Model-Solution Framework for Minimal Risk Planning for URAVs

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Extended Abstract

Unmanned aerial vehicles (UAVs) [1] may be classified based on their application domain – civilian or defense. In most civilian-usage scenarios, external threat to the UAV is negligible. Fuel minimization, collision avoidance, indoor motion planning, and meeting timing constraints are some critical issues that fall under the umbrella of waypoint planning activities for civilian UAVs. However it is obvious that UAVs used for defense can come under inclement fire. Waypoint planning for such UAVs must additionally account for minimization of external risks. These risks may be lowered by minimizing revisitations, coordinating the timing of operation of the UAV with other friendly units or flying along approach and departure vectors that minimize the duration or the intensity of the electromagnetic signature of the UAV visible to hostile units.

In general, the validity of a risk-model or an objective and even the utility of the very goal of lowering the risk-exposure of the vehicle depends on the class of the UAV, its operational environment and mission. UAVs at one end of the endurance spectrum – battery powered or hand-launched over-the-hill UAVs are expendable or even designed for one-time use. On the other extreme, high altitude long endurance UAVs generally operate beyond the risk-envelope of most ground-based threats.

We focus on lowering the risks from static ground-based threats. Our threat-model is a minimal risk density target visitation (MRDTV) sparse graph $G(V, E)$ whose vertices are sites of interest, $\mathcal{S}$, and the airbase, $\mathcal{A}$, and whose edges represent minimal risk density paths obtained from a bounded Voronoi Graph of threats, $\mathcal{T}$, that are not collocated with any site, $s_i \in \mathcal{S}$. Whenever possible, the vehicle flies along the edges $E' \subseteq E(G)$. The problem of uncovering site visitation sequencing plans that are embeddable in the MRDTV graph arises in reference to the goal of minimizing or eliminating revisitations. Our use of genetic algorithms for obtaining such plans finds greater justification when the number of sites to be visited in a single sortie is large.

Our threat-model and solution approach are more suited to low to medium altitude medium endurance unmanned reconnaissance aerial vehicles (URAVs). Here, we briefly mention several objectives that are consistent with the goal of lowering risks for URAVs and discuss how the expressive power of our model can be enhanced and our solution methodology (GAs) be tweaked to provide a broader set of solutions.

Generic Case: No Revisitations. In general, revisitations to a site will result in lower fuel-efficiency and invite mission-risks that are redundant to the mission-objectives. In our case, avoiding revisitations translates into the following requirement –

Given an airbase, $\mathcal{A}$, and a set of nonoverlapping useful vicinities of reconnaissance sites, $\mathcal{S}$, find a set of orderings $\prod_{\mathcal{S}}^*$ such that a URAV can take-off from $\mathcal{A}$, fly to the useful vicinities of each site, $s_i \in \mathcal{S}$, along a subset of the edges of an MRDTV graph exactly once in the order defined by $\prod_{\mathcal{S}}{}^*_i \in \prod_{\mathcal{S}}^*$ and, fly back safely to $\mathcal{A}$.

This is the Hamiltonian (HAM) cycle problem. We used GAs [2, 3] to obtain several HAM cycles in the MRDTV graph. In case the GA was unable to uncover sufficiently many HAM cycles, it reported several maximally long paths; all beginning at $\mathcal{A}$. The gene encoding was a bijective map from the set V to the set of all genes in a chromosome. Crossover was implemented with the PMX [4] operator in order to generate feasible offsprings. The use of gene migration local search operator greatly enhanced the solution quality. $G(V, E)$ was presented to the GA in adjacency matrix representation. Additional improvements to this basic scheme are reported in [2, 3].

Ordered Back-to-Back Visitations. Visiting a subset of sites in an ordered consecutive manner can be helpful in situations involving timing-window or precedence constraints. We deal with this problem at the model-level as follows. GA implementation remains similar.

Consider an acyclic set of sites $n_i \in N \subset V$ that must be visited consecutively. It is clear that beginning (or ending) a tour of sites in N at a site other than n_1 or n_N will lead to violation of the ordered back-to-back constraints. Therefore we can remove from the MRDTV graph the vertices $\{n_i\colon 2 \le i \le N\}$ and their incident edges and let the vertex n_1 denote set N. Edges incident with vertex n_N are added to the adjacency list of n_1. The resulting graph is encoded as genes. In the solution obtained using GA, a visit to n_1 is decoded as a visit to all sites associated with vertices in N. The additional bookkeeping needed for coding and decoding is minor and straightforward.

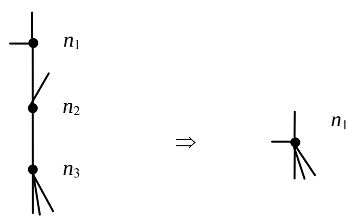

Fig.1 Depiction of graph-modification for Ordered Back-to-Back Visitations

Incrementally Growing Rings: No Revisitations. In our application, MRDTV graphs can have up to 40 vertices and, due to sparseness, discovering several HAM cycles can get challenging. One way out is to forgo the search for HAM cycles and instead search in steps for incremental cycles – a new vertex is added to the current cycle at each step without disturbing the topology of the solution until a maximal length cycle is found. This process may be repeated several times using probabilistic variation of the algorithms described in [5] or a variation of an ant-based heuristic [6]. The chief advantage of this approach over the last is that a return path to the airbase along minimal risk density edges is guaranteed.

Minimize Risk on Return Route. In critical situations, a planner might consider additional risks due to revisitations once the mission goal has been met, i.e., all or a maximal number of useful vicinities have been visited by the URAV. However, minimizing the summation of the integrals of the risk function between adjacent vertices on the return route will obviously help.

$$MIN[\sum_{i=1}^{k} \iint f_i(x,y,z)\rho_i \; dx \; dy \; dz \; d\rho] \qquad \begin{array}{l} f_i(x,y,z) = length \; of \; path \; i \\ \rho_i = risk \; density \; along \; path \; i \end{array}$$

A greater reward may be assigned to strings in which the nodes in the vicinity of the airbase and the airbase are sufficiently separated to bias the GA to provide maximally long paths that end in the ‘vicinity’ of the airbase. Following this, Dijkstra’s algorithm [7] may be applied in $O(|V|\log|V|+|E|\log|V|)$ time to obtain the shortest path to the airbase. And, solutions obtained with GA can be accordingly ranked.

Minimizing the Number of Revisitations on Return Route. This is a variant of the aforementioned case. However, since our model does not account for threats collocated with the sites of interest, minimizing the number of revisitations on the return route has its own advantages. GA procedure remains the same as before. Dijkstra’s algorithm is applied to an unweighted graph instead.

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