



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



João Valente*, Jaime Del Cerro, Antonio Barrientos, David Sanz

Centre for Automation and Robotics (CAR) UPM-CSIC, C/ Jose Gutierrez Abascal, 2, 28006 Madrid, Spain

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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.

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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-de-

finied 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

* Corresponding author.

E-mail address: joao.valente@upm.es (J. Valente).



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 assignment, 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 $A \subset \mathbb{R}^2$ decomposed approximately by a finite set of regular cells $C = \{c_1, \dots, c_n\}$ such that, $A \approx \bigcup_{c \in C} c$;
2. a coverage trajectory P with a finite set of continuous waypoints p , which can be written as $P = \bigcup_{p \in P} p$. Where waypoints correspond to the centroid of a corresponding cell, and consequently a cell corresponds 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 orientation¹ 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 not critical, nevertheless they should be representative of the cost in time required to perform the different amplitude turns. In any case,

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

Finally, for each quad-rotor of the fleet an optimal trajectory can be computed by $\min f(\mathbf{x})$, 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: Harmony 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.

The algorithm was introduced by Geem et al. [Geem and Kim \(2001\)](#) in 2001 and has already been applied in several different engineering fields. Some examples of the algorithm usage for optimization can be found in [Tangpattanakul and Artrit \(2009\)](#), [Xu et al. \(2009\)](#), and [Yazdi and Haghghat \(2010\)](#). Moreover, it has been stated that this algorithm present advantages in comparison to other meta-heuristic algorithms ([Geem, 2009](#)).

The algorithm can be abstractly described as follow: Imagine having a group of Jazz musicians carrying different instrument. They start pitching some notes in order to try to compose a new song. As they search for a sequence of musical notes that give a good musical harmony, the harmonies achieved up to the moment are kept in mind. If a new harmony sounds better than a Harmony played before, then it is replaced by a new harmony. From an optimization point of view, each player represents a variable and each pitch, candidate value that is attained individually as a component of the global “melody”.

The main body of the algorithm is a Harmony Memory (HM) matrix (defined in 4), where rows are candidate solutions vectors, and columns are decision variables. The last column of the HM matrix is the cost function value. The HM matrix is initialized by generating random candidate solutions vectors.

The typical parameters from the HS algorithm are: Harmony Memory Size (HMS), Harmony Memory Considering Rate (HMCR), and PAR (Pitch Adjustment Rate). The HMS is the number of rows, or the number of candidate solutions considered. HMCR is the probability that each element of the HM matrix has to be chosen. Finally, a variable value is adjusted (switched by a neighboring value) with probability PAR. The uniform distribution $U(0, 1)$ is usually employed ([Geem, 2009](#)).

$$HM = \begin{bmatrix} \mathbf{x}_1^{\{1\}} & \dots & \mathbf{x}_{\{N\}}^1 & \mathbf{J}(\mathbf{x}^{\{1\}}) \\ \vdots & \ddots & \vdots & \vdots \\ \mathbf{x}_{\{1\}}^{HMS} & \dots & \mathbf{x}_{\{N\}}^{HMS} & \mathbf{J}(\mathbf{x}^{\{HMS\}}) \end{bmatrix} \quad (4)$$

The algorithm can be synthesized in five steps: *Step 1*, Initialize HM; *Step 2*, Improvise a new harmony vector $\mathbf{x}' = \{x'_1, \dots, x'_N\}$ from the HM (with or without PAR) or by randomness. Improvisation means the generation of a new candidate solution vector. In other evolutionary algorithms (e.g., Genetic algorithms (GA)) this step is addressed by the crossover operation; *Step 3*, Replace the new harmony by the worst in HM if better; *Step 4*, Check if stop criterion has been met (e.g. iterations, cost); if not, go to *Step 2*, or else return the best solution.

3.3. Problem solving with HS algorithm

In order to address the aerial CPP problem with HS algorithm, the main body of the optimization algorithm had to be adapted according to the formulated problem in the previous subsection. In the following lines, the step-by-step procedure of the algorithm is described.

As previously explained, HM is the main body of the HS algorithm. The candidate solutions are herein stored, represented by N dimension vector, which is made up of decision variables from the optimization problem. Each decision variable is a real number that identifies the cell to be visited by the aerial robot. Thus, a simple representation by using a real number is used to identify the UTM coordinates of the center of a cell, that finally stands for a way point in the trajectory of the aerial robot where a picture is going to be taken, such that $X_i \in P$ with $i = 1, \dots, n$, where $n = \dim(P)$ (shown in [Fig. 2](#)).

[Fig. 3](#) shows how the variables are managed in the problem by considering HM with HMS = 2. The depicted coverage trajectories are for example the first two random Harmony vectors in the HM. The dotted lines are the path transversed by the quad-rotors, which in both cases start from the cell with index 1 to the cell with index 4.

Summarizing, for each drone, a HS matrix that contains a set of candidate solutions (i.e., trajectories for an UAV) is created and initiated according to the method explained in [Section 3.3.1](#). After that, the cost function called “Harmony Vector Cost” is optimized by applying the method of “Improvisation” described in [Section 3.3.2](#) that is the core of the HS algorithm until and optimal solution is found. Next subsections explain in detail these procedures.

3.3.1. HM initialization

The first step of the HS algorithm is the initialization of the HM. In the first iteration the Harmony vectors (i.e. solutions) are usually generated through a random process. As observed from the aerial CPP problem, the time represents the main constraint of our problem, which causes other constraints to arise, such as the number of revisited places in the environment. It is obvious that by reducing the number of revisited cells in the environment, the path generated is also shortened, and consequently, its coverage time. In order to solve the problem more challengingly and optimize the time as much as possible, the number of revisited points in the environment should be reduced. As a result, HM with HMS permutation vectors with N elements must initially be generated randomly.

An algorithm denoted Random Breath Coverage (RBC) has been used for generating random Harmony vectors with permutation.

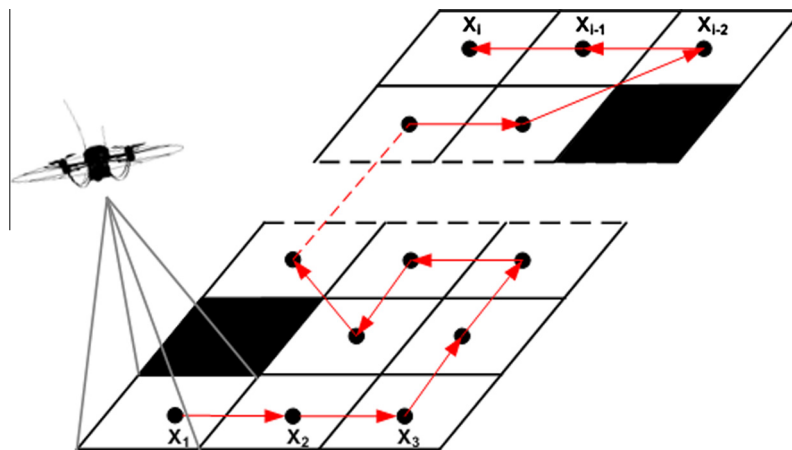


Fig. 2. Decision variables mapped over the field.

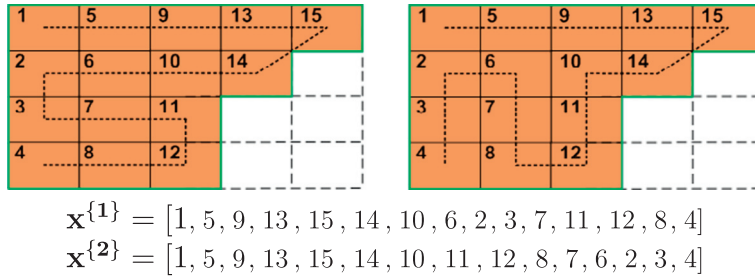


Fig. 3. Numerical example showing how the decision variables are managed to adapt HS algorithm to the problem.

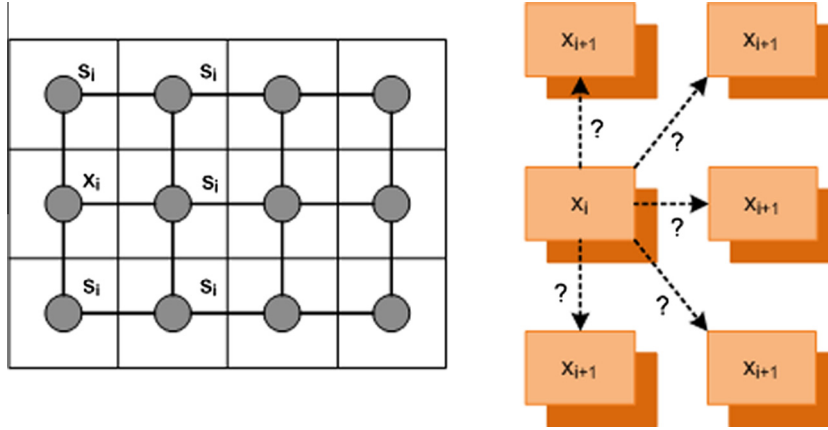


Fig. 4. Sibling set over the unitary graph. Each sibling is a nearest neighbor cell.

RBC algorithm is a hybrid algorithm that employs two algorithms: Random Search (RS) and Breadth-First Search (BFS). This algorithm provides a simple way to handle the HM initialization (Step 1). The algorithm pseudo-code is depicted in Algorithm 1.

Algorithm 1. Random Breath Coverage algorithm

```

1: Initialize FiFo = Start
2: while S ≠ ∅ do
3:   S ← BFS(FiFo)
4:   s ← random(S)
5:   FiFo ← FiFo + s
6: end while
7: if dim(FiFo) = dim(C) then
8:   P ← FiFo
9: else
10:  P ← ∅
11: end if
12: Return P
    
```

RBC algorithm expands all nodes from the unitary graph in a random fashion from the starting position, which is equivalent to take-off deck within the aerial robot workspace. Each node can or cannot have neighboring nodes,² the set that contains all siblings is denoted by S, such that $S = \bigcup_{s \in S} s$ (see Fig. 4). The RBC algorithm finishes when $S = \emptyset$. If the candidate vector size is less than the number of decision variables, it means that the node expansion has stopped without passing through all the nodes. Consequently, that incomplete candidate vector is discarded.

3.3.2. New harmony vector improvisation

An iterative process called improvisation starts after generating HM through the method previously described. In order to ensure the permutation of the Harmony vector, the new vector must be carefully obtained by slightly changing the mechanism of the conventional HS algorithm.

As in Step 2, each element of the new vector x' is either selected from the HM or the entire possible range of values, according to previously mentioned (see Section 3.2) HMCR or 1-HMCR probabilities, respectively. In the following paragraphs, the mechanism for each probability will be explained in detailed.

In the conventional HS algorithm a new x'_i value is randomly chosen with 1-HMCR probability from the possible range of values. On the other hand, an x'_i value is typically chosen from the i th column of the HM with HMCR probability. In the present approach, the same reasoning is applied but taking into account that the trajectory continuity must be ensured due to it has been set as a requirement (i.e., jumps over the cells are not allowed).

This problem can be solved as follows: a new x'_i value is randomly chosen with 1-HMCR probability from the set of the neighbors of that decision variable (i.e. all free cells adjacent to the cell addressed by the decision variable), thus the continuity of the trajectory is ensured due to jumps to furthest cells are not considered. Moreover, a random value from the i th column is selected according to the unvisited neighbor cells with HMCR probability. If there are no unvisited neighbor cells in that column, it chooses a random neighbor in the HM is chosen (see Eq. (5)).

$$x'_i \leftarrow \begin{cases} x'_i \in \begin{cases} S_i \in X_i & \exists \in X_i \\ S_i \in X & \nexists \in X_i \end{cases} & w.p \text{ HMCR} \\ x'_i \in S_i & w.p \text{ 1-HMCR} \end{cases} \quad (5)$$

Besides the aforementioned occurrences, if the probability falls on HMCR, it has to be checked again that a new pitch adjusted (PAR)

² parent-child relationship.

is required or a new value from the decision variable remains unchanged (1-PAR).

In case the pitch is not adjusted, the new value of the Harmony vector remains unchanged. Otherwise, some tuning must be done in this decision variable. Usually, the adjustment relies on the displacement of K neighboring values in the candidate set of values. In such case, the pitch adjustment is the displacement of one neighbor within the neighborhood, by adding or subtracting a unit in the admissible neighbors set (see Eq. (6)).

$$x_i'' \leftarrow \begin{cases} x_i' \pm 1 & \text{w.p PAR} \\ x_i' & \text{w.p 1-PAR} \end{cases} \quad (6)$$

3.3.3. HM update

Every time that a new x_i' vector is created, the Harmony vector cost is computed by using the cost function defined in Eq. (1). If the cost computed is better than the worst Harmony vector cost in the HM, the new vector is then added to the HM, and consequently the Harmony vector with the worst cost discarded from the HM matrix. If not, the HM remains unchanged (Step 3).

3.3.4. Stop criterion

Similar to other optimization algorithms, the role of the stop criterion role is to stop the optimization process when a determinate criterion is achieved. After some iterations, the stop criterion can be set to reach a reasonable number of turns, or even a determinate number of iterations. Since the goal is to improve

the results obtained with the wavefront planner with backtracking approach. After successfully obtaining less than one turn than in the previous approach, the stop criterion was set to stop in 100 iterations. It was experimentally proven that the best solution settles before that value. The stop criterion was initially set to stop when the number of turns decreases a turn with regards to the previous approach presented in Barrientos et al. (2011). This upper-bound iteration was obtained by trial and sufficient to optimize all the aerial trajectories presented in the Section (Step 4). This can be better understood in the Section 4 through Fig. 8.

4. Results

As previously mentioned, the case study presents a vineyard parcel located in the southwest of Madrid, Spain (orthophoto shown in Fig. 5). Furthermore, the results obtained in a previous approach have been compared with the HS algorithm results.

In such manner, the results obtained by using the first approach are shown in Fig. 6. As observed, it is an area with irregular shape that is divided into three quad-rotors through a negotiation-based approach. The results obtained from this process determine that the first area assigned to quad-rotor 1 can be sampled in 14 images (5–40); second area, assigned to quad-rotor 2 can be sampled in 15 images (13–53); and finally, the third area assigned to quad-rotor 3 can be sampled in 25 images (47–99).

The workspace previously used in Barrientos et al. (2011)) was used in order to establish a comparison among the approaches



Fig. 5. Orthophoto of the vineyard parcel and landscape.

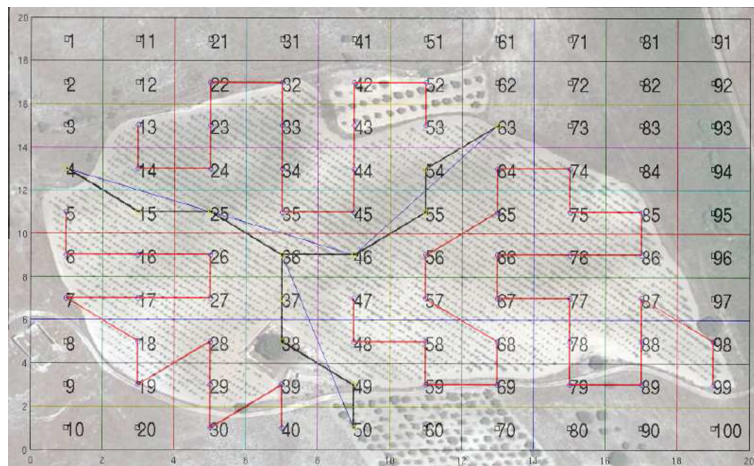


Fig. 6. Coverage trajectories obtained previously for three quad-rotors.

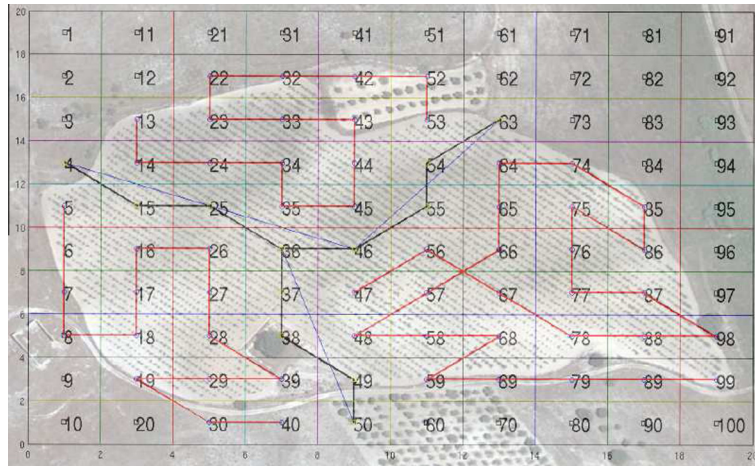


Fig. 7. Coverage trajectories obtained with the HS algorithm for three quad-rotors.

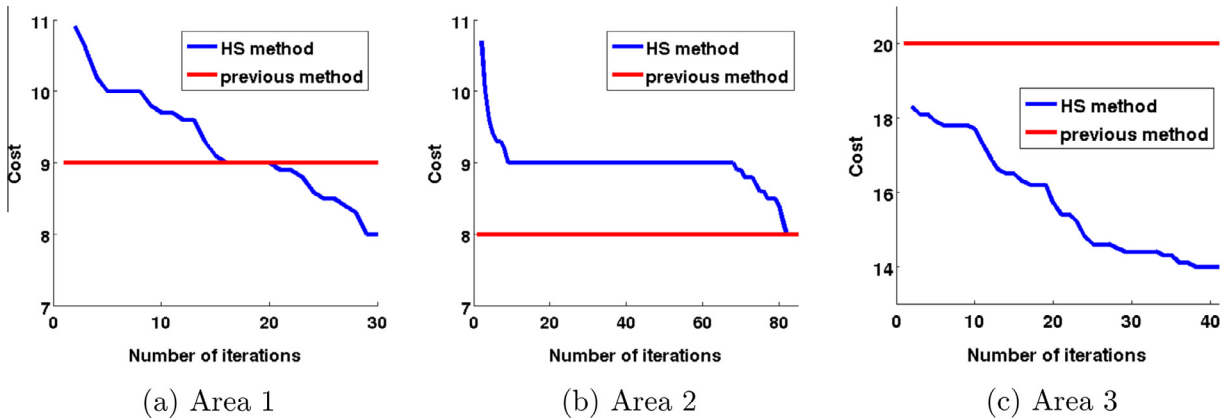


Fig. 8. Optimization through iterations of the coverage trajectories.

mentioned. Therefore, it was assumed that the area negotiation and assignment are the same as in the previous approach. The trajectories obtained with the HS algorithm are shown in Fig. 7. It can be observed that the number of planned images to be acquired is equal in both workspaces, and that the take-off and landing positions are maintained. The HS algorithm parameters employed in each area were HMS = 10, HMCR = 0.9, PAR = 0.3. The results presented were obtained with the following number of iterations per area, respectively: Area 1, 28 iterations, Area 2, 85 iterations, Area 3, 40 iterations. Fig. 8 also depicts the optimization of the trajectories iteration by iteration. It should be noticed that the cost, means the average cost (i.e. turns) in the HM matrix.

A comparison with the results obtained in both approaches are shown in Table 1. It can be observed that the number of turns obtained per trajectory using HS algorithm are lower than the former approach employing wave-front planner and backtracking procedure. Herein, the results considering the number of turns and the computation time of the coverage paths are discussed. The number of turns per area has been improved, which can be better observed in the third area, where the number of turns was significantly improved. For example, in the second area the number of turns was maintained. However, it can be easily noticed that the trajectory is already fully optimized and there is no change that a trajectory can be computed with less turns. Regarding, the computation time, it can be observed that slightly increased. However, on the one hand, this planning is off-line, and on other hand, the worst case required is 13 s, which is an acceptable computation time considering

Table 1 Comparative between the former CPP approach, and the improved one, with the HS algorithm.

	Turns			Computation time (s)		
	Area 1	Area 2	Area 3	Area 1	Area 2	Area 3
Approach in (Barrientos et al. (2011))	9	8	20	0.15	0.02	0.02
HS algorithm approach	8	8	14	0.19	0.5	13

the complexity of the problem, as enhanced in Valente et al. (2011). Thus the computation time is useless to be considered as a drawback in this approach.

5. Conclusions

In this paper, a new approach to improve coverage trajectories was successfully employed. A novel algorithm denoted by Harmony Search was studied to be applied to the optimization of agricultural management tasks.

The results obtained with HS algorithm was compared with a former approach employing a wave-front planner with a backtracking procedure presented in Barrientos et al. (2011). The present approach showed better results in route optimization compared with the former method. The key feature of this approach is that it is able to reduce the number of turns of the

coverage trajectories significantly by holding the former start and goal positions set previously. Although, the computation time is greater than in the previous approach, it is an affordable cost, since the mission planner's aim is not to work on-line.

Moreover, the presented approach can be employed to plan aerial coverage missions using any type of UAV, as well as in any agricultural field with regular or irregular shape. Moreover, the mission completion time is reduced by minimizing the number of turns, improving safety for the operator and UAVs. In addition to this, and not less important, it optimizes the usage of resources and the economical cost involved in the mission.

This meta-heuristic algorithm is potentially a valuable method when employed in optimizing problems with high complexity. In such manner, the present approach can be extended to other problems of PA practices where autonomous robotic systems could be applied.

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