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2D visual area coverage and path planning coupled with camera footprints☆

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ABSTRACT

Unmanned Aerial Vehicles (UAVs) equipped with visual sensors are widely used in area coverage missions. Guaranteeing full coverage coupled with camera footprint is one of the most challenging tasks, thus, in the presented novel approach a coverage path planner for the inspection of 2D areas is established, a 3 Degree of Freedom (DoF) camera movement is considered and the shortest path from the taking off to the landing station is generated, while covering the target area. The proposed scheme requires a priori information about the boundaries of the target area and generates the paths in an offline process. The efficacy and the overall performance of the proposed method has been experimentally evaluated in multiple indoor inspection experiments with convex and non convex areas. Furthermore, the image streams collected during the coverage tasks were post-processed using image stitching for obtaining a single overview of the covered scene.

1. Introduction

Unmanned Aerial Vehicles (UAVs) equipped with remote sensing instrumentation have been emerging in the last years due to their mechanical simplicity, agility, stability and outstanding autonomy in performing complex maneuvers (Kanellakis & Nikolakopoulos, 2017; Kendoul, 2012). Furthermore, UAVs have the ability to offer numerous opportunities in a variety of applications, such as mapping (Zongjian, 2008), landslides (Niethammer, Rothmund, James, Travelletti, & Joswig, 2010), search and rescue missions (Doherty & Rudol, 2007), forest fire inspection (Alexis, Nikolakopoulos, Tzes, & Dritsas, 2009) and aerial manipulation (Kanellakis, Terreran, Kominiak, & Nikolakopoulos, 2017). One of the most common remote sensors is the visual sensor, either monocular or stereo, while the acquired set of images from the UAV's mission can be analyzed and used to produce sparse or dense surface models, hazard maps, investigate access issues, and other area characteristics (Valente et al., 2011). However, the main problem in these approaches is to guarantee the full coverage of the area, a fundamental problem that is directly related to the autonomous path planning of the aerial vehicles. In order to guarantee the full coverage, the problem of the coverage path planning should be mathematically formulated to be coupled with the camera frustum, while maximizing the area coverage, in relation to the camera movement and the corresponding orientation. This problem is well-known in the literature to be NP-hard and thus there is a need of a numerical solution to provide a close to optimal solution. Moreover, in all the coverage path planning methods, there are constraints on the length of the path, as it is desired to follow the shortest one and this can directly affect the overall mission, mainly due to the UAV's limited flight time (Mansouri, Karvelis, Georgoulas, & Nikolakopoulos, 2017). Finally, the coverage path planning approach should be evaluated in real-life scenarios, which would add an important overall technological contribution of the established approach. In the presented approach, it is assumed, without loss of generality, that during the operation, the UAV has the ability to retain a closed loop fixed altitude, while having a downward-looking camera. In this specific case, the camera frustum can be modeled by fixed size rectangles, of size $w_i \times h_i$, $(w_i, h_i) \in \mathbb{R}^2$ as it is indicated in Fig. 1.

In the related literature, the problem of covering the target area with fixed size rectangles has been addressed multiple times, while this typical problem is known to be NP-complete (Daniels & Inkulu, 2001; Heinrich-Litan & Lübbecke, 2005) and one of the several computationally difficult decomposition problems (Franzblau & Kleitman, 1984). Additionally, apart from the coverage approaches for visual inspection, it has several important practical applications, such as in VLSI layout design, pattern recognition, computer graphics, databases, image processing, etc. Thus, inspired by this vision, the main objective

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Fig. 1. Schematic of the field of view in the case of UAV.

of this article is to establish an algorithm to segment the target area in relation to the camera's position and orientation (x, y, ψ) in an offline approach; in the sequel the UAV will be able to plan its shortest possible path through all segments with a fixed take-off/landing area.

On the specific topic of covering polygons with rectangles, most of the works consider a varying size of the rectangles' area (Stoyan, Romanova, Scheithauer, & Krivulya, 2011) or the target area is considered to be convex, rectilinear or a union of convex polygons (Stoyan et al., 2011). Furthermore, most of the previous contributions formulate the problem mathematically, without presenting the numerical solution to the problem, while it should be highlighted that the problem is proven to be NP-hard for the case of the fixed size rectangles (Culberson & Reckhow, 1988).

For the Coverage Path Planning (CPP) problem, there have been many works that address 2D spaces and fewer approaches that address coverage of 3D spaces (Mansouri, Kanellakis, Fresk, Kominiak, & Nikolakopoulos, 2018). A survey on CPP methods in 2D can be found in Galceran and Carreras (2013). In most of the CPP methods for covering the target area, the underlying algorithms decompose the area in sub-regions. Thus, coverage algorithms can be categorized by the type of decomposition into: (a) classical exact cellular decomposition (Lingelbach, 2004), where the decomposition of the area breaks down to simple non-overlapping regions and a robot sweeps these regions, (b) Morse-based cellular decomposition (Acar, Choset, Rizzi, Atkar, & Hull, 2002) where the area is decomposed based on critical points of Morse functions (Milnor, 2016) and a motion planner algorithm guarantees to encounter all the critical points in the target area, (c) landmark-based topological coverage (Wong, 2006), with the area decomposed based on natural landmarks, (d) contact sensor-based coverage of rectilinear environments (Butler, Rizzi, & Hollis, 1999), where the robot follows a cyclic path while building up a cellular decomposition of the area, (e) grid-based methods (Shivashankar, Jain, Kuter, & Nau, 2011) where the target area is decomposed into a collection of uniform grid cells, and (f) graph-based methods (Xu, 2011) for environments that can be presented as a graph, where the graph can be updated based on robot sensors, while performing coverage. The aforementioned methods decompose the area without consideration of the mobile agent's sensor, which can affect the coverage quality. Towards aerial coverage and visual inspection, it is assumed that a top level procedure handles the area segmentation (Avellar, Pereira, Pimenta, & Iscold, 2015; Valente et al., 2011), while there has been no related work to consider decomposition of the target area with relation to the camera footprint. Thus, this decoupling of coverage task and segmentation of the area can reduce the generality of these approaches. Moreover, in case of grid-based methods or lawn-mower problems, the target area is decomposed into a collection of uniform grid cells. As a result, most grid-based methods completeness depends on the resolution of the grid map. Although it is easy to create a grid map and grid-based representations are the most widely used for coverage algorithms, grid maps suffer from exponential growth of memory usage, while the resolution does not depend on the complexity of the area. Moreover this type of algorithms does not consider rotation of the robot, and may yield into suboptimal paths. Furthermore, in the case of the art gallery problem, the problem is to determine the minimum number of guards for observing the whole gallery. This results to static coverage problems, which are about finding a good placement of the sensors, and is categorized under surveillance problems. However, in this article, coverage path planning coupled with area decomposition is studied, which differs from the previous approaches and solutions. In the presented novel approach, the camera footprint is coupled with the UAV position and yaw angle and the area is decomposed while maximizing the covered area. This approach is directly inspired by real life applications of UAVs and the mathematical formulation of the overall problem consists of a novel consideration of the coverage problem.

Preliminary and limited results from the proposed framework have been presented in Mansouri, Georgoulas, Gustafsson, and Nikolakopoulos (2017), while this work has been extended in this article with the following fundamental additional contributions: (1) 3 Degrees of Freedom (DoF) (x, y, ψ) instead of 2 DoF (x, y) camera motion as a result of the natural movement of the UAV, (2) integration of a path planner to provide the shortest path among the centers of the identified rectangles, and (3) multiple experimental verifications of the proposed methods with a comparison and analysis of the results. Based on the aforementioned state of the art, the main contribution of this article is three-fold. Firstly, the problem of covering the polygonal target area, while considering the camera's footprint with 3 DoF is mathematically formulated and solved approximately by three different well-known metaheuristic techniques: the Pattern Search (PS), the Genetic Algorithm (GA) and the Particle Swarm Optimization (PSO). Secondly, this article addresses the problem of the segmentation of a polygonal region with fixed size rectangles for the coverage and inspection tasks for the first time, to the best of the author's knowledge. Thirdly, it should be noted that the coverage path planner is evaluated through multiple experimental trials, where the overview of the covered area is visually represented using an image stitching technique. Finally, it should be highlighted that the main novelty of the proposed scheme stems from the establishment of an overall framework for the path planning for convex and non-convex 2D areas. Thus, a novel mathematical framework for solving the coverage problem by segmentation of the target area and calculating the shortest path will be established. As a fundamental difference, in the proposed approach the cities that the TSP should visit are calculated in order to maximize the covered area. The established theoretical framework has the novelty of providing a path for maximizing the coverage of the area, while considering for the first time, to the authors best knowledge, the camera footprint position and orientation, in contrast to many existing approaches that simplify the effect of the camera footprint in the target area segmentation. Moreover, this article provides an near optimal solution for the well-known NP-hard problem of covering polygons with rectangles. Finally, one of the fundamental technological contributions of this article is the fact that the proposed framework has demonstrated the direct real life applicability and feasibility of coverage in an indoor experiment. The established coverage framework is able to integrate and adapt fundamental principles from the areas of control, image processing, and computer science, in a fully functional and efficient approach that enables the penetration of aerial robotics in real life applications and more specifically in the field of aerial inspection. It should be highlighted that in this approach the camera movement and yaw orientation is coupled with the UAV, while in cameras with gimbals, the camera remains horizontal, regardless of the motion around them and there is no closed loop controller between gimbals and the UAV orientations, a fact that limits the DoFs of the camera motion in relation to the UAV. Additionally, the usage of gimbal is limited, as lightweight UAVs have strong payload constraints.