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A potential game approach to multiple UAV cooperative search and surveillance

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ABSTRACT

In this paper, we developed a game theoretic formulation for multiple unmanned aerial vehicle (UAV) cooperative search and surveillance. The cooperative search problem is decomposed into three sequential tasks: coordinated motion, sensor observation, and cooperative information fusion. Firstly, the coordinated motion is designed as a multi-player potential game with constrained action sets. Then the binary log-linear learning is adopted to perform motion control, which guarantees optimal coverage. Then a consensus based fusion algorithm is introduced to construct the probability map to guide the following coordinated motion. Finally, simulations are performed to validate the effectiveness of our proposed approach. The modular framework enables the separate design of utility functions and learning algorithms, which offers a flexible way to accommodate different global objectives and underlying physical constraints.

1. Introduction

Many search and surveillance missions involve measuring and exploring an unknown region, such as target detection [1,2], environmental monitoring [3,4], and map building [5,6]. In recent years, the unmanned aerial vehicles (UAVs) have drawn much attention in cooperative search problems owing to their increasing autonomy. Apparently, greater efficiency can be achieved in information collection with teams of autonomous UAVs operating in a coordinated fashion [7–13]. The cooperative search involves the design of distributed algorithms that use the localized information to achieve a globally optimized objective for systems composed of interconnected components. Several challenges are deserving to be addressed in cooperative search problems using multiple vehicles [14–16]. Firstly, individuals are required to operate (move and sense) autonomously with limited sensing and communication capabilities [17–20]. Secondly, the system should be designed to provide the network with adaptation and robustness to unexpected situations. Thirdly, consideration must be given to issues of different global objectives and underlying constraints.

A provably convergent Kalman filter combining sensor observations is developed in [21] to explore the scalar field. The optimal formation shape can be achieved by applying estimations from the designed filter into the motion control law. Along with the consensus-based fusion algorithm, a path planning algorithm is proposed based on centroidal Voronoi partitioning to realize a final optimal configuration in [22]. In [23], a self-assessment based decision-making method is designed for cooperative search under various communication structures. This approach shows some attractive features such as less computational complexity, low communication overheads, and excellent scalability. The designed control system in [12] consists of three parallel components: coverage control, data source detection, and data collection. Operations in environments with obstacles are especially important for urban monitoring or disaster management. However, additional efforts are often required to deal with the discontinuities imposed by the obstacles. Moreover, most studies focus on cooperative search with the assumption that UAVs involved in the mission are homogeneous.

The relevance of game theory to cooperative control has been recognized due to the fact that game theory concerns the study of interacting decision makers. Especially, the potential game is beginning to emerge as a valuable paradigm for cooperative control [24,25]. The important aspect of potential games lies in that the potential function guarantees utilities of the individuals are localized to themselves yet aligned with the global objective. Motivated by these facts, we developed a potential game approach to accommodate the challenges imposed by cooperative search problems. In our study, the cooperative search problem is decomposed into

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Nomenclature

UAVs	Unmanned aerial vehicles
Ω	Mission area
n	Number of UAVs
V, S	Set of vehicles and set of players
v_i	The ith UAV, $i = 1, 2, \ldots, n$
t	Time step
g	Position of the partitioned cell
$\mathbf{C}_i$, μ_i	Sensing area and position of vehicle v_i
R_{S_i}, R_{C_i}	The sensing range and the communication range of vehicle v_i
Net	Graph of the UAV network
E	The edge set of graph Net
N_i, κ_i	The neighbor set and the degree of vehicle v_i
G	Strategic form game
A_i, U_i	The action set and utility function of player i
a, $\tilde{a}$, a'	Joint actions of the players
a_i, $\tilde{a}_i$, a'_i	Action of player i
a_{-i}	Action profile of players other than player i
a^*	Joint actions of the players at the Nash Equilibrium
Φ	The potential function of game G
η	The density function
f	The function of signal degradation
$C_{a_i(t-1)}$	Constrained action set of player i at time t
z_i	Maximum number of actions in $C_{a_i(t-1)}$
$P(D)$	The probability of event D
$P(D\|E)$	The conditional probability of D given E
τ	Amplitude of noise in binary log-linear learning
$\pi(a)$	Probability distribution over state space of action a
$P_{a \to a'}$	State transition probability from action profile a to a'
$\mathbf{P}$	State transition matrix
d	Euclidean distance
θ_g	Event that a target is present in cell g
p_c, p_f	Detection probability and false alarm probability
$Z_{i,g,t}$, $P_{i,g,t}$	Measurement and target existence probability of vehicle v_i at time t for cell g
$H_{i,g,t}$	Nonlinear transformation of $P_{i,g,t}$
$Q_{i,g,t}$	Linear combination of $H_{i,g,t}$
W	Metropolis weight matrix
$\omega_{i,j,t}$	Weight on $H_{j,g,t}$ for vehicle v_i
k_η	Positive gain
$\bar{\eta}$	Average uncertainty of all the vehicles
δ_0	Predefined threshold for termination
F_S	Sampling frequency

three tasks: coordinated motion, sensor observation, and information fusion. On the one hand, UAVs autonomously perform coordinated movements to reach an optimal configuration that maximizes the event detection probability. On the other hand, UAVs gather information from observations to construct a probability map and fuse information through interactions with its neighboring UAVs.

The main contribution of this paper is the development of a potential game formulation for cooperative search. By designing the cooperative search as a potential game, UAVs equipping with isotropic sensors are viewed as autonomous decision makers. The binary log-linear learning is adopted to perform motion control with a simplified kinetic model, which guarantees optimal coverage [26]. Sufficient conditions regarding sensing and communication capabilities are given for implementing this learning algorithm. The modular framework enables the separate design of utility functions and learning algorithms, which offers a flexible way to accommodate different global objectives and underlying physical constraints. This potential game formulation makes it possible for UAVs to operate with heterogeneous sensors or even in the mission area with non-convex obstacles without introducing additional treatment. This capability is encoded into the constrained action sets implicitly. Besides, associated learning processes provide UAVs with robustness to failures caused by hardware malfunctions, software faults, or deliberate attacks. This approach can be used in applications of exploring an entirely unknown structured area, such as disaster management, and target detection in urban environments.

The remainder of this paper is structured as follows. Problem setup and some basic assumptions are provided in Section 2. By formulating cooperative search as a potential game, we adopt the binary log-linear learning for coordinated motion in Section 3. Moreover, sufficient communication conditions necessary for implementing this learning algorithm are also provided. Then the entire procedure of coordinated motion and cooperative information fusion to construct the probability map is described in Section 4. The effectiveness of our proposed approach is verified by comparative results in Section 5. The last section offers some concluding remarks.

2. Problem setup and some basic definitions

In this section, procedures for performing a search operation are described briefly to provide an overall view of this problem. Then we introduce some basic definitions and assumptions about exploring an unknown area with multiple UAVs. Besides, some preliminary definitions of potential games are provided.

2.1. Problem formulation of cooperative search

Usually, the cooperative search problem involves the following three parts: coordinated motion, sensor observation, and information fusion. Before starting the search, each vehicle associates its knowledge of the mission space with a probability map. Then UAVs tend to move towards locations with high uncertainty to increase data gathering. After UAVs deploy themselves to new locations, they perform observations to detect data source and collect data. To further enhance the search effectiveness, UAVs usually carry out information fusion through communication with their neighbors, integrating both spatial and temporal estimation. Moreover, observations reduce the uncertainty over corresponding areas, which in turn guide the following coordinated motion. Then the entire procedure continues until the probability distribution over the whole mission space is bellowed a predetermined threshold, as is shown in Fig. 1.

2.2. Basic definitions and assumptions

Consider the problem of searching an unknown area $\Omega \in \mathbf{R}^2$ using n UAVs, labeled as $V = \{v_1, v_2, \ldots, v_n\}$. Each vehicle acts as a self-interested decision maker to gain knowledge about the mission space (as shown in Fig. 2). The continuous area $\Omega \in \mathbf{R}^2$ is uniformly partitioned into equal cells and each cell is identified by the position of its center g. Each vehicle v_i independently takes measurements $Z_{i,g,t}$ over cells within its sensing range $\mathbf{C}_i = \{g \mid |g - \mu_i| \le R_{S_i}\}$, where R_{S_i} represents the sensing range of v_i. Also note that, for simplicity sake, we suppose the signal over cell g could be wholly observed by v_i when its center is within $\mathbf{C}_i$. Only two results can be observed when v_i carries out a measurement, that is, $Z_{i,g,t} = 1$ if $|g - \mu_i| \le R_{S_i}$, or $Z_{i,g,t} = 0$ if $|g - \mu_i| > R_{S_i}$.

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