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 fulfills 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 Doñana 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].

This work has been developed in the framework of the PLANET (INFOSOICT-257649), the CLEAR (DP2011-28937-C02-01) Spanish National Research project and the project of excellence of the Junta de Andalucía WSAN-UAV (P09-TEP-5120).

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1http://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
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 a 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 \( S \subseteq \mathbb{R}^2 \) with a surface \( A \) which has to be patrolled by a team of heterogeneous UAVs \( Q := \{Q_1, Q_2, \ldots, Q_N\} \) 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.](http://dx.doi.org/10.1109/ICUAS.2013.6564734)
can be approximated according to the coverage range \( c_i \) and
the motion speed \( v_i(t) \) as

\[
a_i(t) \approx 2c_i(t)v_i(t).
\]

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 \( T_s \). 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 \( S \).

\[
S_1 \cup S_2 \cup \ldots \cup S_N = S
\]

\[
S_i \cap S_j = \emptyset
\]

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:

\[
A_i = a_i^{\max} \frac{A}{\sum_{j=1}^{N} a_j^{\max}}, \forall i = 1, \ldots, N
\]

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 \( T \).

\[
T = A_i/a_i^{\max} = \frac{A}{\sum_{j=1}^{N} a_j^{\max}}
\]

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 synchroni-
zation 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
Doi\( \hat{\text{i}} \) 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
\( \alpha_i \) be the starting position of the \( i \)th UAV. Furthermore,
for any pair of UAVs, \( i \) and \( j \), \( \phi_{ij} \) 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 \( u \in V_1 \) or \( v \in V_2 \).
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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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 \( \pi \).

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 \( \alpha \), 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 \( O(N) \) time. In Fig. 2, a bipartite graph allows the synchronization of 17 UAVs in the decentralized cooperative surveillance of the Doi\( \text{ï¿½} \)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 cannot 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
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 $m \times n$ 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.

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

$$T_s \leq T + (n - 2)T/2 + T/4 + (m - 2)T/2$$

$$T_s \leq 5T/4 + (n + m - 4)T/2$$

(6)

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:

$$T_s = T + 2T/2 + T/4 + 3T/2 = 15T/4$$

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

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

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\[ T_s \leq T + (N - 2)T/2 = T + (n \cdot m - 2)T/2 \quad (7) \]

For any \( n, m > 2 \), the grid-shape division offers better performance than the tree-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, 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.

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.


can be defined using a point \( u \) interior to \( P \), such that:
\[ A(P_1) = A_1/4 \]
\[ A(P_2) = A_1/4 \]
\[ u \in P \]

   a) If \( A(V) = A_1/4 \), then \( P_3 = V \)
   b) If \( A(V) > A_1 \), then
   
   
   \[ P_4 = [P(links[4] : links[1]) ; u; v], \]
   with
   \[ v \in [P(links[3]) ; u] \]
   
   \[ A(P_3) = A(P_4) = A_1/4 \]
   c) If \( A(V) < A_1 \), then
   
   
   \[ P_4 = [P(links[4] : links[1]) ; v], \]
   with
   \[ [v \in s(links[4]) ; u] \]
   
   \[ A(P_3) = A(P_4) = A_1/4 \]

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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. 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.

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

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 $T_{gap}$, 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 $789 \text{m}^2$ 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 $5 \text{m}$ and initially they are flying at $v_{max}$ speed and $h_{opt}$ altitude. At time $t = 667 \text{s}$, the area to cover is increased to $807 \text{m}^2$. Later, at time $t = 1334 \text{s}$ the UAV flying over the sub-area 2 decreases its speed to $0.4 \text{m/s}$. 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.

<table>
<thead>
<tr>
<th>UAV color</th>
<th>$h_{opt}$ (m)</th>
<th>$v_{max}$ (m/s)</th>
<th>$\theta_{max}$ (rad)</th>
<th>Sub-area #</th>
</tr>
</thead>
<tbody>
<tr>
<td>red</td>
<td>3</td>
<td>0.4</td>
<td>$\pi/8$</td>
<td>1</td>
</tr>
<tr>
<td>green</td>
<td>3</td>
<td>0.5</td>
<td>$\pi/8$</td>
<td>2</td>
</tr>
<tr>
<td>blue</td>
<td>3</td>
<td>0.5</td>
<td>$\pi/6$</td>
<td>3</td>
</tr>
<tr>
<td>yellow</td>
<td>3</td>
<td>0.4</td>
<td>$\pi/6$</td>
<td>4</td>
</tr>
</tbody>
</table>

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.](image1)

![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](image2)

**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 $T_{max}$ 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 %.

$$T_{max} = N \frac{A}{\sum_{j=1}^{N} a_{max}^j} \quad \forall i = 1, \ldots, N$$  \hfill (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.](image3)

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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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 Doñana National Park, which is the demonstration scenario chosen in the European PLANET Project. The goal is to detect polluted zones and inform the ground control station in a minimum time.

The zone to monitor has an area of 65517 m² 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.

<table>
<thead>
<tr>
<th>Patrolling Strategy</th>
<th>$T_d$ (s)</th>
<th>$T_i$ (s)</th>
<th>$T_d + T_i$ (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cyclic</td>
<td>95.5</td>
<td>2810.6</td>
<td>2906.1</td>
</tr>
<tr>
<td>Path partitioning</td>
<td>184.2</td>
<td>2112.6</td>
<td>2295.5</td>
</tr>
<tr>
<td>Area partitioning</td>
<td>137.5</td>
<td>537.3</td>
<td>674.9</td>
</tr>
</tbody>
</table>

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

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

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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.

ACKNOWLEDGMENT

The synchronization problem studied here was introduced and partially solved during the VI Spanish Workshop on Geometric Optimization, June 2012, El Rocío, Huelva, Spain.

The authors would like to thank other participants for helpful comments.

REFERENCES


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