Decentralized strategy to ensure information propagation in area monitoring missions with a team of UAVs under limited communications

Jose Joaquin Acevedo, Begoña Arrue, Jose Miguel Diaz-Bañez, Inmaculada Ventura, Ivan Maza and Anibal Ollero

Abstract— **This paper presents the decentralized strategy followed to ensure information propagation in area monitoring missions with a fleet of heterogeneous UAVs with limited communication range. The goal of the team is to detect pollution sources over a large area as soon as possible. Hence the elapsed time between two consecutive visits should be minimized. On the other hand, in order to exploit the capabilities derived from having a fleet of UAVs, an efficient area partition is performed in a distributed manner using a one-to-one coordination schema according to the limited communication ranges.**

Another requirement is to have the whole team informed about the location of the new pollution sources detected. This requirement is challenging because the communication range of the vehicles is small compared to the area covered in the mission. Sufficient and necessary conditions are provided to guarantee one-to-one UAV communication in grid-shape area partitions, allowing to share any new information among all the members of the team, even under strong communication constraints.

The proposed decentralized strategy has been simulated to confirm that fulfils all the goals and requirements and has been also compared to other patrolling strategies.

I. INTRODUCTION

The deployment and operation of a large-scale system of heterogeneous cooperating objects, including aerial robots, is addressed in the PLANET European Project[1]. The monitoring of the Doï¿½ana National Park in Spain is one of the validation scenarios of the project. In particular, the project considers area monitoring missions to detect and localize pollution sources.

Monitoring missions have been widely studied in different contexts [1], [2]: automated inspection, search and rescue missions, planetary explorations, etc. A decentralized solution using a large-scale team of UAVs in the PLANET monitoring mission is proposed in this paper. The application of multi-UAV systems allows to accomplish them with robustness against failures, higher spatial coverage and an efficient deployment [3], [4], [5].

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[1] http://www.planet-ict.eu/

In this paper, in order to exploit the capabilities derived from having a fleet of UAVs, an efficient area partition is performed in a distributed manner using a one-to-one coordination schema according to the limited communication ranges. The whole area is divided into non-overlapping sub-areas, each one to be monitored by an UAV that cooperates with the other UAVs in the mission. An efficient area division minimizes the time to cover the whole area. Each UAV covers an area size according to its motion and sensing capabilities. This task can be computationally expensive when using a centralized algorithm and the solution may not be fault-tolerant against failures, initial conditions variations and uncertainties. But a decentralized approach offers robustness and dynamism, in a way that each UAV can quickly self-adapt its sub-area. Therefore, the system is able to perform the monitoring mission in the more efficient manner, even when there are not communications between the control station and the UAVs.

However, in a distributed system, the information exchange between UAVs can be difficult in those cases where communication constraints must be faced with. A *one-to-one* coordination technique allows the system to obtain the whole coordination from local decision and information. The resulting system is scalable, because each UAV only needs information from nearby neighbors. This technique was applied to coordinate a team of homogeneous UAVs to cooperate in the surveillance of rectangular areas in [6].

This paper presents a decentralized strategy to ensure information propagation in area monitoring missions with a fleet of UAVs. An irregular area has to be monitored by a team of heterogeneous UAVs searching for possible pollution sources. The objective is not only to minimize the time to detect pollution sources but also the time to share detection data between the whole team, even under communication constraints. Besides this, the system has to be able to self-adapt quickly to changes in the initial conditions (UAV capabilities, area shape and size). The main novel contributions of this paper are to provide sufficient and necessary conditions to guarantee multi-UAV synchronization using an area partitioning strategy and to solve the cooperative monitoring problem jointly for irregular areas and heterogeneous robots.

II. RELATED WORK

Area monitoring missions can be addressed using a frequency-based approach, where the objective implies to

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optimize the elapsed time between two consecutive visits to any position which is known as the refresh time. This approach has been used by many authors, obtaining solutions to guarantee an uniform frequency of visits as in [7], or the maximal minimum frequency as in [8]. The obtained solution is a deterministic motion plan for each vehicle. Some authors, as in [9], address the patrolling problem in adversarial settings. A deterministic solution can be useless to detect intelligent intruders because they could learn the strategy. Therefore, they solve the problem using a probabilistic approach. On the other hand, the frequency-based approach fits well in the pollution detection scenario posed in the PLANET project.

Different algorithms have been proposed to solve the problem of multi-robot area patrolling missions from a frequency-based approach. In [10], partitioning and cyclic patrolling strategies are defined and compared. Authors of [11] analyze the *refresh time* and *latency* in area coverage problems with multiple robots using different approaches. A partitioning method is proposed in [12] to monitor a set of positions with different priorities.

This paper proposes an area partitioning strategy to solve the problem for irregular areas and heterogeneous UAVs. The whole area is divided into non overlapped sub-areas and each UAV covers a different sub-area using an efficient path, i.e. all the positions in the area are monitored while the path is traveled, minimizing the total path length. A similar strategy was presented in [6] to solve the area patrolling problem with a team of homogeneous UAVs and rectangular areas. On other hand, in [13] the problem with irregular areas and heterogeneous UAVs is solved using a path partitioning strategy. A single coverage path is created to monitor the whole area and the path is divided in segments that are allocated to the different UAVs. Other authors as [14] propose cyclic strategies where all the robots patrol the same closed coverage path in the same direction and equally spaced through it. This strategy offers theoretically optimal results from a frequency-based approach with homogeneous robots. However, in scenarios with constrained communications, the robots could not share the required information.

Reference [15] proposes an on-line algorithm where the area to cover is initially unknown that solve the problem for multi-robot systems using Voronoi spatial partitioning. An off-line algorithm, where the area to cover is known *a priori*, is proposed in [16]. Authors creates an spanning tree to generate a coverage path around it. The most well known off-line coverage path planning is called *Boustrophedon Cellular Decomposition* and was presented in [17]. It proposes to divide the whole area into smaller sub-areas which can be covered with a simple *back and forth* method. In our work, a *back and forth* method with some additional modifications to obtain a closed coverage path is proposed. These modifications are directed to keep periodical data interchange between neighbors even under limited communication ranges.

Regarding decentralized coordination, authors of [18] use the technique of *coordination variables* to ensure cooperation between a team of UAVs to accomplish a perimeter surveillance mission. *Coordination variables* are the minimum global information required by each robot to solve the problem in a coherent manner. The selection of that variables can be difficult for complex problems. In [6], the technique called *one-to-one coordination* is presented to solve a rectangular area coverage problem with a team of homogeneous UAVs. This technique implies that each pair of UAVs solves a coordination problem including only their own information. In [19], the authors use a similar technique to coordinate a team of video-cameras in surveillance missions.

A *one-to-one coordination* technique is proposed in this paper to solve monitoring missions of irregular areas with a team of heterogeneous UAVs from a frequency-based approach using an area partitioning strategy.

III. AREA COVERAGE WITH A TEAM OF UAVS ENSURING INFORMATION EXCHANGE

Let us consider an irregular area $S \in \mathbb{R}^2$ with a surface A which has to be patrolled by a team of heterogeneous UAVs $Q := \{Q_1, Q_2, ..., Q_N\}$ to detect pollution sources (see Fig. 1). There is no “a priori” information about the area, so the pollution sources can appear in any position with the same probability. Then, all the positions into the area S should be monitored at the same minimum rate. This problem is an extension of the one described in [6], but addressing the information propagation in large-scale teams of heterogeneous UAVs into large irregular areas and under communication constraints.

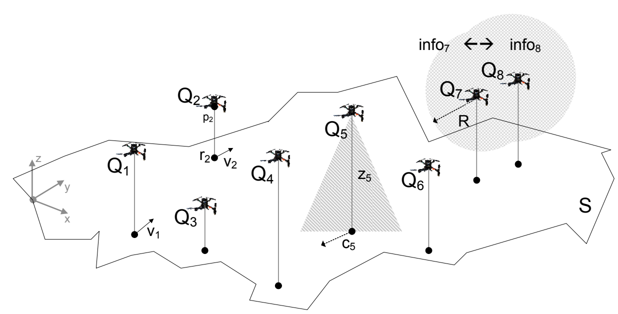

Fig. 1: A team of eight UAVs has to monitor an irregular area S to detect pollution sources that can appear in any position with the same probability. All the positions into the area S should be monitored at the same minimum rate.

At any time t, each UAV Q_i moves along the area S following a path with a motion speed $v_i(t)$ and monitoring an area $C_i(t)$.

$$C_i(t) := \{r \in \mathbb{R}^2 : |r - r_i(t)| < c_i(t)\}, \qquad (1)$$

where $r_i(t) \in \mathbb{R}^2$ is the UAV center projection on the plane $z = 0$ and $c_i(t) = z_i(t) \cdot \tan(\theta_i)$ is the actual UAV coverage range, with $z_i(t)$ as its altitude and θ_i as its angle of view.

Each UAV Q_i could have different capabilities: a maximum motion speed $v_i^{\max}$ and a maximum coverage range $c_i^{\max}$ related to its optimal flight altitude h^{opt}. The *coverage speed* a_i can be defined as the area covered per second and

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can be approximated according to the coverage range c_i and the motion speed $v_i(t)$ as

$$a_i(t) \approx 2c_i(t)v_i(t)\,. \quad (2)$$

A communication range R for the UAVs is also considered: two vehicles can exchange information only if they are close enough, i.e. the distance between them is less than the communication range R.

The objective is to design a cooperative patrolling strategy for minimizing both the maximal refresh time (T_r) and the maximal time to share a detected information with the rest of the team (latency T_s). The second objective is challenging due to the communication constraints mentioned above.

A. Area partitioning strategy

The area S is divided in N non-overlapped sub-areas S_i. The union of them will be the whole area S.

$$\begin{aligned} S_1 \cup S_2 \cup ... \cup S_N = S \\ S_1 \cap S_2 \cap ... \cap S_N = \emptyset \end{aligned} \quad (3)$$

Each UAV Q_i can patrol a sub-area S_i following a different coverage closed path P_i. The minimum maximal refresh time is obtained if the UAVs move at their optimal altitude with their maximum speeds, and each one covers a sub-area S_i with a size of A_i related to its own maximum coverage speed:

$$A_i = a_i^{\max} \frac{A}{\sum_{j=1}^{N} a_j^{\max}}, \forall i = 1, ..., N \quad (4)$$

Because of the minimax criterion, we can assume, without lost of generality, that all UAVs spend the same time T, to complete its own coverage path P_i. Then, the minimum maximal refresh time will be lower limited to T.

$$T = A_i/a_i^{\max} = \frac{A}{\sum_{j=1}^{N} a_j^{\max}} \quad (5)$$

The area partitioning strategy should offer better result with non homogeneous UAVs because it exploits their different capabilities: maximum speed and maximum coverage range. Other kinds of patrolling strategies does not take advantage of the better performance that can have some vehicles in the team.

Ensuring that any information detected by an UAV can be shared with the rest of the team implies that adjacent paths of two UAVs should be linked by a pair of positions near enough (closer than the communication range), and the UAV should be synchronized in time when visiting these positions. Synchronization will be studied in Section IV. Maximum time to share information T_s depends on the division shape and will be considered in Section V.

IV. SYNCHRONIZATION FOR INFORMATION SHARING

Let us assume that the area division is given by N non overlapped sub-areas with N non overlapped closed paths, each one traveled by a different UAV. A communication data link between two UAVs is possible only if the distance between two points of their paths are closer than the communication range R and the UAVs are synchronized in time when visiting these points.

Let us define a *link* between each pair of paths by two points, one for each path, with a distance between them lower than the communication range R. Then, two UAVs are defined as *neighbors* if they have a common link. They can exchange information if they are synchronized, i.e. they pass through the link simultaneously. In order to ensure information exchange in the system, every pair of neighbors has to be synchronized. For a general model, a synchronization between two neighbors cannot be guaranteed. For example, if the speed is constant and the lengths of the paths are not proportionally rational, a synchronized flight is not possible. In this section it is considered a simplified model where the synchronization between a team of UAVs can be achieved. After that, it is shown that the characterization for a solution in the simple model can be useful to guarantee the information exchange in more general scenarios.

A. The simple model: circular paths

Assume that all the UAVs move on unit circles in the counterclockwise direction at constant speed. With this assumption, it is given N pairwise disjoint unit circles $C_1, C_2, \ldots, C_N$ and N UAVs $Q_1, Q_2, \ldots, Q_N$ moving on the circles. A model with the above constraints is named here as the circular model. Let R be the communication range and two UAVs are neighbors if the smallest distance between the circles is less or equal to R. Thus, two neighbors can see each other at the smallest distance between the circles.

Given a set of paths (unit circles), it is defined the visibility graph associated to the range R and the set of circular paths as a planar graph $G(R) = (V, E(R))$ whose vertexes are the centers of the circles and the edges connect two centers if their distance is less or equal than $2 + R$. Figure 2 shows an example of visibility graph for a team of 17 UAVs in Doï¿$\frac{1}{2}$ana Park area. The boundary of the park is a simple polygon.

Let us denote the position of an UAV by the angle on its circle (measured from the positive horizontal axis). Let α_i be the starting position of the ith UAV. Furthermore, for any pair of UAVs, i and j, ϕ_{ij} denotes the angle at which i is closest to j's trajectory (see Fig. 3). A graph $G(V, E)$ is *bipartite* if there are sets $V_1, V_2 \subseteq V$ such that $V_1 \cup V_2 = V$, $V_1 \cap V_2 = \emptyset$, and $(u, v) \in E$ only if $u \in V_1$, $v \in V_2$ or $v \in V_1$, $u \in V_2$. Additionally, a graph is bipartite if and only if it has no subgraph that is a cycle of odd length.

In [20], it has been proved the following result.

Theorem IV.1 *A team of aerial robots in the circular model can be synchronized if and only if the visibility graph is a*

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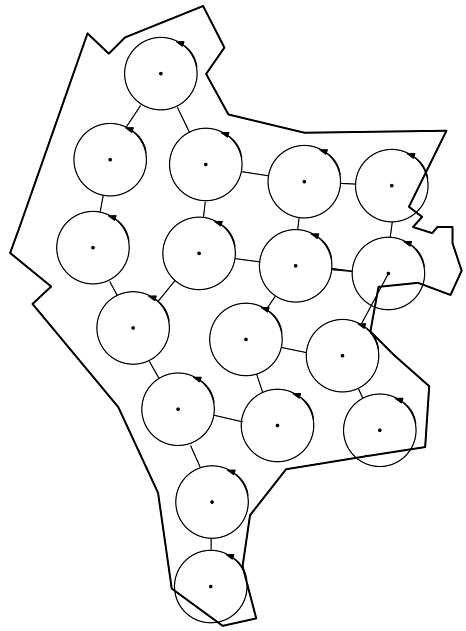

Fig. 2: An example of visibility graph for a team of 17 UAVs in Doï¿$\frac{1}{2}$ana Park area.

bipartite graph. Moreover, the condition $\phi_{ij} = \pi + \phi_{ji}$ for every pair of neighbors $i \neq j$, ensures synchronization of the team.

Figure 3 illustrates Theorem IV.1. It is easy to see that the difference between two starting points corresponding to neighbors is π.

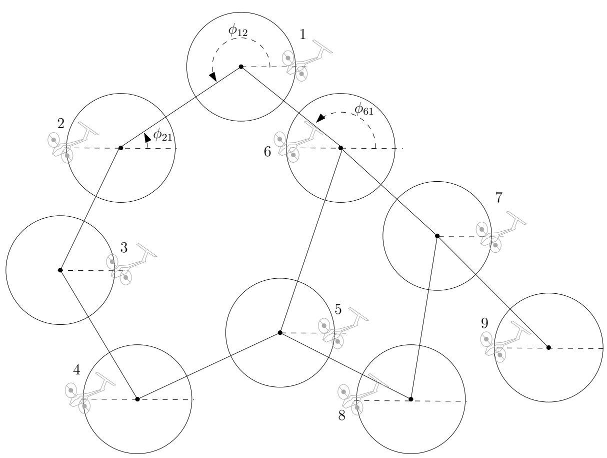

Fig. 3: A synchronized scheduling in the circular model. The UAVs are in the starting position.

Thus, after the area partition is given, Theorem IV.1 suggests the following algorithm:

- Compute the visibility graph, $G(R)$.
- Test if the graph is bipartite.
- If the graph is bipartite, locate each UAV at the starting position as in Fig. 3, that is, if the starting position of one UAV is α, the neighbors start at $\alpha + \pi$.

Notice that if the graph $G(R)$ is bipartite, then a synchronized scheduling of N UAVs is possible and it can be done in $\mathcal{O}(N)$ time. In Fig. 2, a bipartite graph allows the synchronization of 17 UAVs in the decentralized cooperative surveillance of the Doï¿$\frac{1}{2}$ana Park.

As a consequence of above results, it is possible to guarantee the information exchange and minimize the time to share any information between the robots (ensuring that each pair of neighbors pass through the common link simultaneously) under the following constraints:

1) The trajectories are equal-size circles.
2) All UAVs travel in the same direction.
3) The time spent on each path is a constant.
4) The visibility graph is bipartite.

B. Adapting the approach to more general scenarios

Now, it is explored how to relax the above constraints. In general, a strategy to address a more realistic model would be to adapt both the trajectories and connections of the UAVs so that the properties that ensure synchronization are satisfied. Here two examples are considered. Namely, cases of non-circular paths and non-bipartite visibility graphs. Other cases could be addressed as well.

Let us assume that we are given a bipartite visibility graph associated to a system of N non-circular periodic trajectories where the UAVs travel with the same speed in the same direction. Some constraints on the paths can be considered to ensure synchronization. For instance, if the paths are boundaries of geometric shapes that are symmetrical with respect to a point (center), the synchronization can be guaranteed. In this case, the condition of Theorem IV.1 is satisfied and the starting positions of the UAVs can be located by the rule $(\alpha, \alpha + \pi)$ for every pair of neighbors. An example is illustrated in Fig. 4. Notice that since the links connect the centers, they are not necessarily located at the closed pair between the corresponding paths.

Now, let us assume that the visibility graph associated to a system is non bipartite, then a synchronized surveillance can not be scheduled. If the aim is to consider a solution with the maximum number of possible links, it arrives to a classical problem in computer science: the *maximum bipartite subgraph problem*, MBS-problem, for short. Finding a bipartite subgraph with the maximum number of edges is a classical NP-complete problem [21]. However a maximum bipartite subgraph of a planar graph can be found in polynomial time [22]. Since the visibility graph is planar (the links do not cross each other), it is possible to adapt some algorithms from the literature to our problem. Many of them are based on the reduction of the MBS-problem to the *maximum cut problem*. See, for example [22], where the maximum cut problem is solved by means of the *maximum weighted matching problem*.

The general idea of the algorithms is to remove odd cycles in the planar graph, [23]. Thus, in practical situations with few UAVs, the odd cycles can be removed by information exchange between the robots. Figure 4 shows a bipartite

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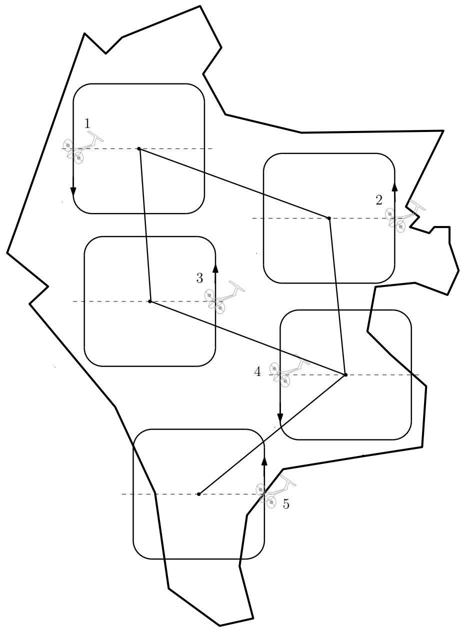

Fig. 4: A synchronized system for non-circular trajectories.

graph that could be obtained after removing the connection link between the robots 3 and 5.

V. GRID-SHAPE AREA DIVISION

Any division of an area S in N non overlapped sub-areas with N closed coverage paths can be associated to a visibility graph G related to a communication range R, when it is assumed definitions described in Sect. IV. The first condition to ensure a complete synchronization of the N UAVs, minimizing the time to share informations between the whole team, is to obtain a bipartite graph.

The challenge is to divide the area S to obtain a bipartite graph maximizing the amount of links and minimizing the time to share an information between the whole team of UAVs. Two simple bipartite graph would be the grid-shape and the vector-shape graphs (see Fig. 5). Given a *mxn* grid, with m rows and n columns, the total number of links will be $m \cdot (n-1) + n \cdot (m-1)$.

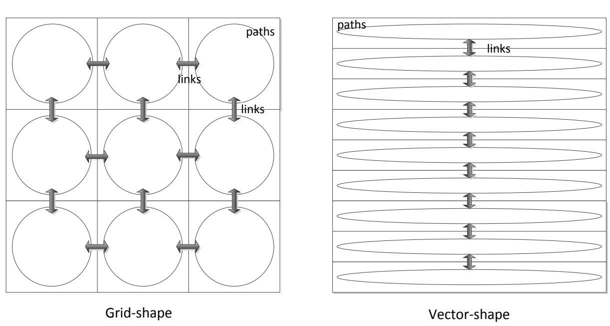

Fig. 5: Grid and vector-shape area division.

Assuming a $m \times n$ grid-shape area division, it is possible to compute the maximum time to share an information between all of them. From Sec. III-A it follows that all the UAVs should take the same time T to cover their own sub-areas. In a grid-shape division (graph), each path (node) has at most 4 link positions, and the distance between each pair of consecutive links is the same $T/4$. The time to share an information between the whole team of UAVs T_s depends on the number of links between the two farthest paths (nodes). The two farthest nodes will be located in two non consecutive corners. The amount of links between them will be $(n-1)+(m-1)$.

The time since an UAV detects any event till that it is communicated with its neighbors is at most T. Now, information can travel to the farthest UAV in three different manners: horizontally, vertically, or diagonally. In any of the three cases, the time to cross a pair of links is the same, see Fig. 6.

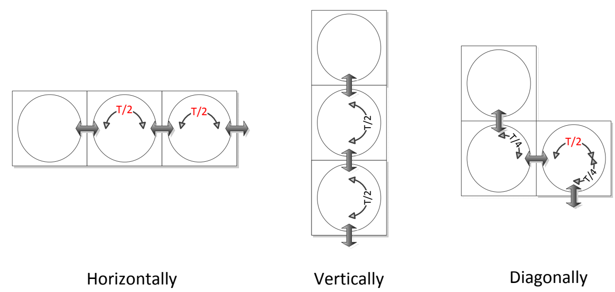

Fig. 6: Different manners to cross a pair of links.

Therefore, following a monotone path, it is easy to compute an upper-bound time to share any information, see Fig. 7:

$$\begin{aligned} T_s &\leq T + (n-2)T/2 + T/4 + (m-2)T/2 \\ T_s &\leq 5T/4 + (n+m-4)T/2 \end{aligned} \qquad (6)$$

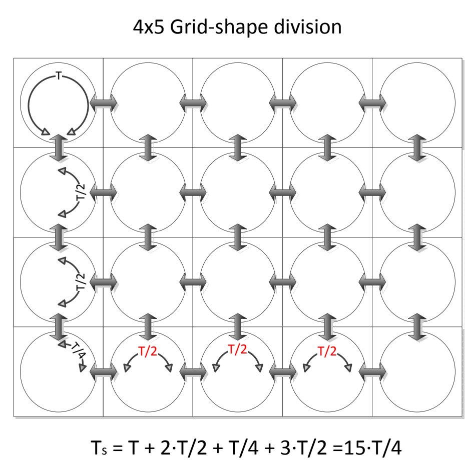

Fig. 7: Maximum time to share between the two farthest paths in a 4x5 grid.

If the area is divided using a vector-shape $N \times 1$, the total number of links in the graph will be $N-1$. To share an information between the two farthest UAVs, this one should cross the $N-1$ links. Then, as $N = n \cdot m$, the upper-bound time to share information will be:

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$$T_s \leq T + (N-2)T/2 = T + (n \cdot m - 2)T/2 \qquad (7)$$

For any $n, m > 2$, the grid-shape division offers better performance than the vector-shape one. Furthermore, it is easy to show that the best $m \times n$ grid-shape division will be one which minimizes the maximal between n and m. If $N = n^2$, the best division will be a square-shape division $n \times n$.

VI. DECENTRALIZED IMPLEMENTATION

In [6], a modular architecture is proposed to solve in a decentralized manner an area surveillance problem with a team of homogeneous aerial robots and assuming only rectangular areas. Now, significant modifications in the decision-making and path generator modules are proposed to ensure synchronization in grid-shapes area division minimizing the time to share information. The resulting system can be applied with heterogeneous UAVs and irregular areas.

A. *Pseudo-symmetric coverage path*

According to Sect. IV the second condition to keep a complete synchronization between the UAVs is that all the paths were symmetric with respect their own center. This condition can be not possible if UAVs cover irregular areas with different shapes.

However, it is possible to ensure synchronization even with no symmetric paths assuming some extra conditions. Given a grid-shape graph, each path should have 4 possible link positions. Consider a non symmetric closed coverage path for each sub-area (node), so that the distance between consecutive link positions is the same, and define it as *pseudo-symmetric path*. Hence, if all the UAVs take the same time to cover their paths, it is possible to ensure synchronization if starting position of neighbor UAVs are non consecutive link positions. Then, if Q_i starts its motion in its own first link position, all their neighbor UAVs start in their own third link position.

The authors define in [13] a quality index to compare the length of a coverage path with respect to the theoretically optimal according to the coverage range. Let us assume that all the generated paths have a perfect quality index of 1. In this case, any pair of areas with the same size could be covered by paths of the same length.

It is proposed a path generator that divides the sub-area to cover S_i in 4 polygons with the same area, such as each one has a pair of consecutive link positions as two of its vertices.

Given the area S_i, it is defined as a set P of counterclockwise ordered points which defines the area boundary. At the algorithm implementation level, a vector $\text{links}[4]$ stores the indexes of link positions. Therefore, $P(\text{links[k]})$ is the k^{th} link position, with $1 \leq k \leq 4$.

The algorithm to obtain that division is composed by the following steps:

1) The size of area S_i is computed as $A_i = A(P)$.
2) Two new polygons:
   $P_1 = [P(\text{links}[1] : \text{links}[2]); u]$
   $P_2 = [P(\text{links}[2] : \text{links}[3]); u]$
   can be defined using a point u interior to P, such that:
   $A(P_1) = A_i/4$
   $A(P_2) = A_i/4$
   $u \in P$
3) Given the polygon $V = [P(\text{links}[3] : \text{links}[4]); u]$:
   a) If $A(V) = A_i/4$, then $P_3 = V$
      $P_4 = [P(\text{links}[4] : \text{links}[1]); u]$
   b) If $A(V) > A_i$, then
      $P_3 = [P(\text{links}[3] : \text{links}[4]); v]$
      $P_4 = [P(\text{links}[4] : \text{links}[1]); u; v]$,
      with
      $v \in [P(\text{links}[3]); u]$
      $A(P_3) = A(P_4) = A_i/4$
   c) If $A(V) < A_i$, then
      $P_3 = [P(\text{links}[3] : \text{links}[4]); v; u]$
      $P_4 = [P(\text{links}[4] : \text{links}[1]); v]$,
      with
      $[v \in s(\text{links}[4]); u]$
      $A(P_3) = A(P_4) = A_i/4$

Now, a coverage path for each polygon is generated from one of the link positions to the other one. A simple *back and forth* strategy is proposed to generate the coverage paths. Assuming that the generated paths have a perfect quality index, the four paths lengths are equal. Therefore, joining the four paths, an UAV which moves with a constant speed would take the same time to move between any pair of consecutive link positions. Figure 8 shows how the presented path generator creates a pseudo-symmetric path to cover an irregular area.

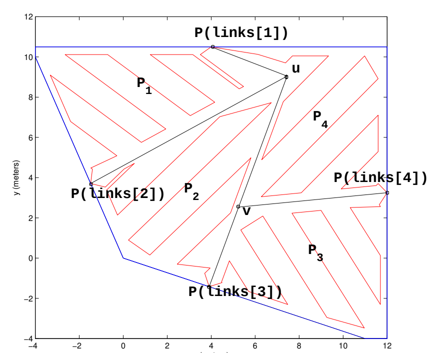

Fig. 8: Coverage closed path computed by the path generator. Blue lines define the area to cover. Red lines correspond to the *back and forth* paths.

B. *Distributed coordination to ensure an efficient area division*

Given an initial simple grid division of area S using equally spaced horizontal and vertical lines, each UAV can initialize its own variables, see Fig. 9. Each UAV has an initial area S_i to cover and initial link positions common with its neighbors, and can generate its own coverage path.

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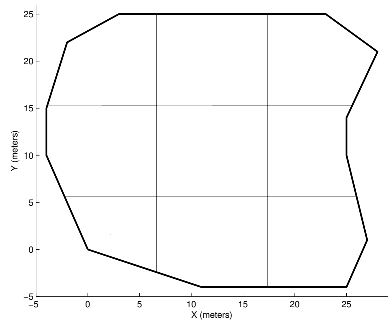

Fig. 9: Initial 3×3 grid-shape area division.

However, for irregular areas or non homogeneous team of UAVs, that initial division is not efficient. Some UAVs take longer times than others to cover their areas using their maximum capabilities. Then, some UAVs would have to slow down their motions to keep synchronization and the maximum refresh time is increased.

Minimizing that time, but ensuring synchronization, implies that each UAV patrols an area whose size is related to its own maximum capabilities, (4). Computing an area division which accomplishes these conditions can be computationally expensive. Also, the obtained solution is not robust to changes in the UAVs capabilities or area shape.

The decision module uses a *one-to-one* coordination technique which allows the UAVs self-adapt to cover an area according to their maximum capabilities and keep the synchronization in a distributed and decentralized manner.

With the proposed technique, each UAV only needs information from neighbor UAVs to obtain a solution convergent to the correct area division, they do not need to know information about the complete system. System converges to a correct area division from distributed decisions and communication between neighbors.

When a pair of UAVs are close enough (distance less than communication range R) to establish a communication, they exchange the area that they are covering and their own maximum capabilities, and they execute a *share & divide* function. Namely, each UAV joins the two areas and divide it according to the capabilities, (8), using a vertical or horizontal line depending on link index, as Fig. 10 shows.

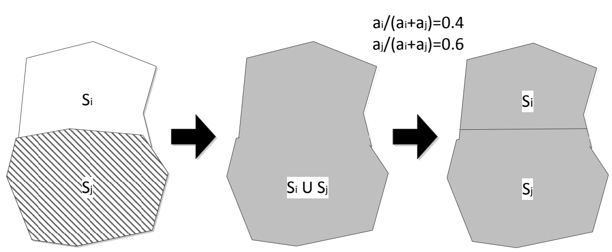

Fig. 10: Two UAVs contact and share their own covered areas. The whole area is divided between the UAVs, according to their capabilities.

$$A_i = a_i \frac{A(S_i \cup S_j)}{a_i + a_j} \tag{8}$$

The decision-making module follows the next guidelines:

1) Given the initial grid division, each UAV generates its own coverage path and starts to move from the opposite link position to its neighbor. Thus, if an UAV goes to link position 1, its neighbors will go to link position 3.
2) UAV follows its own path.
3) If UAV arrives to a link position
   a) If it is a link position without neighbor, then the UAV recomputes the link position and generates the path.
   b) If it is a link position with neighbor
      i) If the UAV does not meet a neighbor, then it waits a gap time T_w, joins a portion of the neighbor area, recomputes the link position and generates the path.
         A) If there are not more neighbor areas, it sets the link position as one without neighbor.
      ii) If the UAV meets a neighbor, then it executes the *share & divide* function, recomputes the common link position and generates the path.
4) Return to step 2.

Also, this system can self-adapt in a decentralized manner to changes in the total area to cover. For instance, if the team of UAV was covering a polluted area, the team can adapt to obtain an efficient area division while the size of the polluted zone is decreasing.

VII. SIMULATION RESULTS

A set of MATLAB simulations has been run to validate the proposed strategies. Each UAV simulation uses the dynamical model in [13] and has been implemented with different and parallel MATLAB objects to run the proposed algorithms in a decentralized manner. The simulations have been performed using quad-rotors. However, the system is useful for any kind of rotatory wing UAV and a slighter modified trajectory planning would be necessary for fixed wing UAVs. Another object has been developed to emulate the limited communication ranges to validate the theoretical advantages of the system under communication constraints.

A. Adaptation capability to dynamic changes

Next simulation shows as a team of four heterogeneous UAVs self-adapt to monitor an irregular area of $789\,\mathrm{m}^2$ from a non efficient initial grid-shape division to one according to their capabilities, which are shown in Table I.

All of them have a communication range of $5\,\mathrm{m}$ and initially they are flying at $v^{\max}$ speed and h^{opt} altitude. At time $t = 667\,\mathrm{s}$, the area to cover is increased to $807\,\mathrm{m}^2$. Later, at time $t = 1334\,\mathrm{s}$ the UAV flying over the sub-area 2 decreases its speed to $0.4\,\mathrm{m/s}$. Simulation results validate that the multi-UAV system converges in a distributed manner to an efficient area division, keeping the whole

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TABLE I: UAV capabilities and sub-areas allocated in the simulations of Sect VII-A.

UAV color	h^{opt} (m)	$v^{\max}$ (m/s)	$\theta^{\max}$ (rad)	Sub-area #
red	3	0.4	$\pi/8$	1
green	3	0.5	$\pi/8$	2
blue	3	0.5	$\pi/6$	3
yellow	3	0.4	$\pi/6$	4

system synchronization. Figure 11 shows the difference (in %) along the time between the sub-area covered by the UAVs and the sub-area that they should do (according to expression (4)). Figure 12 presents some simulation snapshots with the area division obtained at different times. Results show how quickly the system converges to an efficient solution and how it adapts to dynamic changes (area shape, UAV endurance and UAV capabilities).

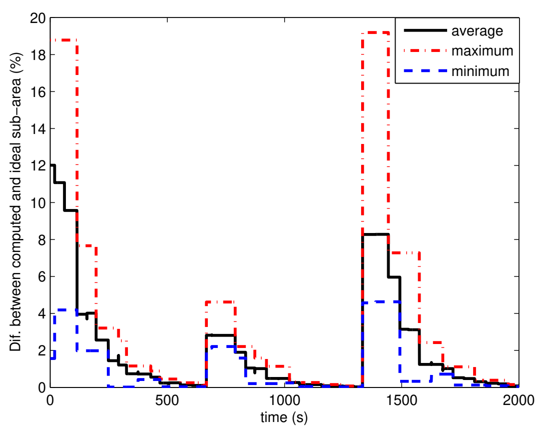
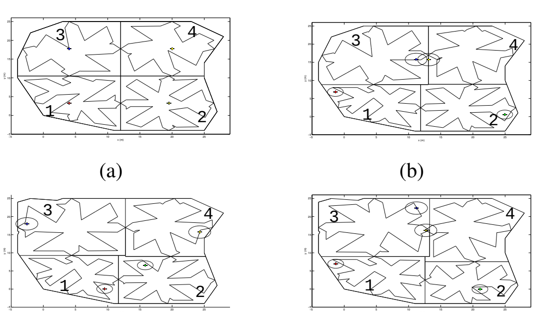


Fig. 11: Difference between real and optimal UAVs sub-area in % along the time with four UAVs.



(a) (b) (c) (d)

Fig. 12: This figure shows the area division between the four heterogeneous UAVs at different times during the simulation: (a) t=0 s, (b) t=500 s, (c) t=1200 s and (d) t=1900 s. A video of the simulation can be found in *http://www.youtube.com/watch?v=BGKaWSyaahA*

B. Temporal performance metrics

A large set of simulations with different teams of UAVs and different irregular areas have been executed to measure different temporal performance metrics: pollution detection and information propagation times, and also algorithm convergence time. Teams of different sizes (4, 6, 9, 12 and 16 UAVs) have been simulated from a non-efficient initial grid-shape area division. The vehicles have a maximum communication range of 5 m, maximum speeds from 0.2 to 0.5 m/s and field of views (FOVs) from $\pi/8$ to $\pi/6$ rad. During each simulation, polluted sources appear at random positions. Percent value between computed times and average maximum time $\overline{T_{\max}}$ that an UAV would take to patrol the whole area are calculated. Average maximum time to cover an area of size A with N UAVs is defined in expression (9) as the relation between the total area to cover and the average coverage speed. Figure 13 shows the average values for the time to detect the pollution sources, to share the information among the whole team (or latency) and the converge time of the algorithm defined as the time when the maximum difference between the optimum and the actual sub-area sizes is lower than 1 %.

$$\overline{T_{\max}} = N \frac{A}{\sum_{j=1}^{N} a_j^{\max}}, \forall i = 1, ..., N \qquad (9)$$

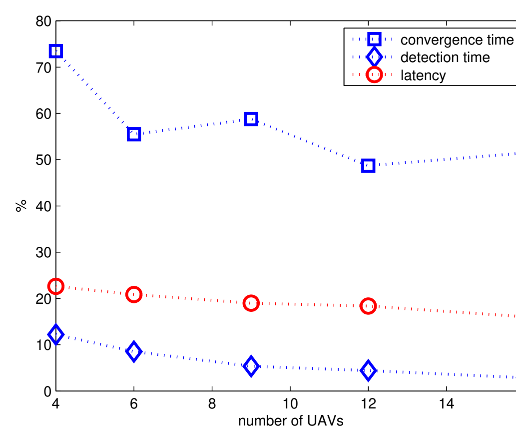


Fig. 13: Temporal performance metrics computed from the simulations with respect to the average maximum time to patrol the area. Pollution detection and information propagation times, as well as the algorithm convergence time are plotted.

Simulation results show how the times to detect and share information about pollution sources decrease when the number of UAVs increases. Also, in any case, the convergence time is lower than the time than a single UAV would take to patrol the whole area. On other hand, the relation between the average computed convergence time and the time that theoretically each UAV takes to complete its own coverage path T is shown in Fig. 14. The results show that the required number of communication links to obtain the convergence increases with the number of UAVs considered.

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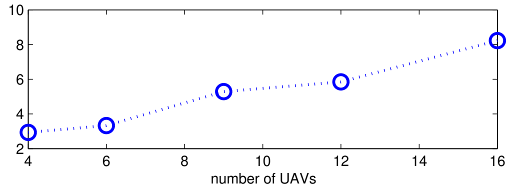


Fig. 14: Convergence times related to the time that each UAV should theoretically take to complete its coverage path.

C. Comparison with other patrolling strategies

The proposed area partitioning strategy has been compared with two other schemas in a simulated scenario:

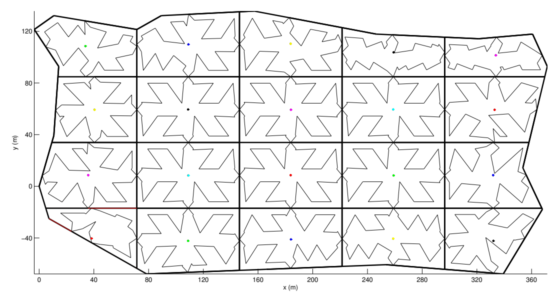
- A cyclic strategy, where all the UAVs follow the same coverage closed path in the same direction, with same motion speed and equally spaced to patrol the whole area. When they are close enough to the central station, they inform it about the detected pollution sources.
- A path-partitioning strategy proposed in [13], where the whole area coverage path is divided in segments and each UAV is in charge of one of them. Pollution sources information is exchanged between neighbors till it is shared with control station.

The proposed scenario (see Fig. 15) is located in the Doï¿½ana National Park, which is the demonstration scenario chosen in the European PLANET Project. The goal is to detect polluted zones and inform to the a ground control station in a minimum time.

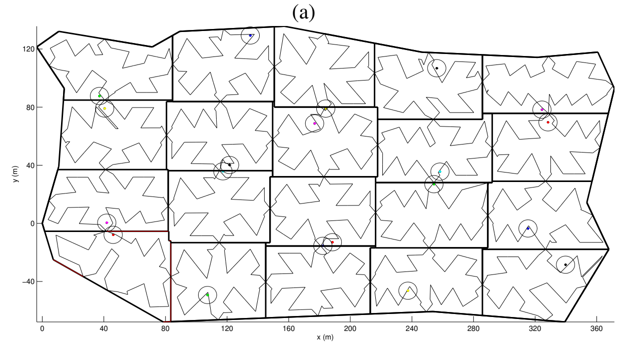
Fig. 15: Zone in the Doï¿½ana National Park selected for the simulations. The ground control station has been located in the “Palacio de Doï¿½ana”.

The zone to monitor has an area of 65517 m^2 and it is assumed a limited communication range of 10 m for the UAVs. The simulations have been executed with a team of homogeneous UAVs in order to properly compare all the strategies, because the cyclic strategy can not exploit the advantages of a heterogeneous team. Each UAV moves with a maximum speed of 1 m/s and an altitude of 6 m, and has a FOV of $\theta = \pi/4$ rad. Theoretical time that a single UAV will take to patrol the whole area can be calculated as $T_v = 5459.7$ s. In the simulations, a large set of more than 35 pollution sources have appeared at random positions.

Using the system proposed in this paper an area partitioning strategy is applied to obtain an efficient area division. Figure 17 shows as quickly the system converges. Figure 16 shows two different simulation snapshots with the initial non efficient area division using parallel lines and the one obtained at time t=3000 s.



(a)



(b)

Fig. 16: This figure shows the area division between the 20 UAVs at different times: (a) t=0 s, and (b) t=3000 s. The ground control station is located in the “Palacio de Doï¿½ana” in the position $(0, 0)$ m with an antenna receiver in $(5, 0)$ m into the monitored area. See video simulation in *http://www.youtube.com/watch?v=8ggxpQp128Y*

Table II presents the average times to detect the pollution sources $\overline{T_d}$, to report to the central station $\overline{T_i}$ and the sum of both for the different strategies.

TABLE II: Average times to detect pollution sources and report to the central station for different strategies.

Patrolling Strategy	$\overline{T_d}$ (s)	$\overline{T_i}$ (s)	$\overline{T_d + T_i}$ (s)
Cyclic	95.5	2810.6	2906.1
Path partitioning	184.2	2112,6	2295.5
Area partitioning	137.5	537.3	674.9

Simulations show that the lowest times to detect pollution sources are obtained using the cyclic strategy. The area

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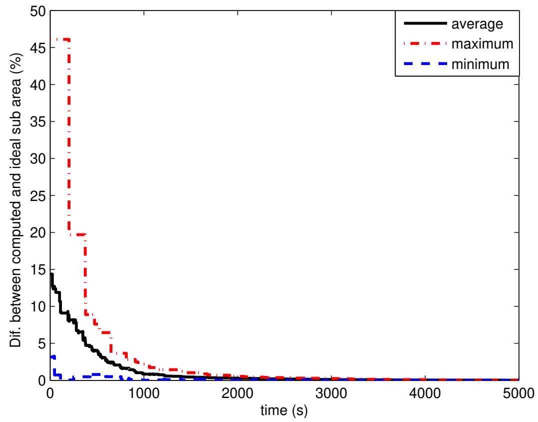

Fig. 17: Difference between real and optimal UAVs sub-area in % along the time in the scenario of Doï¿½ana with 20 UAVs.

partitioning strategy offers slightly higher times, and the path partitioning one obtains the worst results for detection. However, the times to report to the central station using the area partitioning strategy are significantly lower than using the other ones. Adding both times, it is shown in the third column of Table II that the best global performance is achieved using the area partitioning strategy (at least three times lower).

VIII. CONCLUSIONS

An area monitoring mission with a team of UAVs can be solved using an area partitioning strategy, where each UAV has to cover a different non overlapped sub-area according to its capabilities, such that the refresh time is minimized. A grid-shape area division defines a bipartite graph and offers interesting theoretical results regarding to the maximum time to share information between the UAVs or latency.

A *one-to-one* coordination technique allows to redistribute the area between the UAVs in a decentralized and distributed manner in order to obtain a more efficient area division. The proposed coverage path planning algorithm, where the distance between each pair of link positions is the same, allows to keep the synchronization between the UAVs.

Simulation results show a scalable solution which converges to an efficient area division (according to UAVs capabilities) and is able to adapt to changes in the initial conditions (area shape, UAVs capabilities), even under limited communications. Furthermore, results show as the detection time and the latency decrease as the number of UAVs increases. Finally, comparisons with other strategies (path-partition and cyclic strategies) show that the proposed approach offers a better behavior to detect pollution sources and share information about their state.

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