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Aerial coverage optimization in precision agriculture management: A musical harmony inspired approach

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ABSTRACT

The coverage path planning (CPP) problem belongs to a sub-field of motion planning where the goal is to compute a complete coverage trajectory from initial to final position, within the robot workspace subjected to a set of restrictions. This problem has a complexity NP-complete, and has no general solution. Moreover, there are very few studies addressing this problem applied to aerial vehicles. Previous studies point out that the variable of interest to be optimized is the number of turns. Thus, by minimizing the number of turns, it can be ensured that the mission time is likewise minimized. In this paper, an approach to optimize this cost variable is proposed. This approach uses a quite novel algorithm called Harmony Search (HS). HS is a meta-heuristic algorithm based on jazz musician's improvisation through a pleasant harmony. Finally, the results achieved with this technique are compared with the results obtained with the previous approach found in the literature.

1. Introduction

Coverage path planning problem is the computation of a path that passes through all the required points in the workspace from a starting point to a final point. This problem has been mostly addressed to Unmanned Ground Vehicles (UGVs) applied in cleaning, farming, de-mining, etc.

The problem of covering a determinate area with an Unmanned Aerial Vehicles (UAVs) is directly related to the aforementioned problem. However, the aerial coverage path planning (CPP) problem is subjected to harder restrictions. Typically, UAV's have limited working cycles compared with ground robots (i.e. the mission time has to be carefully optimized). Furthermore, they are not able to take off or land in random places (initial and final positions are usually pre-defined).

Depending on the application, the problem restrictions can slightly change. Herein, the problem of covering a wide area with an irregular shape is considered for mosaicking purpose. Mosaicking is the technique of mapping an overall area by stitching a set of geo-referenced images acquired. In order to achieve this objective with an UAV, the workspace is sampled by using a regular grid (kind of Sukarev grid), where each cell corresponds to an image sample. Then, a complete coverage trajectory must be generated ensuring that no points are revisited, taking into account pre-defined take off and landing positions, a required minimum number of turns. In this way, the coverage time is minimized.

The study case presented is based on a vineyard parcel (see Fig. 1), since irregular shape fields are more challenging for addressing the related problem. Mosaicking procedures can be applied in vineyards parcels for weeding, frost monitoring, fruit maturity, as well as for measuring other biophysical parameters of interest.

The organization of the paper is as follows: After this brief introduction, Section 2 reviews some related works. Section 3 introduces the HS algorithm and shows how the CPP problem is addressed by employing this optimization technique. Section 4 presents the results obtained and makes a comparison with other techniques. Finally, Section 5 provides the concluding remarks of this work.

2. Previous work

Coverage path planning is an extensively studied field, and many techniques and works are presented in the bibliography. Two main approaches can be considered according to the execution of the algorithm: On-line and Off-line planners.

On-line planning schemes are mostly reactive, providing the system with much flexibility and robustness. Furthermore, they require sensor information as well as a more powerful CPU. The requirements have a direct impact on power consumption, and also within the admissible flight time, which is a critical constraint

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Fig. 1. Vineyard parcel.

in aerial robotics. On the other hand, Off-line systems are non-reactive to environmental changes but provide most efficient and suitable plans. Furthermore, they require less on-board power consumption and the CPU use, while – in most of the cases – they optimize the rate path/distance covered. The effect of this factor is appreciated in the duration of the mission, which appreciably decreases (Moon and Shim, 2009).

When multiple robots are used, a previous decomposition of the field to cover is required. Two approaches are commonly used: exact cell decompositions (Li et al., 2011; Maza and Ollero, 2007) and approximate cell decomposition (Valente et al., 2011). After this task, the path for every vehicle to cover the area assigned is computed.

There are a few references concerning this planning. One of them is the work presented by Maza and Ollero (2007), where a team of aerial robots have been used for inspection. After performing area assignation, the basic CPP algorithm based back and forth pattern with the minimum number of turns is executed for each robot. The solution proposed only considers convex areas without obstacles. Moreover, such approach is mainly focused on the robot assignment problem rather than the coverage path planning problem that is solved by using basic algorithms in comparison with the proposed approach.

Another approach that reports a solution to the problem of area coverage by using multiple UAVs applied to crop-dusting was presented by Moon and Shim (2009). Independently of the two algorithms presented in order to perform the decomposition of the area, a procedure that selects points inside the sampled set is employed to obtain a coverage trajectory. In the first case, the resulting area coverage path is generated by using a spiral from outside to inside, with no restrictions, which can be a problem in large areas if the UAV runs out of fuel. The second case is based on a well-known exact cell composition method that uses simple back and forth motions to cover the areas. In any case, the provided results are only referred to simulations.

Li et al. (2011) also reports aerial CPP solutions, but the emphasis of the work is focused on a recursive greedy algorithm applied in performing an exact cell decomposition method, not on the coverage path-planning problem which is solved by using back and forth motions. Additionally, the shortest coverage path is determined through an undirected graph, in order to reduce the number of turns. This work does not consider obstacles, and it is assumed that the aerial vehicle just flies over convex polygonal areas. The proposed method was only tested in simulations.

In previous work (Barrientos et al., 2011), an approach based on a wavefront planner with backtracking procedure was presented. Both heuristic and non-heuristic methods were applied. A comparison of the result obtained with the novel approach presented in this work, which employs a meta-heuristic algorithm, has been provided at the end of the work.

3. Coverage path planning optimization

3.1. Problem statement

The area coverage problem oriented to mosaicking missions can be abstractly described as follows: Given,

1. a convex or non-convex shaped area $A \subset \Re^2$ decomposed approximately by a finite set of regular cells $C = \{c_1, \ldots, c_n\}$ such that, $A \approx \bigcup_{c \in C} c$;
2. a coverage trajectory P with a finite set of continuous way-points p, which can be written as $P = \bigcup_{p \in P} p$. Where way-point correspond to the centroid of a corresponding cell, and consequently a cell correspond to an image sample, thus $dim(P) = dim(C)$;
3. a fleet of quad-rotors with attitude and position control, and capable of way-point navigation. Each quad-rotor is characterized by a position in $[X, Y, Z]$ and orientation[1] in $[\Theta, \Phi, \Psi]$.

Considering that valid solutions of P should not visit a waypoint twice, the variable of interest to minimize is the number of changes in directions, (i.e., turns made by a quad-rotor around the z-axis or yaw changes) as stated in Valente et al. (2011) where it was highlighted that both the travelled distances and therefore power consumption remains constant for a given scenario. The objective function can be given as follows,

$$J = K_1 \times \sum_{i=1}^{m} \psi_k^{\{i\}} + K_2, k \in \{\pm 135^\circ, \pm 90^\circ, \pm 45^\circ, \pm 0^\circ\} \quad (1)$$

considering that,

$$\psi_{\pm 135^\circ} > \psi_{\pm 90^\circ} > \psi_{\pm 45^\circ} > \psi_{0^\circ}, \quad (2)$$

where K_i are weights used in order to evaluate the performance of the solution. Thus, K_1 balances the amplitude of the turn and K_2 the displacement. Absolute values are no critical, nevertheless they should be representative of the cost in time required to perform the different amplitude turns. In any case,

$$K_2 > K_1, K_{1,2} \in \mathscr{R} \quad (3)$$

Finally, for each quad-rotor of the fleet an optimal trajectory can be computed by $minJ(\mathbf{x})$, where $\mathbf{x} = [\psi]^T$.

3.2. Harmony Search algorithm

The coverage path planning problem has complexity NP-Complete. As literature indicates (Back, 1996), no polynomial-time algorithm has yet been discovered for NP-complete problems. In many real life situations, high quality solutions to these problems such as multicast routing or vehicle routing are required in a very short amount of time, and many algorithms to tackle them have been developed. In cases, especially when large scale problems are considered, metaheuristics are one of the best alternatives since exact algorithms take exponential time to find an optimal solution. The approach proposed in this work: Harmonic Search (HS), falls inside this category of Metaheuristic algorithms.

Harmony Search is a population-based algorithm inspired in musician's improvisation process for a perfect musical harmony. Often referred as the "vertical" aspect of music (in opposition to the melodic line or "horizontal" aspect), it is understood as the superposition of individual chords that optimizes the global balance between the consonant and dissonant sounds.

[1] Roll, Pitch, Yaw.