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Cooperative Large Area Surveillance with a Team of Aerial Mobile Robots for Long Endurance Missions

Jose Joaquin Acevedo · Begoña C. Arrue · Ivan Maza · Anibal Ollero

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Abstract This paper proposes a distributed approach to solve long duration area surveillance missions with a team of aerial robots, taking into account communication constraints. The system, based on "one-to-one" coordination, minimizes the probability that any event happens in the area without being detected and ensures periodic communication between UAVs. A set of simulations are presented to validate the applicability of the approach and its most relevant features: convergence, robustness with dynamic teams, fault-tolerance and finite information sharing time. It is also shown that "one-to-one" coordination for all the pairs of neighbors allows to obtain an efficient coordination scheme for the whole team to accomplish the area surveillance mission without any central unit.

Keywords Multi-UAS systems · Decentralized systems · Cooperation · Coordination · Area surveillance · Long endurance missions

1 Introduction

The robust distributed decision and the multi-robot coordination are very relevant problems in a cooperative long endurance mission. These missions also pose very important challenges when failure recovery procedures are considered. The CLEAR Spanish National Research project, where the authors are involved, proposes the application of a cooperative system with multiple robots to undertake these kind of problems. All the functionalities should be maintained while some of the robots have to leave the mission to recharge batteries, refuel or be repaired. UAV surveillance missions of large areas are also considered in the PLANET project.[1] So, a high performance

J. J. Acevedo (✉) · B. C. Arrue · I. Maza · A. Ollero
Grupo de Robotica, Visión y Control,
Universidad de Sevilla, Sevilla, Spain
e-mail: jacevedo@us.es

B. C. Arrue
e-mail: barrue@us.es

I. Maza
e-mail: imaza@us.es

A. Ollero
e-mail: aollero@cartuja.us.es

A. Ollero
Center for Advanced Aerospace Technology
(CATEC), Parque Tecnológico y Aeronáutico
de Andalucía, La Rinconada, Spain
e-mail: aollero@catec.aero

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

in large missions can be kept using a system of coordinated aerial or ground robots.

This paper considers the long time surveillance of potentially large areas with a fleet of UAVs by maintaining the mission even when a member of the fleet have to leave the mission because it is damaged or has to recharge its batteries.

The surveillance problem is well known in the literature and different aerial robotic platforms have been developed in the recent years [5, 13, 16] for this type of missions. A robot designed for surveillance missions is proposed in [4]. An efficient system to detect and avoid intruders is presented in [7], using a set of ground stations. However, that paper does not pose the problem of where to locate these ground stations.

Reference [3] poses a video-surveillance system and proves that a solution where each position in the perimeter is visited with the same period is the optimal solution to cover a perimeter with a set of agents. A frequency-based method is also used in [1] and [2] for multi-robot patrolling missions based on the Approximated Cellular Decomposition. In the same way, this paper presents a system which tries to minimize the time in which any position in the area is monitored.

The area surveillance missions can be studied as an area coverage problem. Reference [20] proposes a cooperative system for multiple mobile robots based on Voronoi diagrams for area coverage missions where all the agents keep the contact all the time. Authors of [12] maximizes the area coverage for a Wireless Sensor Network (WSN) from a distributed and scalable approach, however the method does not consider the coverage of large areas.

A distributed and decentralized approach offers more scalability and dynamism to the solution. In [11], the authors propose the perimeter surveillance problem with a team of UAVs, but using a supervisor station and a hierarchical framework to coordinate the UAVs. Reference [9] proposes an efficient and distributed algorithm based on ordered upwind methods, which finds an optimal perimeter to survey, a defined target and coordinates motions of agents, but it uses centralized decisions. On the other hand, a continuous opened communication between all agents is assumed in these works, whereas we consider limited communication ranges.

In [8], a distributed and decentralized system to survey a known area with multiples mobile ground robots in a cooperative way is presented. It assumes communications constraints and it is fault-tolerant. However, our approach is intended to provide the same features not in indoors with ground robots, but in large outdoors areas with aerial robots.

In our approach cooperation and coordination between mobile robots for area surveillance is explicitly considered. In [15], the authors propose a decentralized solution to construct a structure in a decentralized way where a team of ground robots cooperates. The team is coordinated based on mass-property calculation to distribute the area where each one has to work.

The cooperation and coordination for area surveillance mission is studied for other researchers. Reference [6] poses the cooperation between a team of aerial robots and a WSN for surveillance missions maximizing the area coverage but keeping the connectivity of the network. On the other hand, in [18], authors solve the area coverage problem with a team of aerial mobile robots as a task allocation problem using probability decomposition. The distributed task allocation problem with communication constraints is also solved in [21] for surveillance missions with a team of aerial and ground robots.

Reference [14] uses the concept of "coordination variables" to solve a perimeter surveillance mission with a team of homogeneous UAVs in a distributed and decentralized way, assuming communication constraints. In [17], the authors also solve the cooperative problem of path planning with time constraints using "coordination variables". These variables refer to the minimum information that each robot needs to solve the problem in a cooperative way. If all robots have consistent information about the "coordination variables", they could execute their individual tasks and the common aim could be met. In [10], the authors analyze how it is possible to achieve the consensus in a multi-robot system with less iterations using the "coordination variables".

However, for more complex problem, as it proposed in this paper, the definition of the "coordination variables" could be less intuitive. Then, a "one-to-one" coordination, based on the concept of "coordination variables" but applied independently for each pair of neighbors, will be presented in this paper.

Therefore, this paper poses the area surveillance problem with a team of aerial robots (quad-rotors), considering communication constraints. A system which obtains a near-optimal solution, allowing the dynamic reconfiguration when the number of aerial robots changes (any robot goes in or go out), is presented.

The paper is organized as follows. In Section 2 the area surveillance problem is presented. Section 3 computes the optimal solution to the surveillance mission and proposes a near-optimal solution which keeps a periodical contact between the quad-rotors. Section 4 presents a distributed system to solve the problem. Section 5 analyzes the solution features, whereas Section 6 presents simulation results. Finally, conclusions and future work close the paper in Section 7.

2 Problem Statement

This paper proposes an efficient distributed solution for the area surveillance problem with a team of quad-rotors for long endurance missions, assuming a limited communication range (see Fig. 1).

The problem can be defined as follows:

- An area to survey S in the plane $z=0$ is defined as the inside area of the closed curve B.
- A team of agents which has to survey the area S is defined as a set of N quad-rotors: $\{Q_1, Q_2, ..., Q_N\}$. The size N of the team can change during the mission.
- Each quad-rotor Q_i has defined its position at any time t as:

$$p_i(t) = \big(x_i(t), y_i(t), z_i(t)\big) \quad (1)$$

- Each quad-rotor Q_i can move into the area, assuming a constant altitude z, with a variable speed:

$$|v_i(t)| = \left|\frac{d(r_i(t))}{dt}\right| \leq v^{\max} \quad (2)$$

  where $r_i(t) = (x_i(t), y_i(t))$.
- Each quad-rotor Q_i in any time t keeps an information vector, $info_i(t)$, where stores the problem parameters and the monitored variables about the area to share with the rest of the team.
- All the quad-rotors have defined a communication range R_{comm} such that any pair of quad-rotors, Q_i and Q_j, can interchange information only if they are close enough:

$$|p_i(t) - p_j(t)| < R_{\text{comm}} \Longrightarrow info_i(t) = info_j(t) \quad (3)$$

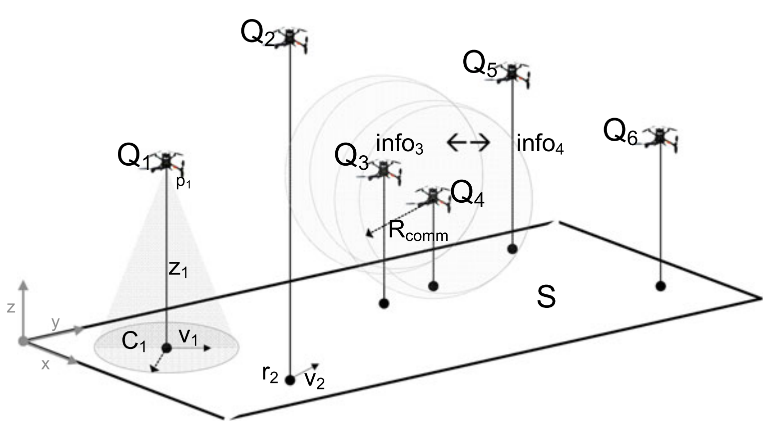

Fig. 1 A rectangular area to be surveyed by a team of six quad-rotors with communication constraints. The *cone* below Q_1 shows the zone which is being monitored in the current time. The *spheres* around Q_3 and Q_4 define their communication ranges

– Each quad-rotor Q_i at each time t can monitor a limited area C_i:

$$C_i(t) := \left\{ r \in \mathbb{R}^2 : |r - r_i(t)| < c(z_i(t)) \right\} \quad (4)$$

where $c(z)$ defines how the coverage range of the quad-rotor Q_i changes with its altitude z_i.

– The coverage range function $c(z) : \mathbb{R}^+ \to \mathbb{R}$ is a proportional function with a proportionality constant related to its field of view angle θ. However, it is assumed a maximum altitude $a^{\max}$ to be able to monitor the area. Then, it can be defined as follows:

$$c(z) = \begin{cases} z \cdot \tan(\theta), \text{ if } 0 < z \leq a^{\max} \\ 0, \text{ if } z > a^{\max} \end{cases} \quad (5)$$

As in [3], it is supposed that the probability that an event appears in any position $r \in S$ without being detected, $f : \mathbb{R}^+ \to [0, 1]$, is strictly increasing with the elapsed time since the position r was monitored by any quad-rotor, $h(r, t)$. Then, it could be defined as a Poisson Counter Process

$$f(h(r, t)) = 1 - e^{\lambda h(r,t)}, \quad (6)$$

where λ is the rate and $h : \{\mathbb{R}^2, \mathbb{R}^+\} \to \mathbb{R}^+$ is the elapsed time since the last visit of any quad-rotor

$$h(r, t) = \begin{cases} h(r, t - \delta t) + \delta t, \text{ if } r \notin \bigcup_{i=1}^{N} C_i(t) \\ 0, \text{ in other case} \end{cases}, \quad (7)$$

where $\delta t \to 0^+$ and $h(r, 0) = 0, \forall r \in S$.

The adopted criteria to solve the proposed problem is to minimize the elapsed time function $h(r, t)$ in the worst case scenario, so the probability that an event were not detected by any quad-rotor will be upper bounded to a known value. Also, it is intended to keep a continuous information interchange between all the quad-rotors at least in periodical times. Then, the team can reply to any change in the team size.

3 Optimal Area Surveillance

The area surveillance mission with multiple quad-rotors is based on the following assumptions.

Assumption 1 *For each coverage range value $c(z)$ and, so, for each altitude of the quad-rotor z, there is a single minimum closed path P which covers the whole area S. Then:*

$$\{z, S\} \longrightarrow P^z : \left\{ p(t) \in \mathbb{R}^2, t \in [0, T^v] \right\}$$

$$r_i(t) = p(t) \Longrightarrow \bigcup_{t=0}^{T^v} C_i(t) \supseteq S, \forall i = 1, ..., N \quad (8)$$

where $p(0) = p(T^v)$ and T^v is the time that a quad-rotor takes to cover the whole path P^z at a speed v.

The optimal solution to the proposed problem is one where it is minimized the probability that an event appears in any position into the area without being detected in the worst case scenario.

Theorem 1 *The optimal coverage planning of an area S with a team of N quad-rotors must verify the following propositions:*

– *Each quad-rotor Q_i should fly with a constant altitude $z_i(t) = a^{\max}, \forall t$, which defines a path $P^{\min}$ for all the quad-rotors to cover the whole area S.*
– *Each quad-rotor Q_i should move through the path $P^{\min}$ with its maximum speed $v_i(t) = v^{\max}$, $\forall t$. So, all the quad-rotors cover the entire path $P^{\min}$ in the same time $T^{\min}$.*
– *All the quad-rotors move in the same direction by the path $P^{\min}$ equally spaced between them. Then, all the robots cover the entire area S.*

$$p_i(t) = p_j\left(t + n\frac{T^{\min}}{N}\right), \forall n \in \mathbb{N}, \forall i, j \quad (9)$$

where $p_i(t) \in P^{\min}, \forall t \geq 0$

Figure 2 shows how a team of quad-rotors should move to survey the area in an optimal manner.

Proof According to the adopted criteria to solve the problem defined in the Section 2, the optimal solution should minimize the elapsed time since any position is monitored. With the previous assumptions, all the quad-rotors cover the entire

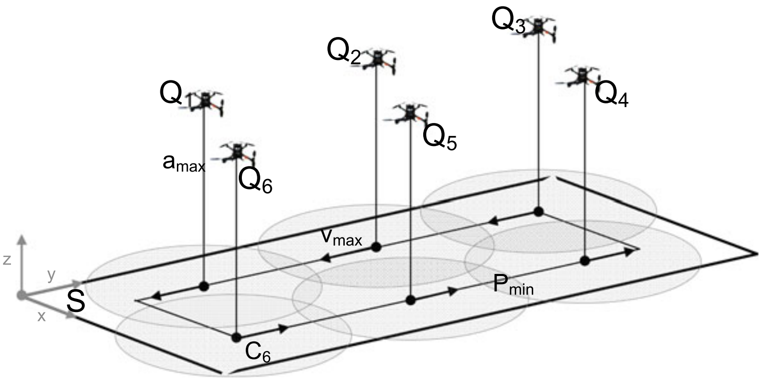

Fig. 2 A rectangular area is surveyed by a team of six quad-rotors in an optimal manner

closed path $P^{\min}$ with a speed $v^{\max}$ in the same direction with a same period $T^{\min}$. If $L(P^{\min})$ is defined as the length of the path $P^{\min}$, this period can be calculated as follows:

$$T^{\min} = \frac{L(P^{\min})}{v^{\max}} \tag{10}$$

Also, given the expression 9, it can be derived that any position in the path is visited by any quad-rotor with a period of $T^{\min}/N$. Following the path it is ensured that any position in the area S is monitored. Then all the positions in the area S are monitored with an elapsed time bounded up to $T^{\min}/N$.

$$h^{\text{opt}} = \max(h(r,t)) \leq \frac{L(P^{\min})}{Nv^{\max}} \tag{11}$$

Given a function A which defines the area of a region, if each quad-rotor Q_i can cover a circular area around its position with a radius of $c(z_i(t))$, the area $A(S)$ covered along a closed path P^z can be easily approximated by the area of a rectangle:

$$A(S) = L(P^z)2c(z) \tag{12}$$

Then, covering the same area S with a shorter path requires a greater value of $c(z)$. From Eq. 5 the following expression can be obtained:

$$L(P^{\min}) = \frac{A(S)}{2c(a^{\max})} < L(P^z) = \frac{A(S)}{2c(z)}, \forall z \neq a^{\max}. \tag{13}$$

So, if a quad-rotor follows a longer path, it will take a greater time to cover the whole perimeter and

$$z \neq a^{\max} \Longrightarrow \max(h(r,t)) = \frac{L(P^z)}{Nv^{\max}} \geq h^{\text{opt}}. \tag{14}$$

On the other hand, if the quad-rotor moves through the path $P^{\min}$ with a speed $v < v^{\max}$, the elapsed time function $h(r,t)$ can be computed as

$$v < v^{\max} \Longrightarrow \max(h(r,t)) = \frac{L(P^{\min})}{Nv} \geq h^{\text{opt}}. \tag{15}$$

Finally, if the quad-rotors were not equally spaced along the path, there is at least a quad-rotor Q_i such that the distance to one of its neighbors Q_j (L_{ij}) is greater than the distance to other neighbor Q_k (L_{ik}). Thus the maximum elapsed time will be given by

$$L_{ik} < \frac{T^{\min}}{N} < Lij \Longrightarrow \max(h(r,t)) = \frac{L_{ij}}{v} \geq h^{\text{opt}}. \tag{16}$$

□

3.1 Coverage with Communication Constraints

Theorem 1 defines the optimal solution to the proposed problem. However, it only ensures a periodical information interchange between all the quad-rotors if the communication range is large enough:

$$\exists t \in [0, T^{\min}] \longrightarrow \left| p^{\min}(t) - p^{\min}\left(t + \frac{T^{\min}}{N}\right) \right| < R_{\text{comm}} \tag{17}$$

However, in a large area, the communication range can not be long enough to keep the contact and it will be necessary to force periodical contacts. Therefore, it is proposed a new area coverage planning strategy for the quad-rotors.

Theorem 2 *A near optimal coverage planning of an area S with a team of N quad-rotors, forcing contacts between neighbors, should fulfil the following propositions:*

- *Each quad-rotor Q_i should cover a region $S_i \subseteq S$, such all the positions into the area S are covered.*

$$\bigcup_{i=1}^{N} S_i = S; \bigcap_{i=1}^{N} S_i = \emptyset \tag{18}$$

- *Each quad-rotor Q_i should fly with a constant altitude $z_i(t) = a^{\max}, \forall t$, which defines an only closed path $P_i^{\min}$ to cover its own sub-area S_i.*
- *Given a function $L(P)$ which computes the length of a path P, all the quad-rotors must cover the same length:*

$$L\left(P_i^{\min}\right) = L\left(P_j^{\min}\right), \forall i, j \tag{19}$$

- *Each quad-rotor Q_i should move through its path $P_i^{\min}$ with its maximum speed $v_i(t) = v^{\max}$, $\forall t$. Then, all the quad-rotors cover their own sub-area in the same time T'.*
- *Each pair of neighbors quad-rotors, Q_i and Q_j, should interchange information at least once in T'.*

$$\exists t \in [0, T'] \Longrightarrow \left| p_i^{\min}(t + nT') - p_j^{\min}(t + nT') \right| < R_{\text{comm}}, \quad \forall n \in \mathbb{N}^+ \tag{20}$$

Figure 3 shows how a team of quad-rotors should move for the surveillance of an area in a near-optimal way, but keeping a periodical information interchange.

Proof According to the previous assumptions, each quad-rotor covers its own sub-area S_i through the $P_i^{\min}$ in a period T'. So, the maximum elapsed time for any position in the area is bounded up to T'.

$$h^{\text{subopt}} = \max(h(r,t)) \leq \frac{L\left(P_i^{\min}\right)}{v^{\max}} \tag{21}$$

The assumptions on the speed and the altitude of the quad-rotors have been already demonstrated.

On the other hand, if the sum of all the sub-areas is greater than the total area, then there should be at least one sub-area S_i such that its path P_i is longer than $P_i^{\min}$.

$$\bigcup_{i=1}^{N} S_i \supset S \Longrightarrow \exists S_i \longrightarrow L(P_i) > v^{\max} T'$$
$$L(P_i) = v^{\max} T'' \longrightarrow \max(h(r,t)) = T'' > T' = h^{\text{subopt}} \tag{22}$$

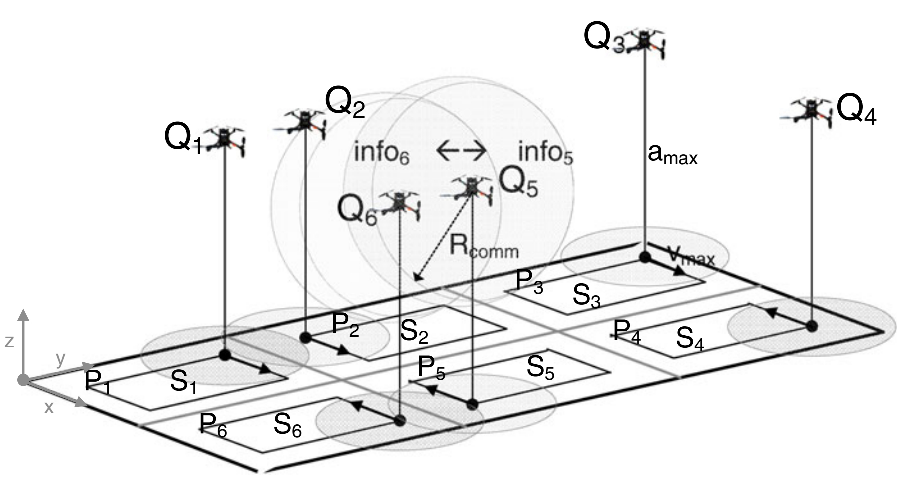

Fig. 3 A rectangular area is surveyed by a team of six quad-rotors in a near optimal manner, but keeping a periodical information interchange

If the sum of all the sub-areas is less than the total area, then there should be a region N not monitored.

$$\bigcup_{i=1}^{N} S_i \subset S \Longrightarrow \exists N \subset S, N \not\subset \bigcup_{i=1}^{N} S_i$$
$$h(r_N, t) \xrightarrow[t\to\infty]{} \infty > T' = h^{\text{subopt}}, \forall r_N \in N \quad (23)$$

If the intersection of all the sub-ares is not the empty set, then there will be any overlapping regions and there should be at least one sub-area S_i such that its path is longer than $P_i^{\min}$.

$$\bigcap_{i=1}^{N} S_i \neq \emptyset \Longrightarrow \exists S_i \longrightarrow L(P_i) > v^{\max} T'$$
$$L(P_i) = v^{\max} T'' \longrightarrow \max(h(r,t))$$
$$= T'' > T' = h^{\text{subopt}} \quad (24)$$

Regarding the lengths of the paths, if there is any path shorter than the rest, there should be also another path longer to cover the whole area or a region in the area will not be monitored.

If there is a longer path, then

$$L(P_i) < v^{\max} T' \Longrightarrow L(P_j) > v^{\max} T'$$
$$L(P_i) = v^{\max} T'' \longrightarrow \max(h(r,t))$$
$$= T'' > T' = h^{\text{subopt}}, \quad (25)$$

and if there is a region not monitored

$$L(P_i) < v^{\max} T' \Longrightarrow A(S_i) < v^{\max} T' c(a^{\max})$$
$$\sum_{i=1}^{N} A(S_i) < A(S) \Longrightarrow \exists N \subset N, N \not\subset \bigcup_{i=1}^{N} S_i$$
$$h(r_N, t) \xrightarrow[t\to\infty]{} \infty > T' = h^{\text{subopt}}, \forall r_N \in N. \quad (26)$$

Finally, expression 20 ensures a periodic information interchange because it verifies the expression 3. □

4 Distributed Approach

The long endurance surveillance of potentially large areas usually involves communication constraints. Moreover, some of the quad-rotors could go out because they are damaged or have to recharge their batteries. Then, a periodical information interchange between all the quad-rotors is required to allow the system to react to changes in the size of the team. Due the communication constraints and assuming that expression 17 is not satisfied, in this paper it is proposed a distributed and coordinated system which forces periodical contacts between neighbors. The proposed system should obtain an efficient solution close to the near-optimal solution defined in Theorem 2.

The system can be described in terms of independent modules which are in charge of different tasks. Figure 4 summarizes the architecture.

In this case, it is proposed "one-to-one" coordination where each pair of quad-rotors contact to share their own tasks (area to survey) and redistribute them in the best way. The set of all the one-to-one coordinations (between neighbors) leads to an efficient distribution for the whole team. The proposed approach improves the scalability when compared to centralized solutions.

The main task to carry out by the team is to distribute an area S between the N quad-rotors. Assuming the "one-to-one" approach, the only required coordination information will be related to the definition of the area S_{ij} to be covered by each pair of neighbors Q_i and Q_j.

The proposed system approximates any region by a rectangle. Then, the required information to define any region are the four vertices of the rectangle.

4.1 Control and Navigation Module

The function of the control and navigation module is to stabilize the quad-rotor and to guide it following a path. Based on the quad-rotor model, this module controls the quad-rotor position and runs a defined navigation strategy to move the quad-rotor along the path P_i, (defined as a set of waypoints) in the direction d_i with a speed v_i at an altitude z_i. This module also computes the current position p_i of the quad-rotor.

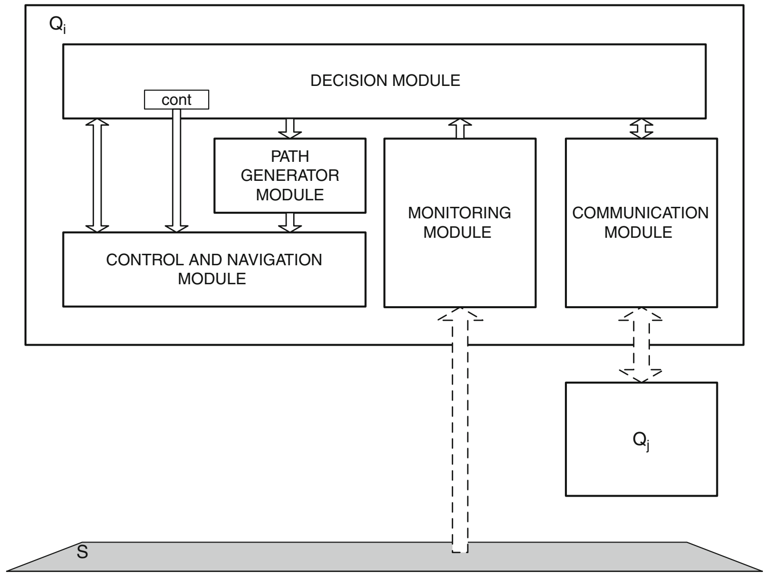

Fig. 4 Proposed system defined at the software level as set of independent modules

The control and navigation module is always running, and if the path P_i changes, the module drives the quad-rotor to the starting location in order to follow the path.

4.2 Path Generator Module

This module obtains a near-optimal path, close to the path defined by expression 8.

This module returns a path P_i which covers the whole area S_i in a time close to the minimum, visiting the list of positions W_i and assuming a coverage range $c(z_i)$. The start position of the path P_i will be the newest position in the list W_i.

The technique adopted to generate an efficient path will be called "sub-perimeter method" (see Fig. 5). This method uses the information about S_i to generate an interior similar region S_i^{sim}, such that the maximum distance from S_i^{sim} to the border of S_i is less or equal than the coverage range $c(z_i)$. Hence the path P_i computed is the perimeter of S^{sim}. Finally, the path P_i is adjusted to cover all the positions in the list W_i, setting the last one in that list as the starting position.

The module assumes that $c(z_i)$ is large enough to satisfy the expression 8 with the path P_i. Otherwise, this module can also generate a new path to solve a defined task according to the information vector $info_i$. The path generator module is triggered only by the decision module described later.

4.3 Communication Module

This module sends/receives information to/from the neighbors quad-rotors.

The communication module has to detect the neighbors and interchange all the required information when they are within the communication range.

The required information to compute the "one-to-one" coordination includes the definition of the region S_i surveyed by each quad-rotor, along with other system variables ($count_i$, $info_i$...).

The communication module is always active searching neighbors within the communication range defined by expression 3.

4.4 Monitoring Module

The monitoring module sends relevant information about the different objects of interest within the area under surveillance.

The monitoring module is always updating the information about the area which verifies the expression 4.

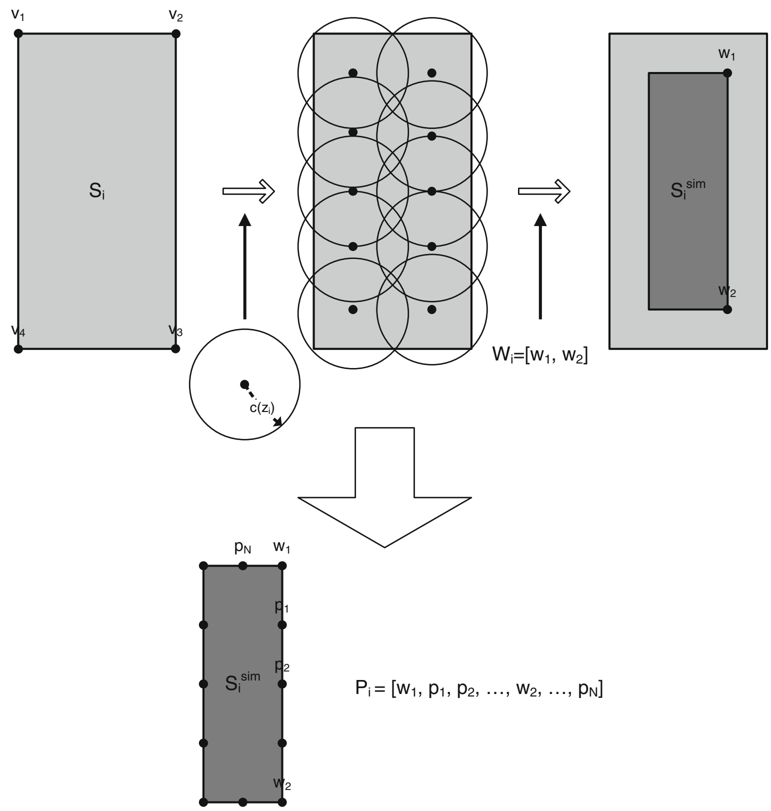

Fig. 5 Sub-perimeter method applied to generate a new path

4.5 Decision Module

The decision module manages the rest of modules and decides the next task to be executed. This module receives information about the current position of the quad-rotor, the area under surveillance, the detected information by the monitoring module and all the information received from the communication module.

The decision module computes the new area to survey S_i, updates the list W_i and decides the direction d_i used to cover the area. It also computes the altitude z_i and the speed v_i of the quad-rotor assuming the same fixed, near-optimal and steady values $v_i = v^{\mathrm{ok}}$ and $z_i = z^{\mathrm{ok}}$ resulting a coverage range of $c^{\mathrm{ok}} = c(z^{\mathrm{ok}})$ for all the quad-rotors in the team.

The module executes a loop periodically which computes the area to cover and actives the path generator module. If the communication module sends information about a new contact with another quad-rotor Q_j, the decision module uses the area S'_j covered by Q_j and its own previously covered area S'_i to calculate its new own covered area S_i (see Fig. 6).

$$\begin{aligned} &\left|p_i(t) - p_j(t)\right| < R_{\mathrm{comm}} \Longrightarrow S_{ij} = S'_i \cup S'_j \\ &S_i \subseteq S_{ij} \\ &S_j \subseteq S_{ij} \\ &S_i \cup S_j = S_{ij} \\ &A(S_i) = A(S_j) = \frac{A(S_{ij})}{2} \end{aligned} \quad (27)$$

Moreover, the decision module adds a new position w_i to the list W_i, such as w_i is the nearest position from the path P_i to the region S_j. If there are more than one solution, it is assumed the nearest to the current position p_i. On the other hand, if the quad-rotor arrives to a position into the list W_i and there is no contact with a neighbor, the

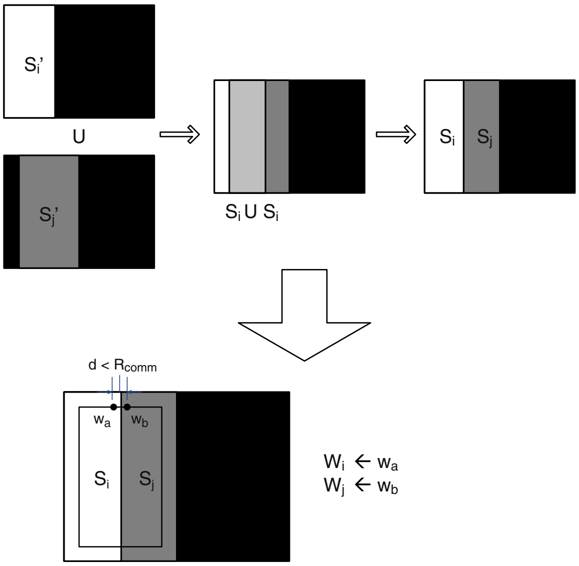

Fig. 6 Two quad-rotors contacts and their decision modules redistribute the areas to be covered by each one

decision module computes the region to survey as the whole area $S_i = S$, and removes that position from the list W_i.

The decision module also processes the information received from the monitoring module $info_i$ and eventually from the communication module $info_j$. A function $decide(info_i)$ is used to select the next action. For instance, if $info_i$ indicates an event in the position p^{info}, the function $decide(info_i)$ could send $info_i$ to the path generator module in order to create a new path to the position p^{info_i} to solve the problem.

$$|p_i(t) - p_j(t)| < R_{\text{comm}} \Longrightarrow info_i = info_i \cup info_j$$

$$decide(info_i) = \begin{cases} \text{nothing, if } info_i = \emptyset \\ path(info_i), \text{ in other case} \end{cases} \quad (28)$$

Finally, the decision module includes a submodule to guarantee convergence with the rest of the team. This submodule decreases periodically a counter $count_i$. When $count_i = 0$, the quad-rotor reverses its direction in the path and then the counter is reinitialized. The initialization value $count_i^{\text{init}}$ is unique for each quad-rotor. When a quad-rotor contacts with a neighbor, the decision module compares its own counter with the counter of the contacted quad-rotor and updates its counter to the maximum value.

$$|p_i(t) - p_j(t)| < R_{\text{comm}} \Longrightarrow count_i = \max(count_i, count_j)$$

$$d_i = \begin{cases} d_i, \text{ if } count_i > 0 \\ -d_i, \text{ if } count_i = 0 \end{cases}$$

$$count_i = \begin{cases} count_i - 1, \text{ if } count_i > 0 \\ count_i^{\text{init}}, \text{ if } count_i = 0 \end{cases} \quad (29)$$

Then, if all the quad-rotors in the area are directly or indirectly contacting, they should share the same counter and reverse their direction at the same time. But, if there are more than one independent groups surveying the area, they reverse their directions at different times and they will finally met.

5 System Features

The system proposed in Section 4 obtains a solution to the area surveillance problem with a team of quad-rotors in a cooperative way for long endurance missions, such that any point into the area will be monitored periodically.

The most important feature offered by this system is that it solves the problem using a distributed and decentralized approach. There is no leader in the team or any central unit which rules the rest of the team. All the quad-rotors decides in a local and independent way their own next actions. Each quad-rotor interchange information only when it is near enough to another member of the team. Then, the proposed system is not only distributed, but also decentralized and obtains a coordinated and cooperative solution interchanging information only in periodical times.

In addition, the system offers a set of interesting advantages to accomplish the long endurance cooperative surveillance mission in a more efficient way, as it is shown in the following subsection.

5.1 Convergence to a Near-Optimal Solution

The proposed area surveillance method converges to the solution defined by the Theorem 2 keeping a periodical information interchange between all the quad-rotors with communication constraints. This convergence ensures that all the quad-rotors will contact in a direct or indirect way and interchange information.

As all the quad-rotors fly at the same altitude and initially all of them try to cover the whole area, the path generator module computes the same initial path for all the quad-rotors.

It is also possible that all the quad-rotor move along the same perimeter but all in the same direction. In this case the quad-rotors would not contact between them, but the use of a timer help to solve this problem forcing the quad-rotor to change its direction as Fig. 7 shows. The initialization value of the timer is unique for each quad-rotor.

Furthermore, it will be shown that the proposed method leads to an optimal area distribution between all the quad-rotors. According to Theorem 2, for a team of N quad-rotors surveying an area S, the desirable solution is the one where each quad-rotor Q_i covers an area S_i, such that $A(S_i) = A(S)/N$. When a quad-rotor Q_i contacts one of its neighbors Q_j, they divide the union of their previous areas $S_i \cup S_j$. Then, each quad-rotor tries to equate the area to be covered between all its neighbors. Then, if all the quad-rotors obtain an equally distribution with their neighbors, the whole system will obtain a equally distribution.

For the sake of simplicity, the problem with only three quad-rotors is posed, but the same analysis can be applied to a larger team. If a team of three quad-rotors has to cover an area S with $A(S) = A$, each of them has to cover a desirable area S_i, such that $A(S_i) = A(S)/3 = A/3$. Figure 8 shows the area to cover by each quad-rotor after each meeting and the difference between the current and the desired area to be covered by the quad-rotor Q_j.

It is easy to see that if n is the number of contacts between two quad-rotors, the difference between the current area to cover and the desirable area according to the Theorem 2 is defined by $A/(3 \cdot 2^n)$. Hence, if $n \longrightarrow \infty$ then $A(S_i) \longrightarrow A(S)/N$.

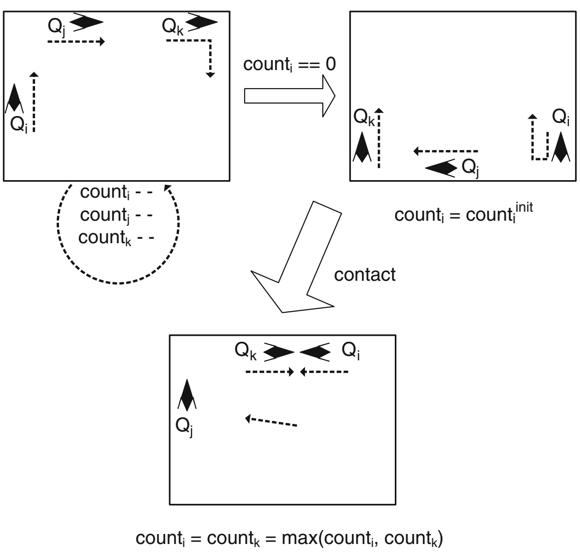

Fig. 7 Three quad-rotor are traveling along the same path in the same direction but the counter system forces them to contact when it changes their direction

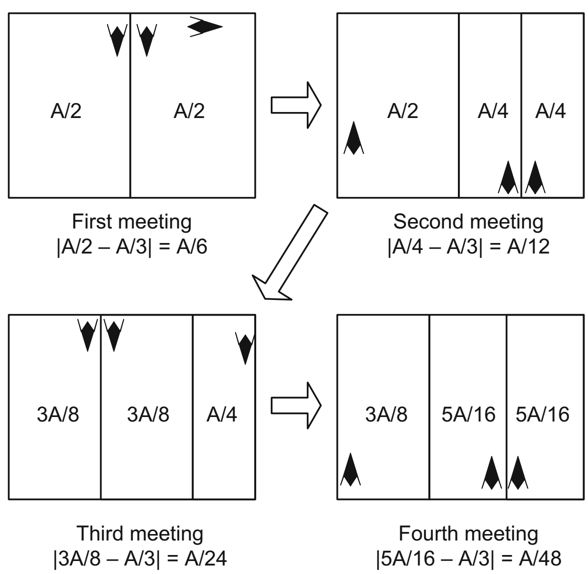

Fig. 8 Convergence of the proposed system in an area surveillance problem with three quad-rotors. Each picture shows the area to cover by each quad-rotor after each information interchange. The difference between the desired area (A/3) and the actual area to survey for each quad-rotor is decreasing with each contact

5.2 Robustness with Dynamic Teams and Fault-Tolerant System

In a long endurance mission, it is possible that any quad-rotor has to leave the area because it has to recharge their batteries or it is damaged. Due to the fact that the system is cooperative and decentralized, it is straightforward that the lost of any quad-rotor can be overcame by the rest of the team in order to keep the area fully monitored.

Given a fixed number of quad-rotors N and a defined area S, the proposed system obtains a convergent and near-optimal solution. In the following it will be considered the case in which the system is in a steady state with all the quad-rotors covering their desired area, and the defined area or the number of quad-rotors change.

Let us assume that a quad-rotor Q_j has a neighbor Q_k. According to the proposed method, there are a pair of positions w_j and w_j in their paths where they have to contact. If Q_j leaves the area, when Q_k arrives to the position w_k, it will not contact any neighbor. Thus Q_k gets back to assume the whole area S and contact with the rest of the team converging to survey a new area S_k, such that $A(S_k) = A(S)/(N-1)$. Figure 9 shows the convergence after a quad-rotor has left the area.

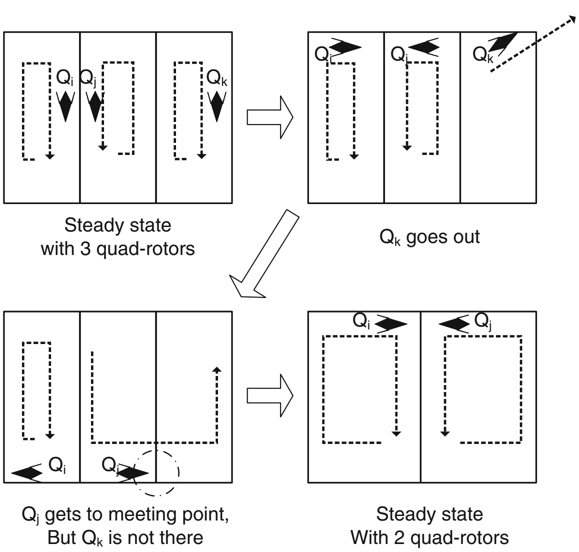

Fig. 9 A system with three quad-rotors in steady state covering an area. Q_k has to leave the area, so Q_j and Q_i redistribute to cover the whole area

When Q_k gets back to the area, a new area surveillance problem has to be solved and Section 5.1 proved the convergence to a close to optimal solution.

5.3 Finite Share Information Time

In a surveillance mission, it is important that all the quad-rotors interchange information in a finite time. For instance, in a mission where N robots have to survey an area searching for fires, but not all them can extinguish the fire, it is interesting to know how long does it take a fire warning to reach the whole team.

Assuming that the system is in a steady state, each quad-rotor Q_i covers an area S_i in a time T' following a path P_i. There are some positions

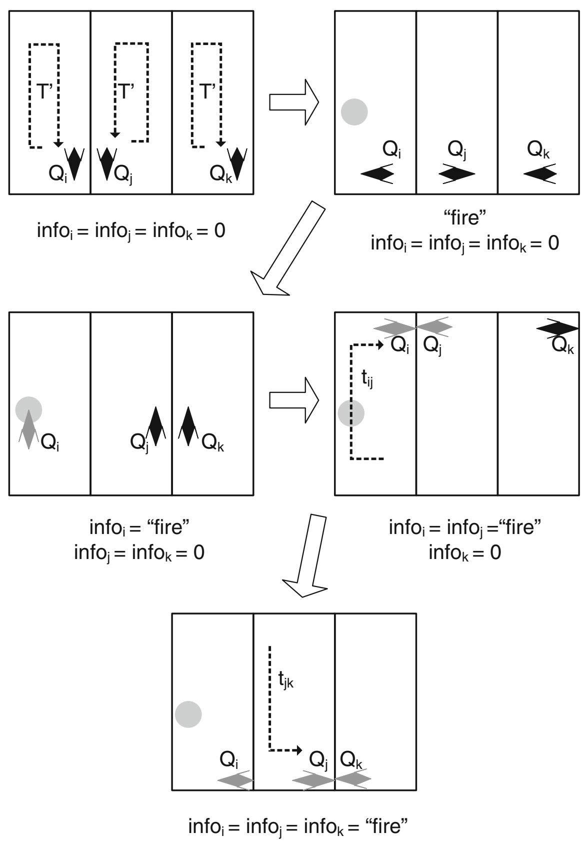

Fig. 10 A quad-rotor Q_i collects some information. In a time $t_{ij<T'}$, that information is communicated to quad-rotor Q_j. Finally, in a time $t_{jk} < T'$, Q_j shares the information with Q_k

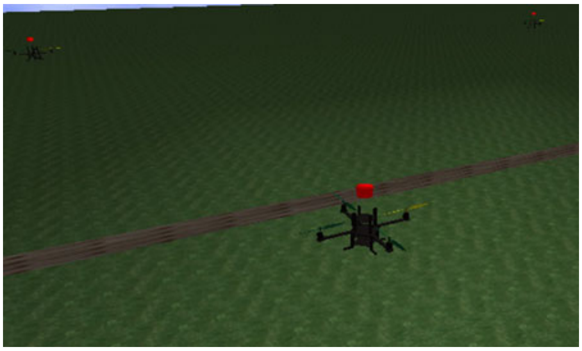

Fig. 11 Quad-rotor model on Gazebo. Videos with the described simulations can be downloaded from http://grvc.us.es/staff/jjacevedo/JINT2012/

$w_i \in P_i$ where Q_i interchanges information with its neighbors. Thus if Q_i and Q_j are neighbors, they interchange information once at T'.

According to the presented approach, each quad-rotor Q_i can have from 1 to 4 neighbors. In the worst case scenario (regarding to minimize the time in which any information is shared), there are two quad-rotors Q_1 and Q_N with a single neighbor and the other $N-2$ quad-rotors with two neighbors.

Hence, the maximum time to share an information takes place when Q_1 detects something in its area S_1 immediately after it has contacted Q_2. In a time $t_{12} < T'$, Q_1 shares the information with Q_2. In $t_{23} < T'$, Q_2 shares the information with Q_3 and so on. Then the maximum time to share is given by

$$T_{\text{share}} = t_{1,2} + t_{2,3} + ... + t_{N-1,N} < (N-1)T'. \quad (30)$$

Figure 10 illustrates how an information is propagated among all the quad-rotors.

6 Simulations with a Team of Quad-Rotors

The proposed system has been developed and tested using the Gazebo simulator over ROS (Robotic Operating System) [19]. Figure 11 shows a screen-shot during a simulation.

In the simulations it is assumed that the quad-rotors fly at an altitude $z^{\text{ok}} = 3$ m, and have a coverage range of $c^{\text{ok}} = 3$ m. All the quad-rotors can move with the same speed. In a large area surveillance task, there are usually communication constraints and a maximum communication range of $R_{\text{comm}} = 4$ m has been used in the simulations.

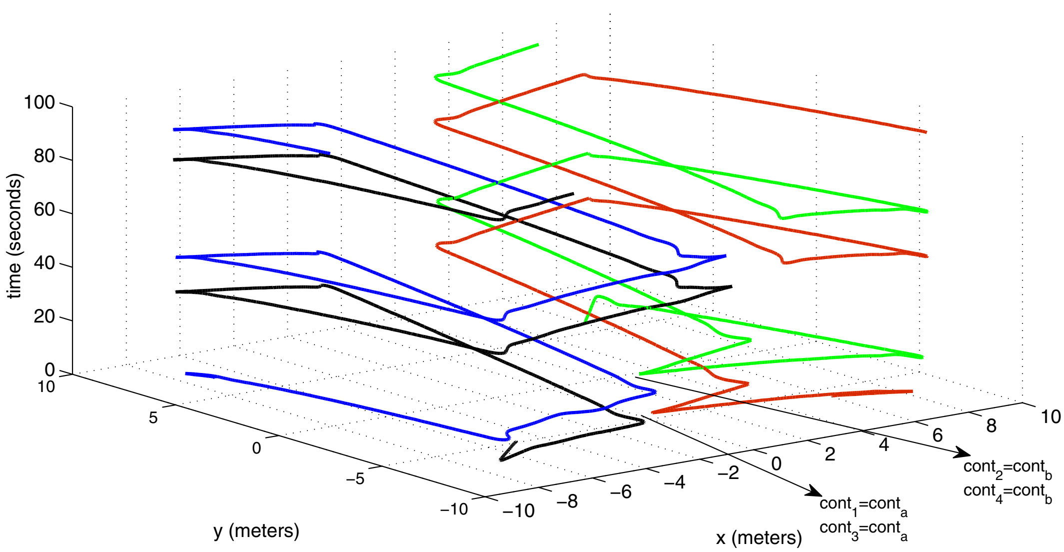

Fig. 12 A quadrangular area to be surveyed by four quad-rotors. Quad-rotors *black* and *green* meet, forming the team A and sharing a common counter, $count_a$. Quad-rotors *blue* and *red* meet, forming the team B and sharing another common counter $count_b$. Each team A and B covers the whole area in an independent manner. Each color represents the position of a quad-rotor into the area along the time

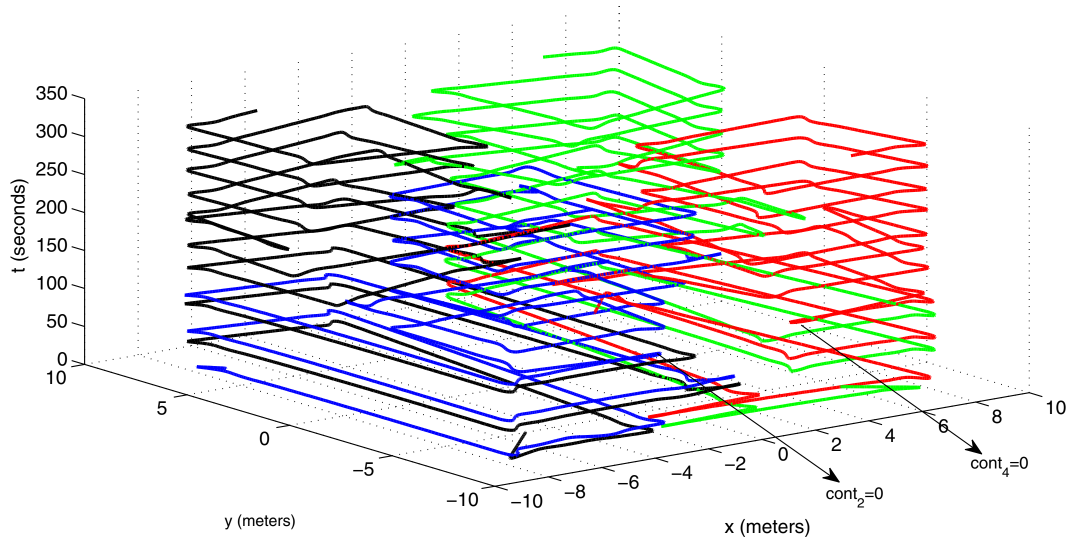

Fig. 13 At the time $t = 120$ s, $count_b = 0$ and the team B (*blue* and *red* quad-rotors) reverses direction forcing a contact with the team A (*black* and *green* quad-rotors). Now the whole team converges to distribute the whole area between the four quad-rotors. Each color represents the position of a quad-rotor into the area along the time

The first simulations are aimed to prove the system convergence even with bad initial conditions. A team of four quad-rotors has to survey a quadrangular area S, such that $A(S) = 400$ m^2. The initial conditions cause that each quad-rotor contacts only one neighbor. So, each pair of quad-rotors survey the same area in an independent way, without knowing about the other pair (see

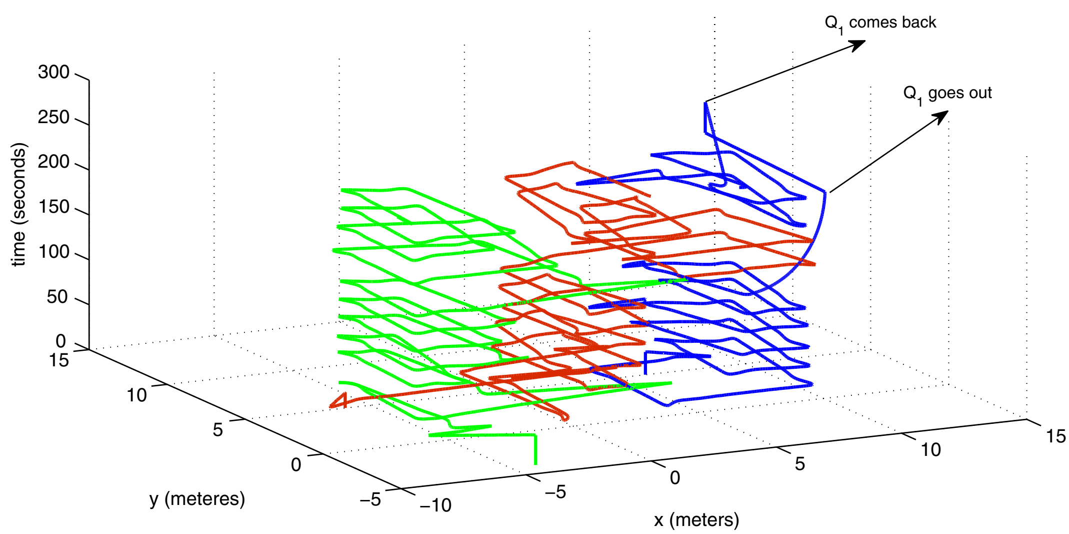

Fig. 14 The system of three UAVs converges to survey the whole area in an efficient way, each UAV covers an area S_i with $A(S_i) = A(S)/3$. However, at $t = 150$ s, an UAV Q_1 has to leave to recharge its battery and can not inform the rest of the team about it. The other two quad-rotors converge to a near-optimal solution to cover the whole area without Q_1, where each one covers an area S_i with $A(S_i) = A(S)/2$. Finally, at $t = 210$ s, Q_1 (*blue*) gets back to the area after recharging the batteries. The whole team of three UAVs converges again to the near-optimal solution where each one covers an area S_i with $A(S_i) = A(S)/3$. Each color represents the position of an UAV into the area along the time

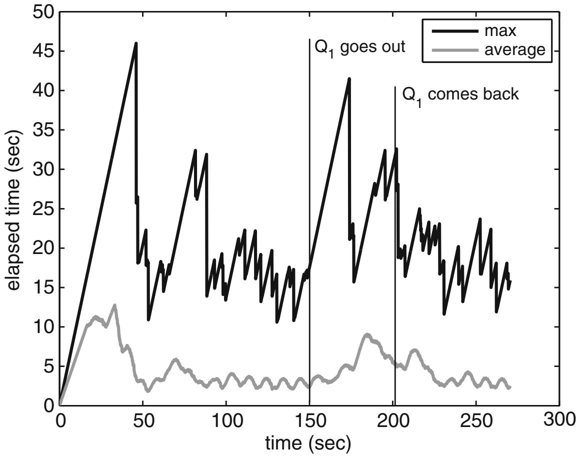

Fig. 15 The *red line* indicates for each time the maximum elapsed time since the last visit of a quad-rotor to any position in the area along the time. The *blue line* indicates the average value of the elapsed times in all the positions into the area along the time

Fig. 12). Then each quad-rotor surveys an area S'_i, such as $A(S'_i) = A(S)/2$. However, in the desirable solution each quad-rotor has to survey an area S_i, such that $A(S'_i) = A(S)/4$.

Later, when the counter of one pair reaches zero, they change their directions and the whole system converges, as it is shown in Fig. 13. Each quad-rotor covers an area S_i, such that $A(S'_i) = A(S)/4$, and all the quad-rotors contact periodically in a direct or indirect way.

The next simulations try to prove that the proposed system is useful for long endurance missions where any quad-rotor has to leave the area to recharge the batteries, getting back to the area later on. The results will show the system robustness in dynamic situations. In the simulations, a team of three UAVs has to survey a rectangular area S, such that $A(S) = 200\ \text{m}^2$. The system converges and the area is surveyed in a near-optimal way, even when the number of UAVs changes dynamically, as it can be seen in Fig. 14.

Figure 15 shows how the maximum elapsed time in the area evolves. It shows that the surveillance has better performance for larger team sizes.

The last simulations show how the information is propagated along the whole team. A team of three UAVs surveys an area S, such that $A(S) = 200\ \text{m}^2$, searching for fires. The system converges such that each UAV covers an area S_i with $A(S_i) = A(S)/3$. At $t = 120$ s, the UAV Q_3

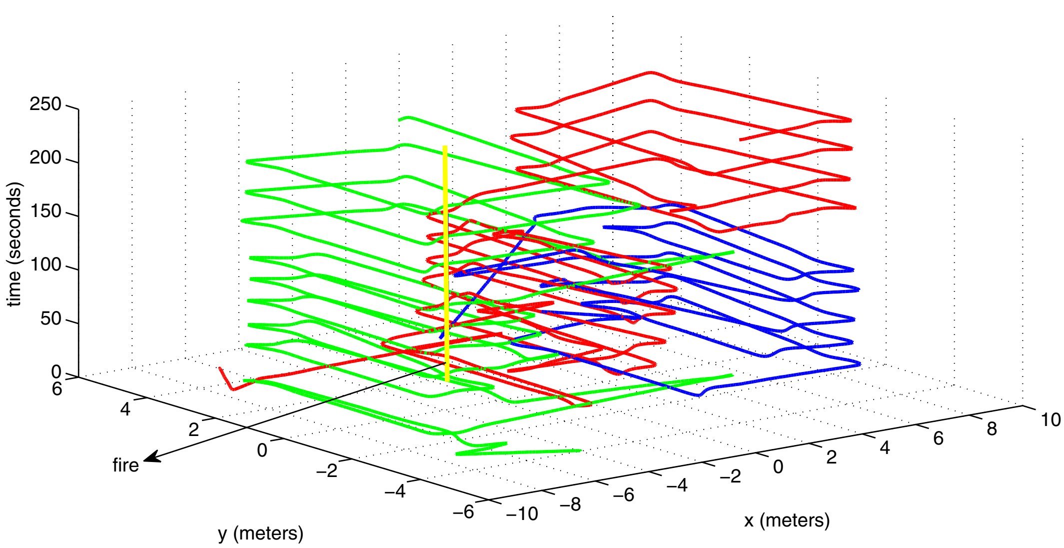

Fig. 16 A team of three quad-rotors covers an area. Q_3 detects a fire in the position (−9,−4). This information is shared between all the quad-rotors. When the information reaches Q_1, it decides to go to the fire position for continuous monitoring purposes and the rest of the team continues surveying the area. Each color represents the position of a quad-rotor into the area along the time. The *orange line* represents the fire

detects a fire in its covered area. Q_3 shares the information about the fire with Q_2 and Q_2 shares it with Q_1. When Q_1 receives the information, it decides to go to the fire location for continuous monitoring purposes, and the rest of the team has to redistribute the whole area in a efficient way, such that $A(S_i) = A(S)/2$. Figure 16 shows how the fire is detected and this information is shared between all the UAVs in the team.

7 Conclusions

This paper has presented a system for long duration surveillance missions in large areas by means of multiple UAVs. The approach proposed in the paper to address this problem allows to get a solution close to the optimum, minimizing the probability that any event happens without being detected and ensuring a periodic communication between UAVs. The approach is based on the "one-to-one" coordination for each pair of neighbors UAVs.

The simulations presented validate the most interesting features of the proposed system and show that the integration of the "one-to-one" coordination for all the pairs of neighbors allows to obtain an efficient coordination for the whole team to accomplish the area surveillance task without any central unit. Moreover, the system ensures the convergence, such that all the UAVs contact in a direct or indirect way. Finally, the simulations prove that the distributed system can deal with any change in the initial conditions.

The future work goes in the direction of conducting real experiments and the extension to non-homogeneous teams of UAS. Finally, the application to other problems of the concept of "coordination variables" and the "one-to-one" coordination will be the subject of next developments.

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