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A New Static Path Planning Strategy for Drones

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Abstract

Unmanned Aerial Vehicles (UAVs) have been progressively used in environmental monitoring and disaster sensing. The drone flight over a set of waypoints on the area in order to achieve their surveillance task. Despite their potential advantages, UAVs have several drawbacks, including a limited energy supply and a short operational duration which made all attempts at planning ineffective. In this paper, we propose a novel UAV path planning for the monitoring task that reduces considerably the energy consumption and minimizes the number of turns. In addition, the proposed path gives the whole area the same level of importance. The proposed path was compared with four static paths: back and forth, spiral, LMAT, and Zamboni. Results show that the proposed path allows a better coverage with less energy consumption compared with the state-of-the-art methods.

Keywords: Unmanned Aerial Vehicles (UAVs), Energy consumption, Completion time, Path planning.

1 Introduction

Drones, also known as mini-unmanned aerial vehicles (UAVs), are aircraft without a pilot on board. They have an autopilot that allows them to execute commands sent from a ground station. They have varying degrees of autonomy depending on the supervision of the pilot on the ground. Drones were used first in the military domain to carry out dangerous missions for a pilot on board (Bomb detection, surveillance at the border, etc.). Their adaptation in the civil applications sector is recent and takes the form of surveillance[1], shooting missions [2], disaster management [3, 4], search and rescue (SAR) operations [5], Data collection [6], smart agriculture [7, 8], power line inspection [9], and many more.

The reconnaissance mission, which involves searching for a target in an open region, is one of the most significant drone operations. The exploring methods with drones are classified into two categories, namely: the random mobility method and the path planning method [10]. The random mobility method has no pre-planned paths for drone movements. This method can overcome unexpected events, such as drone failure, and also provides unpredictability of reconnaissance to targets. On the other hand, in the path planning method, each drone takes its own pre-planned path so that the drones can recognize their own determined regions. In this work, we focus on the path planning method to improve the reconnaissance performance. In certain applications of reconnaissance, a UAV must be able to compute a route between two pre-determined locations while avoiding different obstacles or producing a path that completely covers every location in an area of interest, a process known as coverage path planning (CPP). CPP is categorized as a subtopic of route planning in robotics, where it is necessary to obtain a path that guarantees complete coverage with minimum overlapping[11]. The energy restrictions and flight limitations of drones have piqued the interest of researchers because they have a direct effect on the success of Coverage Path Planning missions [12].

The efficacy of a CPP is primarily determined by success indices such as path length [13, 14], mission completion time [15], and the number of turns. These metrics are linked to energy consumption[16, 17], and the majority of techniques attempt to minimize them in order to conserve energy. In [18], the authors used these metrics to find the optimal path. These metrics were compared and studied in[19]. Based on studies of drones, a path with fewer turns is more efficient in terms of path length, execution time, and power consumption. Reducing the number of turns leads to a more minor delay in completion time, and thus to a shorter path. Hence, it results in lower energy consumption. This work proposes a new flight path that guarantees maximum coverage of the surveillance zone with the minimum cost in terms of flight time and consumed energy. The remainder of this paper is organized as follows. Section 2 summarizes related works. Section 3 provides a detailed description of the proposed system, while Section 4 presents the experimental results. Finally, Section 5 concludes the paper.

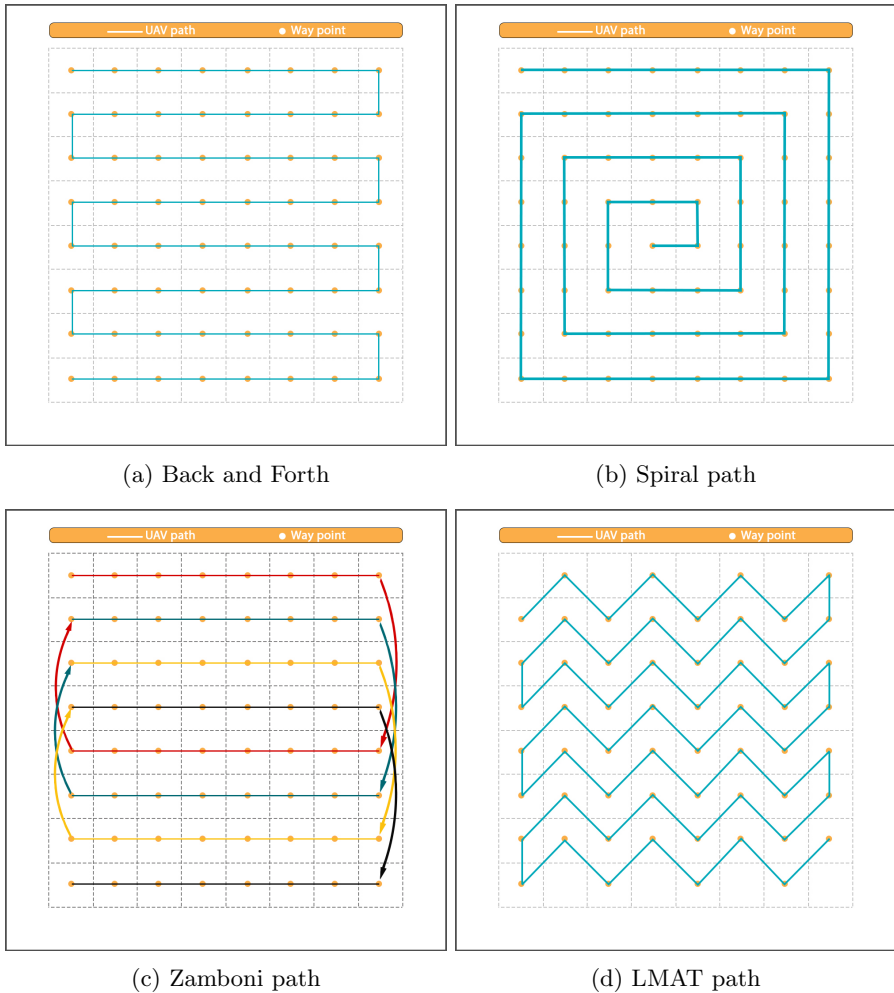


Fig. 1: Basic CPP paths: (a) Back and Forth ; (b) Spiral ; (c) Zamboni; (d) LMAT

2 Related work

Recently, Coverage path planning for drones has received a lot of attention. The majority of drones conduct reconnaissance missions based on CPP using basic geometric flight models [20]. Several authors have discussed the issue of CPP with UAVs in the literature. Cabreira et al.[21] recently published an extensive survey of CPP algorithms and their performances, including back-and-forth motion, spiral, sector scan, barrier patrol, energy-aware spiral, Hilbert curves, gradient-based, wavefront algorithm, harmony search, etc. The authors used Choset's [22] classic taxonomy to categorize current approaches based on the

adopted cellular decomposition technique. Work done in [23] summarizes some geometric patterns for path planning, including spiral/spiral-like, Lawnmower model, Zamboni, Du-bins path, and a modified Lawnmower/Zamboni path planning strategy to take into account different missions features.

For missions in rectangular environments, the back-and-forth (BF) model, also known as the lawnmower model in the literature, is the most commonly seen in real-world scenarios. As presented in [20], where the author analyses five types of flight patterns from the US National Search and Rescue Manual are studied, including two versions of back-and-forth, spiral, sector search, and barrier patrol. Authors in [24, 25] used a grid-based technique to segment the environment into square cells. Each square contains occupancy information for the region of the environment that it covers. The cells are usually explored using a single drone with back-and-forth movements [20, 26]. The authors in [27] used a single UAV to cover an area of interest without obstacles and non-flying zones. The proposed algorithm works in an offline mode and employs a grid-based approach with approximate cellular decomposition. Some works [15, 23, 28, 29] used multiple UAVs and back-and-forth movements to cover the area in offline mode with fewer turning. In [30], the authors proposed a path planning algorithm-based spiral decomposition called Spiral Path Planning (SPP) using a single drone. They plan to cover an area in offline mode in less time and to complete the mission with shorter distances.

Artemenko et al. [13] found that turning a drone consumes a significant amount of time and energy because the drone must decelerate, rotate, and accelerate each time it performs a turn. Thus, using the principle of Bézier curves, the algorithms smooth maneuvers along a given path to adjust conventional trajectories such as back-and-forth, HILBERT, and LMAT (Localization algorithm with a Mobile Anchor node based on Trilateration). Di Franco et al. [31] presented an energy-aware coverage path planning solution for a single multi-rotor. They derive energy models from real measurements to model the energy consumption as a function of the UAV dynamic in different conditions. However, they only consider distance and ignore the impact of turns in their formulation. Torres et al. [16] presented a coverage path planning strategy for 3D terrain reconstruction with a single UAV. They divided the region into one or more polygons and used a raster scan to cover each polygon. They calculated the ideal line sweep direction in order to reduce the number of rotations.

While most of the previous work attempts only to generate paths with minimum distance; this paper proposes a new path that can reduce the energy consumption, minimize the number of turns and avoid a larger rotation angle of the turn while ensuring maximum coverage of the surveillance area.

3 Proposed path planning

In this paper, we use the same assumptions found in the related work, namely: the use of a single drone for each path, an offline mode, an area without

obstacles, and non-flying zones. We observed over the studied state-of-the-art methods that a UAV spends a significant amount of time making turns, wasting a significant amount of energy; because a turn is generally defined as a series of three steps: deceleration, rotation, and acceleration.

To overcome the problems mentioned above, we propose a new flight path planning that has the potential to cover the target area with the shortest path while ensuring less computational time, fewer turns, and less energy consumption.

3.1 Area decomposition

After getting the geographical specification of the coverage area, it is transformed into a regular shape (square), The Area of interest is segmented through an approximate cellular decomposition. In this technique, the working area is divided into regular cells $C = \{c_1, c_2 \dots c_n\}$ in such way,

$$E = \bigcup_{c \in C} c \quad (1)$$

Note that the number of cells must be odd in each side ($3 \times 3, 5 \times 5, 7 \times 7, \dots$). One of the major benefits of using a grid-based decomposition technique is that the area of interest can be converted into a kind of unit distance graph, known as a grid graph $G_{(V,E)}$ (see Figure 2), where V denotes the vertices and E the edges of the cells. Each vertex represents the center of the cell, and each edge represents the path between two adjacent cells. The proposed path was designed to pass through the cells' centers represented by way-points.

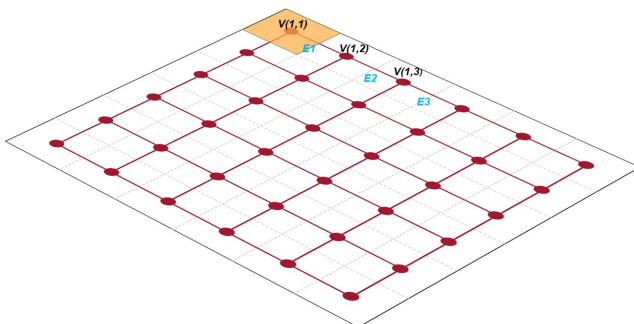


Fig. 2: Projected Area to Grid

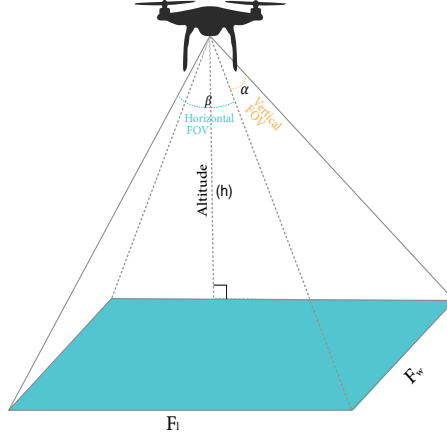


Fig. 3: UAV footprint representation

3.2 UAV footprint

The portion of the area captured by a drone's camera while it is flying at a height (h) is known as the UAV footprint, also known as the camera's field of view (FoV). As shown in Figure 4, the FoV of a camera is determined by (h) and the angle of view. The following equations can be used to calculate the dimension (F_w, F_l) of the projected area:

$$F_w = 2h \times \tan\left(\frac{\alpha}{2}\right) \quad (2)$$

$$F_l = 2h \times \tan\left(\frac{\beta}{2}\right) \quad (3)$$

Where F_w is the width of FoV , F_l is the length of FoV , (h) is the altitude of the UAV, α is the vertical degree of camera, and β is the horizontal degree of camera.

In this work, the footprint of the drone is assumed square in shape and extends below the drone. So the length F_l and the width F_w of FoV are equal ($F_w = F_l = C_i$). As a result, each grid cell represents the inscribed square in the estimated footprint of the drone.

3.3 Navigation strategy

The geographical area is divided into $(n \times n)$ sub-squares where $(n \bmod 2 = 1)$ as mentioned previously. Only one drone is used to cover the area. Note that the planning phase is executed offline, and the proposed path is loaded on the drone in the form of a waypoint list. The proposed path is based on a zigzag pattern, and the drone diagonally scans the deployment area. The drone moves in a straight line along with the centers of the sub-squares and takes a 'Z' trajectory according to the proposed model. More formally, the drone is

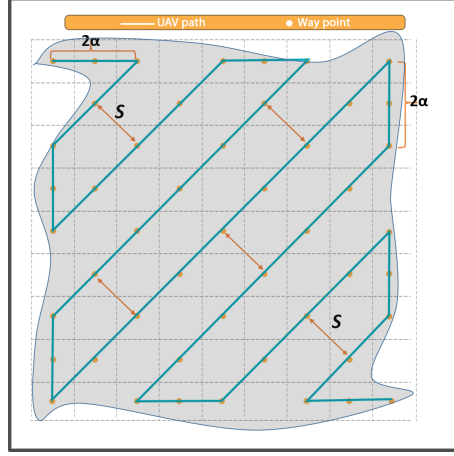


Fig. 4: The proposed path

guided by the waypoints to know which direction must be followed through the environment. Since the area is modeled as a square shape, the drone can start with the closest corner to the main station and then move horizontally with 2α where ($\alpha = c_i$) toward to $(V_{1,3})$. Upon reaching the vertex $(V_{1,3})$, the drone turns 135° (clockwise) and moves to the next cell until reaching the side boundary of the area. When the drone reaches the vertex $(V_{3,1})$, it turns 45° but this time in a counterclockwise direction and move with 2α toward the vertex $(V_{1,5})$. After, it turns 135° again and makes the return movement. After moving straight again and reaching the upper boundary of the area, a return action is executed in the same manner as the previous phases. The resolution, which is an important parameter, is represented as the distance of two diagonal lines. The resolution of the proposed trajectory is denoted as $s = \alpha\sqrt{2}$. The movement of the drone is illustrated in Figure 4.

4 Evaluation Metrics

Measuring the quality of the results requires to pass the system through a well known metrics. Four metrics were used to compare the proposed path's improvements: Time needed for the Mission, path lengths, the number of turns, and energy consumption.

4.1 The time needed for the mission

For evaluating mission performance, optimizing the trajectory duration and mission completion time are critical metrics for UAVs [12, 13, 32].

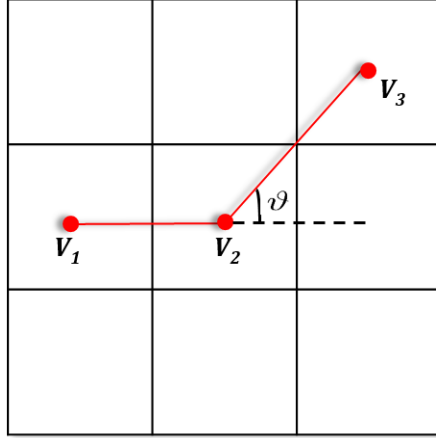


Fig. 5: The external angle for three vertices of the trajectory

To calculate the completion time denoted T , the equation from [24] were used:

$$T = \frac{S}{V} + \sum_{i=1}^k \frac{\vartheta}{\omega} \quad (4)$$

Where S for path length, V for UAV movement speed, k for the number of turns, ϑ is the angle of i^{th} turn and ω is the UAV rotation rate.

4.2 Turning Angle

The turn rate has a great impact on power consumption. One of the most important considerations is the number of turns required throughout the mission. The external angle between vertices V_1 , V_2 , and V_3 at point V_2 is the turn angle (Figure 5). It can be calculated from the internal angle $\widehat{V_1V_2V_3}$ as follows:

$$\vartheta = \pi - \cos^{-1}(\widehat{V_1V_2V_3}) \quad (5)$$

Where \cos^{-1} is calculated by using the law of cosines in the triangle $V_1V_2V_3$.

$$\vartheta = \pi - \cos^{-1} \left[\frac{(d(V_1, V_2))^2 + (d(V_2, V_3))^2 - (d(V_3, V_1))^2}{2d(V_1, V_2)d(V_2, V_3)} \right] \quad (6)$$

4.3 Energy Consumption

To evaluate the proposed path, we used the following energy model:

$$E_{Total} = E_t + E_{Turn} \quad (7)$$

Let E_t and E_{Turn} , the energy consumed to travel the total distance and the energy consumed to perform the turns, respectively.

$$E_t = \lambda D_t \quad (8)$$

$$E_{Turn} = \gamma \frac{180}{\pi} \vartheta_t \quad (9)$$

where the energy consumption per unit length is denoted by λ , D_t represents the total distance traveled and ϑ_t represents the sum of turning angles. In this study, λ and γ are set to 0.1164 KJ/m and 0.0173 KJ/degree, respectively.

The total consumed energy E_{Total} is the sum of two weighted components. The first component is proportional to the traveled distance, and the second is proportional to the sum of turning angles along the generated path.

5 Simulations and Results

The target of this section is to perform various simulations to show the advantages of the proposed solution for the CPP problem with a single drone. The simulation results were performed using Mission Planner version 1.3.74 on a computer running Windows 10 with a 2.9 GHz Intel Core i7 CPU and 16 GB of RAM.

Mission Planner Simulator (MP) [33] is an open-source tool developed by Michael Osborne for the open-source APM autopilot project and supported only by Windows operating system. MP has a graphical user interface that shows information about the UAV, such as GPS status, battery life, airspeed, and video, etc. It also offers the possibility to download and check the mission's log files.

To show the effectiveness of the proposed path compared with the other state-of-the-art methods, four well-known paths, namely: (a) Back and forth, (b) Spiral, (d) Zamboni, and (c) LMAT, were implemented with the same simulator and the same area.

To be able to compare the different approaches in all of the scenarios fairly, we assume that:

- The UAVs are homogeneous.
- The UAVs travel with constant velocity (UAV speed = 5 meters/sec).
- UAV rotation rate $\theta = 30degree/sec$.
- The distance between two waypoints is 20 meters.

The working area chosen to put the proposed model in practice is near 8 May 1945 University, which is located in Guelma, Algeria. The area of interest is a square with the dimensions of $180 \times 180 m^2$. The initial map of the area is obtained from a satellite image as shown in Figure 6.

To show the behavior of the chosen paths in different area sizes, the simulation was performed with three areas segmented to 5×5 , 9×9 , and 15×15 , respectively. The comparison of the efficiency of each path is based on the time



Fig. 6: Workplace

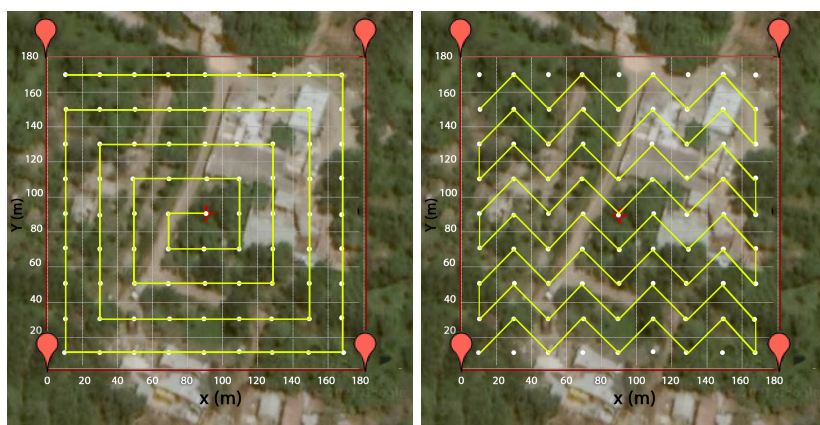
taken by the drone to complete the mission and the total amount of consumed energy. Figure 7 illustrates the area shown in Figure 6 (red), the performed paths during the simulations for each strategy (yellow). Figure 8 shows the calculation time for all tested paths in the three areas, while Figure 9 shows the corresponding energy consumption.

Table I summarizes the obtained results of the selected pathways (number of turns, total degree of turns, path length, time computation, and energy consumption).



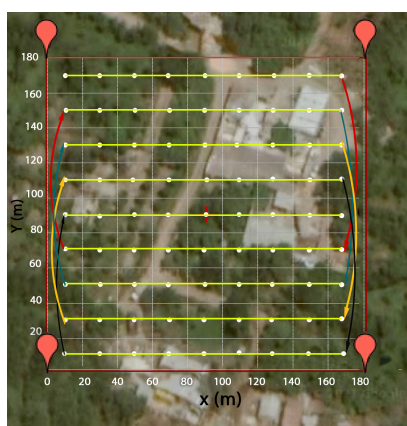
(a) Proposed Path

(b) Back and Forth Path



(c) Spiral Path

(d) LMAT path



(e) Zamboni Path

Fig. 7: Five simulated paths in the same selected area

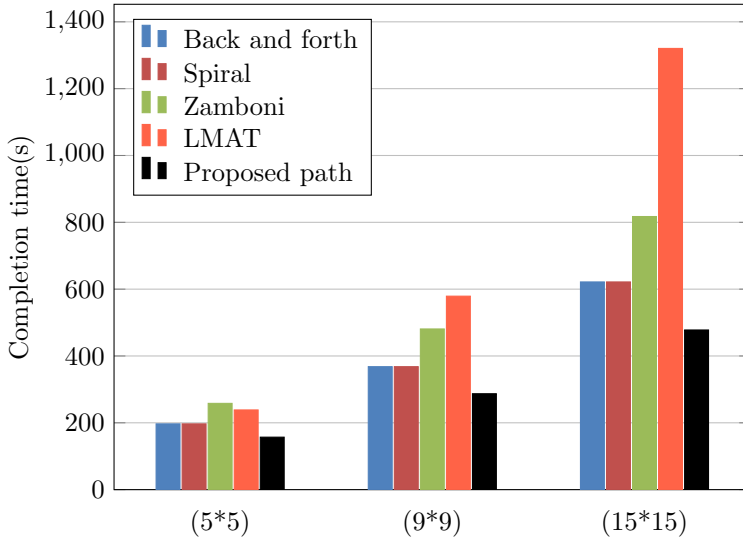


Fig. 8: Completion Time comparison of paths with 5x5, 9x9, and 15x15 Grids

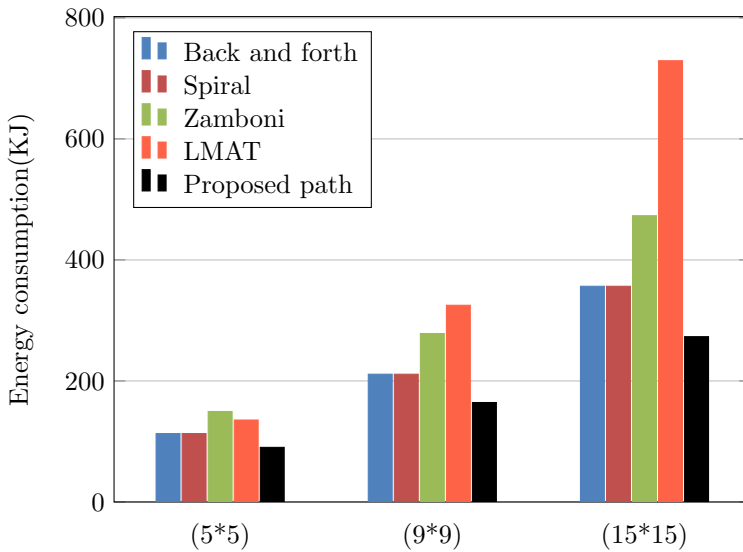


Fig. 9: Performance comparison of paths with 5x5, 9x9, and 15x15 Grids

Paths	(1) Back Forth Path	(2) and Spiral Path	(3) Zamboni Path	(4) Lmat Path	(5) Proposed Path
Area 1 (5*5)					
Number of Turns	8	8	4	18	6
Total degree of turns (°)	720	720	355.96	1620	540
Path length (m)	864	864	835	922.59	695.29
Completion-time (s)	196.8	196.8	258.22	238.52	157.058
Energy consumption (KJ)	113.0256	113.0256	149.54	135.42	90.27
Area 2 (9*9)					
Number of Turns	16	16	8	70	14
Total degree of turns (°)	1440	1440	699.68	5670	1260
Path length (m)	1600	1600	2287.8	1950.18	1225.09
Completion-time (s)	368	368	480.88	579.04	287.02
Energy consumption (KJ)	211.15	211.15	278.40	325.1	164.4
Area 3 (15*15)					
Number of Turns (KJ)	28	28	14	208	26
Total degree of turns (°)	2520	2520	1231.58	18720	2340
Path length (m)	2688	2688	3881.15	3482.23	1999.1
Completion-time (s)	621.6	621.6	817.36	1320.45	447.2
Energy consumption (KJ)	356.48	356.48	473.07	729.19	273.18

Table 1: Comparison of the obtained results.

As it can be seen in Table I, the proposed path significantly reduces the time needed to complete the mission, achieving an improvement that varies from 22% to 50.4% compared to the other models. In addition, it is shorter than the existing paths with 23.43% to 46.45% less distance. In terms of the number of turns, the proposed model managed to eliminate more than 12.5% of unnecessary turns compared with other paths which mean less energy consumption. Indeed, from "the energy consumption" point of view, the four tested paths consume more energy than the proposed path, with energy loss varying from 22.14% to 50.43%. This is essentially due to the overlap problem created by the repetitive passage of the drone on the same surface. Based on the results obtained, one can say that the proposed model surpassed all the tested paths in terms of energy consumption, mission completion time, and traveled distance. These results demonstrate the effectiveness of the proposed path compared with state-of-the-art methods.

6 Conclusion

In this paper, we presented a new static path, for reconnaissance with a single drone. The proposed model divides the area of interest into cells using a grid-based technique. The main goals of the proposed path are to cover an area in offline mode, decrease the computational time, reduce the path length and the number of turns, and minimize the energy consumption during the missions. The results show that the proposed trajectory provides better performance compared to other existing paths. As future work, we intend to study the coverage path planning in the presence of obstacles and no-flying zones in the Area of Interest.

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