Reconnaissance in Complex Environment with No-fly Zones using a Swarm of Unmanned Aerial Vehicles

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Abstract

This research deals with the model of reconnaissance of the area of interest performed by a swarm of cooperative Unmanned Aerial Vehicles. The reconnaissance operation of the area may be conducted in a complex environment in which obstacles and/or terrain may block the line of sight from sensors and, thus, occlude some parts of the area. Also, the no-fly zones can be defined where no vehicle is permitted at any time of the operation. The model focuses on planning trajectories of all the vehicles in the swarm in such a way that the vehicles avoid the no-fly zones, the sensors of the vehicles explore as large area as possible during the operation and, at the same time, the operation is performed as quickly as possible. Exact and stochastic (metaheuristic) algorithms are proposed to find a solution to the task at hand. A set of experimental tasks, based on the real military reconnaissance scenarios, is proposed to verify the presented model and algorithms.

Objective

The use of Unmanned Aerial Vehicles (UAVs) for tasks such as monitoring, exploration, surveillance or reconnaissance for information gathering has become commonplace in many domains – civil as well as military. The reasons are the precise and fast results, easy control, and technological and financial availability.
This paper presents the use of UAVs for military purposes – in a reconnaissance operation. The objective is to plan trajectories of available UAVs in the swarm to explore as large area of interest as possible as quickly as possible.

The contributions and new innovations in this paper are as follows:

- No-fly zones. These are areas in which no UAV can be located at any time of the reconnaissance operation; i.e., trajectories must be planned so that the vehicles avoid these zones during the operation. The objective of the task remains the same: the complete and fast reconnaissance.
- Exact algorithm for initial waypoints deployment. This algorithm was proposed to increase the efficiency of the metaheuristic algorithm used for deployment of waypoints.
- Extension of the algorithm for waypoints deployment. The algorithm was modified so that the waypoints are not to be deployed in no-fly zones.
- Extension of the algorithm for planning routes. The algorithm was modified so that the routes avoid the no-fly zones.

Model

The planning of UAVs trajectories during the reconnaissance operation is conducted in two phases: (a) deployment of waypoints from which sensors perform monitoring; (b) planning routes between waypoints. The goal of the first phase is to deploy a number of waypoints in such a way that as large area as possible is explored; the goal of the second phase is to plan routes of individual UAVs so that the whole operation is performed in mutual cooperation as fast as possible.
The objective of the first optimization problem is to determine the number of waypoints and their positions in such a way that (a) there is as low number of waypoints n as possible whereas (b) the total explored area a_{total} of the entire area of interest a_0 is as large as possible. As these two conditions go against one another, the minimum portion of the explored area ω_{min} needs to be specified ($0 < \omega_{min} \leq 1$). Formulae (1) and (2) shows the objectives subject to condition (3).

$$Minimize(n) \tag{1}$$

$$Maximize(a_{total}) \tag{2}$$

$$|a_{total}| \geq \omega_{min} \cdot |A_0| \tag{3}$$

In the second optimization problem, the trajectories of all available UAVs are planned so that all the waypoints are visited by at least one UAV and the reconnaissance operation is performed as fast as possible. R_i denotes a route for a UAV $U_i \in U$. Every route is composed of an infinite number of points through which the UAV flies in the correct order during the operation: $R_i = \{R_i^1, R_i^2, \dots\}$. T_i is the time necessary for a single UAV $U_i \in U$ to fly along its route and then return back to its home position. Then, the objective is in formula (4).

$$Minimize\big(max(T_1, T_2, \dots, T_m)\big) \tag{4}$$

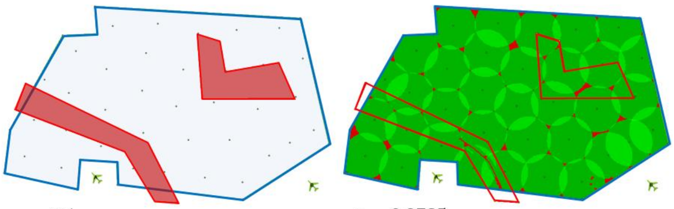
The no-fly zones limit both the positioning of waypoints and planning the routes. In the former, condition (5) must be satisfied; that means no waypoint $W_i \in W$ can be positioned inside any no-fly zone $Z_j \in Z$. In the latter, condition (6) must be satisfied; no point $R_i^k \in R_i$ laying on the route of any UAV can go through no-fly zones $Z_j \in Z$.

$$W_i \notin Z_j \quad \text{for all } W_i \in W \text{ and } Z_j \in Z \tag{5}$$

$$R_i^k \notin Z_j \quad \text{for all } U_i \in U, R_i^k \in R_i \text{ and } Z_j \in Z \tag{6}$$

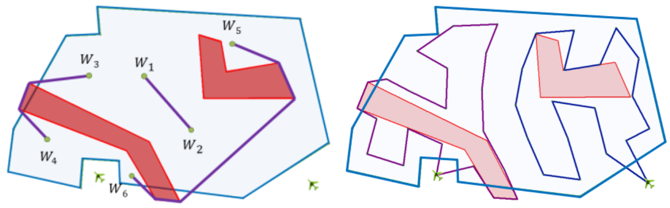
Solution

The first optimization problem (waypoints deployment) is illustrated in the figures below. On the left, the blue lines border the area of interest, red areas are no-fly zones. The goal was to explore at least 97% of the area of interest ($\omega_{min} = 0.97$). To do this, a number waypoints (green dots) were deployed ($n = 35$). On the right, the green colour represents the explored area; i.e. the area covered by sensors from waypoints which is 97.85%. There are two UAVs available for the reconnaissance operation.



$n = 35$ $\omega = 0.9785$

For solution, the exact algorithm was proposed for the estimation of the number of waypoints necessary to cover the specified portion of the area of interest using the optimization criterion in formula (1), and the metaheuristic algorithm based on the simulated annealing principle was proposed for the optimization of the positions of n waypoint using the optimization criterion in formula (2).
The second optimization problem (planning trajectories) is illustrated in the figures below. The existence of no-fly zones means that the direct connection between arbitrary pair of waypoints may not exist. In that case, the shortest route avoiding the no-fly zones is calculated. Violet lines on the left show the connections between three pairs of waypoints. Whereas there is a direct connection between waypoints W_1 and W_2, the route around no-fly zones must be found in case of connections between waypoints W_3 and W_4, and W_5 and W_6. On the right, the trajectories are planned for both UAVs (violet and dark blue lines). For solution, the metaheuristic algorithm using Ant Colony Optimization (ACO) principle were proposed.



Experiments

A set of experiments was designed to verify the proposed algorithms. The experiments are composed of five benchmark instances which are based on the reconnaissance scenarios typical in the real reconnaissance operations. The parameters of the scenarios are summarized in table below.

Scenario	Area of interest	No-fly zones	UAVs available	Min. coverage ω_{min}
s01	2.539 km^2	0.414 km^2	2	97%
s02	2.539 km^2	0.617 km^2	3	90%
s03	13.492 km^2	1.489 km^2	4	95%
s04	13.492 km^2	1.008 km^2	5	94%
s05	7.713 km^2	2.026 km^2	8	96%

Conclusions

This paper deals with the model of reconnaissance of the area of interest performed by a swarm of cooperative UAVs. The original research of the authors was extended in several ways:

- The new tactical constraint in the form of no-fly zones was inserted into the model and its impact on the two optimization problems (deployment of waypoints and trajectories optimization) was examined.
- The new exact algorithm for the estimation of the number of waypoints needed was proposed and verified.
- The stochastic algorithms used for the both optimization problems were extended to reflect the new constraint.

The new features proposed in this paper were implemented into the Tactical Decision Support System and are available now to be used for commanders on the battlefield to support them in their decision-making process.