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Cooperative perimeter surveillance with a team of mobile robots under communication constraints

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Abstract— **This paper presents the perimeter surveillance problem using a set of cooperative robots with heterogeneous speed capabilities under communication constraints. The problem is solved using a frequency-based approach. In the proposed path-partition strategy, the robots patrol a segment length related to their own capabilities and interchanges information with its neighbors periodically. An efficient decentralized algorithm is applied to coordinate the robots from local information and decisions. Finally, simulation and experimental results are presented to illustrate the convergence and the robustness of the solution.**

I. INTRODUCTION

Different motion strategies have been applied to optimize a given criteria while the robots are patrolling a given perimeter. One criteria may be to optimize the frequency of visiting different locations along the path (frequency-based approach) as it can be found in [1] or [2]. Other authors address the problem without optimizing a frequency criteria. In [3], authors maximize the probability of detecting intruders using a stochastic approach and assuming potential intelligent intruders that could learn a deterministic strategy. Reference [4] proposes a robust solution to the presented problem using behavioral control. In [5], a distributed algorithm is presented based on ordered upwind methods, which coordinates motions of agents assuming a continuous opened communication and centralized decisions.

In this paper, the perimeter surveillance problem will be faced from a frequency-based approach. In [6], the cyclic and partitioning strategies are applied and compared to solve the min-idleness problem. Both strategies are also analyzed from a frequency-based criteria in [7]. The cyclic patrolling strategy is better explained in [8], assuming identical robots and a closed path. And a method with the goal of monitoring a set of positions with different priorities using homogeneous robots is presented in [9].

In large scenarios, a opened communication between all the robots can be no possible. Therefore, a distributed approach would be more appropriate in these cases. Also, decentralized and distributed approaches offer increased robustness, adaptability and scalability. These methods usually rely on the interchange of a reduced amount of variables (so called *coordination variables*) required to obtain a solution in a cooperative manner. This concept is applied in [10] to ensure cooperation in a perimeter surveillance mission using a team of small homogeneous UAVs. In [11], the authors analyze how consensus is achieved in a multi-robot system with few iterations using this concept.

This paper applies a similar decentralized coordination algorithm based on *coordination variables* to solve the perimeter surveillance problem under communication constraints for a team of cooperative mobile robots. It proposes a path partitioning strategy to patrol the perimeter in a cooperative manner from a frequency-based approach (optimizing the *refresh time* or elapsed time between two consecutive visits to any position of the perimeter). In [12], authors propose a *one-to-one* method to coordinate a team of homogeneous aerial robots to cooperate in an area surveillance mission, assuming communication constraints. The same technique is used in [13] to patrol a path in a cooperative way using a set of heterogeneous aerial robots. Other research groups propose similar methods to solve the problem with a team of video-cameras and asynchronous communication between neighbors, as in [2], [14]. The idea is sharing the tasks of each pair of contacting robots and dividing the sum between them. As it will be shown later, this paper contributes with a distributed algorithm which converges faster than the proposed ones in previous works. Also, it works with heterogeneous robots and under communications constraints.

The paper is structured as follows. Section II describes the problem statement, whereas Sect. III explains the proposed path-partitioning approach followed to solve it. In Section IV the proposed solution is presented and some relevant features are analyzed. Sections V and VI show a set of simulation and experimentation results to validate the proposed approach. Conclusions and future work close the paper in Sect. VII.

II. PROBLEM STATEMENT

Let us consider a set of N mobile robots $\{M_1, M_2, ..., M_N\}$ that has to patrol a perimeter $P := \{p(x) \in \mathbb{R}^2 : x \in [0, L]\}$, see Fig. 1. L is the entire perimeter length and x indicates the distance along the perimeter P from each position $p(x)$ to a given initial position.

Each robot M_i can move along the perimeter P in two directions $d_i = \{-1, 1\}$ with a variable speed in module v_i so that

$$\frac{dx_i(t)}{dt} = d_i(t)v_i(t), \forall i = 1, 2, ..., N, \tag{1}$$

where $x_i(t) \in [0, L]$ is the distance along the perimeter P from the robot M_i to the initial position $p(0)$ at time

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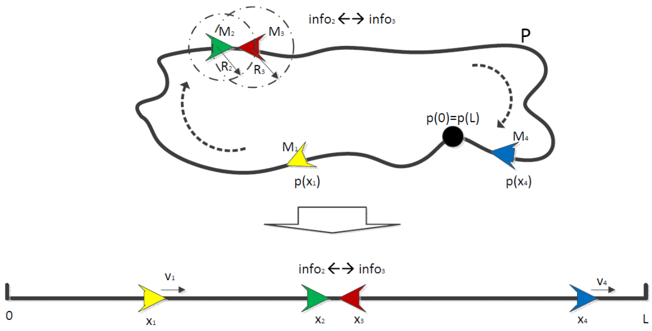

Fig. 1. A setup with four robots that illustrates the different variables considered in the problem statement.

t. It is assumed that robots can have different maximum speeds $v_i^{\max}$ and can reverse direction instantaneously. In addition, each robot M_i can have different communication ranges $R_i > 0$. Thus, two robots will be able to interchange information, if they are close enough, i.e. a distance lesser than the minimum of their communication ranges. Hence, the robots are heterogeneous at least in their maximum speeds and communication ranges.

In the context of surveillance missions and assuming that there is no “a priori” information about the potential location of the objects of interest along the perimeter, the main goal is to maximize the frequency of visits to any perimeter position. Maximizing this frequency is equivalent to minimizing the *refresh time* $T_r(x,t)$ (or elapsed time between two consecutive visits to any position of the perimeter) as it is defined in [7]. Thus, the problem addressed is a variant of the min-idleness problem described in [6] applied along the perimeter.

Let us denote the maximum and the average values of $T_r(x,t)$ at time t as $T_r^{\max}(t)$ and $\overline{T_r}(t)$ respectively. The bounds for these parameters are given by

$$T_r^{\max}(t) \geq \frac{L}{\sum_{j=1}^{N} v_j^{\max}} \tag{2}$$

and

$$\overline{T_r}(t) \geq \frac{L}{2\sum_{j=1}^{N} v_j^{\max}}, \tag{3}$$

but, assuming communication constraints, a non-closed perimeter or robots with different maximum speeds, those limits would not be reached.

Otherwise, so as to increase the robustness of the system against failures, the problem should be solved in a decentralized manner. As the communication range of the robots is limited, the solution should guarantee that the robots exchange information periodically. Then, the computed motion for the robots should allow them to be within their communication range periodically. The information exchange is required to coordinate the surveillance task and to share the information about the objects of interest found during the mission in a finite time.

Fig. 2. Path-partition strategy applied to the cooperative perimeter surveillance problem with the team of four mobile robots depicted in Fig. 1.

III. Path-partitioning strategy

A path-partitioning strategy is proposed for the surveillance of the perimeter, such as it is stated in the previous section. Each robot M_i should cover a non-overlapping segment P_i with a length L_i and the whole perimeter should be covered by the team.

In order to maximize the surveillance frequency, the robots would move at their maximum speed and any robot takes the same time T' to cover its own segment. Then, the length of the segments L_i is related to the robots maximum speed according to

$$L_i = v_i^{\max}\frac{L}{\sum_{j=1}^{N} v_j^{\max}}, \forall i = 1, ..., N, \tag{4}$$

and the resulting value for T' is given by

$$T' = \frac{L_i}{v_i^{\max}} = \frac{L}{\sum_{j=1}^{N} v_j^{\max}}. \tag{5}$$

Each robot M_i patrols a length L_i, moving between the endpoints of its allocated segment at its maximum speed $v_i^{\max}$, as it is illustrated in Fig. 2. Each pair of neighbor robots meet in the common endpoint of their segments periodically, ensuring the information propagation between all the robots.

The maximum *refresh time* T_r can be calculated as the time in which a robot M_i covers twice its own segment S_i which is

$$T_r^{\max}(t) \leq 2T'. \tag{6}$$

Figure 3 shows the *refresh time* along the segment covered by a robot in the position x_i in a steady state and using the path-partitioning method described above. As all the robots would take the same time T' to cover their own segments, the average refresh time can be computed as the relation between the area shown in the figure and the length of the segment. Maximizing it with respect to the position x_i, the maximum average *refresh time* is obtained when each robot is located in the middle of its own segment ($x_i = L_i/2$):

$$\overline{T_r}(t) \leq \frac{3}{4}T'. \tag{7}$$

Finally, the maximum time T_s to share a information with the rest of the team or *latency* as it is defined in [7] can be calculated. At worst, a new event is detected by robot in the endpoint of a segment. This robot takes a maximum time of $2T'$ to meet its neighbor robot and share that information. Now, this neighbor robot takes a maximum of T' to share it with its other neighbor. This sequence is followed until the

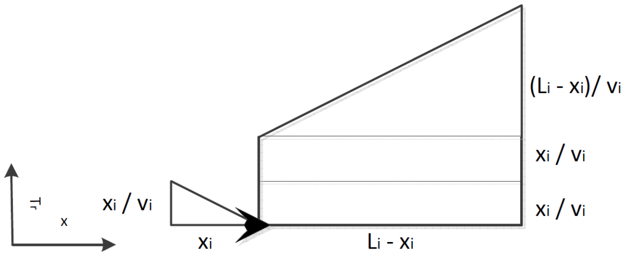

Fig. 3. Refresh time in a segment L_i covered by a robot following the proposed path partitioning strategy.

new information reaches the last robot in the other segment endpoint. So, the value of T_s is given by the following expression:

$$T_s \leq 2T' + (N-2)T' = NT'. \tag{8}$$

Cyclic strategies such as [8] are also proposed to solve the same problem, assuming a closed perimeter. Then, the robots patrol the whole perimeter in the same direction, with the same speed and equally spaced. Under these conditions, the system could obtain optimal results similar to the minimum limits defined in expressions (2) and (3). However, these conditions are not always possible. Communication constraints are tackled in [8] stopping a robot to exchange information with the rest of the team. A failure in the fixed robot would leave the rest of robots with no communication between them, limiting the system robustness.

On other the hand, when all the robots can not move at the same maximum speed (assuming $v_1^{\max} \geq v_2^{\max} \geq ... \geq v_N^{\max}$), there are two possibilities. The first one implies than all the robots patrol the entire perimeter at their maximum speeds. Hence, in the worst case scenario, the maximum *refresh time* is limited by the fastest robot M_1 as

$$T_r^{\max} \leq \frac{L}{v_1^{\max}} \tag{9}$$

and

$$\overline{T_r} \leq \frac{L}{2v_1^{\max}}. \tag{10}$$

The second one implies that some robots decrease their speed to accomplish the conditions assumed in [8]. Thus, a different solution could be obtained depending on the speed, and the minimal maximum and average *refresh time* using the cyclic strategy would be

$$T_r^{\max} \leq \min_k \frac{L}{kv_k^{\max}}, \tag{11}$$

and

$$\overline{T_r} \leq \min_k \frac{L}{2kv_k^{\max}}, \tag{12}$$

where $k = 1, ..., N-1$ and $v_1^{\max} \geq v_2^{\max} \geq ... \geq v_N^{\max}$.

The slowest robot M_N would stop to share information. Robots with a maximum speed greater than $v_k^{\max}$ could adapt their speeds to it. Slower robots would not take part of the solution. In this case, when a robot detects an event, it has to get to the stopped robot to exchange information with it. Then, when the rest of the robots get near to the stopped one, they can be informed about the new event. Therefore, the maximum *latency* can be computed as

$$T_s \leq \frac{L}{v_k^{\max}} + (k-1)\frac{L}{kv_k^{\max}}. \tag{13}$$

In general, the path-partition method obtains better results according to the frequency-based criteria compared to the cyclic strategy when the robots have different speed capabilities.

IV. From Local Information Exchange to Global Coordination

When the communication ranges are short relative to the size of the perimeter, any robot will be disconnected from the rest most of the time. A distributed coordination technique should be used to ensure that the multi-robot system converges to the path partition strategy described in Sect. III. The entire perimeter length and the sum of speeds for all the robots will be used as coordination variables.

A. Distributed algorithm

The proposed distributed and decentralized method to implement the strategy described in Sect. III is listed in Algorithm 1, where x_i is the perimeter position defined in Section II. Each robot runs it in an independent manner and no different hierarchical levels are considered among the team members.

The robots M_i move at their maximum speed $v_i^{\max}$ to patrol their segments in the minimum time, while they update its information database $info_i$. Even if a robot gets the end of its own segment $[a_i, b_i]$, it continues on moving until it communicates with another one M_j (and updates its local information) or arrives to end of the perimeter.

When robot M_j communicates with robot M_i arriving on its right, M_j trusts in all the information that M_i sends about his right side (for instance, sum of speeds $speed_i^{right}$ and length on its right L_i^{right}), and M_i trusts in all the information that M_j offers about his left side. They exchange the required information to calculate the parameters used to coordinate the team: sum of speeds $speed_i^{sum}$ and total perimeter length L_i. With these variables, each robot can compute the segment $[a_i, b_i]$ to cover.

If any of the robots is out of its own segment, they go both to their common endpoint, adjusting their speeds v_i. Then, each robot moves to its own other segment endpoint.

When a mobile robot gets the initial $x_i = 0$ or end position in the perimeter $x_i = L$, it sets up its information according to its direction d_i and turns back. The algorithm minimizes the required information exchange with or without communication constraints because robots only has to communicate with their neighbors.

Algorithm 1 Distributed algorithm proposed to implement the perimeter surveillance strategy described in Sect. III.

$a_i = b_i = x_i$
$speed_i^{left} = speed_i^{right} = L_i^{left} = L_i^{right} = 0$
for all t **do**
  $v_i = v_i^{\max}$
  if contact(M_i,M_j) **then**
    $info_i = info_i \cup info_j$
    $v_i = \min(v_i^{max}, v_j^{max})$
    if $d_i > 0$ **then**
      $speed_i^{right} = speed_j^{right} + v_j^{\max}$
      $L_i^{right} = L_j^{right}$
    end if
    if $d_i < 0$ **then**
      $speed_i^{left} = speed_j^{left} + v_j^{\max}$
      $L_i^{left} = L_j^{left}$
    end if
    $speed_i^{sum} = speed_i^{left} + speed_i^{right} + v_i^{\max}$
    $L_i = L_i^{left} + L_i^{right}$
    $a_i = speed_i^{left} \frac{L_i}{speed_i^{sum}}$
    $b_i = a_i + v_i^{\max} \frac{L_i}{speed_i^{sum}}$
    if $x_i \leq a_i$ **then**
      $d_i = 1$
    end if
    if $x_i \geq b_i$ **then**
      $d_i = -1$
    end if
  end if
  if $x_i = 0$ **then**
    $speed_i^{left} = L_i^{left} = 0$
    $d_i = 1$
  end if
  if $x_i = L$ **then**
    $speed_i^{right} = L_i^{right} = 0$
    $d_i = -1$
  end if
  $x_i^{old} = x_i$
  $x_i = move(x_i, d_i, v_i)$
  $L_i^{left} = \max(0, L_i^{left} + x_i - x_i^{old})$
  $L_i^{right} = \max(0, L_i^{right} - x_i + x_i^{old})$
  $info_i = update(p(x_i))$
end for

B. Robustness and fault-tolerance

A decentralized and distributed approach should increase the robustness and fault-tolerance of the system, since the mission can be completed if one or more robots are lost. The algorithm is dynamic and allows us to deal with variations in parameters such as the amount of robots, their speeds, the length of the perimeter and others, providing flexibility and fault-tolerance (for instance, a communications fault). Robots continuously update their own coordination variables and decide their own tasks according to the local information, periodically updated with the information of other team members.

For example, let us assume a system in fully steady state where a set of N robots is covering a perimeter of length L. Robot M_{j-1} periodically receives from M_j information about the sum of speeds on its right given by
$speed_{j-1}^{right} = v_j^{\max} + speed_j^{right}$.

In a similar manner, robot M_j receives periodically from M_{j+1} the information about sum of speeds on its right as
$speed_j^{right} = v_{j+1}^{\max} + speed_{j+1}^{right}$.

At any time t, M_j could be lost, and neither M_{j-1} nor M_{j+1} will contact it. Thus, robot M_{j-1} will communicate with M_{j+1} after a while. Robot M_{j+1} reports to M_{j-1} the information about the sum of speeds on its right given by
$speed_{j-1}^{right} = v_{j+1}^{\max} + speed_{j+1}^{right}$.

Finally, robot M_{j+1} receives information about the left side of M_{j-1}. Then, both robots can update their coordination variables and calculate correctly the segments to cover. That information is propagated to the rest of robots when they contact with a robot which is aware of the new scenario. In finite time, all the robots will have updated correctly their coordination variables. It should be mentioned that the process would be similar if the perimeter changes for instance.

C. Convergence analysis

The use of the Algorithm 1 by each robot makes the whole team behaviour converge to the solution described in Sect. III. All the robots move always into a finite perimeter with only two possible directions. As the robots reverse direction when they reach endpoints, all the neighbors robots have to meet and exchange information. Therefore, they can calculate coherently and share the required coordination variables to solve the problem.

Now, the issue is to analyze time-complexity of the convergence. Let us assume a team of N robots. When the first robot M_1 communicates with robot M_2, both robots will know that at least two robots are present in the team. If M_2 communicates with M_3, they will know that at least three robots are available. Nevertheless, M_1 could continue operating according to the scenario with two robots. This reasoning can be extrapolated to robot M_N, and after $N-1$ information exchanges, M_N and M_{N-1} will have all the information about the N robots (although the rest could not have it). When robot M_{N-1} gets back to communicate with M_{N-2}, it will know the whole scenario and will compute the intended solution. In the same manner, after $N-2$ new meetings, information will have been spread out and will have reached the first robot M_1. Therefore, all the robots will have the necessary information to compute correctly all the required coordination variables.

Therefore, each robot will need at most $2N$ information exchanges with its neighbors to converge to the solution explained in Sect. III and the convergence time-complexity increases linearly with the number of robots.

A similar path-partitioning strategy was previously suggested by other authors as a solution to the problem under discussion using different coordination techniques [14], [13]. In those algorithms only the sum of the segments of both

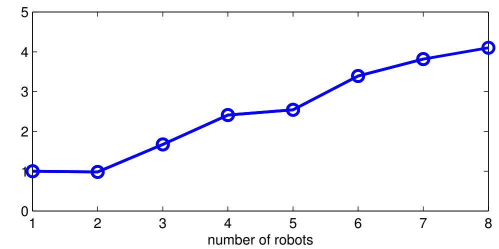

Fig. 4. Relation between the convergence times using the algorithm based on one-to-one coordination and the algorithm described in this paper.

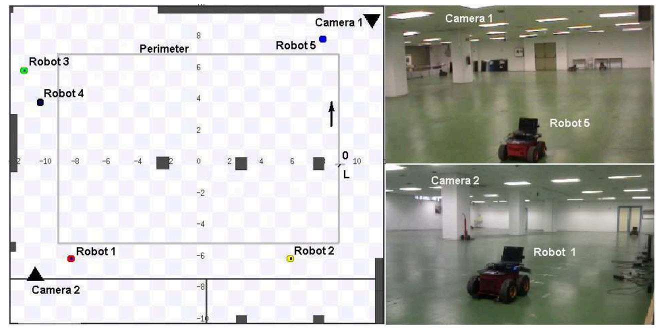

Fig. 5. Initial setup of the first experiment. Grey line near to the wall indicates the perimeter shape. The initial and end perimeter position have been established in the coordinates $(9, 0)$.

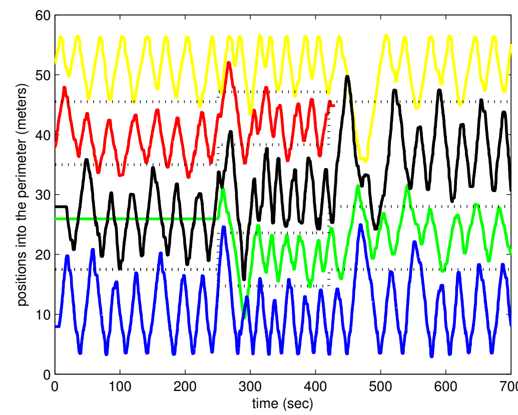

Fig. 6. Perimeter positions x_i of the robots along the perimeter in the first experiment. Each color represents a different robot. The dotted lines indicate the theoretically optimal perimeter division. A video of the experiment can be seen in *http://www.youtube.com/watch?v=WqRKXqcuWKg*.

communicating agents was shared between them. Information about the number and capabilities of other robots, or the total length of the perimeter was not required to be stored. Then, less information storage capabilities are required, but according to [14] the convergence time-complexity increases quadratically with the number of robots, whereas in our strategy it only increases linearly.

V. Simulation results

A large set of 240 simulations has been executed in MATLAB to validate the proposed algorithm and compare it with other approaches based on the "one-to-one" coordination technique (namely the algorithms presented in [13] or [14]).

Different scenarios with different perimeter lengths and different number of aerial robots (with the same dynamical model used in [13]) has been launched using both the presented distributed algorithm based on coordination variables and the algorithm proposed in [13]. The initial robots positions and directions of motion have been created randomly. Their maximum speeds have been chosen using an uniform distribution from 0.2 to 0.5 m/s. The communication range between robots has been limited to 4 m. Both algorithms converge to the same path division between the robots, but the convergence times are different. It is assumed that the system has converged when the difference between the segment that each aerial robot covers and the one that theoretically should cover (according to expression (4)) is less than 5 %.

Figure 4 shows the average value for the relation between the convergence times using the algorithm based on the *one-to-one coordination* technique and using the one based on the technique presented in this paper. The simulation results shows that as the number of robot increases it converges more quickly than an algorithm based on the *one-to-one coordination* technique.

VI. Experimental results with a team of mobile robots

In the experimental setup, a team of Pioneer-3AT has to patrol the room perimeter shown in Fig. 5. The maximum speed of the robots is 1 m/s, but for robots 1 (yellow), 2 (red) and 3 (green), it has been artificially limited to 0.6 m/s to test the system theoretical features for heterogeneous robots. In the experiments, it is assumed a sensing range of 2 meters for the robots, whose effect is to decrease the total length to patrol. Each Pioneer executes a Player Server [15] that talks to an application running the Algorithm 1. Pioneers do not need any localization system to run the algorithm, they just use the laser to keep near the perimeter (wall). However, a localization system is used to limit the communication range to 4 meters via software.

Two different types of experiments has been developed. In the first one, the convergence and robustness of the system with dynamic teams of mobile robots were tested. Four mobile robots patrolled the whole perimeter at the beginning. At $t = 250$ seconds, the fifth mobile robot starts moving, and at last at $t = 420$ seconds, a robot leaves the perimeter. In Fig. 6 it can be seen that the algorithm converges while each robot was covering a length related to its speed.

Figure 7 shows the maximum and average values of the *refresh time* parameter. Results show an efficient behavior, according to the frequency-based criteria, with values close to the lower bounds defined in (2) and (3). Obviously the results are better with a larger number of robots.

The second type of experiment shows how this approach can adapt to changes in the perimeter and how any information is shared between all the robots. A team of four mobile robots is patrolling the perimeter and at $t = 180$ seconds, the

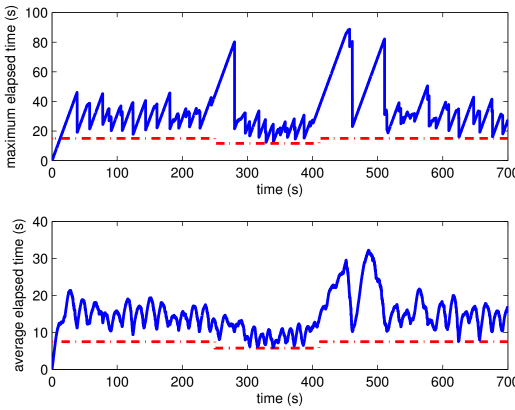

Fig. 7. Maximum (above) and average (below) values for the refresh time. Red dash-dotted line indicates the lower bounds defined in expressions (2) and (3), according to the robots capabilities along the time.

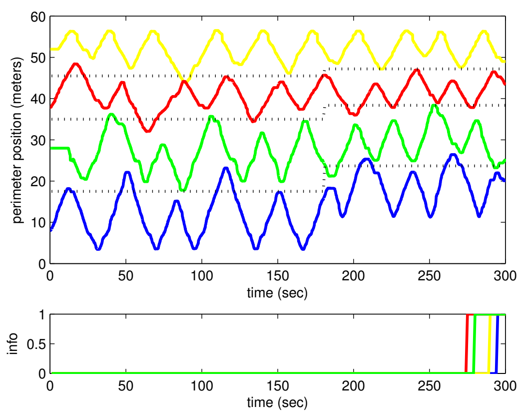

Fig. 8. The top graph shows the position of the robots along the perimeter in the second experiment. The dotted lines indicate the theoretically optimal perimeter division. In the bottom graph a value of "1" represents that the robot knows the new detected information. Each robot is represented by a different color. A video of the experiment is available in *http://www.youtube.com/watch?v=m2cVLo7nmLs*.

perimeter length is decreased. On the other hand, one of the robots detects an event at $t = 275$ seconds. Figure 8 shows as the whole multi-robot system adapts when the perimeter length changes. It also shows that any new information is shared between all the robots in a short time, consistent with the expression (8).

VII. Conclusions

The proposed path partition strategy allows the multi-robot system to cooperate in the perimeter surveillance mission, exploiting the different robots capabilities (maximum speeds). Also, it ensures that any information detected will be shared between the whole team in a finite time, even under communications constraints.

A distributed and decentralized algorithm based on the concept of *coordination variables* enables the system to converge to the proposed strategy from local decisions in few iterations (linearly related to the number of robots). The proposed system is robust in changes to the initial conditions. Experimental and simulation results validate the approach and shows some relevant features.

Acknowledgement

The experiments presented in Sect. VI have been performed using a robotic testbed of the CONET project.

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