Coverage path planning by swarm of UAVs for UGV traversability analysis

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Abstract. In rough or risky environments, such as minefields, landslides or volcanic eruptions, it is extremely complex to plan safe trajectories for an Unmanned Ground Vehicle (UGV), since both robot stability and path execution feasibility must be guaranteed. In these scenarios, the adoption of a swarm of Unmanned Aerial Vehicles (UAVs) to survey the area and reconstruct 3D models of the environment can be really helpful. In this paper we will present a complete solution combining three different aspects. The first is the coverage path planning and concerns the definition of UAV trajectories for photogrammetric aerial image acquisition. When non-coverable zones are present, a suitable decomposition into subregions of the whole area to survey is performed. The second aspect is then related to the use of a swarm of UAVs to implement the coverage in a parallel way. A solution to assign the different regions among the flying vehicles will be presented, which optimises the path length of the whole swarm. The last aspect concerns the path planning of the ground vehicle, by means of a traversability analysis performed on the terrain 3D model (reconstructed from the previous aerial survey). The computed paths will be optimal in terms of difficulty of moving across the rough terrain. The results of each step of the overall approach will be shown.

1. Introduction

The problem of autonomous navigation of a UGV in outdoor environments, which are most of the times *unstructured environments*, cannot be considered fully solved in current robotics literature. In fact, the problem of path planning in such scenarios is still hard due to the difficulty of taking into account many aspects at once, such as robot kinematics and stability, terrain geometry and so on [1]. Furthermore, most of research has been carried out on structured environments, such as roads, indoor rooms, factories, where the vehicle is expected to move along clearly defined paths or regions.

A rather common approach to cope with the problem of autonomous navigation in the outdoors is to employ UAVs to provide an aerial overview of the considered environment [2,3]. In particular, photogrammetric 3D reconstruction, from aerial surveys, has gained more and more relevance over the years, thanks to the enhanced quality of results and the increased computation power available.

In this paper, an integrated strategy to solve the problem of rover path planning in unstructured environments will be presented. The three main issues faced are:

1. Coverage path planning
2. Coverage subregions assignment to a swarm of UAVs
3. Traversability costmap generation for rover optimal trajectories computation

All of these aspects will be discussed in the following sections.

2. Coverage path planning

Coverage path planning refers to a special kind of planning algorithms used for large regions surveys. Although this kind of planning can be used for any type of vehicles, namely ground, aerial or underwater vehicles, here we will focus on trajectory computation for UAVs. The first step is to define the area to survey as a 2D region, thanks to georeferenced maps. In our work we use a georeferenced Digital Elevation Model (DEM) of the environment and the area to survey is defined as a top-view over such model. A DEM is gridded representation of the environment and its cells contain the height values of the 3D structure. After that, *non-coverable zones* are defined, namely those zones where we do not want the UAV to fly above. These zones can be defined as a sequence of vertices, thus obtaining polygonal zones. At this point, the whole area is decomposed into free-to-fly subregions via a *Morse-based decomposition algorithm* [4]. A linear decomposition has been considered in this work, along either the vertical or the horizontal axis of the map frame (Figure 1). Eventually, coverage trajectories along each side of each subregion are computed. As coverage pattern the so called *back-and-forth motion* has been considered (Figure 2). Within each subregion, the optimal trajectory is chosen, which is the one with minimum number of turns. In fact, many works proved that turns are the main loss of energy and time during the execution of such kind of patterns [2-3,5]. Therefore, at the end of this step, the coverage paths for each subregion are defined. An example is shown in Figure 3.
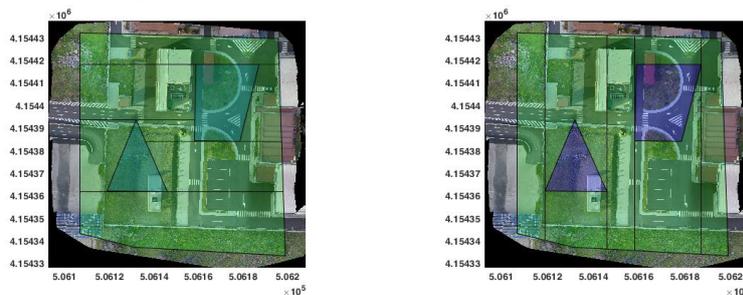

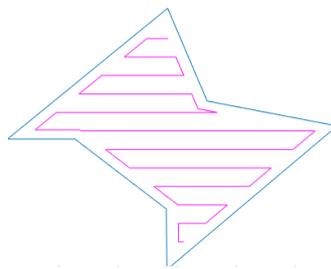**Figure 1.** Example of vertical and horizontal decompositions

Figure 2. The back-and-forth pattern chosen as coverage trajectory within each subregion
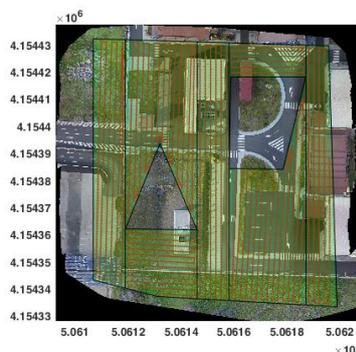

Figure 3. Example of environment decomposition and optimal coverage trajectories

These trajectories are useful in photogrammetry. In fact, by taking regularly spaced aerial pictures, if a suitable overlap is guaranteed, it is possible to derive the 3D structure of the environment, thanks to the so-called *structure from motion* approach. Nowadays, several mapping programs are available which can deliver different kinds of 3D models by processing the aerial pictures. In this work Pix4D Mapper has been used [6].

3. Coverage subregions assignment

Once subregions' coverage paths are defined, our approach exploits the use of a swarm of UAVs to parallelize the mission. This implies the definition of a rule to negotiate subregions assignment to each UAV. The strategy described in [7] has been adopted. It consists of computing the path lengths to each subregion via a 3D implementation of the A* algorithm for each UAV, from their starting positions. After that, all the possible combinations of UAVs/region are derived and, then, the combination with minimum total path length for the whole swarm is chosen. This is obtained by simply summing up the computed trajectory lengths for each UAV, for a certain combination. The enhancement in this work, with respect to [7] consists of considering both ends of the coverage trajectories as possible target positions while computing UAVs/subregion combinations. In fact, as underlined also by [2], coverage paths can be travelled indistinctly along two possible directions. In Figure 4 an example of targets assignment to a swarm of 6 UAVs is shown. It is possible to note that 3D terrain geometry is considered in trajectories computation.
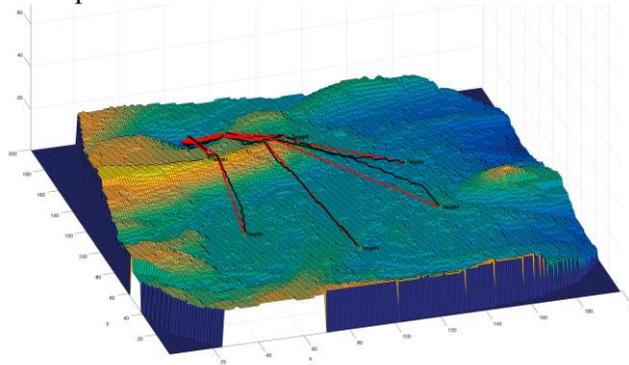

Figure 4. Terrain 3D model and UAV target assignment

4. Traversability costmap generation

Once the coverage mission is carried out by the swarm and the 3D model of the environment is computed by the mapping software, a terrain traversability analysis is performed on such model as reported in [8]. The outcome of this processing is a map including traversability costs derived by an analysis of the geometric properties of the environment. In particular, the Digital Elevation Model of the terrain is considered. In this manner the costmap can be given as heuristic to classical grid-based path planning algorithms. Thus, computed paths will result optimal in terms of crossing difficulty through the rough terrain. In this case, a D* algorithm has been used for the rover path planning. For the experimental testing the U-Go rover has been adopted [9], which is depicted in Figure 5.

Figure 5. The U-Go UGV robot adopted for the experimental tests.

5. Conclusions and future work

In this paper an integrated strategy for the efficient navigation of a rover in an outdoor unstructured environment has been presented. It exploits 3D photogrammetric reconstruction of the considered area, with the help of a swarm of UAVs to speed up the coverage mission and, therefore, the successive reconstruction.

As future development we aim at improving the subregion/UAV assignment by taking into account the coverage path lengths within each subregion, beside the distance to reach the subregion itself. Furthermore, if at least a rough 3D model of the environment is a priori known, a future enhancement would be to consider such geometry in order to keep a constant *relative* distance between the surveying UAV and the ground below.

6. References

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