Evaluation of Coordination Strategies for Heterogeneous Sensor Networks Aiming at Surveillance Applications

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Abstract— **A new challenge in the sensor network area is the coordination of heterogeneous sensors (with different sensing, mobility and computing capabilities) in an integrated network. This kind of sensor networks have clearly high relevance in surveillance systems, in which both low-end static ground sensor nodes and more sophisticated sensors carried by mobile platforms, such as Unmanned Aerial Vehicles (UAVs), cooperate. This paper provides an analysis of two different strategies to guide the collaboration among the sensor nodes mentioned above, applied to area surveillance systems. The first analyzed problem is related to the choice of the UAV instance that will respond to a given alarm issued by a ground sensor node. The second issue is the estimation of the response time until any UAV can be engaged in handling an alarm and effectively handles it. Two strategies are introduced and compared: one based on a pheromone inspired approach and another based on utility functions inspired on risk profiles that models decisions of investors in the stock market.**

I. INTRODUCTION

The use of UAVs in military missions such as Suppression of Enemy Air Defense (SEAD) is being studied by several research groups [1][2]. In addition, the advance of the Wireless Sensor Network (WSN) technologies allows the utilization of UAVs equipped with sophisticated sensors (e.g. radar, infra-red cameras, etc) in conjunction with WSN nodes to perform surveillance missions [3]. However, the design of coordination strategies to make these heterogeneous sensor networks work efficiently brings new challenges to researchers. The coordination among these surveillance nodes presents a higher complexity if compared to traditional approaches, as for instance, the ones used in SEAD missions. This increasing complexity comes from concerns that range from energy consumption of the low-end ground nodes to WSN communication issues. The study of these differences and the adaption of strategies used to solve these coordination problems motivate this work, as described further in the text.

A first motivation for using low-end ground sensor nodes in cooperation with more sophisticated sensors embedded in UAV platforms is to reduce the overall cost of the system, as the price of ground sensor nodes is several times lower than the price of UAVs, even taking into account small UAV platforms such as MLB models [4]. Another motivation is related to the increase in the system efficiency, as the low-end nodes can provide information about the surrounding environment in advance to the UAVs, before they decide to move to a given location. In a system in which the UAVs have different capabilities, this information can be used to support the decision about which UAV is more suitable to a specific situation, due to the types of sensors they carry, for instance.

The main contribution of this paper is the introduction and comparison of two different strategies to coordinate heterogeneous sensor networks composed by low-end wireless sensor nodes deployed on the ground and more sophisticated sensors embedded in UAV platforms, applied to area surveillance systems. The first approach uses a pheromone metaphor to drive the selection of a UAV needed to respond an alarm issued by a ground sensor node. The second approach uses a utility-based function, which drives the negotiation among the UAVs to decide which one is more suitable to respond a given alarm, according to a risk analysis. These two approaches are then compared according to relevant efficiency metrics.

The remainder of this paper is organized as follows. Section II presents the description of the scenario and the UAV model adopted in this work. Section III introduces the pheromone-based coordination strategy, while Section IV provides the description of the utility-based one. Section V presents the evaluation of the obtained results and a discussion on pros and cons of each strategy. Section VI discusses related works, while Section VII concludes the paper, giving the directions of the future works.

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II. SCENARIO AND MODEL DESCRIPTION

A. *Scenario Description*

The operational scenario studied in this work is composed by a large square area, divided in equal number of contiguous columns and rows, forming a grid. Each cell of this grid is identified by its Cartesian coordinates, *x* and *y*, covering a unitary part of the entire area. All elements of the scenario (targets and sensors) are supposed to occupy only one cell of the grid at a time. However, one cell may be occupied by more than one element at a time.

Targets are considered as non-authorized individual vehicles or persons, or groups of vehicles or persons, which appear in a non-deterministic way (modeled as a Poisson distribution P(*r*), where *r* is the number of new targets that enter in the surveillance area at a given instant in time t). A given target τ_i^k is said to be of kind "k" and having an identifier "i", which represents its entrance order in the surveillance area. There are K possible kinds of targets that may appear in the surveillance area, so k = 1,…, K. The movement of the targets is considered to be performed with a constant speed $v_{\tau i}$, but different targets may move with different speeds. Targets may randomly change the direction of their movement.

The surveillance system is composed by heterogeneous sensors, which have different sensing and movement capabilities. There are "G" static sensors on the ground (sn_i, i = 1,…, G) and "N" UAVs flying over the area (u_i, i = 1,…, N). It is assumed that a static sensor node on the ground is capable of detecting a target when it passes in its coverage area, also called sensor range. This range is tunable, depending on the type of sensor used, but for simplicity it is assumed that the range is within the sensor cell. When a detection is made, an alarm is issued, and sent to all sensors nodes (static or carried by UAVs) that are positioned within the communication range of the alarm issuer node. This range is also a tunable parameter. An alarm is kept issued until at least one UAV receives it.

B. *UAV Model*

The UAVs move autonomously over the surveillance area, according to a given movement pattern described by the user when establishing the mission. The focus of this work is not on the movement pattern itself; for more details about different approaches that may be applicable, interested readers are referred to [5]. The idea is that UAVs move according to a predefined movement pattern and then send and respond to coordination events needed to handle targets, according to the adopted strategy.

1) Internal State: The internal state $S_i(t)$ of a UAV u_i at a giving time "t" is composed by three elements: Physical State, Current Task State and Alarm List. The Physical State includes information about its current position $p_i(t) = (x_i(t), y_i(t))$, speed ($v_i(t)$), heading angle ($\psi_i(t)$), sensor device types and status ($\varsigma_{ji}(t)$), which describes the accuracy level provided by the sensor, and energy resources ($e_i(t)$). As for Current Task State, UAVs can perform one of the following tasks: *search*, *analyze* or *track*. The *search* task implements the sequence of actions that the UAV is performing to detect a new target. The *analyze* task gathers detailed information about the detected target, while the *track* task makes the UAV capable of keeping track of a target movement. When an UAV is engaged in a mission, the Current Task State also includes information about which target this task is referred to. The Alarm List contains the alarms that an UAV has knowledge about, possibly with the information about which UAV is handling the target subject of that alarm.

2) Kinematic Model: The UAV kinematic model adopted in this work is almost the same as adopted by several others, such as [1] and [2], in which the UAVs move on continuous trajectories with constant speed and with a constrained variation in the heading angle. In the present work, the assumption of a constant speed does not hold in order to make possible the speed adjustment to allow target tracking. Assuming this, the following formulas describe the model:

$$\frac{dx_i}{dt} = v_i \cos\psi_i \;;\quad \frac{dy_i}{dt} = v_i \sin\psi_i \,;\quad \frac{d\psi_i}{dt} \le \eta \,. \tag{1}$$

where (x_i, y_i) denotes the position of the UAV u_i, v_i represents its speed, and ψ_i is its heading angle, which has η as a constraint to its variation. A fourth assumption is added to the model, namely that the UAVs' maximum speed may be higher then the targets' maximum speed (targets of any kind k), depending on the particular characteristics of a given UAV. This assumption allows the system to address the needs related to surveillance of large areas with a high-level of responsiveness to handle new targets.

$$v_{iMAX} > v_{kMAX} \,. \tag{2}$$

However, due to constraints like energy consumption minimization, the UAVs are assumed to maintain constant speeds almost all the time. Variations in speed only occur when a UAV engages in a tracking task and has to tune its speed to track a target moving on the ground.

3) UAV Sensing Capability Model: The sensors that equip the UAVs are supposed to detect members of the set of possible targets and precisely analyze and track, only a subset of the various types of targets. Which and how many depends on the types of sensors and targets under concern. In case that a sensor, needed for analysis or tracking of a target, is missing or does not match well, poor results will be generated.

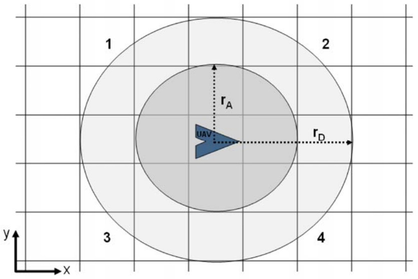

Figure 1. Sensor coverage area and ranges.

The range of the detection, analyze and track task capabilities are tunable, according to the types of sensors that equip the UAVs in the fleet. This tuning is done by the adjustment of the number of cells around the UAV that are able to be detected and/or analyzed/tracked. It is assumed that the ranges to detect and analyze/track are defined by an actuation range, which is called r_D for detection and r_A for analysis/tracking. Figure 1 illustrates this idea. It is important to highlight that it is assumed that the cells inside the range are only considered if their center points are inside the respective radius. In Figure 1, cells 1, 2, 3 and 4 are out of the range (r_D).

III. PHEROMONE-BASED COORDINATION

As mentioned, this paper describes two approaches to coordinate a network composed by low-end ground sensor nodes and UAVs. In this section, the pheromone-based approach is presented. Artificial pheromones are usually applied to distributed coordination by means of stigmergy, the indirect communication using environment cues [6]. A pheromone trail is deposited in the environment when the entities are moving. The pheromone provides information to other entities when they pass over it. Artificial pheromone also looses its strength along the time, modeling the evaporation of the real pheromones. In the UAV research field, pheromones are used to guide the movement of UAV swarms, for instance in surveillance and patrolling applications [5] [7].

Differently from the existing approaches, in the present one, pheromones are used to guide the assignment of an UAV to a given target. When an alarm is issued by the detection of a target, the network is responsible for selecting an appropriate UAV to respond to the alarm. This is performed by routing a given alarm to the UAV that has the strongest pheromone trace over the area. Having this information, the UAVs would base their movement decisions in a way to respond to the received alarms. This strategy is called here *heuristic-P*.

Following the above outlined ideas, the UAVs that are not engaged in the handling of any target leave pheromone traces over the area which they cross. This pheromone trace is represented by a piece of information that is taken by the ground sensor nodes that are deployed in the area where the UAVs have passed. When a target is detected by a ground sensor node, it issues an alarm, as already mentioned in the problem description. The decision about which UAV will handle the target that refers to the issued alarm will be taken by the ground sensor nodes, by routing the alarm in the direction that points to the UAV which has the strongest pheromone trace over that area of the network. This process does not consider any other condition, just the pheromone trace left by the UAVs. This means that the only parameter taken into account is how long time an UAV passed by that specific location, and the strategy is to route the alarm into the direction that points to the UAVs that passed by that location more recently. *Heuristic-P* is inspired in [8], which presents a pheromone-based strategy to migrate services in a sensor network, in which the pheromone concentration determines the places where the services are required. In *heuristic-P*, instead of services, alarms are moved through the network following the pheromone concentration.

When an alarm reaches the UAV indicated by the pheromone trace, if it is not engaged in the handling of another alarm it engages this received one and sends a confirmation message to the node in the network that had delivered the alarm. If the suggested UAV is already engaged in another alarm, the current alarm follows the second strongest pheromone trace to find another UAV to engage.

When an idle UAV detects a new target, it takes the responsibility for handling it. In case that the UAV is already busy with another target, it issues an alarm that will be routed to another UAV, according to the pheromone-based *heuristic-P* strategy explained above.

In order to increase the robustness of the proposal, in case an alarm is issued by a node that has no pheromone trace, a direction is randomly chosen and the alarm is sent in that direction until it finds a pheromone trace. When the trace is found, it follows the trace as explained above. This situation is more likely to occur in the initialization of the system, especially in cases in which the number of UAVs deployed in the system is very low.

IV. UTILITY-BASED COORDINATION

The utility-based coordination approach, called *heuristic-U*, totally transfers the decision making responsibility related to the handling of alarms to the UAVs instead of leaving this decision to the ground sensor nodes. This approach considers a larger range of variables if compared to the previously presented *heuristic-P* based on pheromones. The decision concerning which UAV that will engage in a task over a given target is modeled by a maximization of a multi-attribute utility function, which considers both the applicability of the sensor carried by the UAV in order to engage in that task, and a energy consumption factor, which is based on the distance between the UAV and the target under concern.

This modeling of the problem includes the three elements of a decision making theory presented in [9], which views the problem: 1) as a game in which the decision maker gathers information about the environment state, and 2) based on that knowledge then proposes an action to be performed, which finally 3) is assessed in terms of the utility, i.e., the gains that are originated from the consequences of the decision maker's choice of action. This is done by means of the assessment of the multi-attribute utility function.

Similarly to *heuristic-P*, when an alarm is issued by a ground sensor node, it is retransmitted until it arrives to the first UAV that is not engaged in the handling of any target. The first difference is that in this approach (*U*), there is no information driving the spread of the alarm over the network like in *heuristic-P*. Moreover, when the alarm is received by the UAV, it will share this alarm with all UAVs in its communication range, as well as its capability in handling that alarm. Like this, a negotiation takes place, in which the best UAV to handle the alarm takes the responsibility. The two key concepts of *heuristic-U* are thus the sensor applicability factor and the utility function that uses it.

A. *Sensor Applicability*

The sensor applicability is a number calculated by the UAV u_i that estimates the value of applying a given type of sensor (type j) to the handling of a given type of target (k) informed by an alarm, in a specific time instant.

$$\theta_{i,j,k}(t) = \begin{cases} \varsigma_i^j(t) - We_{i,j}(t), & \text{if } k \in \kappa_j \subset \kappa \\ 0, & \text{otherwise} \end{cases} . \qquad (3)$$

where $We_{i,j}(t)$ is a function that estimates the degree of degradation in the measurements offered by a sensor of type "j", due to the weather conditions at time t, and $\boldsymbol{\kappa}_j$ is the subset of all types of targets containing those that match the sensor type "j". In this model of the *heuristic-U*, poor results offered by sensors that do not match the type of target, are mapped to a value zero.

B. *Utility Function*

The utility function is used to evaluate the task to be performed over a target subject of an alarm, which is defined by the commands established in the mission directions. Then the results provided by the utility function calculated by each UAV are compared. Taking the one that has the maximum value, it is decided which UAV that will engage in the alarm and perform the required task. In the long run, this will maximize the usage of the entire system. This reduces the problem to the maximization problem:

$$U_{\max}^{TSK_j}(t) = \max\left(U_i^{TSK_j}(\theta_{i,j,k}(t), C(e_i(t), p_i(t), p_j))\right). \qquad (4)$$

where C is the cost in terms of energy consumption required to take the UAV from the current position $p_i(t)$ to the target position p_j reported in the alarm, based on the current energy resource status (provided by $e_i(t)$).

It is important to highlight that the computation of (3) carries a certain degree of uncertainty due to the possible imprecision or incomplete information about the weather conditions. This is also true for the computation of C used in (4), which carries an uncertainty about the location of the target, due to its unpredictable (unknown) movement pattern. The uncertainty in the proposed approach is translated into a risk of a wrong estimation according the model of "risk profiles" presented in [10].

According to the referred work in [10], which models the behaviour of investors in the stock market using utility functions, the investors can be classified in different risk profiles. These profiles can represent investors more or less prone to risk when performing their trades. Different types of functions are used to represent these profiles, as a mapping of the how prone to risk the investor is. The complete theory includes additional details, such as coefficients to tune the degree of risk aversion and concerns about the most suitable types of functions depending on other factors. However, in the present approach a simplified model is adopted without all the elements presented in the original theory.

The metaphor used to define *heuristic-U* is to associate the idea of risk profiles of the investors to profiles that can be assigned to the UAVs in the sense that they can be more or less prone to take risks when estimating their utility to handle a given target. The UAVs that have better resource conditions and more powerful capabilities are more likely to take risk in computing their utility, while considering the uncertainty of the input data, as they expect to have good results, i.e. to be really useful in handling a given target. On the other hand, UAVs that are "weaker" in the sense of having less capabilities and lower resources are more likely to use a more conservative utility function. The choice of which type to use is based on threshold values of the considered capabilities.

This study considers the use of two functions to express the profiles for the UAVs, a logarithmic one for the risk tolerant UAVs and a quadratic one for the conservative ones. Moreover, different weights can be attributed to the two components of the utility function used in (4), namely sensor applicability and the energy cost, by means of a parameter "α" that tunes which part will contribute more with the utility computation. Equation (5) shows the version for the more risk tolerant UAVs, while (6) presents the one for those less risk tolerant. The assumed valid intervals for $\theta_{i,j,k}$ and C is [0, 1], while for α it is (0, 1).

$$U_i^{TSK_j}(\theta_{i,j,k}, C) = \begin{cases} \alpha \cdot \ln\left(\theta_{i,j,k} \cdot (\mathrm{e} - 1)) + 1\right) + \\ \left(1 - \alpha\right) \cdot \ln\left(C \cdot (\mathrm{e} - 1)) + 1\right), \ \text{if } \theta_{i,j,k} > 0 \\ 0, \ \text{otherwise} \end{cases} \cdot \qquad (5)$$

$$U_i^{TSK_j}(\theta_{i,j,k}, C) = \begin{cases} \alpha \cdot \left(\theta_{i,j,k}\right)^2 + \left(1 - \alpha\right) \cdot C^2, \ \text{if } \theta_{i,j,k} > 0 \\ 0, \ \text{otherwise} \end{cases} . \qquad (6)$$

V. EVALUATION AND COMPARISON

The evaluation and comparison is based on simulations conducted using ShoX [11], which is a powerful wireless network simulator implemented in Java that provides easy extension mechanisms. The metrics evaluated in the simulations were the mean response time to the alarms generated in the system, the time to handle a target, and the relative utility, in terms of how suitable the assigned UAV is to handle a given target. The following subsections details the setup of the simulation and provides a discussion about the obtained results for the two coordination approaches.

A. *Simulation Setup*

The surveillance area has dimensions 10 Km x 10 Km, in which 20000 ground sensor nodes are randomly deployed with independent uniform probability (homogeneous Poisson point process in two dimensions, which generates a geometrical random graph). This distribution gives around 70% of probability that the nodes in the network form a connected graph [12], for a communication range of 500 meters. Six UAVs of three different types, equally distributed, patrol the area, having a communication range of 1,5 Km and are flying at speeds from 100 Km/h up to 120 Km/h. Four different runs were simulated, with one, three, and five targets for both heuristics. The targets can be of five different types, randomly chosen.

The energy resources start randomly distributed between 90% and 100% for all UAVs. These resources are consumed according to a decreasing linear function per part, having the time as parameter and weighted by the current speed of the UAV in each of its parts. Sensor status is randomly started for each UAV, starting from values between 70% and 90%, and may decrease after the utilization of the UAV in handling a target. This decrease is randomly chosen, simulating some possible damage due to hostile target attacks, for instance. For the simulations of *heuristic-U*, it was considered that UAVs with less than 30% of remaining energy resources or less then 30% of sensor capability use the utility function presented in (6), while the others use the one presented in (5). The value of α in (5) and (6) is randomly chosen between 0.1 and 0.5 if the sensor status is lower than the percentage of remaining energy and between 0.5 and 0.9 in the other case. Table I presents the summary of the main setup parameters.

TABLE I. SIMULATION PARAMETERS

Parameter	**Value**
Scenario Area	10Km x 10Km
Number of UAVs	6
Types of UAVs	3
UAV Speed	100Km/h – 120Km/h
UAV Communication Range	1,5Km
Number Ground Static Nodes	20000
Ground Nodes Communication Range	500m
Number of targets	1, 3 and 5
Types of targets	5
Target speed	50 Km/h – 80Km/h

B. *Results and Discussion*

The results of the three metrics provided in this section present the assessment of the efficiency of each strategy introduced before. The first metric provides a comparison between the two heuristics in terms of time to assign a UAV to handle a target that is the subject of an issued alarm. The second measures the time to handle a given target. These two metrics are important assessment parameters, as it is desired that the system respond to the alarms and handle the targets as faster as possible. The suitability in using an adequate UAV to handle an alarm is also an important parameter, as it represents the efficiency in the resource allocation in the system and the quality of the information provided to the users.

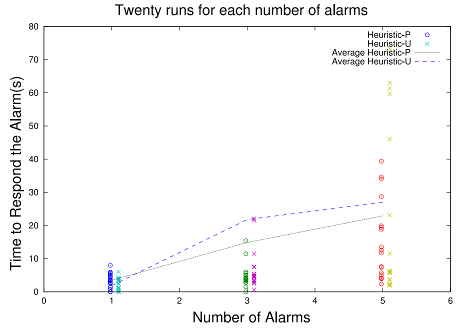

Figure 2. Time to respond the alarms for the two considered approaches.

Figure 2 presents the simulation results for the two approaches in terms of time to respond to the alarms. Both raw data from each run (total of 20 runs for each number of targets) and the mean values are plotted in the figure. It is possible to observe that the results provided by the pheromone-based strategy, *heuristic-P*, are slightly better than the ones provided by *heuristic-U*. An explanation for this behavior is that the pheromone approach provides an easier way to the sensor network to find an UAV and deliver an alarm to be handled, by making the alarm follow the pheromone traces, without requiring a negotiation. On the other hand, in the utility-based approach the sensor nodes have no indication regarding to where it is better to retransmit the alarms in order to find a suitable UAV, so a controlled flooding is done.

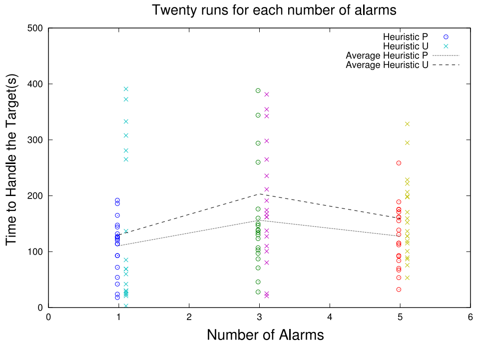

Figure 3. Time to handle targets for the two considered approaches.

Figure 3 presents the values obtained for the “time to handle targets” metric. It is possible to see that *heuristic-P* presents better values, which can be explained because it just follows the pheromone traces to the nearest UAV, without considering its utility, while in *heuristic-U* the utility is the basis upon which it is decided which UAV will handle the target. Even considering that the utility function takes the distance between UAV and target into account, it happens that a UAV that is far from the target may win the negotiation and go to handle the target, since it can be better than other UAV in the other criteria evaluated by the utility function.

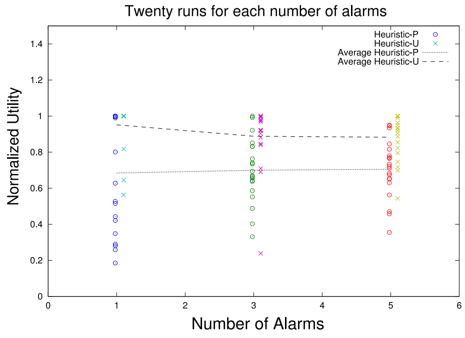

Figure 4. Normalized utility for each approach.

Figure 4 presents the results of the measurements of the utility values, which are normalized by the optimum solution (the best assignment UAV-target that could be done). As expected, *heuristic-U* provides the best results. This is explained firstly because it considers additional parameters when compared to the pheromone approach used in *heuristic-P*, which implicitly takes into account only the positions of the

UAVs and targets. Moreover, even discarding UAVs that are completely unable to handle the type of target of a given alarm, the *heuristic-P* solution looses because the negotiation among the UAVs, comparing their utilities in the *heuristic-U* solution avoids poor assignments, which is a feature that does not exist in the pheromone-based solution used in *heuristic-P*.

The results presented express a tradeoff between time and utility in selecting one of the proposed solutions. The pheromone-based approach was more effective in terms of time to respond to an alarm and to handle a target. However, the utility evaluation of the second approach provides a better fit UAV-target. Moreover, the pheromone approach uses significantly less messages than the utility-based one, which uses a controlled flooding that is more costly in terms of network resource usage.

VI. RELATED WORKS

Jin et al. [1] provide a very consistent proposal to handle the problem of balance between target search and response by a team of UAVs. The work evaluates the tradeoff between search and response within the framework, presenting a predictive algorithm that provides a good balance between these tasks. The first difference between our approach and this work is that we handle only the alarm response, abstracting the UAVs movement planning to perform the search for new targets. This difference is due to the peculiarity of the distinct mission addressed by each one. We focus on area surveillance, while they focus on target acquisition. In our case, the whole area must be covered, without the assumption of preferred locations to move to, which is true in the target acquisition they address. Another difference is that we use the UAVs in coordination with ground sensor nodes. Besides, the assumption of a centralized information base considered in that work is not used in our proposal. The initial centralized off-line task assignment is another premise that is not valid in our work but holds in their proposal.

The AWARE project is presented in [3]. This project aims at integrating a sensor network of resource constrained ground nodes with mobile sensors, both on the ground and carried by UAVs. In the large sense this work is closely related to ours. The common idea presented in both works is to use ground sensors and UAVs taking part of the same sensor network, cooperating in order to achieve the mission goals. In our paper, the focus is to describe how the UAVs cooperate among them, after the alert emitted by the ground nodes using ad hoc communication. Compared with our approach, AWARE does not provide the same flexibility in relation to the coordination among nodes. In AWARE, the nodes make part of a group that is linked to a given task, or set of tasks, and to change this formation, new commands must be sent explicitly from a central control base. Instead, in our approach, the coordination is done autonomously by the nodes.

VII. CONCLUSION AND FUTURE WORKS

This paper presented two different strategies to drive the coordination among heterogeneous sensor networks applied in surveillance systems. A detailed problem formulation was also provided to support the assumptions done in each of the proposed strategies. An assessment of the efficiency of both approaches was done, by means of three metrics of interest and a critical analysis of the resulting data was performed.

Our study pointed out the strengths and weaknesses of each strategy. A combination of both strategies, in which a pheromone-based alarm routing is used to search for UAVs according their capabilities, transferring part of the negotiation to the pheromone trails in the ground sensors, will be developed. The selection of most suitable trail to route an alarm in its search for an UAV will reduce dramatically the amount of messages when compared to the controlled flooding used in *heuristic-U*, and at the same time, will select a highly suitable UAV to a given target, by means of its utility.

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