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Research Article

Choosing Between Coverage Vs. Path Efficiency for Unmanned Aerial Systems: A Case Study Utilizing Hector Quadrotor UAV In ROS

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ABSTRACT

Efficient strategies for achieving comprehensive area coverage are imperative in the context of search and exploration missions carried out by patrolling UAVs. Diverse methodologies pertaining to coverage path planning were meticulously examined and assessed within the ROS-Gazebo simulation environment, utilizing the Hector quadrotor model. While the concept of opting for an optimal coverage-oriented path is captivating, it necessitates a trade-off, as it often demands a higher frequency of maneuvers to effectively encompass the designated region. Furthermore, the typical oversight of the robots' hardware limitations is prevalent. This study undertook an analysis of the interplay between coverage area and coverage path, employing techniques such as raster-scan exploration, expanding spiral searches, and zigzag pattern coverage, all aimed at enhancing the selection of the most appropriate path. Furthermore, this research delved into investigating the implications arising from the hardware limitations intrinsic to the Hector quadrotor UAV when simulated within the ROS environment. The assessment metrics encompassed variables including the proportion of the area covered, the count of executed turns, and the time taken by the UAV to complete the maneuvers. The outcomes strongly advocate for the inclusion of hardware limitations in both path planning and path structure considerations in order to attain optimal outcomes.

1. Introduction

To keep up with the development of technologies in this modernization era, usage of UAVs has been increasing rapidly in many applications over time. However, existing surveys state that the critical issues related to UAVs such as control, perception, and guiding has been major problem for UAVs to do a certain task that will reduce the inefficiency of the UAV. This issue has been a concern that must be tackled by any method. A few studies have looked at the Coverage Path Planning (CPP) issue, however they only look at ground vehicles and mention UAVs or drones as an extension of aircraft. Although land exploration techniques revised in previous surveys can be extended and applied to drones, there are several other factors that to be considered when dealing with aerial vehicles, including the vehicle's physical characteristics, endurance, maneuverability limitations, restricted payload, and external environmental conditions, among others [1]. On-board cameras and sensors may add weight to the vehicle and lower its endurance, which is already restricted in multi-rotors. Even with more modern versions produced in 2018, the endurance of such aircraft is about 20–25 minutes (Wilson, 2021). Furthermore, in outdoor missions,

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turning maneuvers [2] and wind fields [3] enhance energy usage.

The problem of Coverage Path Planning (CPP) means to find a route that passes through all the points of interest in a certain region. Most of the time, CPP problem is considered in isolation, meaning, the nature of vehicle or robot is not considered as an influential factor that may influence the ideal path. Several coverage area methods considered ground vehicles as primary mobile units while Unmanned Aerial Vehicles (UAVs) were considered as an extension [1]. Nevertheless, there is a crucial perspective to this problem: the design, structure, and certain components of a UAV's subsystems, influence their maneuverability and moveability. Consequently, the coverage paths generated from the coverage model, at times, remains inefficient despite covering the required area.

One of the fundamental differences for a path required for area coverage arrives from the type of UAVs; rotor-based and fixed wing UAVs. In terms of maneuverability, rotor-based UAVs have a natural advantage because the motor-mixing algorithms can generate any direction through certain combinations of the speeds of all motors. On the other hand, fixed wing UAVs are more energy efficient as they glide through the air, hence, possess an edge by covering more area, however, these types of aerial vehicles need to follow a curved-like path, requiring a minimum turning radius, [4], which naturally restricts quick maneuvers like sharp turns and so on. The type-selection of UAV is based on the nature of the missions to be carried out and a trade-off exists between the two.

For this particular work, a quadrotor UAV is required to patrol for the detection of a heavier gas, therefore, optimizing the coverage path for better coverage and optimal number of maneuvers was required. It is assumed to be understandable that having a higher number of maneuvers, leads to a lesser energy-efficient flight, which directly affects the coverage. Therefore, this work evaluates the flight paths through the extent of area that is covered, the time taken to cover and the number of maneuvers taken by the quadrotor.

2. Literature Review

The literature review primarily focuses on the most recent studies where the challenges and ideas, pertaining to the practical constraints, addressed or discussed.

One of the most overlooked aspects in coverage path planning is that there is no differentiation between speed of UAV in a straight direction and taking turns. The costs of turning, acceleration and deceleration are not considered. This was addressed by introducing and energy-constrained and time efficient path planning technique [5]. The paths are usually generated through an algorithm by introducing some areas of interest in the coverage area. A notable work from literature proposed to assign costs in terms of time and energy to all the possible maneuvers of a UAV. These include, take-off, landing, turning, hovering and cruise [6]. It is a great idea to consider such parameters in path generation algorithms to optimize coverage path in an area.

A chunk of literature emphasized the need of pre-determined information from the area required to be covered. It can be in the form of region of interests, customized waypoints (keywords like mission points and checkpoints are also used by authors) [7].

One of the recent works, introduced the ideas of checkpoints in the area require to be covered and utilized improved genetic algorithm to generate 2D paths [8]. On the similar tracks, one of the works introduced mission-points in the coverage area and generating the path using greedy strategy and ant colony optimization [9], [10]. However, these works require pre-determined information to place the checkpoints which adds a limitation to these works.

Another noteworthy idea is to introduce the concept of Quality of Service (QOS) for path vs. area coverage as proposed by [11], however, the target application was to minimize data loss during UAV's communication.

It was inferred from the literature that the aspect of considering a hardware to analyze its impact on coverage path has not been conducted exclusively. Therefore, the need was felt to set up a simplistic scenario with an objective to assess the hardware specific impacts on the generated paths.

3. Problem Statement

This research focuses on addressing the challenge of coverage area for a UAV engaged in indoor searches for heavier gas emissions, such as butane, at a height of a few meters. Additionally, the UAV might be required to pinpoint a specific sub-region and navigate towards the emission source within it. Consequently, the UAV may frequently alternate between search and localization modes of operation. Given this context, even slight disparities between the ideal path derived from the Coverage Path Planning (CPP) model and the actual path followed by the UAV can yield significantly divergent outcomes.

Recognizing the necessity to understand these variations and to assess the influence of hardware limitations on the coverage path, an exploration was undertaken. To investigate this impact, it became crucial to employ a UAV with a practical simulation model that takes into account the constraints of its individual components or subsystems while adhering to a path generated by an algorithm. The 'Hector quadcopter UAV' emerged as a highly suitable option to fulfill these requirements. The Hector quadrotor UAV simulation project has been developed within the Robot Operating System (ROS)-Gazebo simulation framework.

One notable advantage of opting for ROS is its capacity to seamlessly transition the code from simulation to hardware execution. Moreover, the Hector quadcopter UAV emulates quadcopters that align well with open-source hardware and software technologies, making it particularly apt for academic research purposes. Notably, the project remains active and is made available under a Creative Commons license, allowing for modification and utilization [12].

4. Formulating a CPP problem

Multiple viable solutions can arise for a given Coverage Path Planning (CPP) problem, taking into account variables such as the configuration of the coverage area, the presence of obstacles within that area, and the proportion of the space requiring coverage. However, the constraints stemming from the UAV's sensors and physical structure, which affect its ability to maneuver and navigate, have often been disregarded. To begin our exploration, it is worthwhile to examine the process of formulating a coverage problem for a specified area.

4.1 The shape of coverage area

The predominant consideration revolves around the configuration of the coverage area, which may manifest as standardized shapes (such as squares, rectangles, or triangles) or intricate and asymmetrical forms. Given the scope of this study, the intricate implications of shape complexity are not within its purview. The primary objective is to analyze how the limitations inherent to a particular entity influence the path derived from a Coverage Path Planning (CPP) model. Consequently, for the purposes of this research, a 10x10 meter area with a square shape is chosen as the focal point.

4.2 Cell definition and area decomposition

After determining the configuration of the coverage area, an optional subsequent action is to partition the designated region into individual unit cells, although certain algorithms might not necessitate this step. These cells establish the granularity of the overall map, significantly influencing computational demands and the accuracy of data collected by the exploring vehicle. Opting for a smaller cell size entails that the vehicle only needs to traverse a cell once, which elongates the flight time required to cover the entire area. Conversely, when the cell size is larger, multiple exploration excursions within a single cell may become necessary [1]. Essentially, the size of a cell is contingent upon the UAV's capability, specifically its sensor subsystems, to survey a designated unit of area in a single instance.

4.3 Significance of the availability of information for coverage area

In cases where there exists pre-existing data pertinent to coverage, it has the potential to enhance the overall efficacy of the Coverage Path Planning (CPP) process. For instance, having information regarding the desired location during a search mission can prevent superfluous exploration. Furthermore, prior knowledge might propose intricate patterns that could assign higher importance to specific sub-areas. It is advisable to incorporate an endeavor to acquire such existing information as an integral aspect of the planning procedure.

4.4 Area of interest

Following that, the subsequent aspect to address involves the method of cell decomposition, with a key focus on the area within the coverage region that is most likely or preferred. For instance, regions situated closer to the coverage area's boundary might hold lesser significance compared to central regions, contingent upon the underlying objective. A strategy involving the placement of 'dot-points' throughout the coverage can effectively tackle this consideration. The distribution of these dot-points can be either uniform or uneven. Regions of greater interest can be distinguished by a denser concentration of dot-points.

4.5 *Performance Metrics*

Performance metrics entail quantifiable outcomes that arise when an activity is executed to achieve a specific objective. Several facets warrant consideration in the realm of performance metrics. These include factors such as the total distance traveled or route length [13], the time required for mission completion [14], the maximization of coverage area [15], and the count of turning maneuvers [16]. However, it's important to note that as the total area expands, the UAV's travel distance also increases, and conversely. Furthermore, the extent of the area of interest can impact the time taken by the UAV to successfully accomplish the coverage mission. Consequently, when faced with the constraints of drone technology, achieving area coverage maximization becomes challenging, especially when dealing with exceedingly large areas of interest. This scenario underscores the fundamental principle of measuring the percentage of area covered within a specific unit of time, all while taking into account the requirements of flight duration.

4.6 *Pattern identification / selection*

The conclusive phase of Coverage Path Planning (CPP) in this context involves the identification and choice of a pattern that encompasses the designated dot-points (areas of interest). The selection of this pattern hinges upon the specific distribution pattern of the dot-points. In numerous investigations, efforts are primarily directed at refining the distribution of dot-points (areas of interest), introducing innovations in constrained optimization (such as minimizing time or maximizing coverage), and similar approaches. However, in the context of this study, three valuable CPP patterns have been deliberately selected. This choice aligns with the research's objective, which is to scrutinize the influence of hardware limitations.

5. Simulation Setup

5.1 *ROS (Melodic)-Gazebo Framework*

Initially crafted for compatibility with the Ubuntu 18.04 (Bionic) version, ROS Melodic Morenia is nevertheless adaptable to various other Linux distributions, in addition to being functional on Mac OS X, Android, and Windows platforms [17]. In terms of simulation, Gazebo stands out as the premier choice, boasting superior precision and efficiency in replicating intricate scenarios involving robot ensembles within diverse indoor and outdoor environments. This simulator is bolstered by a robust physics engine and high-resolution visual capabilities [18].

5.1.1 HECTOR Quadrotor

Hector, an open-source ROS project, encompasses a collection of software designed by Meyer et al. [19] for the modeling, control, and simulation of quadrotor UAVs. These components are encapsulated within various packages, which facilitate the development of system design, operational aspects, simulation capabilities, and a Unified Robot Description Format (URDF) model. Moreover, there are diverse iterations of these packages available, featuring distinct sensor configurations.

5.1.2 UAV's Field of View (FOV)

The camera's Field of View (FOV) in Hector refers to the area encompassed when the UAV is airborne at a specific altitude, denoted as 'h'. The camera's dimensions can be derived using the equation presented in Eq. 1 and Eq. 2, and this relationship is visually depicted in Fig. 1:

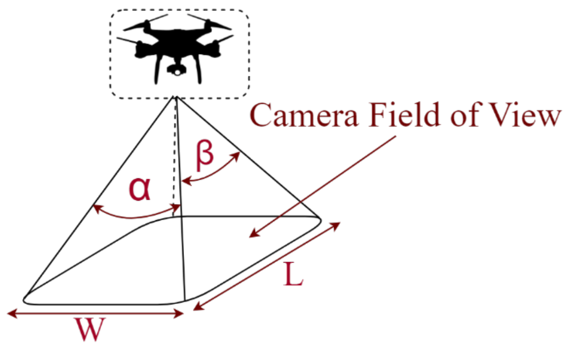

Fig. 1 Field of View (FOV)

$$W = 2h \times \tan(\frac{\alpha}{2}) \quad (1)$$

$$L = 2h \times \tan(\frac{\beta}{2}) \quad (2)$$

Where**:**

W = width of the FOV
L = length of FOV
h = height of altitude
α = camera vertical degree
β = camera horizontal degree

For this project, the UAV flies at a height of 1.2m, the value of α given is 45 degrees and β is also set to 45 degrees.

5.1.3 Hokuyo Laser Range Finder

The Hokuyo laser range finder is employed to identify nearby boundaries or obstacles in the vicinity of the UAV. This laser system encompasses an array of 1081 beam lights that span across the UAV's left, front, and right sides. The maximum distance at which the Hokuyo Laser Range Finder can detect an obstacle or boundary for the drone is configured at 2 meters. A visual representation of the range finder is provided in Fig. 2, alongside the algorithm's corresponding parameters.

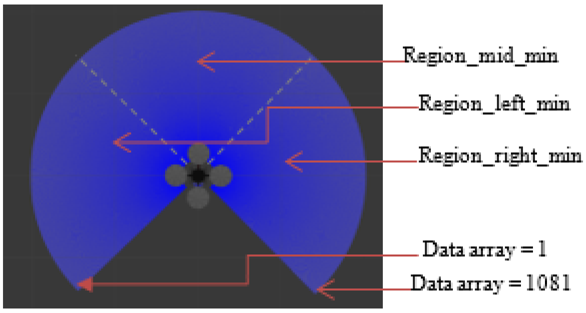

Fig. 2 Data variables through Hokuyo Laser Range Finder

6. CPP Models

6.1 Workspace Setup

The workspace is partitioned into individual one-by-one meter squares that are seamlessly aligned, forming what is referred to as a unit cell. Each segment of the cell is designated with a central point to indicate the region of interest, as outlined in this study. Additionally, upon the UAV's arrival at any point within a cell, that cell is considered effectively covered. The dimensions of the cells are determined by the camera's field of view during the mosaicking process. Consequently, a 2D grid graph is established, with cells demarcated by their centers, effectively creating a network of dots, as exemplified in Fig. 3.

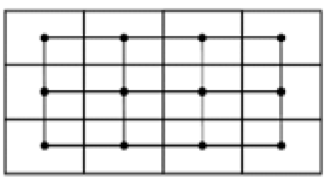

Fig. 3 Cellular decompositions of proposed workspace with equidistance dot-points

6.1.1 Patterns generation through Back-and-Forth Motions

Quadcopter UAVs possess a distinct advantage due to their capability to generate an extensive array of patterns by employing diverse motor combinations through motor mixing algorithms. These patterns can be executed by programming fundamental back-and-forth movements. It's noteworthy that every individual cell maintains interconnections with its eight neighboring cells, collectively referred to as the Moore neighborhood connectivity. This particular configuration has demonstrated its efficacy in the realm of coverage area planning involving UAVs [20]. Harnessing this potential, a myriad of patterns can be generated by adjusting the velocities of each motor, thereby enabling the UAV to execute rotations to specific yaw angle values, such as ±45, ±90, and ±135 degrees. The visual representation in Fig. 4 elucidates the generation of these patterns through the manipulation of motor velocities.

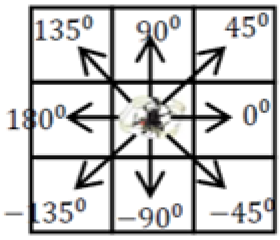

Fig. 4 Moore Neighborhood of quadcopter UAV

6.1.2 Raster-Scan Exploration

Considering this mechanism of pattern generation, the raster-scan search pattern stands out as a prominent and widely utilized technique in exploration missions. The algorithm detailing this pattern is visually represented in a flowchart presented in Fig. 5.

In Fig. 5 the parameters used in the flowchart have already been introduced in Fig. 2. These points are actually the data points generated from Hokuyo Laser Range Finder attached with the Hector quadrotor UAV. There are 1081 data points of the laser range finder which are divided into three regions: region_left, region_right and region_mid. All these values are initialized as 2, just greater than the starting value of the range finder.

There are only 3 maneuvers in this method of area coverage. For the raster scan, the Hector Quadrotor UAV is required to follow a straight path, mentioned ‘move-forth’, and take turns when it reaches the ending value of any region, either right or left, as in Fig. 5. After taking a turn, the UAV gets back into the move-forth loop, depicted as self.loop till it reaches again the edge of the region following the conditions on the data points.

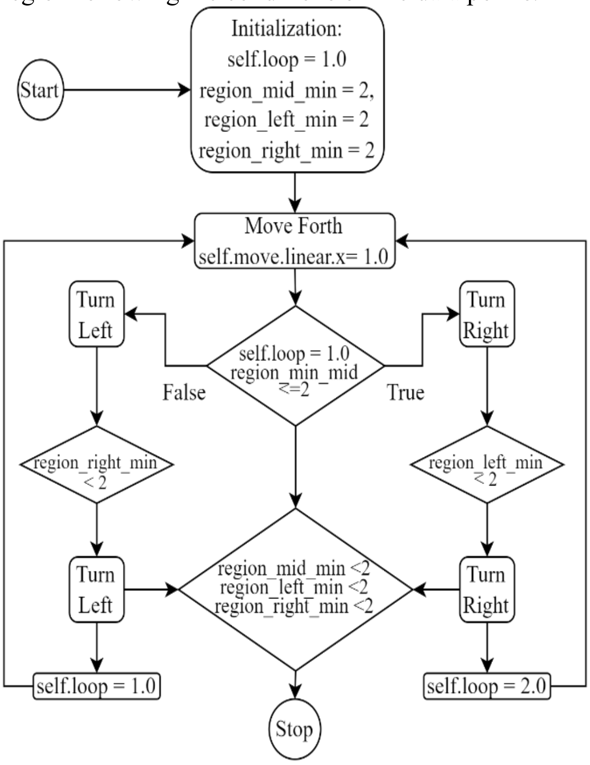

Fig. 5 Flowchart depicting Raster-Scan

6.1.3 Expanding Spiral Search

In the context of the spiral pattern, the UAV initiates its coverage mission by taking off from the central point of the designated area. During this phase, the distance covered by the UAV is measured and increased with each successive iteration. Each iteration is indicated by the UAV's shift from straightforward movement to initiating a turn. As the pattern persists, the distance the UAV needs to travel is gradually extended, guaranteeing that the UAV covers a more extensive path in contrast to its earlier traversals. The process of the expanding spiral algorithm is visually presented in Fig. 6.

The expanding spiral is mixture of 3 maneuvers which are turn left, move-forth and a fixed range of yaw movement. The flowchart in Fig. 6 depicts how fixed range of yaw movement adds into the linear motion, ‘move-forth’ till a specific distance and turns left. It can also be seen from Fig. 6 that the beginning of each iteration increase the distance before the yaw movement and hence makes the coverage algorithm to keep the spiral expanding till the final diamond box, which stops the algorithm when it reaches the boundary of the area.

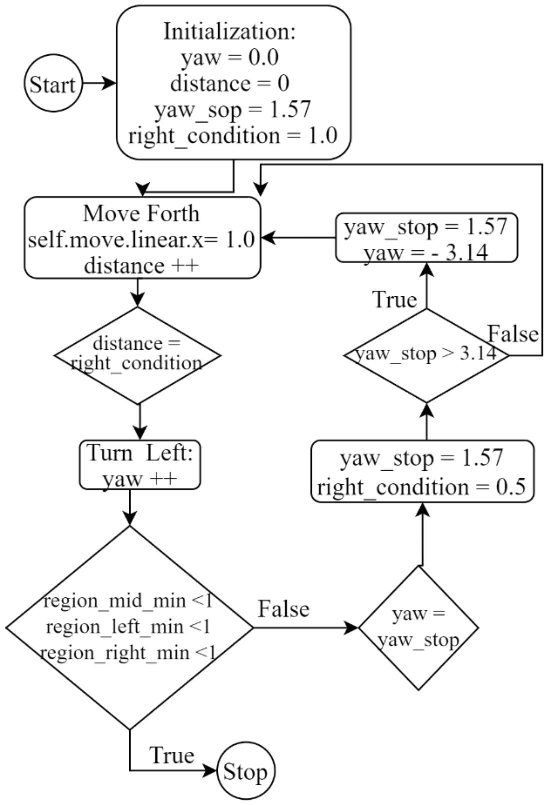

Fig. 6 Flowchart presenting Expanding Spiral Exploration

6.1.4 Zig-Zag Coverage

The zigzag pattern bears a strong resemblance to the back-and-forth pattern, yet it diverges in a significant manner: the current trajectory deviates from running parallel to the preceding one. It's important to note that the angle difference between two consecutive trajectory paths remains constant at 60 degrees, covering a span that ranges from 150 degrees to -150 degrees. The flowchart detailing the zigzag algorithm can be found in Fig. 7.

The zigzag algorithm is quite similar to raster-scan as it contains the same number of maneuvers which are, move-forth, turn left and turn right except a small change. The difference is between the value of region_left_min and region_right_min after following a move-forth trajectory till all the data values; left, right and mid, reach their minimum values which can be seen in Fig. 7.

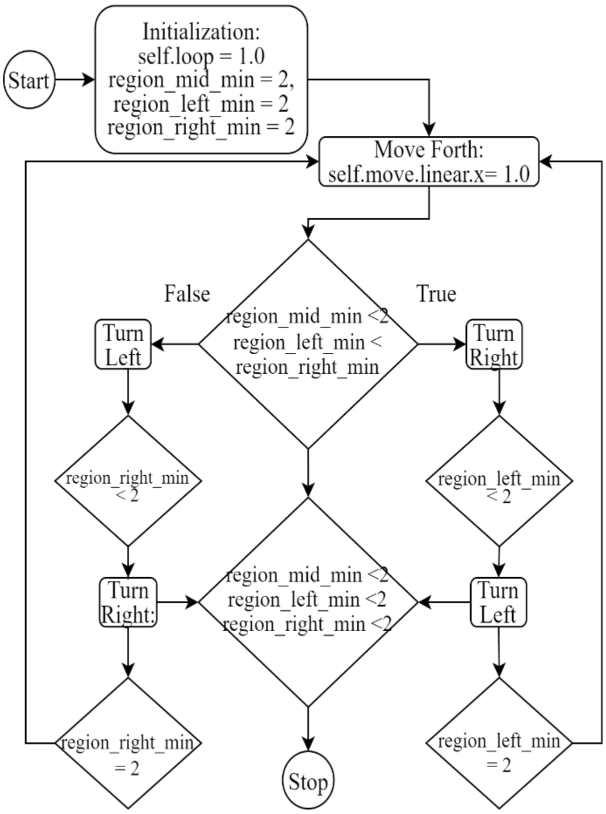

Fig. 7 Flowchart for zigzag coverage

7. Results and Discussion

7.1 Coverage Area Vs Exploration Time

Within RVIZ, the workspace has been constructed using a multitude of cells, each occupying an area of one square meter. The cumulative area of the workspace spans 100 square meters. In pursuit of coverage maximization objectives, a cell is regarded as fully covered when the trajectory path crosses through it. This determination is grounded in the field of view of the UAV, which operates at an altitude of 1.2 meters. The coverage percentage is established by computing the count of explored cells intersected by the trajectory line, as depicted in Eq. 3.

$$Coverage\ [\%] = \frac{cells\ visited\ per\ trajectory}{total\ number\ of\ cells} \times 100\% \qquad (3)$$

The duration required to execute the coverage path planning for each pattern is directly extracted from the ROS software, specifically the elapsed time recorded by ROS. This timer can be reset as necessary and is calibrated to account for Hector's actual translation and rotational capabilities. Hector UAV's position is governed by instructions for both translation and rotation. For instance, the subsequent instructions yield a combination that drives the motors for linear and rotational movements: "self.robot_velocity.linear.x" and "self.robot_velocity.angular.z." In the simulation, the outcomes for each coverage path planning pattern will be juxtaposed to identify the most optimal candidate among the three.

To navigate the drone, either positive or negative values are assigned to these commands, which facilitate the UAV in executing actions such as moving back-and-forth or turning left-and-right.

7.2 Raster-Scan Exploration

The raster-scan pattern was formulated by employing a sequence of instructions for back-and-forth motions, as visually demonstrated in Fig. 8 during simulation. The coverage achieved through the raster-scan technique in this particular scenario encompasses approximately 90 percent of the designated area. To accomplish this coverage, the raster-scan pattern necessitated a total of sixteen turns. The timeframe taken by the drone to execute the coverage within this context amounted to 157.48 seconds.

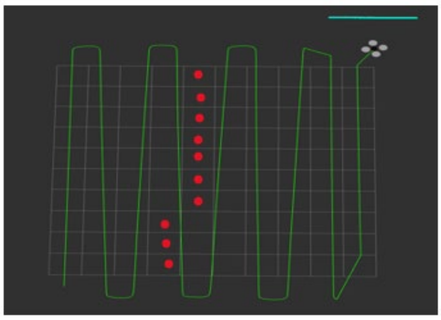

Fig. 8 Visualization of Raster-Scan Exploration of Hector quadcopter where red dots depict unexplored regions

7.2.1 Brief analysis

The repercussions of the UAV's limitations are evident as each trajectory path exhibits non-parallelism with the preceding one. This divergence stems from the drone's rotational adjustments based on input data received from the Hokuyo laser range finder. Specifically, the drone enters a continuous rotation if it continues to receive readings from the Hokuyo Laser. In contrast, when the input data stream ceases, the drone initiates straight movement.

7.3 Expanding Spiral Search

Applying the algorithm outlined earlier in Fig. 6, the outcome of the expanding spiral search is illustrated in Fig. 9. The spiral pattern necessitated a total of sixteen turns to successfully cover the designated path. In terms of time, the completion of the pattern took 130.68 seconds.

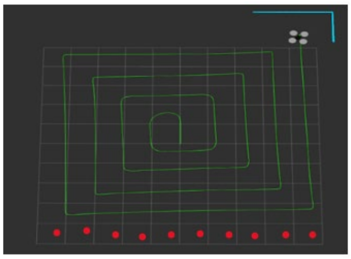

Fig. 9 Visualization of Expanding Spiral Search by Hector quadcopter, red dots representing unexplored regions

7.3.1 Brief analysis

To begin, the UAV's motion doesn't precisely mimic a square-spiral pattern, even when the boundary employed is perfectly square. This discrepancy arises due to limitations in achieving a precise execution of a 90-degree or 1.5708 radian sharp turn, which results from precision constraints. This limitation is rooted in the floating-point data used to obtain the yaw value, wherein the increment isn't linear in nature. This challenge can be mostly mitigated by incorporating acceleration, which is necessary for the aerial vehicle to transition from a halt into any translational motion.

For instance, consider the scenario where the break condition is set for the drone to halt its rotation at a yaw > 1.5708 radians. In practice, the yaw value's data obtained might exceed approximately 1.65 radians. Consequently, the discrepancy between the obtained yaw value and the desired yaw value becomes 0.08 radians or roughly 4.5 degrees. This disparity, although seemingly small, is sufficient to significantly influence a trajectory that encompasses multiple turns.

7.4 Zigzag Coverage

Within the context of the zigzag pattern, the straight movement is standardized across all the patterns, specifically through "self.move.linear.x = 1.0," in order to ensure consistent drone velocity throughout the simulation. A subtle variation was introduced to the command governing rotational movement, aimed at generating a broader angle between successive paths. The outcome of the zigzag pattern is illustrated in Fig. 10. The Zigzag Pattern accomplished a coverage maximization percentage of 73%, necessitated twelve turns, and exhibited the shortest time span of 121.66 seconds.

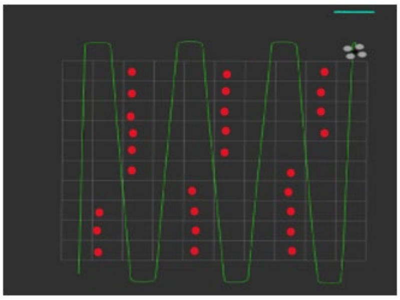

Fig. 10 Visualization of zigzag pattern search by Hector quadcopter, red dots are unexplored cells

7.4.1 Brief analysis

It is noticeable that the vertices produced by the drone do not exhibit sharpness. This behavior can be attributed to the fact that the linear.x value is not set to 0.0 while the drone executes rotational maneuvers. The consequence of setting linear.x = 0.0 was evaluated during algorithm testing and led to the drone colliding with the boundary and experiencing a crash. This indicates that Hector would have to remain stationary until linear.x reaches zero before executing a rotation, resulting in a significant wastage of flight time, especially considering the pattern's twelve turns.

7.5 Comparative Analysis

An evident trade-off has been identified, as illustrated in Table 1 between the coverage maximization achieved by the zigzag pattern and the expanding spiral search. This trade-off involves enhancing coverage area at the expense of incurring a greater number of turns, which can potentially impact the coverage pattern due to the constrained maneuverability of the Hector quadrotor UAV.

Table 1 Summary of results & Comparative Statements

Coverage Scheme / Algorithm	Time taken (s)	Coverage %age	Number of turns
Raster-Scan Coverage	157.48	90%	16
Expanding Spiral	130.68	90%	16
Zigzag Pattern	121.66	73%	12
Comparative Statements			
Raster-Scan Coverage	One of the most frequently technique of exploration took highest time with 16 turns and covered 90%. area.		
Expanding Spiral	Expanding spiral took lesser time than Raster-Scan with 16 turns and 90% area coverage.		
Zigzag Pattern	Zigzag took least number of turns, 12, and least time, however, 73% area was covered.		

7.6 Cost Evaluation Function

Based on the results mentioned in Table 1, an evaluation function has been presented modelled against the experimental results. Using 't' as time take, 'c' as coverage percentage and 'n' as number of turns, the following evaluation function can help determine the best performing algorithm, based on the above mentioned three parameters. The evaluation function fundamentally computes the cost for each algorithm where closer to 1 represents higher cost and closer to 0 represents lower cost. Lower is the better. The cost evaluation function is presented in Eq. 4:

$$f(m) = mean(\frac{t_m}{T_{min}} + \frac{c_m}{C_{max}} + \frac{n_m}{N_{min}}) \quad (4)$$

m: method (coverage algorithm)
T_{min}: maximum of time taken by each method.
C_{max}: maximum of coverage %age of each method.
N_{min}: minimum of steps taken by each method.

Based on the formula mentioned above, the overall score of each method is mentioned in Table 2, which reinforces the results from the simulations as well:

Table 2 Cost evaluation for each coverage algorithm

Method (m)	t_m	c_m	n_m	Score (0-1)	Ranking
Raster Scan	157	90	16	0.84	3rd
Spiral	131	90	16	0.86	2nd
Zigzag	122	73	12	0.85	1st

Where: T_{min} =157, ,C_{max}= 90, N_{min} = 12

8 Conclusion

It is evident that, for each coverage path planning method, achieving an exact replication of the model provided by the drone is unattainable. This is primarily due to limitations stemming from the structure of the robot or aerial vehicle, the characteristics of sensors, the dynamics of motion, and data precision. These factors exert a direct influence on the UAV's behavior in terms of its maneuverability and mobility, thereby impacting the performance within coverage path planning applications. Consequently, a higher number of turns may result in a larger deviation from the theoretical model, while simultaneously aiming to reduce exploration time. In this study, three distinct strategies were meticulously selected and tested within a straightforward exploration scenario utilizing the Hector quadcopter in the ROS environment. This exercise aims to underline the criticality of accounting for hardware limitations during the development of CPP models. The study devised a framework that orchestrates the navigation of the Hector quadrotor through custom environments. To enhance realism, authentic sensor data was effectively integrated into the simulation environment within the Robotic Operating System (ROS). Throughout the simulation, the UAV's behavior, encompassing turning movements and real-time data processing, was meticulously observed. The drone's motion was contingent upon data inputs from the Hokuyo Laser Range Finder and the yaw angle. It is worth noting that, given the intricacies of drone behavior such as turning maneuvers and the data being fed to the drone for execution during coverage path planning, achieving an identical path as specified in the methodology section remains unfeasible for each coverage path planning method. However, it's observed that the actual drone path closely approximates the model path for each coverage path planning method. To determine the optimal coverage path planning approach within the square area, each pattern underwent an evaluation based on two criteria: the time taken to complete coverage and the percentage of maximized coverage. Although the expanding spiral exploration pattern achieved a quicker attainment of maximum coverage, reaching 90% coverage area in sixteen turns (equivalent to the raster-scan search), a trade-off was evident. The zigzag coverage pattern exhibited the shortest completion time and required the fewest turns, achieving a coverage area of 73%. This indicates that for minimizing the impact of hardware limitations, the zigzag pattern would be better suited, additionally offering an extended flight duration.

9 Future work

The future work in UAV coverage path planning should be emphasized more on assessment on UAV control assessment, particularly in the open air among uncertainties and unanticipated disturbances. Plus, the limitation of the of flying time faced by the drone that was restricted due to their consumption of huge amount of energy, additional studies regarding energy-efficient control must be conducted especially for quadrotors.

The idea of swarm configuration should be implemented for improved site investigation by validating and testing appropriate control algorithms in the swarm configuration region. Compliance with air space regulations, separation management in the case of multiple UAVs, route planning and rerouting, congestion management, dynamic geofencing, terrain avoidance, contingency management, sequencing, and spacing, and severe-weather redirection are all challenging aspects of using UAV in last-mile delivery.

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