Cooperative perimeter surveillance using Bluetooth framework under communication constraints

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Abstract. The work presented focuses in the simulations and real experiments of perimeter surveillance under communication constraints, performed by teams of UAVs using a Bluetooth communication framework. When UAVs work in a colaborative manner, communication among them is essential to properly perform their task. Moreover, energy consumption and weight of the devices equipped in a UAV are important to be reduced at minimum possible, particularly in micro-UAVs. A coordination variables strategy is implemented to perform the perimeter division.

Keywords: Bluetooth Low Energy, UAV, communication, coordination variables

1 Introduction

Nowadays, there is a great development and investment in the field of the unmanned air systems or UAS, commonly called drones. There are uncountable applications thanks to their adaptability to different tasks, as for instance in agriculture, mapping, delivery services, border defense, search and rescue operations, etc. Due to this, they have been the subject of much research to improve their autonomy, obstacle avoidance, localization, cooperation, path planing...

This article focuses in a group of robots which divides a perimeter to surveil it in a cooperative manner. Any surveillance system is made of many activities that can be summarized in three main activities:

- The detection of new events, intruders or information of interest. This task is strongly dependent on the movement planification strategy of the aerial robots, which is based on the information available and the estimations about the problem, the environment and the situation of the rest of the aerial robots.

- The communication between the elements of the system, so each of them is aware of the whole system. This also involves the movement planification strategy as it needs the system status.

- The assignment of the best robot to handle every detected event. This can be made of two manners: as a centralized system, in which case a control station decides which aerial robot should handle each task; and as a distributed system, in which case a dynamic target allocation among the aerial robots can be addressed to assign the targets in the most efficient way.

The work of this article is focused in the test of communication among the robots of a team when range constraints exist. Real experiments have been performed with UAVs equipped with Bluetooth devices in order to allow them to communicate themselves, and also with an algorithm based on coordination variables to partition the total perimeter assigned to the group.

This system has been tested on simulations and on a real location in the *Escuela Tecnica Superior de Ingenieria* of Seville (Spain). The remain of the article is structured as follows:

- Section 2 summarizes the state of the art work.
- Section 3 introduces and explains how works the Bluetooth devices chosen for the experiments, and a brief description of the operating framework.
- Section 4 details the developed perimeter division protocol used.
- Section 5 shows both simulation and real experiments, and their evaluation.
- Section 6 presents the conclusions of the article.

2 State of the Art

The cooperation among robots to carry out a widely range of tasks has been studied in all kind of robots. In [17], [14] authors develop a system with multiple ground robots capable of covering area and tracking targets in a cooperative manner. One robot behaves as the master and reaches its objectives by other robots who behave as the slaves. In [19] authors paid attention to aerial robots, which track targets in the optimal way using the information of their neighbors. In [15], the system is also conformed with UAVs, the algorithm asigns missions in autonomously way based on their level of importance.
The way the robots communicate among them depends on the application pursued. For instance, Zigbee is an standard protocol widely used for DIY projects. In [18], [3] authors used this protocol for communicating nodes and robots in relative large distance, but its main disadvantage is its greater energy requirements in comparison with other systems.
Authors in [13], [6] used bluetooth technology to connect the robots as opposed due to its lower energy consumption and weight. In [16], [11], [5] authors worked in the localization of the robots given the communication framework, though due to being focused in ground robots the task was simpler.
In this article the commmunication framework used is the one exposed in [8], based on standard Bluetooth Low Energy 4.1 connections. It works with the Nordic nRF51 chipset in combination with the S130 SoftDevice [12].

The perimeter surveillance has been a field of study in lately years. A way of approach to this problem is through UAS and ground stations in the perimeter to manage the communication [2], or also using a method based on linear programming and Markow chain as it is posed in [4].

Other methods, more interesting when there are communication constrains, are distributed and decentralized: authors in [9] proposed a robust solution based on behaviour control of the multi-robot system. Another possibility are the coordination variables methods, which are proved to be fast convergent solution. In [7], it is developed an algorithm to coordinate a team of small homogeneous UAS to perform cooperatively a perimeter partitioning strategy, using coordination variables. This aforenamed algorithm slightly modified to consider heterogeneous robots is the one used in this paper, as poses in [**?**]

3 Bluetooth devices and framework

The use of Bluetooth Low Energy (BLE) has been steadily growing just since its initial launch in the market of the wireless communications, aimed at applications such of Internet of Things (IoT). This involves monitoring of wireless sensor networks and control of applications that are in continuous communication of state variables. The coordination of UAVs problem is very similar to this statement.

In this work it is taken as a development framework an opensource implementation of a mesh network offered by M-Way Solutions [10]. This approach is placed in the upper layers of application and host of the Nordic nRF51 chipset in combination with the S130 SoftDevide so that it manages the roles of the different devices in the communications including self-healing capabilities and implementation with battery powered devices. This device is advantageous small and low power consumption, which suits for micro-uav teams.

The S130 SoftDevice from Nordic enable the use of three central device connections and one peripheral. To manage the communication, the device establishes connections with its neighbors and also assigns group identifiers. All the nodes that got the same group identifier will be considered part of a swarm, so they can exchange information between them. Due to this, this structure conforms a scatternet topology (figure 1) which interconnects all the robots.

Everytime a connection is made, the SDK serves an ID and the RSSI for that connection, which is corresponded to a power indicator in the received signal in a radio communication, and this can be used in different wireless protocols.

About the specifications of the BLE technology, there is one specially important and remarkable, its data transfer limit. The conception of the BLE is focused on the transmission of small amounts of data at 1 Mbps, and in short distances up to 10 meters. Due to the management of limited data packages in

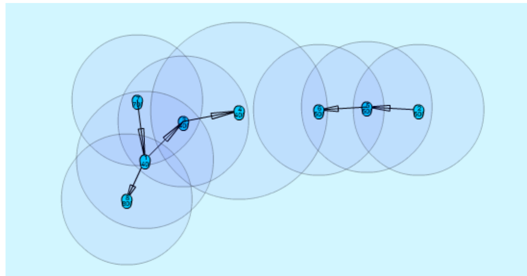


Fig. 1. Example of the scatternet topology. Blue dots are the nodes, and the blue circles represent the range of the communications

the connections, the BLE technology has another fundamental characteristic: a transmission time under the 3 ms, letting it to work in real time developments.

4 Perimeter division protocol based on coordination variables

The algorithm implemented to perform the perimeter surveillance is the one exposed in [1] based on coordination variables. It is a distributed and decentralized algorithm. Due to the short range of communication most of the time a robot of the patrol will be isolated from the others robots, so this kind of model allow the multi-robot system to converge to the final path partitioning through local decisions and asynchronous information exchanges, without any kind of hierarchical levels among the robots.

Being B the entire perimeter defined as:

$$B := \{b(s) \in \mathbb{R}^k : s \in [0, L]\} \tag{1}$$

where b is a curve to cover the whole path B, s is defined as the distance to the initial path position $b(0)$ along the curve b, and L is the length of the path B, being $b(L)$ the final position.

Each robot Q_i decides autonomously its own segment $B_i := [b(s_i^{inf}), b(s_i^{sup})]$ in order to the total amount of robots patrol the entire perimeter B. Thus, each Q_i uses a back and forth motion between its own first segment point $b(s_i^{inf})$ and its own last segment point $b(s_i^{sup})$.

Hence, any robot Q_i knows its maximum motion speed v_i^{max}, its current direction movement (right or left in its own segment) d_i, and its current position s_i into the curve b.

The algorithm implemented uses a set of variables called *coordination variables*, which represent the minimum information necessary for each robot Q_i to calculate its own segment L_i. These variables are:

$$\begin{aligned} length_i &= L \\ speed_i^{sum} &= \sum_{j=1}^{n} v_j^{max}, \forall i = 1, 2, ..., n \end{aligned} \tag{2}$$

Being $length_i$ the length of the total perimeter, and $speed_i^{sum}$ the sum of all robots maximum speed. In addition to these, each robot Q_i has a set of intermediate variables which are required to calculate the coordination variables:

- $length_i^{left}$ is the length of perimeter that Q_i has currently on its left.
- $length_i^{right}$ is the length of perimeter that Q_i has currently on its right.
- $speed_i^{left}$ is the sum of the speed of all the robot which are at left of Q_i.
- $speed_i^{right}$ is the sum of the speed of all the robot which are at right of Q_i.

The sequence of the algorithm is as following: the robot Q_i moves at its maximum speed v_i^{max} along its segment B_i. In the case that it reaches the end of B_i, Q_i does not stop its movement but continues till it communicates with another Q_j, and both exchange their variable information and updates their segments, or it arrives at the end of the perimeter.

If robot Q_j meets robot Q_i by Q_i right side, Q_j sends it all the information about its right side, scilicet, its sum of speeds $speed_j^{right}$ and its length on its right side $length_j^{right}$. Q_i does the same but with the left side variables.

Then, both Q_i and Q_j use this new information to update their coordination variables, $length_i$ and $speed_i^{sum}$:

$$\begin{aligned} speed_i^{sum} &= speed_i^{left} + speed_i^{right} + v_i^{max} \\ length_i &= length_i^{left} + length_i^{right} \end{aligned} \tag{3}$$

And with this update they can calculate their segment $[s_i^{inf}, s_i^{sup}]$ as follows:

$$\begin{aligned} s_i^{inf} &= speed_i^{left} \frac{length_i}{speed_i^{sum}} \\ s_i^{sup} &= s_i^{inf} + v_i^{max} \frac{length_i}{speed_i^{sum}} \end{aligned} \tag{4}$$

If one robot reaches the initial $s_i = 0$ or ending $s_i =$ L position in the perimeter, it also updates its variables according to its direction d_i and turns back.

The algorithm minimizes the information exchanges because robots only has to communicate with their neighbors.

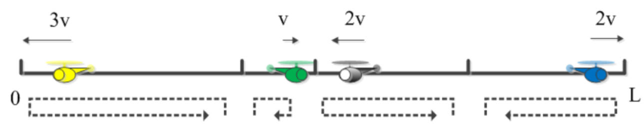


Fig. 2. A team of 4 UAVs with different speeds implementing a perimeter division strategy

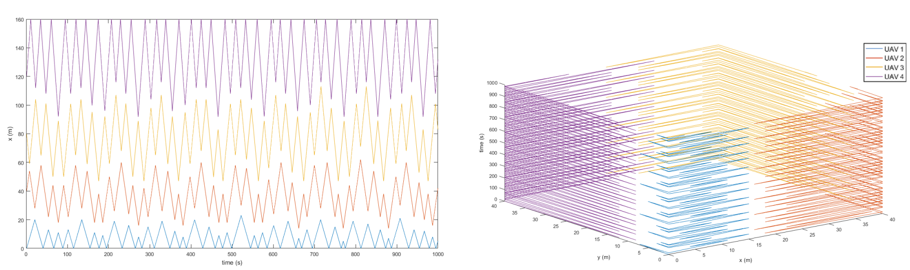
5 Experimental testing

A set of simulation and experimental results are provide to demonstrate the effectiveness of the communication framework works and validate Bluetooth devices. Results show that UAVs divide the perimeter proportionally to their own capabilities.

5.1 Simulation results

The proposed distributed algorithm is based on the coordination variables. UAVs' model and communication framework simulation have been developed in C++. The initial positions has been defined randomly, but the speeds have been chosen proportionally between them in order to obtain a visual result understable at one glance.

The first simulation consist on 4 UAVs patrolling single line of 160 m, similar to figure 2, being their speeds 1 m/s, 2 m/s, 3 m/s, and 4 m/s. Figure 3 (a) shows the result. As it can be observed, each UAV patrol a length proportional to their speed. For instance, the slower UAV patrol a length which is a quarter of the faster UAV, accordingly to the relation between their speeds. It is highlighted that the final solution is not a unique point but a cycle. This will be discussed in the next simulation.



(a) Patrolling a line

(b) Patrolling a square

Fig. 3. Graphic representation of the UAVs movements in the experiments

The second simulation is the same 4 UAVs patrolling not a single line, but the square made of the previous line of 160 m, namely, a square of side 40 m. Figure 3 (b) and figure 4 shows the result of this simulation.

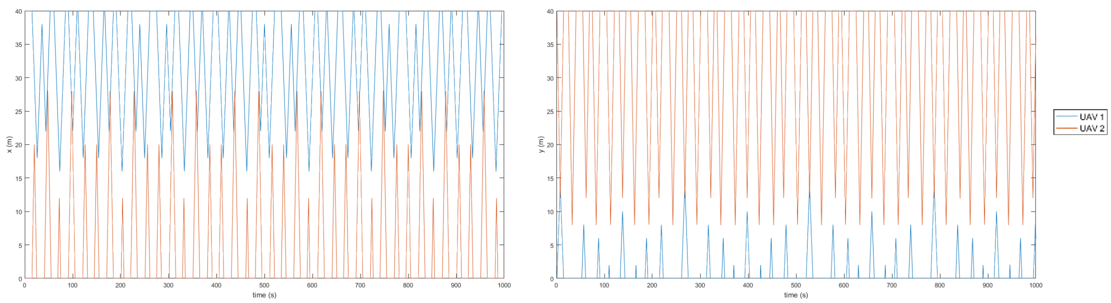


Fig. 4. Simulation results of 4 UAVs patrolling a square of side 40 m. Images only show the position of 2 of the 4 UAVs for clarity. Left image shows position X in meters against time; right image shows position Y in meters against time

Though it seems that the UAVs have converged in no solution, the final solution of this division problem is not a single point but a cycle. Indeed, taking a careful glimpse, for instance, the left image of figure 4, we can easily see how the system converges quickly to a cycle of 10 points which are clearly signaled in figure 5. Through different simulation experiments, modifying the number of robots, their speeds, the perimeter to surveil and other sets of variables, it is enough clear that all them affects the number of points of the final solution of the system, but which is the exact relation is not utterly determined, because of being out of the scope of this article.

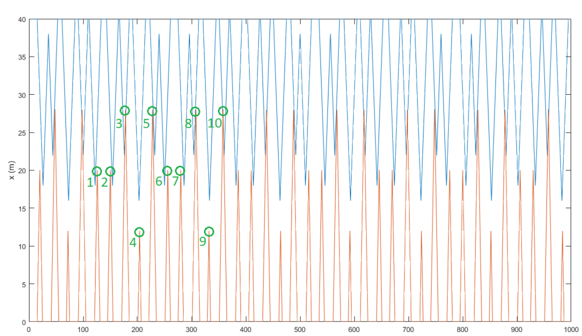


Fig. 5. Signalization of the cycle of ten points

The algorithm proposes is robust enough to variations in the system. The last simulation performed present the same 4 UAVs patrolling the square of side 40 meters, but two of them get lost at the middle of the mission. As it can be observed in the figures 6 and 7, the other two UAVs patrolling the whole perimeter converging in a new cycle solution.

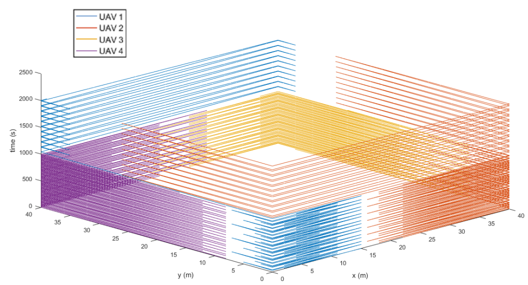


Fig. 6. Simulation results of 4 UAVs patrolling a square of side 40 m, getting lost two of them

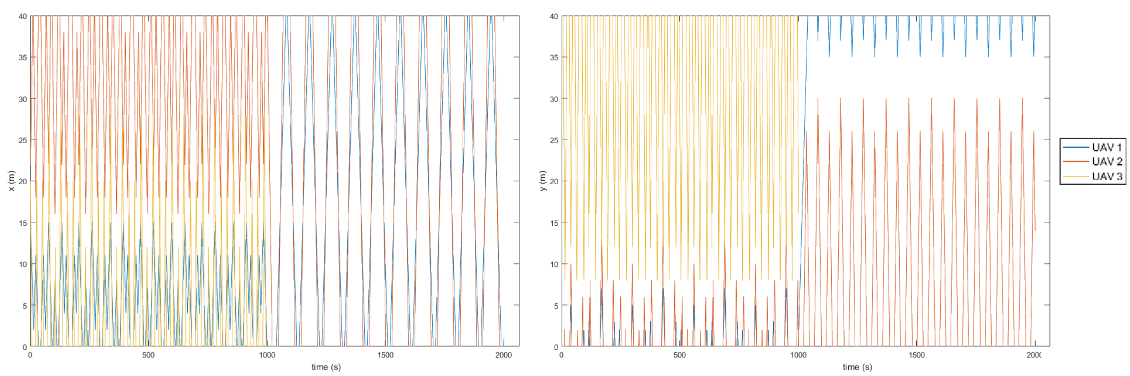


Fig. 7. Simulation results of 4 UAVs patrolling a square of side 40 m. Images only show the position of 3 of the 4 UAVs for clarity. Left image shows position X in meters against time; right image shows position Y in meters against time

5.2 Real experiment

The location selected to carry out the real experiment was an outdoor zone of the laboratories of the University of Seville *Escuela Tecnica Superior de Ingenieria* that is shown in figure 8 (a). Only two UAVs were used in the experiment, in order to demonstrate the communication framework. Thanks to the scalability of the perimeter division algorithm, which was proved in the simulations, two UAVs are enough: more robots would increase the number of point of the final cycle solution, and would make the graphics more difficult to read.

(a) Zone of the experiments (b) Perimeter division

Fig. 8. Satellite images of the experiments

Both UAVs were equipped with the required sensor to know their own GPS position, and the aforenamed Nordic BLE device. Also they have an Intel NUC computer to compute the perimeter division algorithm and the communication instructions load in them. The experiment takes approximately 3 minutes to complete.

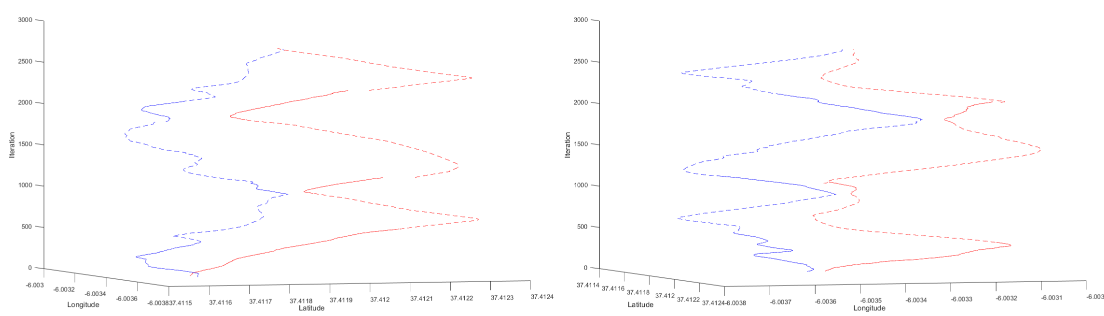


Fig. 9. The 3D representation is turned in order to ease the visualization of the connections (continuous line) and disconnections (dashed line) of the UAVs

Figure 8 (b) shows the result of the experiment over the satellite image of the experiment zone. The UAVs patrol the perimeter till they meet themselves or reach the end of the perimeter, in both case they updates their coordination

variables, recalculate their routes and turn back to continue their patrol. Figure 9 is included to show the connection and disconnection between both UAVs.
It is a remarkable fact that the bluetooth devices are able to maintain the connection further away than the 10 meters specified, even though to establish that connection they do need to be in the 10 meter range. Finally, the figure 10 is the same 3D representation but projected to over the latitude-longitude plane: in this image is easier to see the perimeter, but slightly more difficult to see when they connect or disconnect.

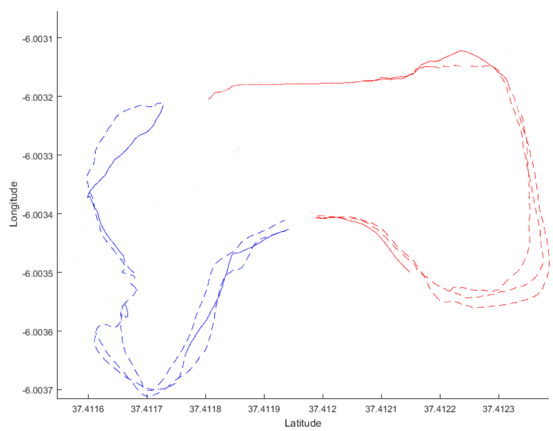


Fig. 10. 3D representation of the connections (continuous line) and disconnections (dashed line) of the UAVs projected over the longitude-latitude plane

6 Conclusions

Real outdoor experiments have been performed with satisfactory results. Both communication framework and perimeter division algorithm have been demonstrated to be robust and efficient. The Nordic bluetooth devices are proved to work properly, being an excellent option to use for UAVs communication thanks to their low consumption energy and weight. The devices connect within the 10 meters range, and even maintain the communication till the 20 meters.
As future work it would be interesting evaluate the existent relation between the number of UAVs, their capabilities, the length and shape of the perimeter, etc., and the number of points of the final solution cycle. Likewise, another future work could be an experiment with more UAVs not only performing a perimeter division but also allocating tasks, as tracking different moving targets. Also measuring the energy consumption of the BLE devices along the experiment would be a good subject of study.

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