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Coverage path planning with unmanned aerial vehicles for 3D terrain reconstruction

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ABSTRACT

Three-dimensional terrain reconstruction from 2D aerial images is a problem of utmost importance due its wide level of applications. It is relevant in the context of intelligent systems for disaster managements (for example to analyze a flooded area), soil analysis, earthquake crisis, civil engineering, urban planning, surveillance and defense research.

It is a two level problem, being the former the acquisition of the aerial images and the later, the 3D reconstruction. We focus here in the first problem, known as coverage path planning, and we consider the case where the camera is mounted on an unmanned aerial vehicle (UAV).

In contrast with the case when ground vehicles are used, coverage path planning for a UAV is a lesser studied problem. As the areas to cover become complex, there is a clear need for algorithms that will provide good enough solutions in affordable times, while taking into account certain specificities of the problem at hand. Our algorithm can deal with both convex and non-convex areas and their main aim is to obtain a path that reduces the battery consumption, through minimizing the number of turns.

We comment on line sweep calculation and propose improvements for the path generation and the polygon decomposition problems such as coverage alternatives and the interrupted path concept. Illustrative examples show the potential of our algorithm in two senses: ability to perform the coverage when complex regions are considered, and achievement of better solution than a published result (in terms of the number of turns used).

1. Introduction

Unmanned aerial vehicles (UAVs) have multiple uses at present besides obvious military applications. Search or exploration (Sujit, Sousa, & Pereira, 2009), impact analysis after an earthquake (Xu et al., 2014) and others like forest health monitoring, mine surveys or air quality monitoring (Watts, Ambrosia, & Hinkley, 2012) are some examples of civil applications of UAVs. Another interesting example is the 3D terrain reconstruction from 2D images taken from the UAV: the vehicle flies over an area taking overlapped images that will be used next to obtain a 3D reconstruction of the ground. The whole reconstruction problem is far from trivial and it can be decomposed into two different tasks: (1) the coverage path planning problem (CPP), and (2) 3D reconstruction from 2D images, which includes others like image alignment or features detection.

In this contribution we focus on CPP whose aim is to find a path for a vehicle in order to completely visit an area. The problem can be formalized when considering unnamed ground vehicles (UGVs; Choset, 2001; Choset & Pignon, 1998; Lee, Baek, Choi, & Oh, 2011), underwater robots (Bagnitckii, Inzartsev, & Senin, 2011; Hert, Tiwari, & Lumelsky, 1996) or UAVs but for the case of the 3D reconstruction of the terrain, a UAV is needed. CPP with UGV is a well studied problem in the context of robotics, see for example Galceran and Carreras (2013), where some considerations about its computational complexity are also stated. In this sense, several similar problems are considered as NP-hard.

UAVs are commonly used for the task allocation problem (Besada-Portas, De La Torre, Moreno, & Risco-Martín, 2013; Choset & Pignon, 1998) but, as long as we know, CPP using UAVs is a lesser studied problem sometimes simplified to deal only with

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convex polygons as in Maza and Ollero (2007). When dealing with concave polygons, other researches propose methods focused on the path's construction regardless of the area's shape Valente, Cerro, Barrientos, and Sanz (2013) or Franco and Buttazzo (2015) where the UAV's path is made as if it was a convex polygon and turning back to cover a remaining sub-area caused by a concave zone. A more complex method presented in Huang (2001) is based on the subdivision of the area to simplify the surface into different areas covered by a determined motion. This simplified approach is similar to one proposed in Ji, Wang, Niu, and Shen (2015) where a concave polygon is decomposed into convex polygons.

In Li, Chen, Er, and Wang (2011), the authors propose a covering strategy where the beginning of the path is defined by the user but the endpoint is given by the algorithm (the user can not define it). As the UAV lands at the end of the path, it could happen that this point is unreachable for the user and the UAV could not be recovered.

In this context, the aims of this contribution are: firstly to propose and secondly, to evaluate a set of strategies to solve the CPP problem using a UAV, when considering both convex and non-convex areas.

From a practical point of view, and in contrast to Li et al. (2011), the take off and landing points for the UAV are chosen by the user. In real scenarios, the experts starts and finishes the UAV flight or mission at the same point, so from now on, we assume that the take off and landing point of the UAV are the same.

Also, the proposed strategies can be used with any rotorcraft UAV able to perform waypoint navigation and rotate around its own axis.

The paper is structured as follows. Section 2 presents an overview of the CPP problem for 3D terrain reconstruction, stating the inputs and output that an algorithm will need to solve the problem. Section 3 provides additional background information. Then, in Section 4 we propose a method to solve the coverage problem when the area is represented as a convex polygon. This is then expanded in Section 5 to address the cases of concave polygon or multiple connected convex polygons. We comment how to transform the problem of a concave polygon coverage into a multiple convex polygon coverage, stating when this transformation is really needed. Finally, in Section 6 we outline some considerations based on practical experiences, that allows us to speed up the solution of the problem.

Illustrative examples and results are shown in Section 7, while conclusions and further discussion are presented in Section 8.

2. Coverage path planning problem for 3D terrain reconstruction

As we stated before, we wish to design a path for the UAV that allows to obtain images fully covering the area of interest. As these images will be later used for terrain reconstruction, several considerations arise:

- *Overlapping:* Consecutive pictures should have a given percentage of overlapping. The greater the overlap is, the higher the accuracy of the 3D model will be.
- *Time contiguity:* The quality of the 3D texture will be higher when the pictures of contiguous areas of the terrain are taken at similar time. Otherwise, uncorrelated shadows or visual differences may appear, leading to a more difficult reconstruction and a less quality texture.
- *Orientation:* It is desired to have the pictures taken in the same orientation because it leads to a simplification in the 3D reconstruction phase (correlation among them are easier to find).

The coverage problem considered in this contribution needs as input:

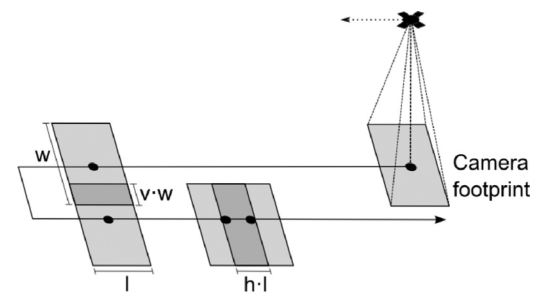

Fig. 1. The camera footprint on the terrain has length l and width w. Parameters h and v denote the horizontal and vertical overlapping percentage among images.

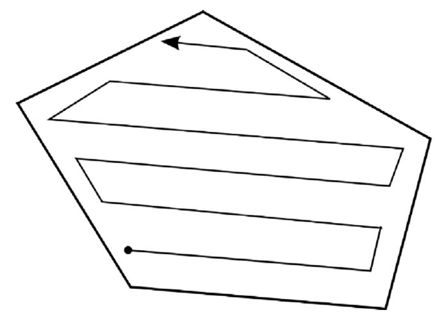

Fig. 2. Example of a CPP' solution. The path fully covers the polygon.

- The polygonal region.
- The start-end point: The start (take off) and the end (landing) points which are considered the same.
- The camera footprint: The length, l, and width, w, on the terrain taken by one image as shown in Fig. 1. These footprints are determined by the flight's height and the camera's features.
- The horizontal, h, and vertical, v, overlapping percentage among images, as depicted in Fig. 1.

A solution to the problem is a path for the UAV that allows a complete coverage of the region. An example is shown in Fig. 2.

3. Background information

The most critical point when using a UAV in this kind of problem is to minimize power consumption. As stated in Li et al. (2011) the fuel consumption can be reduced by decreasing the number of turns. For a fixed distance, the time is increased when the rotorcraft turns, because it has to completely stop before start moving into a different direction, wasting time while it slows down and accelerates once it has changed the direction. The path will be created with a zigzag motion (a.k.a a back and forth motion) trying to minimize the number of turns the rotorcraft must do along the coverage.

Rotorcrafts are able to move backwards in the same way as they can move forwards and sideways. Actually, they can perform movements on any direction. That simplifies the turns, because the rotorcraft can change the movement direction without changing the heading orientation.

Taking advantage of this feature and to reduce the time spent in every turn, the rotorcraft will not turn itself, instead the rotorcraft will be always heading to the same direction and will move sideways and backwards when it is required. As a side and necessary effect, the pictures' orientation will be the same for all pictures taken, facilitating the following reconstruction problem.

Having these ideas in mind, our algorithm will return a path that will be traversed as a zigzag or back and forth motion composed by longitudinal (the rows), transverse and possibly slightly diagonal moves.