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UAV-UGV Cooperative Area Exploration

By

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Chapter 1

Literature Review

The field of optimizing cooperative UAV-UGV area exploration has been extensively researched throughout the last decade, in terms of increasing explored area and reaching desired targets in minimal running time.

Xu et al, 2020 explored the field cooperative path planning for multi-UAV system as used in military and civil applications, such as target striking and regional surveillance, in order to increase the probability of task completion and minimizing the risk of the UAVs being captured, by proposing an optimized cooperative path planning for multi-UAV system optimizing a combination of fuel/energy consumption and risk of capture, under the constraints of exploration area and time, establishing a multi constraint objective optimization model, followed by the testing of multiple optimization algorithms, such as an improved version of the grey wolf optimization algorithm, where the algorithm is improved in three main aspects, population initialization, decoy factor updating and individual position updating, simulation results showcase that the algorithm has optimized the generated paths by lowering the path cost, while reaching faster convergence when compared to other tested techniques [1].

In their research, Qiming et al, 2021 have evaluated the use of different meta-heuristic optimization techniques in solving the UAV swarm search task. In their research, the goal was to detect targets as fast as possible, while using the least number of UAVs, in another simulation environment, the goal was to maximize the search area with the UAV swarm. The search area was divided into discrete cells of MxN size and the used UAV model was assumed to be the basic UAV model by treating each UAV as a particle in a 2-Dimensional space. Some of the constraints taken into consideration were the curve angle θ, flight speed v, flight altitude h, the table shown in Table: 1.1 provides more constraints.

Constraint name	**Expression**	**Meaning**
Curve angle constraint	$\theta_{\min} \leq \theta_i \leq \theta_{\max}$	θ_i: turning angle of the UAV at time i $\theta_{\min}$: minimum turning angle $\theta_{\max}$: maximum turning angle
Flight speed constraint	$v_{\min} \leq v_i \leq v_{\max}$	v_i: speed of the UAV at time i $v_{\min}$: minimum speed of UAV $v_{\max}$: maximum speed of UAV
Flight altitude constraint	$h_{\min} \leq h_i \leq h_{\max}$	h_i: altitude of the UAV at time i $h_{\min}$: minimum flight altitude $h_{\max}$: maximum flight altitude
Climb angle constraint	$0 \leq \alpha_i \leq \alpha_{\max}$	α_i: UAV climbing angle at time i $\alpha_{\max}$: maximum climbing angle
Subduction angle constraint	$0 \leq \beta_i \leq \beta_{\max}$	β_i: UAV subduction angle at time i $\beta_{\max}$: maximum subduction angle
Communication constraint	$d_{ab} \leq r$	d_{ab}: distance between two UAVs r: communication radius
Boundary constraint	$l_i \in D$	l_i: UAV location D: restricted area
Collaborative constraint	$d_{\min} \leq d_{ab} \leq d_{\max}$ $t_a \leq T$	d_{ab}: distance between two UAVs $d_{\min}$: shortest distance between UAVs $d_{\max}$: maximum flight range t_a: time of arrival a T: latest time of arrival a

Table 1.1: UAV Constraints Table

In their evaluation, the researchers tested the Genetic Algorithm (GA), Ant Colony (AC), Particle Swarm (PSA), with other optimizing algorithms, in GA, when minimizing the time was taken as the objective function, the total task time was reduced by 65%, however, the algorithm needed a certain number of UAVs and showed linear increase in energy consumption as the number of UAVs increases [2].

In their article, Ramasamy et al, 2022 have explored parameter tuning using genetic algorithm with a set of constraints such as fuel limitations of the UAVs and the speed limitations of the UGVs, reducing the time and/or fuel consumption were important in assessing the validity of the algorithms, taking into consideration the resource and terrain constraints. The paper compared between the Genetic Algorithm and the Bayesian Optimization, despite the fact that the GA provided relatively similar results to BO, it required 3 times more local-search optimization and required 6 times the computation time [3].

In their research, Lui et al, 2016 used quantum ant colony algorithm (QACA), to optimize the path taken in evacuation practices, while being robust and and high efficiency, comparing their findings with the traditional Ant Colony Algorithm (ACO). In their research, minimizing the time of evacuation evacuation path optimization was critical in assessing the algorithm, as less time equates to less human losses in cases of environmental crisis. The primary objective is to consume as little time as possible to evacuate all evacuees from the danger zones to safe zones, making the time the most significant factor to be considered, another objective was to minimize total density in the paths. There were three benchmark functions used to compare the results of QACA and ACO, where the tests showed that QACA was more efficient in solving the problem, as well as expand the solution as the iterations advance [4].

In their paper, Wu et al 2020 discussed the same topic of cooperative UAV-UGV exploration, but in surveillance applications. In this paper, the path planning problem was formulated to be a 0-1 optimization problem, in which the on-off states of the discrete points are to be optimized. A hybrid algorithm, combining the Estimation of Distribution Algorithm (EDA) and the Genetic Algorithm (GA) was proposed to solve the problem. The goal is to minimize the required time by the vehicles to complete a circular path, where the objective function can be expressed as shown in equation 2.1.

$$J = max(\frac{D_u}{N_u * v_u}, \frac{D_g}{N_g * v_g}) \tag{1.1}$$

Where $D_u \& D_g$ are the lengths of the circular paths, and $N_u \& N_g$ are the number of drones and UGVs and $v_u \& v_g$ are their velocities.

The decision variables are the on-off states of the active points, where each point can either be ”open” (1) or ”closed” (0), and open points must be covered during exploration.

The constraints for UAVs in this paper lied in avoiding collisions with buildings, which are represented as inaccessible grids, also, the vehicles must cover all assigned 2D grids to ensure complete coverage, where the on-off states must satisfy the coverage constraint. In their results, they validated the superiority and rationality of the proposed hybrid algorithm, where the workload can be balanced between the UAVs and UGVs, moreover, the cooperative planning yielded better results than using either systems alone, by significantly reducing the total surveillance time, the suggested algorithm combined the strengths of EDA and GA's strengths, resulting in minimizing the time of task completion, while increasing adaptability since the path is being assessed during runtime rather than before runtime, increasing flexibility in real-world applications[5].

Chapter 2

Methodology

Our goal is to optimize the next step taken by the UAVs, optimizing the next step allows the UAVs to reach the target areas with the least possible travel distance, maximum possible exploration in the least possible time, giving more importance to the time taken to find the targets. Based on this, we chose our decision variables to be $x_{next} \& y_{next}$ of the UAVs, which represent the next step taken in the path, allowing us to optimize the path online, instead of optimizing it all before runtime, providing the UAVs with more optimally viable paths, while abiding to the constraints that are mentioned below.

Cost Function

The cost function aims to maximize the explored area while minimizing the time taken, subject to penalties for constraint violations (e.g., communication and collision avoidance).

$$J = w_1 \cdot \frac{ExploredArea}{TotalArea} - w_2 \cdot \frac{TimeTaken}{MaxTime} - Penalty \tag{2.1}$$

Where:

- w_1 and w_2 are weight parameters for the explored area and time taken.
- $Penalty$ accounts for violations of constraints such as UAVs moving outside the communication range or colliding with each other.

Fitness Function

The fitness function computes how well the UAV configuration performs based on the objective to maximize the explored area and minimize time, while satisfying constraints.

Objective

Maximizing the explored area:

$$J_1 = \frac{ExploredArea}{TotalArea} \tag{2.2}$$

Minimizing the time taken:

$$J_2 = -\frac{TimeTaken}{MaxTime} \tag{2.3}$$

Constraints

1. **Flight speed constraint:**

$$v_{min} \leq v_i \leq v_{max} \tag{2.4}$$

2. **Communication constraint** (distance between two UAVs d_{ij} should be within communication radius r):

$$d_{ij} \leq r \tag{2.5}$$

3. **Collision avoidance constraint** (distance between two UAVs d_{ij} should be at least a safe distance d_{safe}):

$$d_{ij} \geq d_{safe} \tag{2.6}$$

Final Fitness Function

Combining the objectives and penalties for constraint violations:

$$Fitness = w_1 \cdot J_1 + w_2 \cdot J_2 - Penalty \tag{2.7}$$

Where the $Penalty$ is calculated based on any violation of the communication or collision avoidance constraints.

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