0 & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 1 & T^2 & T^2/2 \\
0 & 0 & 0 & 0 & 1 & T \\
0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\]

Measurement model is
\[ Z(n) = KX(n) + V(n) \]  

where \( Z(n) \) is measure value, \( V(n) \) is observation noise. \( W(n) \) and \( V(n) \) are independent to each other. \( K \) is sensor observation matrix.

\[ K = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 \end{bmatrix} \]  

**Collaborative Searching Strategy**

\( N \) UAVs search for targets with velocity \( V \) and flight height \( H \). Searching radius of sensors is \( R_s \), and minimal turn radius of UAV is \( R_v \). Quantity and position of targets in searching area are unknown. The purpose of searching is to find a best strategy to cover the whole area with minimum cost. Searching process should follow the following principle:

1. \( N < W / 2R_v \), which means UAVs must turn once at least.
2. UAV take off vertically from the left bound, and the distance between the neighbors UAV is fixed, and satisfies \( D_s = 2R_s \).

Following the above principle, the searching model can be described as:

\[ J = \min \frac{\max l_i}{V_u} \quad i = 1, \ldots, N_v \]  

s.t. \( S = \bigcup_{i=1}^{N_v} S_s, R_s \geq R_v, \left| \max l_i - \min l_i \right| < \varepsilon \)  

where \( l_i \) is the total distance of one UAV, \( S \) is the whole area, \( S_s \) is searching area of each UAV, \( R_s \) is the turning radius of each UAV. Improved ‘Z’ route is designed as described in Fig. 1.
A straight route is adopted within the searching area, A, B, C, D, E, F, G, H are eight navigation points, and the flight order is A->B->C->D->E->F->G->H->A. Variables in Fig. 1 are described as:

- **TurnRadius** - the minimum radius of UAV (decided by flight ability)
- **Straightdistance** - the straight distance of each UAV in searching area
- **SearchwidthX** - the width of searching area
- **SearchwidthY** - the distance of half cycle
- **SensorWidth** - the searching width of sensor

*Annotation:* Straightdistance is vector variable, downward is positive. For whole cover of the searching area, the variables TurnRadius, SearchwidthY, SensorWidth and Straightdistance satisfy

\[
SensorWidth = SearchwidthY = 2 \times TurnRadius + Straightdistance
\]  
(9)

When Straightdistance>0, the flight distance of UAV is minimum. When Straightdistance<0 (Point D/H is above C/G, as shown in Fig. 2), for whole cover searching, additional route is needed (yellow line).

The order of designing navigation points is A->B->C->E->D->F->G->A->H, A is Pre-determined, B is selected by SearchwidthX distance translate to the east of A. C is selected by TurnRadius distance translate to the east and TurnRadius distance to the south of B. E is selected by k*SensorWidth distance translate to the south of B, ans k is the number of UAVs. D is selected by TurnRadius distance translate to the east and TurnRadius distance translate to the north of E. F is selected by SearchwidthX distance translate to the west of E. Point G is selected by TurnRadius distance translate to the west and TurnRadius distance translate to the south of point F. The final point of is selected by k*SensorWidth distance translate to south of F. Then, we get one whole cycle of the route. Variables TurnRadius, Straightdistance, SensorWidth and Totaldistance satisfies

\[
Totaldistance = 2 \times SearchwidthX + TurnRadius \times \pi + 2 \times Straightdistance
\]  
(10)
Simulation Study

One UAV partition searching model: One UAV in each partitioned area.

Three UAV partition searching model: Three UAV in each partitioned area.

Carpet searching model: No partition is needed, all UAVs search for one area at the same time.
Above results show that all the three models can search for the area successfully. One UAV partition searching model has the largest flight distance. Carpet searching model is the easiest one to accomplish. Three UAV partition searching model has the minimal flight and is the best one.

**Summary**

In this paper, Collaborative searching strategy is proposed to solve the searching task of targets. UAV model and target model are built and three simulation model including one UAV partition searching model, three UAV partition searching model and carpet searching model are proposed. Simulation study shows that three UAV partition searching model is the best.

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