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Optimized 2D ground area coverage through unmanned aerial vehicle using metaheuristic approach

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Abstract

2D ground area coverage is essential for various applications like rescue operation, ground target detection, agricultural inspection, etc. In order to successfully implement the above-mentioned applications, researchers have used unmanned aerial vehicles (UAVs) for the ground area coverage. UAVs equipped with visual sensors are extensively used in various coverage applications. The performance of the coverage applications is dependent on maximum target area inspection, which leads to an optimization problem. For any optimization problem, researchers have used various metaheuristic approaches. For the proposed work, authors have considered the maximization of a 2D target area coverage using a single UAV system through the optimization approaches as Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Cuckoo Optimization Algorithm (COA). The effectiveness of the proposed work is measured by the proportion of both interior and exterior space that is covered.

Subject Classification: *68M18.*

Keywords: *Area partitioning, Ground-area coverage, Metaheuristic approach, UAV.*

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1. Introduction

Due to the necessity of accessing humanly inaccessible areas as well as technological advancements in the fields of electronics and robotics, an unmanned aerial vehicle (UAV) has been developed. This vehicle can either operate on its own or be controlled remotely, and it does not have an on-board pilot. The advancement in technology makes the UAV more usable by improving their flexibility in terms of autonomy and agility, reducing the cost and size, having more carrying capability of mission-specific payloads, etc. The upgraded quality of UAVs makes them more suitable for the accomplishment of various applications such as ground target detection, agricultural inspection, traffic monitoring and management, package delivery, forest fire detection, etc [1]. A group of UAVs forms a multi-UAV network to collaboratively achieve the required result of an operation successfully. If the communication between the UAVs does not take place through an infrastructure but over wireless communication connections, then the multi-UAV network is referred to as a flying ad hoc network, or FANET for short [2].The mobile ad hoc network and the vehicle network are not the only types of ad hoc networks; there is also a form of ad hoc network known as FANET, which possesses properties that are distinct from those of mobile ad hoc networks and vehicular networks [3, 4, 5].

- Mobility of nodes is low in case of MANETs and high in case of VANETs and FANETs.
- Mobility model is random and restricted in case of MANETs, VANETs, and FANETs respectively.
- Due to the great mobility of UAVs, etc., link connection regularly varies in VANETS and FANETs, but it only occurs rarely in MANETs.

Recently, FANETs realise a huge research interest in both civil and military domains. Data acquisition is a primary part of various key applications, and to achieve that, an efficient way of area coverage is required. Thus, the proposed work focuses on optimizing ground area coverage by a single UAV system. It can also be applied for a multi-UAV system that aims to accomplish a specific application. The following list provides an explanation of the proposed methodology's objectives:

1) To develop an approach that would maximise the coverage of the bottom surface by a single UAV system.
2) To determine the performance improvement of the suggested approach as a result of the percentages of outside and actual area covered.

The following outline provides an overview of the paper's structure. In the Section 2, a variety of works connected to the procedure of area coverage are discussed. In Sections 3 and 4, respectively, an explanation is given of the work that is going to be presented and of the simulation result analysis. A summary of the findings as well as an outlook for the future is presented in Section 5.

2. Literature Survey

The coverage of the complete target area is a crucial component in a wide variety of applications, including ground area mapping, various monitoring applications, ground target detection, rescue operations, and many more. Thus, for the required area coverage, an efficient mobility model is needed for a UAV. In literature, various area decomposition techniques are used to find a mobility pattern for the movement of a UAV/robot. Coverage path planning (CPP), which encompasses all target area locations, is one of the most prevalent route planning techniques [6]. Most CPP techniques begin with decomposing the target region into many sub-regions. The coverage algorithm is divided into the following categories according to the type of decomposition used. Exact cellular decomposition breaks the target region into a number of distinct sections that do not overlap with one another, as described in [7]. The critical points of Morse functions are utilised in the process of Morse-based cellular decomposition, which results in the formation of sub-cells [8]. Cells are broken down using the natural landmarks in the method known as land mark based topological coverage, which is referenced in [9]. The environment is converted into either a dynamic or static graph via the Graph-based technique, which is then used to design a path for coverage [10]. The grid-based strategy involves dividing the region of interest into a number of grid cells that are all the same size [11]. This grid method has been the basis for a fair amount of coverage area research. The exponential increase in memory use is a key shortcoming of this approach. When performing aerial coverage, the UAV performs top-level decomposition to investigate the ground area from above [12, 13].

For this kind of inspection, visual sensors are typically utilized. Several research studies in the literature have combined camera footprint with aerial segmentation [14, 15]. In these works, the position and orientation of the camera footprint have been coupled with the aerial deconstruction. In contrast to the grid-based method, the rotation of the unmanned aerial vehicle (UAV) is taken into consideration in these studies. For the purpose of coverage in [15], a camera with three degrees of freedom (DoF) was taken into consideration, and an objective function was developed to help maximize the effectiveness of the aerial decomposition process. The only thing that the goal function is concerned with is maximizing the coverage of the inner target region. Hence, the suggested work develops an objective function that prioritizes both the maximizing and the minimizing of the interior and exterior target area coverage, to enhance the performance of coverage in terms of the actual target area coverage. Three metaheuristic approaches, including Particle Swarm Optimization (PSO), Genetic Algorithm (GA), and Cuckoo Optimization Algorithm (COA), are used to evaluate the proposed optimization process. The next part provides a comprehensive illustration of the working procedure of coverage utilizing the proposed way of decomposition.

3. Proposed work

A proper inspection of a ground area of interest (G_{intrst}) is an important task for the successful execution of various applications. A suitable mobility pattern of a UAV is totally responsible for its efficient coverage of G_{intrst}. To find an optimal mobility pattern, the proposed work performs an aerial decomposition of the corresponding G_{intrst} by incorporating the position and orientation of the footprints of the camera that is equipped in a UAV. In this work, UAV uses the three degrees of freedom (DoF) camera for area coverage purposes.

The G_{intrst} is partitioned into several camera footprints ($C_{ft\text{-}prnt}$) of rectangular shapes. A set of waypoints for the UAV is formed by considering the midpoint of each $C_{ft\text{-}prnt}$ as a waypoint. To cover the entire G_{intrst}, UAV needs to travel through all the generated waypoints. Figure 1 illustrates a scenario of the aerial decomposition of a G_{intrst}, $A'B'C'D'E'$ into ten rectangles of similar size with the footprints of the camera. A set of waypoints {W_1, W_2... W_{10}} is found to cover the entire $A'B'C'D'E'$ ground area.

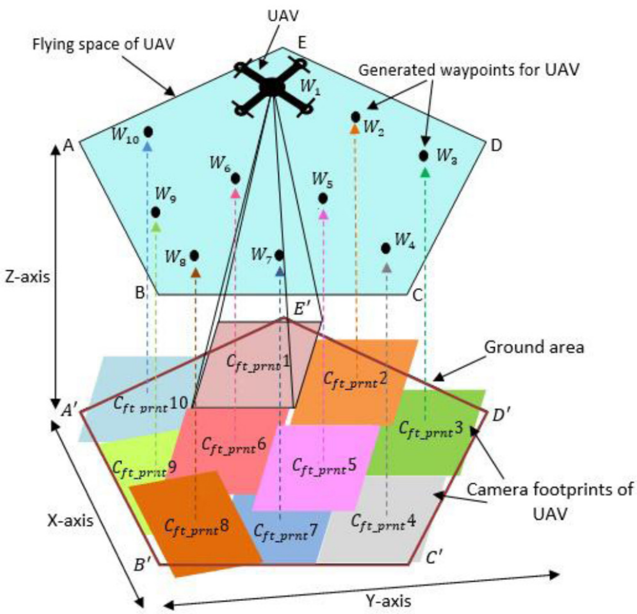

Figure 1

Aerial decomposition to generate a set of waypoints for the movement of UAV

The suggested approach of aerial decomposition makes use of optimization techniques to ensure that producing a near-optimal collection of waypoints in a feasible amount of time. A multi-objective function is designed by focusing on the maximal inside area inspection by minimizing the coverage of the exterior regions of G_{intrst} by a UAV. Thus, the objective function aims to increase the coverage of the actual area as well as to reduce unwanted information processing. Equation 1 represents the mathematical expression of the proposed objective function, where the midpoints, orientations, and number of rectangles/camera footprints are given as the inputs to perform the optimized decomposition.

$$Minimize_{C,O,N}\left| \underbrace{A(G_{intrst}) - A(Comb(C_i, O_i, N) \cap G_{intrst}}_{1^{st}\ Segment} + \underbrace{(A(Comb(C_i, O_i, N)) - A(Comb\ (C_i, O_i, N) \cap G_{intrst}))}_{2^{nd}\ Segment} \right| \quad (1)$$

The parameters which are used in the above optimization function defined below:

$A(G_{intrst})$ = Area of the ground area of interest, N = Number of $(C_{ft\text{-}prnt})$s, initially the value of N is considered as $\left\lceil \frac{A(G_{intrst})}{A(C_{ft-prnt})} \right\rceil$ and then, in the second step of optimising, the value of N can be upgraded based on the area of G_{intrst} is not covered.

C_i is the mid-point of $C_{ft\text{-}prnt\ i}$

$$C_i(X,Y) = \begin{cases} X_{lowr} \leq X \leq X_{upr} \\ Y_{lowr} \leq Y \leq Y_{upr} \end{cases}$$

O_i = The orientation of $C_{ft\text{-}prnt\ i}$ and $0 \leq O_i \leq 2\pi$.

$A(Comb(C_i, O_i, N))$ = Area of the union of the all $C_{ft\text{-}prnt}$s,

Where, $Comb(C_i, O_i, N) = \cup_{i=1}^{N} C_{ft-prnti}\ (C_i, O_i)$.

This objective function is broken up into two parts, the first of which strives to maximize the amount of space covered on the inside, while the second seeks to limit the amount of space covered on the outside of the target. Figure 2 depicts an example scenario, where the inside and outside gray portions of ABCDE G_{intrst} is maximized and minimized by using the first and second segments of the used objective function, respectively.

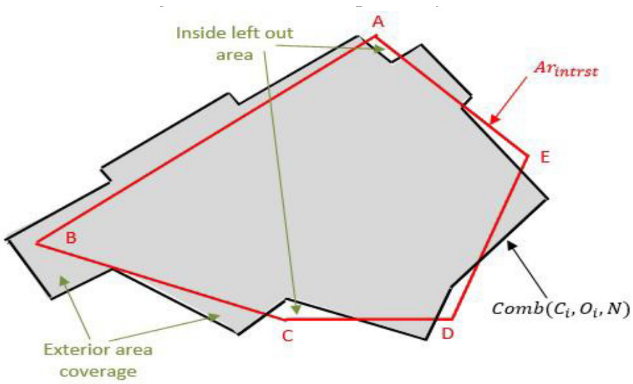

Figure 2

Region covered by the proposed optimization method

This optimization procedure employs PSO, GA, COA, and compares their respective outcomes.

4. Simulation result analysis

The implementation for the area coverage is carried out by decomposing the G_{intrst} into numerous rectangular forms of camera footprints. This allows for the coverage of the whole area. The PSO, GA, and COA metaheuristic approaches are used to get the outcome of the optimization process for the decomposition of a G_{intrst}. These methods are used to find the optimal solution. For the purpose of conducting the analysis described below, three distinct configurations of the ground area of interest, namely a rectangle, a convex polygon, and a concave polygon, are taken into consideration.

Type 1: A rectangular form with an area of 240000 m^2 is taken into consideration. The coordinates [(100, 100), (900, 100), (900, 400), (100, 400)] make up the set of vertices for this rectangle. The camera footprint of a UAV is 80 metres wide and 70 metres long. The size of the camera footprints is presumed to be the same for each of the three distinct varieties of G_{intrst}. Figure 3 presents a chart that illustrates a comparison of the cost values that were determined by PSO, GA, and COA.

Type 2: For this category, a convex polygon shape with an area of 330000 m^2 is taken into consideration. This polygon has the following set of vertices: [(0, 200), (400, 0), (600, 0), (800, 500), (400, 700)]. Figure 4 presents a chart that illustrates a comparison of the convergence of cost values while utilizing PSO, GA, and COA.

Type 3: For this particular category, a concave polygon with an area of 368000m^2 is taken into consideration. The collection of vertices that make up this polygon is represented by the notation [(0, 50), (700, 50), (600, 400), (720, 600), (100,700)]. The results of a comparison of the cost values determined by PSO, GA, and COA are depicted in Figure 5.

Table 1 shows a comparison between the percentage of the UAV's total coverage area that fell inside the initial interested ground region and the percentage of the UAV's total coverage area that fell outside the target area. Each of the aforementioned three geographical areas is taken into account in this analysis.

Table 1

Comparison of the result by PSO, GA, and COA

Proposed objective function	Type 1		Type 2		Type 3	
	Inside	Outside	Inside	Outside	Inside	Outside
PSO	99.9%	0.8%	97.5%	1.9%	97.8%	2.3%
GA	99.9%	0.9%	98%	2.1%	97.5 %	2.4 %
COA	99.7%	0.85%	97.2%	1.4%	97.5%	2.3%

The proposed optimization approach's average inside and outside coverage is compared to that of the method developed by Monsouri et. al. [15]. In this analysis, we focus on the first three of these G_{intrst} variants.

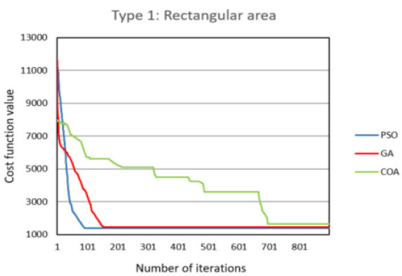

Figure 3

Cost function value vs. number of cover a rectangular area

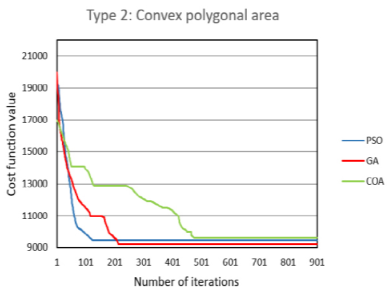

Figure 4

Cost function value vs. number of iterations to area iterations to cover a convex polygonal area

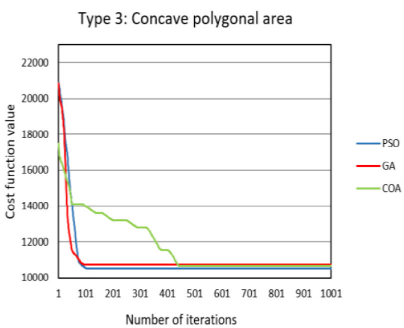

Figure 5

Cost function value vs. number of iteration to cover a concave polygonal area

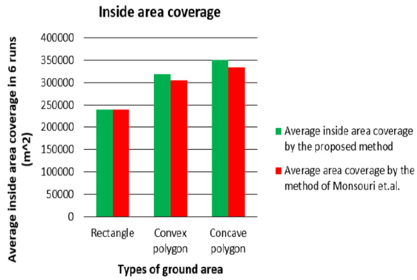

Figure 6

A comparison of the average inside area coverage

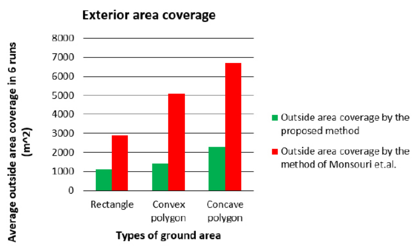

Figure 7

A comparison of the average exterior area coverage

COA employs both techniques for decomposing G_{intrst}. The average inside and outside coverage in six iterations are shown in Figure 6 and Figure 7, respectively.

The enhanced findings based on the aforementioned G_{intrst} types are shown in Table 2.

Table 2

The percentage of an overall improvement in the outcome of area coverage

Percentage of improvement	Inside G_{intrst} coverage	Exterior G_{intrst} coverage
	4.5%	65.66%

5. Simulation result analysis

An efficient way of area coverage is an important element in achieving many UAV-based applications. To find a near-optimal set of waypoints within real-time, the proposed work performs an aerial decomposition using the optimization process. Both interior and exterior coverage of a ground area are prioritized in the designed objective function. The findings of the comparison demonstrate that the proposed way of coverage is superior to the existing approach, with an improvement of 65.66 % for outside coverage and 4.5 % for interior coverage correspondingly. In future, the authors would try for real life implementations of the drone for various applications depending on area coverage.

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