A Study on the Impact of Hardware Limitations in Multi-Rotor UAVs on Coverage Path Planning Models

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Abstract

Search and explore missions through patrolling UAVs need effective strategies for area coverage. Various methodologies for coverage path planning were explored and analyzed through the ROS-Gazebo simulation environment using the Hector quadrotor model. Considering the impact of hardware limitations, simulations were conducted, for such missions where the UAV is needed to switch frequently between search and localize modes. This study investigated raster-scan exploration, expanding spiral search and zigzag pattern coverage to analyze the impact of limitations from Hector UAV on these models. The evaluation parameters were percentage of covered area, number of turns and time taken by the UAV.

Keywords: Area Coverage, Path Planning, Coverage Path, UAVs, ROS, Gazebo.

1. Introduction

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 pris considered in isolation, meaning, the nature of vehicle or robot is not considered as an influential factor that may influence the ideal path. Several others considered ground vehicles as primary mobile units while Unmanned Aerial Vehicles (UAVs) were considered as an extension [1]. However, 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 do not match the actual path, at times.

1.1. *Problem Statement*

Since, this work targets the coverage area problem for a UAV in search and explore emissions, the same might also need to localize a sub-region as well. Subsequently, a UAV might have to switch between search and localize modes of operation, quite frequently. Therefore, the impact of slight differences in the ideal path generated from the CPP model and the actual path executed by the UAV, can be substantial. It was felt needed to investigate the reasons and study the impact of hardware limitations on the coverage path. To study the impact, a specific UAV with a realistic simulation model was needed that considers its subsystems limitations while following a path generated from an algorithm. 'Hector quadcopter UAV' is one of the most suitable choices to meet this requirement. Hector quadrotor UAV simulation project is developed for Robot Operating System (ROS)-Gazebo simulation framework. One of the greatest advantages selecting ROS is that the codes written in ROS run 'as it were' when needed to be transferred on hardware. Moreover, Hector emulates those quadcopters that well-suite opensource hardware and software technologies for academic research purposes. The project is still active and available under creative common licensing, permissible to modify and use [2, 3].

The rest of this article is organized as, Section 2 briefly presents background of CPP problem, Section 3 describes the simulation setup, Section 4 introduces CPP models under consideration, Section 5 explains the results with brief analysis while Section 6 concludes this article.

2. Formulating a CPP problem

There can be more than one useful solution for any CPP problem that considers factors like shape of coverage area, obstacles in the area and percentage of area needed to be covered. However, the limitations in maneuverability and mobility from its sensors and structures have been overlooked. Let us first consider how a coverage problem is formulated for a given area.

2.1. *The shape of Coverage Area*

The primarily factor is the shape of the coverage area which can either be in the form of regular structures (like, square, rectangle, triangle) or irregular and complex. The implications of the shape-complexity are beyond the scope of this work, since the prime focus is to study the impact of limitations of a specific on the path generated by a CPP model. Therefore, a 10x10 meter square-shaped area is considered for this work.

2.2. *Cell Definition and Area Decomposition*

Once the shape of a coverage area is identified, one of the optional next steps is to decompose the target area into unit cells, however, some algorithms might not need it. These cells define the resolution of the overall map, drastically affect computation overhead, and precision of information gathered by the exploring vehicle. For a smaller cell size, the vehicle would require to just go through once in a cell needing more flight time to cover the area. However, if the cell size is bigger, multiple exploration trips may be needed within a cell as well [1]. Fundamentally, a cell size depends on the UAV's ability (sensor subsystems) to explore a unit of region at a time.

2.3. *Availability of Information for Coverage Area*

If some prior information related to the coverage is available, this can improve the overall performance of CPP, *e.g.*, a piece of information related to the target location in a search mission can avoid unnecessary exploration. Moreover, prior information can also suggest more sophisticated patterns that may prioritize a certain sub-area. It is suggested that an attempt to acquire any prior information must be made as part of the planning process.

2.4. *Area of Interest*

Next thing in line comes the technique for cell decomposition and the primary consideration is most probable or favorite region within the coverage area. As an instance, closer to the boundary of the coverage area may be of a lesser significance as compared to central ones, depending on the objective to attain. A technique to place 'dot-points' within the coverage can address this concern. The concentration of dot-points can either be equally distributed or uneven. The sub-areas with higher interests may have a higher dot-point density.

2.5. *Performance Metrics*

Performance metrics associate a measurable outcome when an activity is executed to meet an objective. There are a few aspects that need to be considered in performance metrics. The total travelled distance or route length [4, 5], the time to accomplish a mission [6], the area coverage maximization [7], and the number of turning maneuvers [8]. However, as the total area increases, so the total distance travelled by UAV increases and vice versa. Furthermore, the area of interest may also affect the time taken by UAV to complete the coverage mission. Thus, area coverage maximization seems difficult if the area of interest is too huge due to limitations of drone technology. This brings the metrics to the basic form of measuring the percentage of area covered in a unit of time, considering flight duration requirements.

2.6. *Pattern Identification / Selection*

The final stage of CPP here is the pattern identification and selection that covers the dot-points (area of interest). This depends upon the nature of distribution of the dot-points. In most of the studies, the enhancements are fundamentally attempted through improved dot-points distribution (area of interests), novelty in constrainedoptimization (minimizing time or maximizing coverage), and so on. For this study, three useful CPP patterns are handpicked since the objective here is to study the impact of hardware limitations.

3. Simulation Setup

3.1. *ROS (Melodic)-Gazebo Framework*

ROS Melodic Morenia is originally designed for the Ubuntu 18.04 (Bionic) version, although it also works on other Linux distributions, as well as Mac OS X, Android, and Windows [9]. Gazebo is the most accurate and efficient simulator for simulating robot populations in complicated indoor and outdoor situations with a powerful physics engine, high-resolution visuals [10].

3.1.1. HECTOR Quadrotor

Hector is also an opensource ROS project that contains programs for quadrotor UAV modeling, control, and simulation developed by Meyer *et al.* [11]. These come in the forms of packages that develop its systems design, operation, simulation, and a Unified Robot Description Format (URDF) model as well as versions that include different sensors.

3.1.2. UAV's Field of View (FOV)

Hector's Field of View (FOV) of the camera is the region that is covered when the UAV flies at a certain height h. camera's dimension can be obtained as the equation below and illustrated in Fig. 1:

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

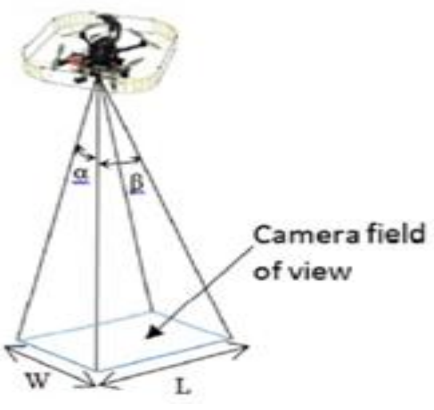

Fig. 1. Field of View (FOV)

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

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.

3.1.3. Hokuyo Laser Range Finder

Hokuyo laser range finder is used to detect any boundary or obstacles that is available near the UAV. Hokuyo Laser consists of a 1081 set array of beam light that covers the left side, front side, and right side of the UAV. The longest distance for the Hokuyo Laser Range Finder for the drone to detect any obstacle or boundary is set to 2 meters. A visualization of range finder is presented in Fig. 2 alongside parameters used in algorithms.

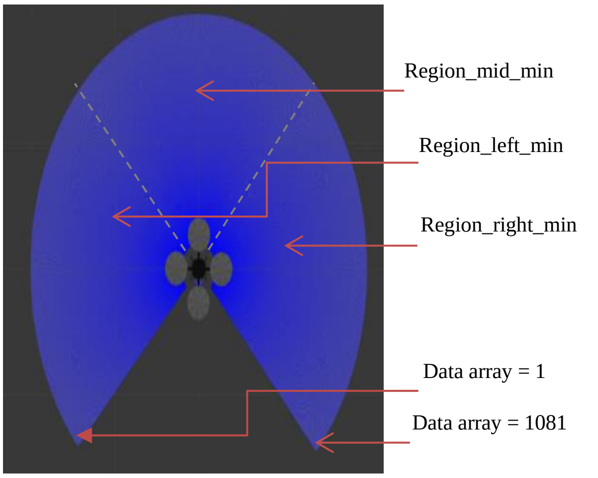

Fig. 2. Data variables through Hokuyo Laser Range Finder

4. CPP Models

4.1. *Workspace Setup*

The workplace is divided into one-by-one meter square with no gaps among them and is called a unit cell. Each part of cell is put with one point at the center to mark the region of interest, in this study. Moreover, if the UAV reaches any point in a cell, it is anticipated as that cell has been covered. Camera field of view calculates the size of the cell in the mosaicking process. Hence, a 2D Grid graph is formed with cells having and a dot has been marked as the center point of each cell as shown in Fig. 3.

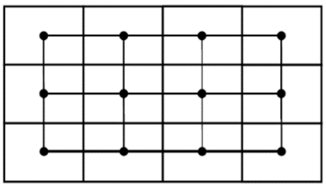

Fig. 3. Cellular decompositions of proposed workspace with equidistance dot-points

4.1.1. Patterns Generation

One of the advantages of UAVs like quadcopters is that through the varying combinations of their motors, using motor mixing algorithms, a substantial number of patterns can be generated by programming simple back-and-forth. Each cell is connected to eight neighboring cells. The connectivity of grid-cells, also known as Moore neighborhood, has been found effective for coverage area planning through UAVs. Through this capability, to rotate to any yaw angle value, which are $\pm 45, \pm 90$ and ± 135, series of such combinations can generate numerous patterns by switching the velocity of each motor, illustrated in Fig. 4.

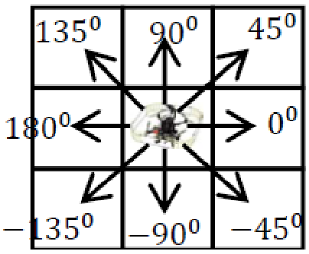

Fig. 4. Moore Neighborhood of quadcopter

4.1.2. Raster-Scan Exploration

Considering this mechanism of pattern generation, the raster-scan search pattern was considered as one of the key techniques that is widely used for exploration missions. The algorithm is presented through a flowchart in Fig. 5, while the simulation results and brief analysis are presented in Section 5.2 and 5.2.1, respectively.

4.1.3. Expanding Spiral Search

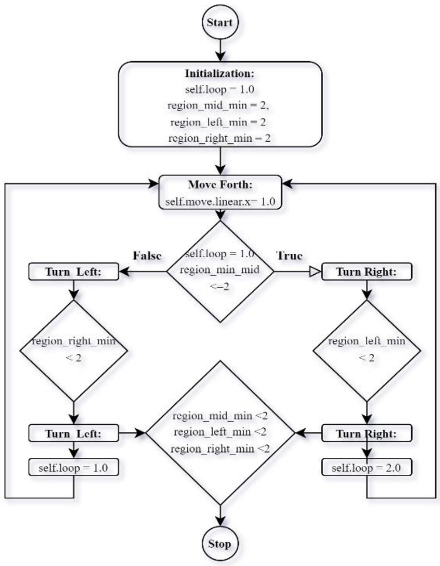

Fig. 5. Flowchart depicting Raster-Scan Exploration

In the spiral pattern, UAV starts the coverage mission by flying at the center point of an area. In this stage, the distance travelled by the UAV will be counted and increased for each iteration. One iteration is considered when the UAV finishes the straight moving and starts to turn. For the next iterations, the distance that needed to be travelled by the UAV will be increased to make the UAV fly longer than the path travelled before. Fig. 6 is presented to illustrate the expanding spiral algorithm while Section 5.3 and 5.3.1 presents simulation and brief analysis.

4.1.4. Zig-Zag Coverage

The zigzag pattern is similar as the back-and-forth pattern except the difference is this that the current trajectory is not parallel to the previous trajectory. The difference between two trajectory paths is set to 60 degrees which is 150 degrees to -150 degrees. The flowchart for the zigzag algorithm is presented in Fig. 7. Section 5.4 and 5.4.1

visualizes simulation and presents analysis, respectively.

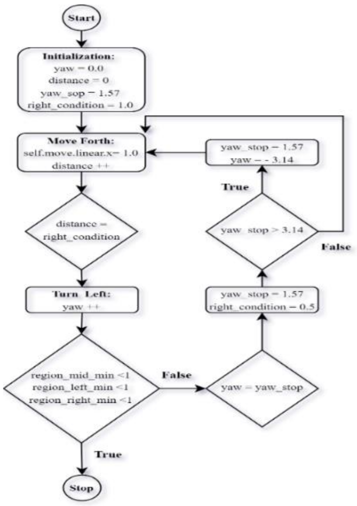

Fig. 6. Flowchart presenting Expanding Spiral Exploration

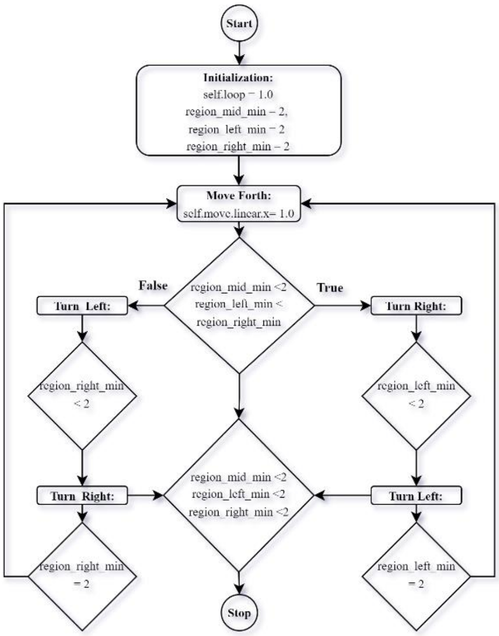

Fig. 7. Flowchart for zigzag coverage

5. Results and Discussions

5.1. *Coverage Area Vs Exploration Time*

In the RVIZ, the workspace has been built with numbers of cells and each cell has an area of one-by-one m^2. The total area of the workspace is $100m^2$. For coverage maximization purposes, one cell is considered entirely covered when the trajectory path flies through the cell. This consideration is based on the field of view of the UAV that flies at a height of 1.2m as stated in Section 3.1.2. Coverage percentage is based on the count of explored cell under the trajectory line:

$$\text{Coverage} = \frac{\text{cells visited per trajectory}}{\text{total number of cells}} \text{ x } 100\% \quad (3)$$

Time taken to complete coverage path planning for each pattern is taken directly from the ROS software, ROS elapsed, which can be reset when needed and considers the actual translation and rotation capacity of Hector to record time. The position of Hector UAV goes through translation and rotational instruction. As an instance, the following instructions generate a motor driving combination, for linear and rotational motions: *self.robot_velocity.linear.x* *and* *self.robot_velocity.angular.z*. The simulation results for each coverage path planning pattern will be compared to determine the most optimum coverage path candidate among the three. To maneuver the drone the positive or negative values are assigned to these commands, which can make the UAV to either move back-and-forth or turn left-and-right.

5.2. *Raster-Scan Exploration*

Raster-scan pattern was generated through a sequence of back-and-forth motion instructions whose simulation visualization is presented in Fig. 8. The area covered through raster-scan technique for this scenario is roughly 90 percent. Raster-scan was required to make sixteen turns in total for the coverage. The time taken for the drone to complete the coverage in this scenario is 157.48 seconds.

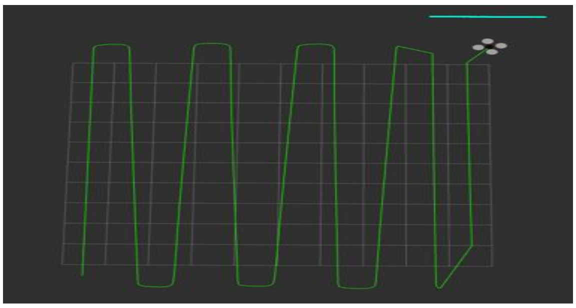

Fig. 8. Visualization of Raster-Scan Exploration of Hector quadcopter where red dots depict unexplored regions

5.2.1. Brief analysis

The impact of limitations from the UAV is also visible as every trajectory path is not parallel from the previous path. This is because the drone rotates according to the data fed from the Hokuyo laser range finder. The drone will continuously rotate if the drone gets the reading from Hokuyo Laser. If the data is no longer fed to the drone, the drone will start to move straight.

5.3. *Expanding Spiral Search*

Following the algorithm presented previously in Fig. 6, the result of the expanding spiral search is shown in Fig. 9. It took the spiral pattern sixteen turns in total for the coverage to complete the path coverage. As for the time, it took 130.68 seconds.

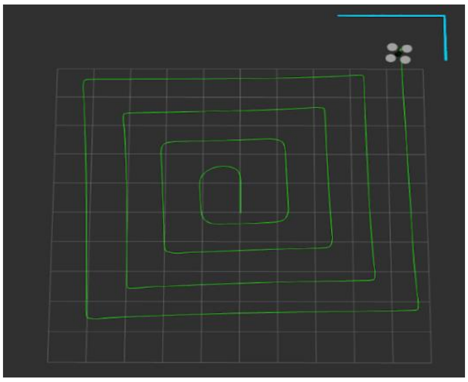

Fig. 9. Visualization of Expanding Spiral Search by Hector quadcopter, red dots representing unexplored regions

5.3.1. Brief analysis

First, the UAV movement is not exactly a squared-spiral pattern even if the boundary used is exactly square. This is because of limits in precision for exactly executing a 90-degree or 1.5708 in radian sharp turn. This limitation is occurring because of the data with floating numbers obtained from the yaw value whose increment is not linear in nature. This is almost preventable because an acceleration is needed by the aerial vehicle to execute any translation motion from halt. For instance, when the break condition for the drone to stop rotate at yaw > 1.5708. the data of yaw value obtained may exceed to about 1.65 rad. This makes the difference between the yaw obtained and the yaw desired is 0.08 rad or 4.5 degrees which is enough to create an impact on trajectory that includes multiple turns.

5.4. *Zigzag Coverage*

In the zigzag pattern, the straight movement is equated with the other patterns which is the self.move.linear.x = 1.0 to balance the velocity of the drone along the simulation. A slight difference was made to the command used for the rotation movement to generate a wider angle between paths. The result of the zigzag pattern is as portrayed as Fig. 10. The percentage of coverage maximization performed by the Zigzag Pattern is 73% and made twelve turns and took the least time, 121.66 seconds.

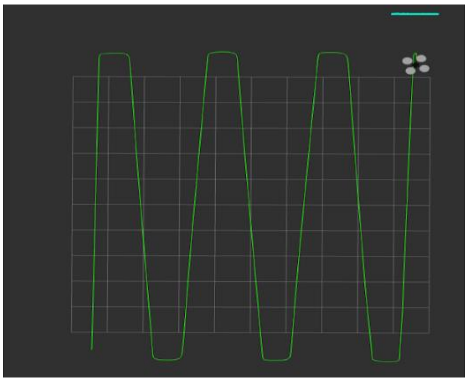

Fig. 10. Visualization of zigzag pattern search by Hector quadcopter, red dots are unexplored cells

5.4.1. Brief analysis

It can be observed that the vertices that were generated by the drone are not sharp. The reason for this behavior is due to the fact that the linear.x is not set to 0.0 during performing rotation maneuvers. The value of linear.x = 0.0 has been assessed during testing the algorithm and resulting in the drone hitting the boundary and crashing. This means, the Hector would need to hover till linear.x is zero before taking a rotation and that is a substantial waste of flight time with twelve turns.

5.5. *Comparative Analysis*

A trade-off has been observed, Table 1 among zigzag coverage and expanding spiral search, to maximize coverage area on the cost of a higher number of turns that possibly affect the coverage pattern due to the limiting maneuverability of 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.		

6. Conclusion

It is portrayed that for each coverage path planning method, it is impossible for the path generated by the drone to be exactly the same as the model provided. This is mainly because of limitations from the Robot or Aerial Vehicle structure, sensors, physics of motion and data precision. These factors directly impact the UAV's behavior in terms of maneuverability and mobility which further affects the performance in coverage path planning applications. Consequently, a higher number of turns may lead to a higher deviation from the theoretical model, alongside the desire to reduce exploration time.

This study handpicked three different strategies in a simple exploration scenario with Hector quadcopter in ROS, to prove how critical and essential it is to consider hardware limitations while developing CPP models. Though the expanding spiral exploration took less time to reach maximum coverage area, 90% and with sixteen turns (same as raster-scan search), a trade-off was observed. The zigzag coverage took the least time and least number of turns with 73% of coverage area. This means, if it is needed to minimize the impact of hardware limitations, the zigzag pattern would suit better, alongside, offering a higher flight duration.

Acknowledgment

The study is supported by "IIRG003(b)-19IISS", University of Malaya, Malaysia.

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