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A decentralized algorithm for area surveillance missions using a team of aerial robots with different sensing capabilities*

Jose J. Acevedo, Begoña C. Arrue, Ivan Maza and Anibal Ollero

Abstract— **This paper addresses the area surveillance problem with a team of multiple aerial robots under communication constraints. In previous work of authors [1], a decentralized modular architecture was proposed for surveillance missions with a team of homogeneous robots. This paper presents a decentralized decision-making algorithm that solves the problem for heterogeneous aerial robots with different sensing and motion capabilities. The proposed frequency-based approach offers a dynamic and robust solution able to adapt to changes in the area size and robot capabilities, and even to total robot failures. The algorithm can run properly under communication constraints and there is no robot which rules the others. Simulations and experimental results validate the proposed system for heterogeneous robots that can be dynamically added/removed during the execution of the mission.**

I. INTRODUCTION

The application of multi-UAV systems allows users to accomplish a broad spectrum of missions with robustness against failures, higher spatial coverage and an efficient deployment [2], [3], [4]. In particular, the benefits of systems with multiple aerial robots are clear for area surveillance or monitoring missions in general [5], [6], [7]. Assuming robots with different capabilities, the area monitoring problem can be addressed as a task allocation problem where each robot assumes a task related to its capabilities [8], [9]. Therefore, the area monitoring mission can be divided in sub-area monitoring tasks assigned to the robots depending on their capabilities. This is equivalent to a partitioning patrolling strategy.

Either when the areas to monitor are very large or when the robots have limited capabilities, the communication constraints represent a challenge for the operation of a multi-robot system [10]. When the connectivity between the robots can not be guaranteed in a multi-robot system because of communications,it would be assure that robots can meet periodically (it is the idea of *periodic connectivity* as was defined in [11])Also, in long endurance missions, the number of robots accomplishing the mission can change along time and the system should adapt to these changes [1]. Hence, robust distributed decision-making and multi-robot coordination capabilities are important issues in this these types of missions.

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J.J. Acevedo, B.C. Arrue I. Maza and A. Ollero are with Grupo de Robotica, Visión y Control, Universidad de Sevilla, Spain. E-mails: {jacevedo, barrue, imaza, aollero}@us.es

As will be described in this paper, the strategy presented converges to an area partitioning strategy in a distributed manner. Furthermore, it guarantees that the robots get close enough to exchange the minimum required information, obtaining a dynamic and fault-tolerant solution using only local information. As it will be described along the paper, this strategy adds some features to previous work of the authors and provides experimental validation using a team of quadrotors.

The rest of the paper is organized as follows. In Section II an overview of the literature related to the problem is presented. Section III describes formally the area coverage problem to be addressed. An area partitioning patrolling strategy is proposed to solve the problem in Section IV. Section V describes the modular architecture proposed to implement that strategy in a distributed manner. Section VI presents both simulations and real experiments with a team of quadrotors used to validate the approach and to compare it with a path partitioning strategy. Finally the conclusions and future developments of Section VII close the paper.

II. RELATED WORK

Some authors address the multi-robot area monitoring missions using team formation techniques. The approach is similar to the area patrolling mission with a single robot with larger coverage capabilities [12]. Two different and parallel problems have to be solved: close paths planning for area coverage and coordinated patrolling along the paths.

Coverage path planning algorithms generate an efficient path which ensures that every point in the area can be monitored from (at least) one position along the path [13]. In the online coverage algorithms, the area to be covered is unknown “a priori” and step-by-step the team has to discover obstacles and compute their paths avoiding collisions [14]. On the other hand, offline algorithms assume a known map. The Boustrophedon Cellular Decomposition [15] is one of the most well known methods to obtain a coverage path. This technique implies a previous area division in smaller sub-areas that can be covered with a simple *back and forth* motion. Another method which creates a spanning tree and generates the coverage paths as the boundary around it can be found in [16].

In patrolling tasks a path has to be covered many times. Many authors have applied a frequency-based approach [17]. Reference [18] analyzes and compares the cyclic and partitioning strategies. A cyclic strategy with identical robots under communication constraints is presented in [19]. A path partitioning strategy is proposed for cooperative monitoring

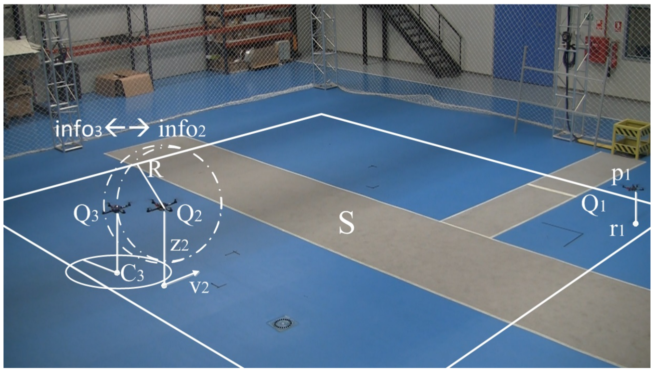


Fig. 1: A rectangular area S being patrolled by a team of three quadrotors in the indoor testbed used in the experiments. Quadrotors Q_2 and Q_3 are within the communication range R so they can exchange information. The sensor coverage range of quadrotor Q_3 is also overlayed on the floor as a circular area C_3.

missions in [20], [21]. Authors of [22] present a partitioning-based strategy to monitor a set of positions with different priorities and homogeneous robots.

Coordinating a fleet of robots to accomplish a surveillance mission in a distributed manner and assuming communication constraints is a challenging problem. References [23], [24] apply the concept of *coordination variables* to ensure cooperation in a perimeter surveillance mission. Authors in [25] analyze how this technique allows to achieve consensus between the robots in few iterations. On other hand, *one-to-one* coordination with less memory storage requirements is presented in [1] to solve area surveillance missions in a distributed and decentralized manner assuming homogeneous robots under communication constraints. The same problem is solved in [10] by using also one-to-one coordination with the drawback that the system can not adapt to changes in the number of robots during the execution. A similar technique is proposed in [26] to solve a perimeter surveillance task with a team of video-cameras and asynchronous communication between them.

III. PROBLEM STATEMENT

Let us consider an area $S \in \mathbb{R}^2$ with a surface A that has to be patrolled by a team of aerial robots $\{Q_1, Q_2, \ldots, Q_N\}$ with different capabilities (see Fig. 1) and holonomic kinematics. The probability of detection is assumed uniform in the whole area, so all the locations inside the area should be monitored periodically. The information about any detected event should be propagated to all the members of the team even under limited communication.

At time t each robot Q_i has a position $p_i(t) \in \mathbb{R}^3$, whose projection onto the plane $z = 0$ is $r_i(t) \in \mathbb{R}^2$, and a speed $v_i(t)$. The robot monitors a circular area $C_i \in \mathbb{R}^2$ defined by its sensor coverage range $c_i(t)$ computed from the current altitude $z_i(t)$ and field of view angle $\theta_i(t)$. The so called coverage speed $a_i(t)$ defines the area monitored per second and will be approximated as

$$a_i(t) \approx 2c_i(t)v_i(t) \ . \tag{1}$$

Then the capabilities of each aerial robot are defined by its maximum altitude $z_i^{\max}$, field of view $\theta_i^{\max}$ and speed $v_i^{\max}$. The maximum altitude and field of view define the maximum coverage range $c_i^{\max}$, as well as the maximum coverage speed $a_i^{\max}$ is given by the maximum coverage range and speed. Obviously it is just an approximation which depends strongly on the area shape. On the other hand, a pair of robots only can exchange information if they are within their communication range R.

In the frequency-based approaches the usual parameter to be optimized is the frequency of visits of any position of the area. Maximizing it is equivalent to minimizing the elapsed time since the last visit or refresh time T_r.

A. Minimizing the elapsed time

Different frequency-based performance criteria can be applied for the elapsed time: uniform criteria, average criteria, minimal maximum criteria, etc. In this paper, the average and maximum elapsed time will be used as the metric for the performance of the approach.

Theorem 1 *The minimum maximal elapsed time in the area coverage mission with multiple mobile robots is lower bounded by*

$$T = \frac{A}{\sum_{j=1}^{N} a_j^{\max}} \ . \tag{2}$$

Proof: The maximum area covered by a single robot Q_i in a period T can be lower bounded by

$$A_i^{\max} = a_i^{\max} T \ . \tag{3}$$

Assuming that the monitored area by any robot Q_i does not overlap the area covered by the rest of robots, the total area monitored by the team in a period T can be computed as

$$\sum_{j=1}^{N} A_j^{\max} = T \sum_{j=1}^{N} a_j^{\max} = \frac{A}{\sum_{j=1}^{N} a_j^{\max}} \sum_{j=1}^{N} a_j^{\max} = A \ . \tag{4}$$

Then for any $T' < T$ there will be a position in the area S not monitored by any aerial robot. ■

Corollary 1 *The minimum average elapsed time is computed as T/2 in the optimal case.*

IV. PATROLLING STRATEGIES WITH MULTIPLE AERIAL ROBOTS

Given a team of N robots, a cooperative area monitoring mission can be solved by defining a patrolling strategy. Many authors propose a cyclic strategy for cooperative monitoring missions [19]. In a cyclic strategy, the same closed path P which covers the whole area is traveled by all the robots.

According to the minimal maximum period criteria, the optimal solution implies that the robots move in the same direction and equally spaced along the path.

Another patrolling approach is the path partitioning strategy [21] that also starts with the generation of a single path P to cover the whole area S. Each robot Q_i covers a non-overlapping segment P_i of the path with a length L_i related to its own maximum speed $v_i^{\max}$. As all the robots take the same time to cover their own segments, neighbor robots can meet to communicate and coordinate periodically in their common segment endpoints (periodic connectivity).

The maximum and average refresh times as well as the maximum latency are analyzed in [24] for both strategies. In short, the cyclic strategy theoretically could reach the minimum maximal refresh time defined in (2) but only for teams of homogeneous robots and assuming no communication constraints. On other hand, the path partitioning strategy can adapt to heterogeneous robots and communication constraints but even under ideal conditions it can not reach the optimal performance defined in (2). Therefore, in this paper an area partitioning strategy is proposed to overcome these limitations.

A. Area partitioning and multiple paths generation

In this strategy, the maximum speed and the maximum coverage range capabilities of the different robots are exploited to obtain an efficient solution. The whole area S is divided among the robots and each robot Q_i has to cover a non-overlapping sub-area S_i with a surface A_i related to its own maximum coverage speed $a_i^{\max}$ according to the expression

$$A_i = a_i^{\max} \frac{A}{\sum_{j=1}^{N} a_j^{\max}}, \forall i = 1, \ldots, N \ . \tag{5}$$

Each aerial robot generates its own cyclic path P_i with length L_i to cover its own sub-area S_i and moves along it periodically with its maximum coverage speed $v_i^{\max}$. Any robot takes the same time T' to cover its path

$$T' = \max_k \frac{L_k}{v_k^{\max}} \ , \tag{6}$$

so neighbor robots periodically reach positions within their communication ranges where they can exchange information, obtaining a theoretical periodic connectivity.

Applying the partitioning area strategy to the problem defined in Section III, the minimal maximum refresh time along the area S can be computed as

$$T_r^{\max} = T' \ . \tag{7}$$

Finally the maximum elapsed time since any event is detected in the area by a robot till that information is shared with the rest of the team (or latency T_L) can be computed as

$$T_L \leq (N-1)T' \ . \tag{8}$$

The adopted strategy exploits the different capabilities of the robots (both maximum speed and sensing coverage range). In ideal conditions, each robot can cover its own assigned area with the shortest coverage path of length $L_i = \frac{A_i}{2c_i}$ and the minimum maximum refresh time defined by expression (2) could be theoretically reached.

V. DECENTRALIZED DECISION-MAKING ALGORITHM

In previous work [1] of the authors, it was proposed a decentralized modular architecture for area surveillance missions with a team of homogeneous robots. The obtained solution converged to the area partitioning strategy described in the Sect. IV-A in a distributed and decentralized manner. From local decisions, the whole team obtains a coordinated and efficient strategy to monitor a whole area.

A modified version, assuming different decision-making and coverage path planning algorithms, is presented here to solve the problem with heterogeneous aerial robots (different sensing and motion capabilities). The proposed approach offers a dynamic and robust solution able to adapt to changes in the area size and robot capabilities, and even to robot total failures. The algorithm can run under communication constraints and there is no robot which rules the others.

The decision-making process on-board each robot is based on Algorithm 1. It is based only on its local information, making the method scalable with the number of robots in the team. As it will be shown later, the system converges to the patrolling strategy described in Sect. IV-A following this approach.

The aerial robots use a path planning algorithm based on *back and forth* strategy that computes a closed path P_i to cover their assigned sub-areas S_i according to their coverage range $c_i^{\max}$. Initially, the assigned sub-area is the whole area S and the robots move along their own paths P_i monitoring the environment. When two robots are within their communication range, they exchange information about the sub-areas they are covering $info_i = [S_i, a_i^{\max}]$. Each robot computes the union of these sub-areas, divide it according to their coverage speeds $(a_i^{\max}, a_j^{\max})$ and estimated path lengths, and obtains the new sub-area to cover S_i. Figure 2 illustrates this one-to-one technique for rectangular sub-areas. A new path P_i is computed and the robot navigates following it. That path includes a new meeting point between both robots that is added to the list W_i. If a robot arrives to a meeting point and there is no communication with its neighbor, it generates a path to cover the whole area S and continues moving along it. Although the generated path depends on the covering range of each robot, all the generated paths use the same pattern (assuming rectangular areas), enabling but not ensuring neighbors meeting even if some of them delays. Moreover, it guarantees that the whole area S is covered even if several robots are lost.

VI. VALIDATION RESULTS

This section presents both simulations and real experiments with a team of quadrotors used to validate the

Algorithm 1 Decentralized decision-making algorithm running on-board the i-th robot of the team. W_i is a list defined to store the positions where the robots should meet their neighbors.

Require: S
  $P_i \leftarrow$ `path`(S,$c_i^{\min}$)
  $W_i \leftarrow \emptyset$
  while !ABORT **do**
    $v_i \leftarrow v_i^{\max}$
    if comm(Q_i, Q_j)==OK **then**
      `info`$_i \leftarrow$ `union`(`info`$_i$,`info`$_j$)
      $S_i \leftarrow$ `divide`(d_i, S_i, $a_i^{\max}$, S_j, $a_j^{\max}$)
      $P_i \leftarrow$ `path`(S_i,$c_i^{\min}$)
      while $r_i \notin P_i$ **do**
        $p_i \leftarrow$ `navigate`(P_i)
      end while
      $W_i \leftarrow W_i$ + $\{r_i\}$
    else
      if $r_i \in W_i$ **then**
        $P_i \leftarrow$ `path`(S,$c_i^{\min}$)
        $W_i \leftarrow W_i$ - $\{r_i\}$
      end if
    end if
    $p_i \leftarrow$ `navigate`(P_i)
    `info`$_i \leftarrow$ `monitor`(p_i,C_i)
  end while

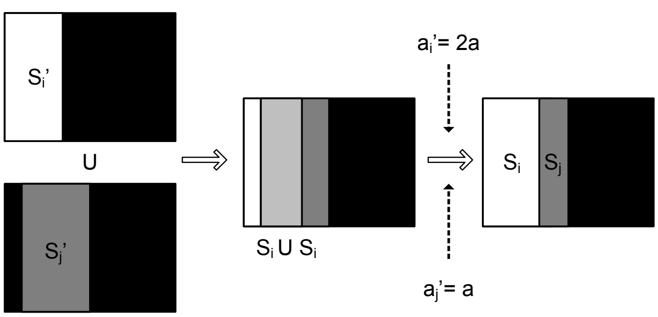


Fig. 2: An example of the method called "divide" in Algorithm 1. It is used to compute new sub-areas each time two robots interchange information. The initial sub-areas are S'_i and S'_j and the new division is made according to the coverage speeds ($a_i^{\max}, a_j^{\max}$) and estimated path lengths of the robots. The resulting sub-areas are S_i and S_j.

approach and to compare it with a path partitioning strategy.

A. Simulations

A set of simulations has been executed in MATLAB to compare the proposed area partitioning strategy with the path partitioning strategy described in [21]. The scenario is a rectangular 40×20 m^2 area defined by the vertexes $(-10,-10), (30,-10), (30,10), (-10,10)$ m that has to be patrolled by a team of four aerial robots. Table I shows the capabilities and initial positions of the robots. These values have been computed randomly from uniform distributions.

TABLE I: Capabilities and initial positions of the robots.

Robot color	red	green	blue	yellow
x_0 (m)	2.05	-3.17	-2.61	6.35
y_0 (m)	-0.58	-5.45	8.10	1.90
$v^{\max}$ (m/s)	0.44	0.24	0.28	0.35
$c^{\max}$ (m)	0.99	1.41	1.06	0.99

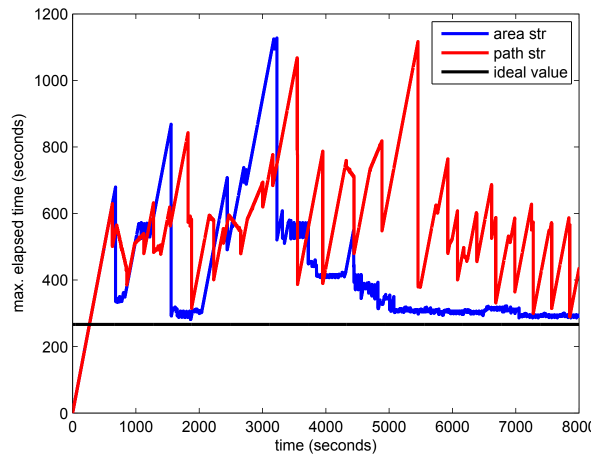
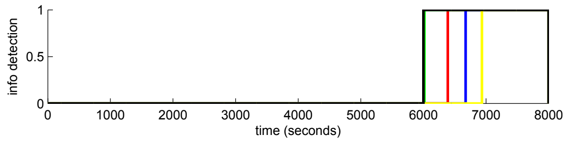


Fig. 3: The maximum elapsed time since the last monitoring task for all positions in the area is represented along the time, for both the area division strategy and the path division strategy. Also, the maximum elapsed time for the ideal case (Theorem 1) is shown. Videos from both simulations are available in *http://www.youtube.com/watch?v=ePJHlgJPwrM* and *http://www.youtube.com/watch?v=qt5iQq984Tg*

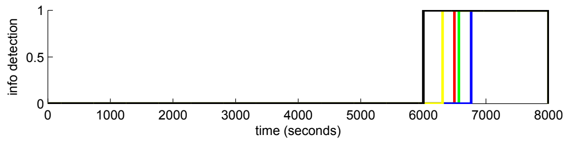
In the simulation, the blue robot leaves the mission at time $t = 2000$ s and comes back later at time $t = 4000$ s. On the other hand, an intruder is simulated in the position $(-8,-8)$ m at time $t = 6000$ s. This location has been chosen far from the area center to measure the maximum time to share that information among all the team members. Figure 3 summarizes the simulation results for both the dividing path and the dividing area strategies using the frequency-based maximum elapsed time criteria.

The simulations show that the area division strategy has better results than the path division strategy, comparing both the minimal maximum and the average elapsed time metrics. Also, the area division strategy allows the robots to converge in the steady state to a solution close to the ideal case of Theorem 1. Obviously, while the blue robot is out of the area the results are worse for both strategies. However, the area partitioning strategy adapts faster to change in the number of available robots for the mission.

Figure 4 shows that after the intruder appears, it is detected by a robot and the information about it is propagated to all the team members. It can be seen that the area division strategy offers a slightly faster information propagation performance compared to the path division strategy.



(a)



(b)

Fig. 4: The black line indicates when the intruder appears in the simulation. The plot changes from zero to one when a robot receives the information about the intruder (the colors of the robots are shown in Table I). The results are shown for: (a) the dividing path strategy, and (b) the dividing area strategy.

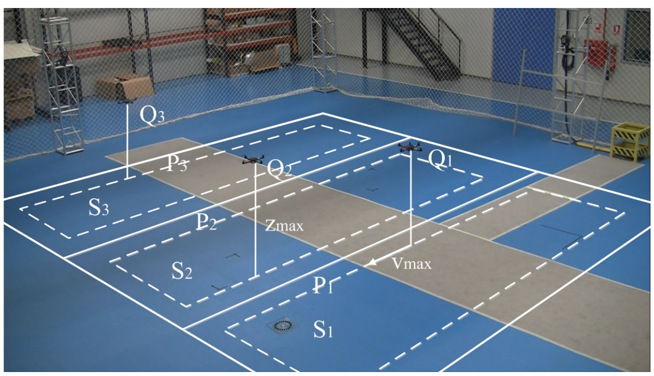


Fig. 5: The rectangular area S is patrolled by a team of three quadrotors using the area partitioning strategy. The experiments were performed in the indoor testbed of the Spanish Center for Advanced Aerospace Technologies (CATEC) in Seville.

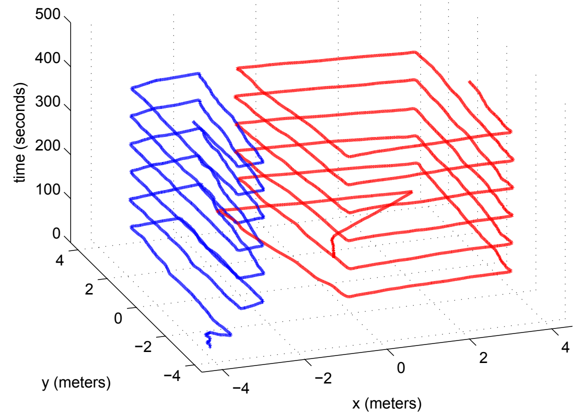
B. Experimental tests

Real experiments to validate the proposed distributed system have been carried out in the indoor testbed of the Spanish Center for Advanced Aerospace Technologies (CATEC) in Seville. The robots were a team of Hummingbird quadrotors by Ascending Technologies with 200 g payload and up to 20 minutes of flight autonomy. Their maximum flight altitude was fixed by software to 2.5 meters.

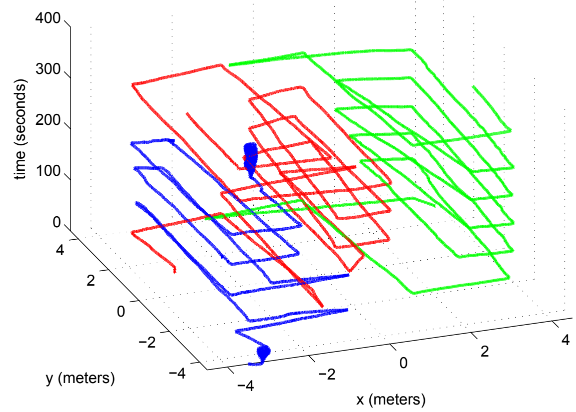
The testbed uses a localization system based on 20 VICON cameras and is able to offer the position and altitude of each quadrotor with centimeter accuracy in real time.

The area to cover is a rectangular area of 9×9 m^2 in the center of the testbed (see Fig. 5). A limited communication range of 2 meters has been simulated by software using the locations provided by the VICON system. The sensing coverage range of the robots is 1.5 meters.

In the first experiment, a team of two quadrotors has to cover the whole area. It is assumed that one robot is faster than the other one. Figure 6a shows that each robot covers an



(a)



(b)

Fig. 6: This graph shows the robots position (x, y) over time (vertical axis) when they use a dividing area strategy for: (a) the experiment with two robots with different capabilities that can be viewed in *http://www.youtube.com/watch?v=h8UnTPCdgzo*, and (b) the experiment with three robots in dynamic conditions that can be found in *http://www.youtube.com/watch?v=9IqY8eE9Dtw*.

area related with its own maximum speed taking advantage of the different capabilities in an heterogeneous multi-robot system. The first robot (blue in Fig. 6a) has limited its maximum speed to 0.35 m/s and the other one (red) can move with a maximum speed of 0.45 m/s.

In the second experiment, a team of three quadrotors with a maximum speed of 0.3 m/s covers the area. One of the robots is lost at time $t = 250$ s and Fig. 6b shows how the system can adapt the area distribution in a decentralized manner dynamically.

VII. CONCLUSIONS

This paper has addressed the area surveillance problem with a team of multiple aerial robots under communication constraints. A frequency-based approach has been proposed to accomplish the missions using an area partitioning strategy designed to minimize the refresh time. A simple analysis showed that this technique offers better results than a cyclic strategy: it can exploit the different capabilities of the robots and keep periodical communication between them.

Furthermore, a decentralized decision-making algorithm has been also presented. This algorithm computes a solution that converges to the designed area partitioning strategy using *one-to-one* coordination. Hence the system is scalable with the number of robots and also allows to deal with dynamic changes (robots added/removed during the execution).

Simulation and experimental results were used to validate the proposed system and to compare it with the path partitioning strategy described in Sect. II. Simulations show a better performance, obtaining close to optimal results for the maximum refresh time. Other interesting features found in the simulations and experiments were: decentralized convergence to the proposed strategies, robustness against changes in the number of robots, periodic interchange of information and exploitation of the different robot capabilities.

Future developments will be oriented to address the coverage problem considering priorities and adversarial settings.

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