Enhanced Pheromone-based Mechanism to Coordinate UAVs and WSN Nodes on the Ground

TALES HEIMFARTH[1], EDISON PIGNATON DE FREITAS[2,3],
IVAYR FARAH NETTO[1], LUIZ H. A. CORREIA[1],
CARLOS EDUARDO PEREIRA[3], ARMANDO MORADO FERREIRA[4],
FLÁVIO RECH WAGNER[3], TONY LARSSON[2]

[1] Computer Science Department, Federal University of Lavras, Lavras, Brazil.
(tales,lcorreia)@dcc.ufla.br; ifarah@bsi.ufla.br
[2] IDE, Halmstad University, Halmstad, Sweden.
(edison.pignaton,tony.larsson)@hh.se
[3]Institute of Informatics, Federal University of Rio Grande do Sul, Porto Alegre, Brazil.
flavio@inf.ufrgs.br; cpereira@ece.ufrgs.br
[4] Defense Engineering Graduate Program, Military Institute of Engineering, Rio de Janeiro, Brazil.
armando@ime.eb.br

Abstract. This paper presents a step forward of a pheromone-based mechanism used to coordinate Unmanned Aerial Vehicles (UAVs) and Wireless Sensor Networks (WSNs) on ground that together compose a surveillance system to detect and acquire information of possible targets in an area of interest. The proposed enhancement aims at to diminish the overhead in terms of communication needed to provide the desired coordination among these different nodes that compose the network. This is done by means of a more efficient UAV pheromone information distribution among the sensor nodes on the ground. Simulation results are presented comparing the proposed enhancement with the original mechanism, denoting the advantage of the enhanced one.

Keywords: Wireless Sensor Networks, Unmanned Aerial Vehicles, Coordination.

(Received January 18, 2010 / Accepted May 23, 2010)

1 Introduction

A trend that is gaining strength in the wireless sensor network (WSN) area is the use of heterogeneous sensor nodes, in order to fulfill the requirements of sophisticated applications, such as area surveillance systems [1]. An important thread of this trend is the combined use of mobile sensors working in cooperation with static ones, as presented in [2]. A fact that gives more strength to this trend is the recent advances in Unmanned Aerial Vehicles technologies, especially for those with small dimensions, such as mini-UAVs [3]. As small UAV platforms are much more affordable than larger UAVs, such as Predator or Globalhawk, the use of a number of them working as a network connected group becomes tangible, and thus their interoperational usage with WSN on the ground.

One of the main concerns when developing such sensor networks, composed by UAV-carried sensors and static WSN nodes on the ground, is how to provide coordination among these heterogeneous nodes, in order to enable them to efficiently respond to the users' needs. This refers to issues such as how to make the nodes efficiently use their communication resources in order to provide data to the other nodes so that the system as a whole works according the current demands. In general, systems with such heterogeneous sensor composition work as follows: Simpler sensor nodes on ground, deployed in a great quantity, are configured to identify patterns that indicate phenomena of interest. When such an evidence is observed, more sophisticated sensors (UAV-carried ones), which are deployed in a smaller number if compared with ground-based nodes, move to the area in order to confirm or gather additional data about the occurrence. Thus, it is possible to say that the ground static sensor nodes *call* the mobile ones to come to their location. Such a call can be done by means of an alarm, which is issued by the ground sensor node that detected a given pattern, and then is delivered to one of the mobile sensor nodes that will handle the occurrence.

As the mobile sensor nodes are supposed to be in small number, it is very probable that the alarm issuer node will not be able to make the alarm delivering by itself. What is supposed to happen is that the alarm has to be routed through the network of sensors on the ground until it can reach one of the UAVs. This delivery mechanism has to take into account the dynamicity of the system, i.e. the movement of the UAVs, as well as the efficient usage of energy resources, as communication is the most energy demanding operation in WSN [4].

In [5] a pheromone-based mechanism to deliver alarms issued by ground sensor nodes to UAVs was presented. The idea to use artificial pheromones to provide awareness about the location of the UAVs is inspired in [6][7], but with some differences to adapt it to the context in which the UAVs interoperate with static nodes on the ground, as discussed in [5]. In this work it was considered a uniform distribution of the ground sensor nodes in an area. In [8] this strategy was used in a scenario in which the ground sensor nodes were randomly distributed. However, a drawback of such solution applied to this scenario was the increased number of messages that were required to guarantee the correct pheromone information distribution among the sensor nodes, due to the way the pheromones are distributed over the nodes in the network, and due to the redundant messages generated by the alarm forwarding process to follow the UAVs' pheromone trace, as detailed explained in [5].

In this paper an improvement of the pheromone-based alarm delivery mechanism is presented. This improvement allows the use of fewer messages by the ground sensor nodes to forward alarms and eliminate the need of a number of redundant messages. This is done by enhancing the way the pheromones are represented and distributed when the UAVs send pheromone beacon messages, resulting in a diminishment of the message exchanging overhead in the system. This is achieved by means of organizing the sensor nodes on the ground in layers according to the pheromone levels that they store. This is an important contribution that enhances the original proposal, in terms of lesser energy consumption, achieved by diminishing the communication demands among the ground sensor nodes.

The content of this paper is divided as follows: Section 2 presents the application scenario and the problem description. In Section 3, the proposed alarm delivering mechanism is presented. Section 4 is dedicated to the simulation results presentation, while Section 5 discusses related works. Section 6 concludes the paper giving the directions of future works.

2 APPLICATION SCENARIO AND PROBLEM STATEMENT

The application scenario investigated in the context of this work is area surveillance systems based on the usage of static WSN nodes on the ground and mobile sensors on the air, carried by UAVs, which are referred from now on as UAV-carried sensors of just as UAVs. The focus of the present paper is in the coordination among the static sensors placed on the ground and the UAVs, which is detailed in the statement of the problem.

A. *Surveillance System*

As mentioned above, the surveillance systems considered in this work are composed by static ground sensors and UAV-carried sensors. There are G static ground sensor nodes spread on the area, which are individualized by an identifier sn_i, $(i = 1, \cdots, G)$. The ground sensor nodes are distributed according to a given probability distribution, which can be random, uniform or following a given specific pattern. UAVs flies over the area, in a random or a predefined movement pattern, and are identified by u_i $(i = 1, \cdots, N)$. G, the number of ground sensor nodes, is assumed to be much bigger than the maximum number N of UAVs. These two groups of sensor nodes are further divided according to their sensing capabilities. The considered capabilities are the type of measurements that can be made, and the sensing range. For the ground sensor nodes, the considered measurements are, for example, difference in the magnetic field, vibration, temperature, humidity and acoustic signature. Examples for the UAV-carried sensors are visible light cameras, infrared cameras and SAR/ISAR radars. The sensing range is a tunable parameter that remains constant for the ground sensor nodes, but may vary for the UAV-carried ones, due to the influence of their movement.

The sensors nodes wirelessly communicate with one another within a given range, which is a tunable parameter. Due to the broadcast nature of wireless communications, all nodes in the range receive a message issued by a given node.

The dynamics of the system works so that the ground sensor nodes are configured to detect possible targets, which is defined by a set of threshold levels of its measurements. A $match$ with the detecting criteria is achieved when the acquired measurements reach a configured threshold level that also can correspond to a large enough discrepancy to some expected $normal$ or background level. In an occurrence of such a match, the sensor node issues an alarm, which is received by all the nodes within the alarm issuing node's communication range.

Alarms are single communication packets containing a timestamp, the position of the issuer node, and the type of the possible target. The two first components of the alarm enable its unique identification, avoiding alarm duplications. For the purposes of this work, each alarm indicates one target. Even in the case in which the indicated target is a group of persons or vehicles, and are handled as a unique entity by the system.

Figure 1 presents the main elements of this scenario, in which the detection of a possible target by a ground sensor node is illustrated. This node issues an alarm that is received by all other nodes in its communication range. One of these neighbors relays the alarm, which is received by a UAV passing close by, thus characterizing the alarm delivery.

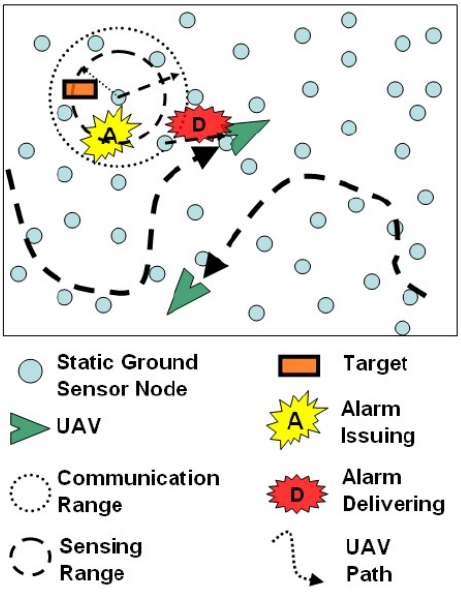

Figure 1: Overview of the application scenario.

The goal of this type of system is to allocate one of the UAVs, preferably the most suited one, to fly towards the area where the alarm was issued. Then, this UAV can gather further information about the possible target, and confirm it as a target, for example if it is an intruder or a threat.

B. *Problem Statement*

According to the description presented above and the goals of the surveillance system, two main coordination problems can be recognized: 1) how the alarms should be delivered to the UAVs, and; 2) how to make a decision on which UAV that will be assigned to respond a given alarm.

The first problem refers to the way the alarms, issued by the ground sensor nodes, will reach the UAV. This includes the issues about how to provide awareness of the locations where to find the UAVs to ground sensor nodes, as well as how to make the alarms come to these locations in an energy efficient way.

The second problem is related to the assignment of the most appropriate UAV to handle a given alarm. This decision can be taken by considering a number of different parameters, such the applicability of the sensor to handle a given situation due to the type of the target or weather conditions, for example. Moreover, it may also consider other parameters as the distance of the UAVs from the location where the alarm was issued, or the density of UAVs in this location, among others.

The goal of this paper is to propose an energy efficient way to solve the first problem, i.e. the alarm delivery mechanism. The focus is on how to make a mechanism that provides the desired features to support the alarm delivery process, i.e. the location awareness of the UAVs to the ground sensor nodes, and the correct routing of alarms through the network so that they reach the UAVs, using as little energy from the nodes in the network as possible.

Details about the handling of the second problem are not taken into account in this paper. For a complete discussion about it and a description of the proposed approach, interested readers are referred to [9].

Focusing on the description of the first problem, the proposed pheromone-based alarm delivery presented in [5] works well for uniform ground sensor distributions and randomly distribution of massive numbers of ground sensor nodes, but with an increased overhead due to a number of redundant messages in this last case. Following the presentation of this problem, some possible solutions are discussed, analyzing their pros and cons, which provide the motivation for the proposed enhancement presented in Section 3.

A straight forward way to handle the above mentioned problem is to include the signal strength information of the UAVs' pheromone beacon in the calculation of the pheromone strength level that should be stored by the ground sensor nodes, and eliminate the indirect beacon messages among ground sensor nodes. However, a problem with this solution is that when the UAVs leave their pheromones, depending on the distance of the nodes and the way the UAVs fly, distorted pheromone information can be stored by the ground sensor nodes, indicating a wrong direction of the UAV.

Figure 2 presents an example of this problem.

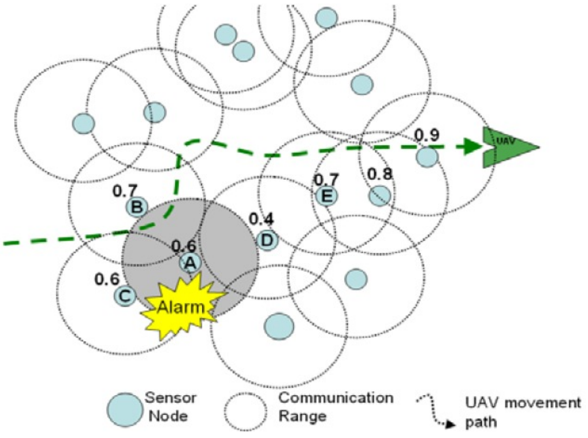

Figure 2: Miscalculation of the pheromone marks by randomly distributed sensor nodes, when signal strength is added to the pheromone level calculation.

It occurs because of the combination between signal strength of the beacon pheromone message and the time elapsed from its reception, used in the computation of the pheromone level. This may lead to values that do not reflect the real direction of the UAV's path, as shown in Figure 1. In this example it is possible to observe that the alarm issued by sensor node A will be received by its neighbor nodes, namely B, C and D. The last node, D, is the one in the right way towards the UAV. However, due to the miscalculation of the pheromone levels caused by the non-uniformity of the nodes distribution and the particular way of the UAV path, nodes A, B and C have stronger pheromones marks than D, which makes the alarm follow a wrong path, being forwarded by nodes B and C, instead of being forwarded by node D.

One way to solve this new problem is augmenting the number of sensor nodes on the ground. This approach provides redundancy in the alarm forwarding, which result in that eventually the alarms will come to their right destination. However, such a solution may lead to another problem, which is the reduction in the efficiency of the proposed strategy, in terms of energy consumption, cancelling the advantage in using the signal strength information instead of the indirect beacons among ground sensor nodes. As there is an increased redundancy in the alarm forwarding, an inefficient usage of available resources also will result. This happens because since many sensor nodes may have the same pheromone level in an area (level required to determine the node as forwarder), many unnecessary alarm forwarding's will take place, thus consuming energy that could be saved. Moreover, the alarm will be also forwarded to directions where it should not be forwarded until it reaches nodes with lower levels of pheromone and stop to follow the wrong directions. In the worst case, even a broadcast storm may happen in the areas close to the alarm issuer.

Figure 3 presents this problem.

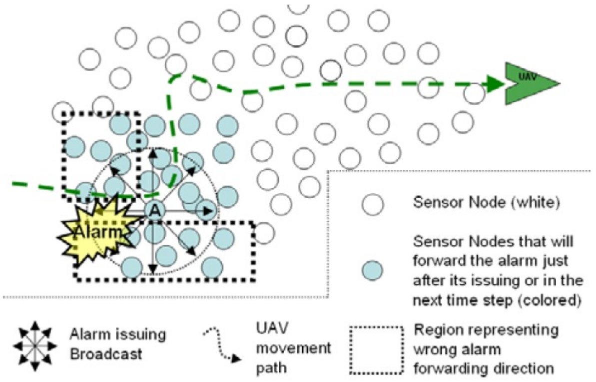

Figure 3: Example of the problem generated by the massive usage of sensor nodes.

It is noteworthy that, even presenting this undesirable overhead which constraints it's gains, the proposed strategy presents good results in terms of functionality and still manages to present efficiency if compared with traditional approaches, as discussed in [10]. However, this fact provides the opportunity to enhance the efficiency of the system as a whole and it is what will be presented in the following.

3 ENHANCED PHEROMONE-BASED ALARM DELIVERY

Aiming at overcoming the efficiency constraints discussed above, the proposed enhancement of the pheromone strategy applied to a network of randomly distributed sensor nodes is based in the two modifications of the original proposal. The first is to divide the sensor nodes on the ground in layers with a gradient pointing to the path followed by the UAV. The sum of these layers forms a *pheromone corridor* indicating the direction of the UAV. The second is to determine the minimum number of sensor nodes that keeps the network connectivity in the central layer and make this layered approach to work correctly and more effectively.

The division of the nodes in layers is done by taking the nodes with stronger pheromone traces to form a *backbone* of the pheromone corridor. This points more precisely to where the UAV currently is. Surrounding the backbone, the nodes with weaker pheromone levels are divided in layers, according to their levels.

Figure 4 presents an example of the proposed division of the nodes in layers. In this example there are just two layers, the backbone with pheromone level equal to 1.0, and an immediate surrounding level, with pheromone level equal to 0.5. All the other nodes outside these layers have no pheromone information about that UAV, so pheromone level equal to zero. Alarms issued by nodes located inside the backbone follow the backbone until they are delivered to the corresponding UAV. Alarms issued by nodes in the other layers are forwarded towards the backbone until they come there, and then follow the backbone as previously explained. This approach bounds the flooding of the alarm, the overhead of the alarm forwarding, to the limits of the backbone. This avoids the alarm retransmission by a large number of nodes, as it occurred before.

Figure 5a presents an example of an alarm issued by a node in the backbone and its way to be delivered to the UAV, while Figure 5b presents an example of an alarm issued by a node in a layer outside the backbone (Layer 1) and its possible way towards the UAV.

The implementation of this idea required a modification in the pheromone representation in the ground sensor nodes. Instead of calculating the pheromone level only with the elapsed time since the beacon reception, as originally done, or combining this information with the signal strength as explained above, these two peaces of information are kept separately. The signal strength defines the region, backbone or one of the surrounding layers, which the node will belong, while the elapsed time will provide the direction of the UAVs, which means, a gradient inside each layer or inside the backbone.

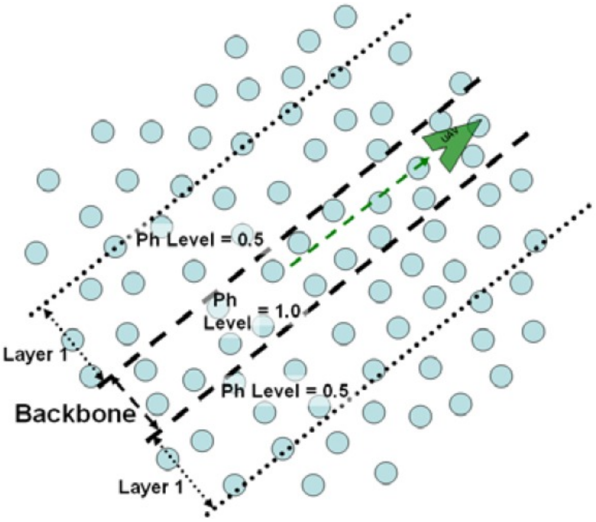

Figure 4: Example of the division the sensor nodes in two layers, the Backbone and the Layer 1.

The number of surrounding layers may vary and they can be defined according to the desired accuracy and density of the nodes distributed in the area.

This layered approach allows even the usage of simpler pheromone representations, such as with the usage of the sequence number of the beacons messages sent by the UAVs, instead of the elapsed time. This alternative has an advantage that it does not require any calculation and is independent of the local clock in the nodes, but has a small drawback in relation to the pheromone evaporation, which requires operations with time anyway.

In order to make this approach works properly, a condition must hold: the nodes in the backbone region have to be connected, which means that from any node it has to be possible to send a message to any other node. As the UAVs may fly over any location of the network, any set of nodes in the network may compose the backbone region. This implies that the whole network has to be connected. The problem is then to find the minimum number of nodes that are required to compose the network in order to make this condition holds for a given area.

Without lost of generality, assumes a random distribution of the sensor nodes on the ground. Considers further that this distribution has independent uniform probability (homogeneous Poisson point process in two dimensions that generates a geometrical random graph – the same process that models rain drops falling on a surface), which mimics, for example, the a deployment of sensor nodes by dropping them from an airplane. This representation provides a general representation of the

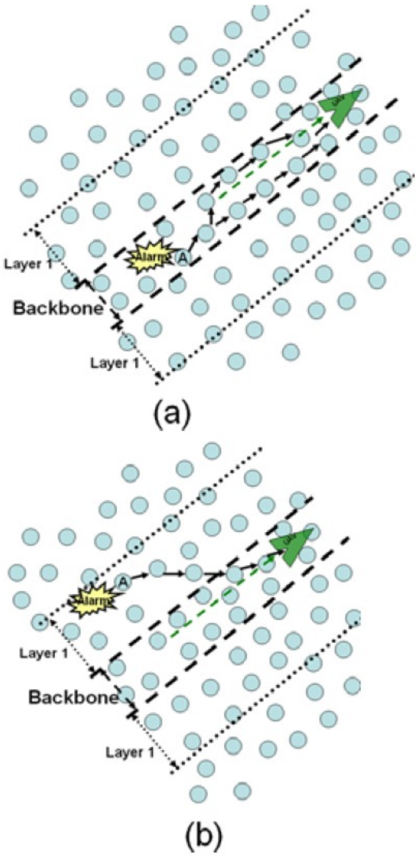

Figure 5: Examples of alarms issued by a node inside the backbone (a), and in the Layer 1 (b).

distribution of the sensor network on the ground.

Considering the above described nodes' distribution and the results for connectivity analysis presented in [11], which defines the connectivity in a network of random distributed nodes with a Poisson point process in two dimensions by equation 1 :

$$P(d_{min} > 0) = (1 - e^{-\rho\pi r^2})^n \tag{1}$$

where $P(d_{min} > 0)$ is the probability that the minimum connectivity degree of the network (d) is higher than zero. ρ is the node density, r is the communication range, and n is the total number of nodes in the network.

The network degree mentioned above is the number of links existing between any pair of nodes in the network. In order to the network be considered *connected*, its degree has to be at least 1, i.e. at there is at least one possible path linking any pair of nodes. As d is an integer, it is possible to state that the number of nodes n needed to fulfil the network connectivity condition explained above is the one that gives by equation 2 :

$$P(d_{min} > 0) = 1 \tag{2}$$

The condition presented in 2 can be relaxed, providing by equation 3 :

$$P(d_{min} > 0) \cong 1 \tag{3}$$

4 EXPERIMENTS AND RESULTS

In [10], simulations of the original pheromone-based alarm delivery mechanism were performed and their results compared with those achieved with a similar system solution that implemented a centralized approach to assign alarm to UAVs. The results from those simulations presented evidences that the decentralized pheromonebased one outperforms the centralized approach in terms of network resources usage, besides other parameters related to the mission accomplished that were analyzed in the referred work.

The experiments reported in the current paper provide a comparison between the results achieved by the original pheromone-based alarm delivery mechanism [5] compared to the current presented enhancement of the original mechanism and to a reference mechanism based on a flooding of the alarm. The evaluated metrics were: 1) total number of messages; 2) number of hops from the issuer node until it reaches a UAV.

One hundred simulation runs were performed for each mechanism, and the results will present the statistics of the obtained results. The simulations were performed using an extension of ShoX ad hoc network simulator [12], which is being evolving by the additional features and restructuration provided by the work of this research group.

A. *Simulation Setup*

The experiments performed in this work hade the goal to specifically assess the networking features of the proposed enhancement in relation to the original one, regarding less the analysis of employing a given UAV to respond a given alarm, as studied in previous publications [5][10]. For this reason, instead of simulate scenarios with different numbers of UAVs and targets, the focus was kept on the occurrence of one alarm, triggered by the presence of one target, and the analysis of the mentioned metrics until this alarm reaches a UAV.

The choice of setup parameters were based on the characteristics of the scenario analysed in this study, which considers Mini or Micro UAVs. These UAVs have an operational range of 10 Km and fly at an altitude around 250 meters [3]; and communication ranges for both UAVs and ground sensor nodes based on technologies such as IEEE 802.15.4 (extended range version). When a UAV is not responding an alarm, it may fly following a random movement pattern, with collision avoidance capability.

The ground sensor nodes are randomly deployed, following the independent uniform probability discussed above. 140 nodes are distributed over a 2Km x 2Km area giving approximately 100% of probability that the nodes in the network form a connected graph [11], for a communication range of 300 meters. This distribution fulfils the necessary condition above presented. Table I summarize the main simulation parameters.

Table 1: SIMULATION PARAMETERS.

Parameter	Value
Scenario	Area 2Km × 2Km
UAVs' Communication Range	400m
UAVs' Flying Altitude	250m
Number of Ground Static Sensor Nodes	140
Ground Static Sensor Nodes Communication Range	300m

Figure 6 presents a screenshot from a simulation run of the enhanced pheromone-based mechanism. The nodes with border represent those with pheromone information, composing the pheromone trail. The labels inside the trail represent the number of hops that the alarm moved so far. The labels outside the trail just represent the nodes that the alarm passed by while searching of a trail. The node with the label with value 6 is the one that delivers the alarm to the UAV.

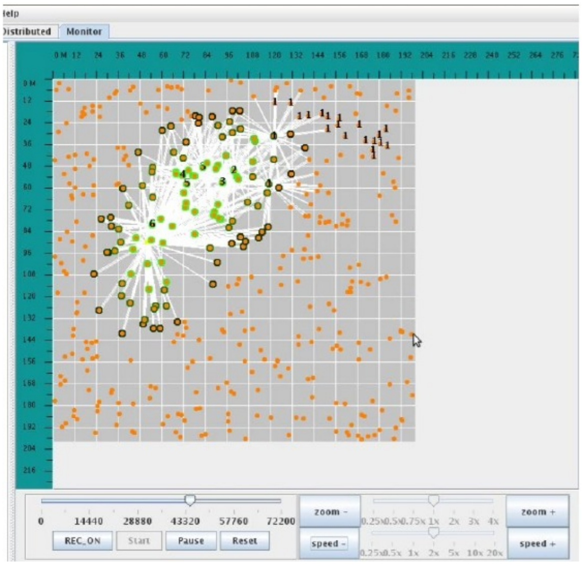

Figure 6: Simulation run screenshot.

B. *Results Presentation and Discussion*

Figure 7 presents the results for the first metric, total number of messages used to deliver an alarm. It is possible to notice that the flooding mechanism uses much more messages than the other two based on pheromones. Between the pheromone-based ones, the enhanced approach outperforms the original one by a factor of 1.6. An explanation for these reported results is that for the flooding mechanism, a massive number of messages are sent to all directions in a try to reach a UAV. On the other hand, the pheromone-based strategies the alarms follow a path defined by the presence of pheromones traces on the sensor nodes. When the node that issues an alarm does not have any trace, the alarm follows just one random direction instead of being broadcasted in all direction, until it reaches a pheromone trail and then follows it until reach the corresponding UAV. The explanation for the best performance of the enhanced version of the pheromone-based mechanism is that it constrains the alarm forwarding to regions defined by the layers, as explained in Section 3. This approach diminish the number of nodes that have the same pheromone level, and it is the reason why it outperforms the original approach, as in this one, a number of nodes may have similar pheromone levels.

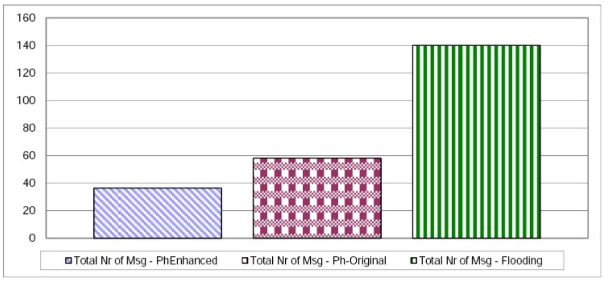

Figure 7: Results for the Total Number of Messages.

For the total number of hops from the alarm issuer to the UAV, the results in Figure 8, again the flooding mechanism presents better results, i.e. fewer hops to reach the UAV. This is explained by the fact that the alarm is broadcasted in all directions, instead of follow one as it is the case in the pheromone-based approaches. However, it is noteworthy to highlight that the difference is not big, and it is due to the occurrence of some alarms that are issued by nodes that do not have any pheromone trace. Otherwise, if all nodes in all simulations had pheromone traces, the alarms would directly follow it, and there would not be cases in which they have to follow random direction to try to find a pheromone trail. In fact, these occurrences are the responsible for the number of extra hops in average.

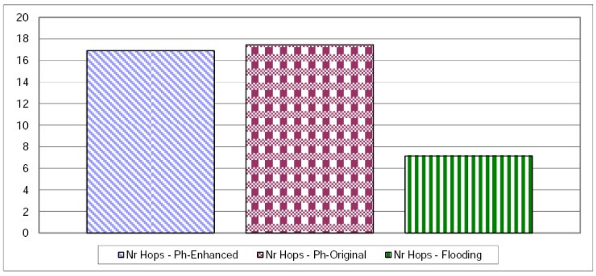

Figure 8: Results for the Number of hops.

5 RELATED WORK

The AWARE [2] is a project that aims to integrate a sensor network of resource constrained ground nodes with mobile sensors, both on the ground and carried by UAVs. The AWARE platform consists of two networks, a high bandwidth network (HBN) and a low bandwidth network (LBN). The first one, HBN, is composed of high-end nodes, such as personal computers, UAVs, and mobile robots, while the LBN constitutes a WSN composed of low-end nodes, with very limited resources. The integration of these two networks is done through gateways that are devices capable of communicating with both networks.

The common idea in relation to our work is the integration of ground sensors and UAVs working in cooperation in order to achieve mission goals. However, differently from AWARE, in our approach the networks integration does not rely on a certain number of gateways, but any node may directly communicate with all other nodes. The cooperation among the different nodes is done by means of a data-centric mechanism based on the concept of groups and channels, in which the first is responsible for the definition of conditions of interest to associate different nodes of the network.

At a certain extent, this concept can be compared with the pheromone approach presented in our work, first in the formation of the layers in the pheromone corridor, and second if one considers that the issuing of an alarm by a ground sensor and the pheromone of a UAV over this sensor node, link them in a similar way as the groups link different nodes in AWARE. However, at the extent of our knowledge, there is no study about the overhead imposed the mechanism used by AWARE that is directly comparable with the study currently presented.

In [13], a work reporting an effort to improve routing to mobile sinks in WSN is presented. Considering the UAVs as mobile sinks, the intention of deliver sensed data to mobile sinks reported in this related work is comparable with the alarm delivery to UAVs presented in ours. The main difference between the two works is the way the problem is approached.

Besides, in [13], the authors try to build and updated a routing tree from the mobile sinks to the each sensor node that composes the network. They try to achieve this using a compromise between the optimal routes to the mobile sinks and the number of messages needed to update these routes. On the other hand, in our approach the intention is not to provide a route linking all the nodes in the network to the UAVs.

This may happen that depending on the number and the movement pattern of the UAVs, in given instants of the system ron the ground have pheromone traces of all UAVs, and like that may reach any of them. However, it is not the goal. The goal is really to explore the locality nature of the mechanism, in which the ground sensor nodes get and keep pheromone information of the UAVs that fly close to their location, and there is no forwarding of routing updates to distant nodes.

Other approaches explore the concept of mobile sinks to retrieve data from static sensor nodes by assuming controlled mobility, so that mobile sinks decide about their movement in order to facilitate the message delivery by static sensor nodes, and thus optimizing the energy usage in network as a whole [14][15]; or assume that movement of the sinks is at least predictable [16]. Using both assumptions, these related works achieves good results in terms energy efficiency. In spite of these approaches handle a similar problem, the delivery of information to mobile sinks, they have a crucial difference if compared with ours, which is that they assume information about the mobile nodes, or even control them in order to achieve their goals, which is an assumption that does not hold for the movement of the UAVs as described in our work.

6 CONCLUSIONS AND FUTURE WORK

This paper presented the continuation of a work that aims at to provide an efficient coordination mechanism to support interoperability among static sensor nodes on the ground and mobile sensor nodes (carried by UAVs), by the use of a biological inspired approach using artificial pheromones.

The focus of the paper was to present the possibilities to make the approach more efficient and then propose an enhanced mechanism based on the original one previously proposed. Simulations comparing the original and the enhanced mechanism provided evidences of the gains in efficiency achieved by the enhanced mechanism. Moreover, the comparison did also consider as reference mechanism based on flooding.

Directions of future works point to evaluation of the new enhanced mechanism in a complete scenario and further studies to integrate its features with those presented in [5] and [9], referring to the utility in employing a given UAV to handle a given target, considering UAVs with different capabilities.

ACKNOWLEDGMENT

T. Heimfarth thanks the Fundação de Amparo à Pesquisa do Estado de Minas Gerais (FAPEMIG) the given support to conduct this research. E. P. Freitas thanks the Swedish Knowledge Foundation for the given grant to follow the PhD program in Embedded Systems in Halmstad University in cooperation with UFRGS in Brazil. Luiz H. A. Correia thanks the CNPq for the given support in this work.

7 References

[1] V. P. Mhatre, C. Rosenberg, D. Kofman, R. Mazumdar, N. Shroff, "A Minimum Cost Heterogeneous Sensor Network with a Lifetime Constraint," IEEE Transactions on Mobile Computing, vol. 4, no. 1, 2005, pp. 4-15. doi:10.1109/TMC.2005.2

[2] A.T. Erman, L. Hoesel, P. Havinga, "Enabling Mobility in Heterogeneous Wireless Sensor Networks Cooperating with UAVs for Mission-Critical Management," IEEE Wireless Communications, vol. 15, is. 6, 2008, pp. 38-46.

[3] 2009/2010 UAS-Yearbook UAS: The Global Perspective. 7th Ed., Blyenburgh & Co, 2009.

[4] R. Mini, A. Loureiro, B. Nath, "The Best Energy Map of a Wireless Sensor Network," Proc. of the 7th ACM Intl Symposium on Modeling, Analysis and Simulation of Wireless and Mobile System, Venice, Italy 2004, pp. 165-169.

[5] E. P. Freitas, T. Heimfarth, R.S. Allgayer, F. R. Wagner, A. M. Ferreira, C. E. Pereira, and T. Larsson, "Coordinating Aerial Robots and Unattended Ground Sensors for Intelligent Surveillance Systems," in International Journal of Computers, Communications & Control, 2010, pp. 55-72.

[6] E. Bonabeau, M. Dorigo, G. Theraulaz, "Swarm Intelligence: From Natural to Artificial Systems," Oxford University Press, Santa Fe Institute Studies in the Sciences of Complexity, NY, 1999.

[7] J.A. Sauter, R. Matthews, H.V.D. Parunak, S.A. Brueckner, "Performance of Digital Pheromones for Swarming Vehicle Control," in Proceedings of 4th International Joint Conference on Autonomous Agents and Multi-Agent Systems, ACM Press, 2005, pp. 903-910.

[8] E. P. Freitas, T. Heimfarth, C. E. Pereira, A. M. Ferreira, F. R. Wagner, and T. Larsson, "Pheromone-Based Coordination Strategy To Static Sensors On The Ground And Unmanned Aerial Vehicles Carried Sensors," in Proceedings SPIE 7694, 769416, Orlando, USA, 2010, doi:10.1117/12.852478

[9] E. P. Freitas, T. Heimfarth, C. E. Pereira, A. M. Ferreira, F. R. Wagner, and T. Larsson, "Evaluation of coordination strategies for heterogeneous sensor networks aiming at surveillance applications," in Proceedings of 8th IEEE Sensors, Christchurch, New Zealand, 2009, pp. 591–596.

[10] E. P. Freitas, T. Heimfarth, C. E. Pereira, A. M. Ferreira, F. R. Wagner, and T. Larsson, "Decentralized Task Distribution among Cooperative UAVs in Surveillance Systems Applications," Proc. of 7th International Conference on Wireless On-demand Network Systems and Services, IEEE, Kranjska Gora, Slovenia, 2010, pp. 121–128.

[11] C. Bettstetter, "On the Minimum Node Degree and Connectivity of a Wireless Multihop Network", in Proceedings of the 3rd ACM International Symposium on Mobile Ad Hoc Networking & Computing, ACM, New York, NY, USA, 2002, pp. 80–91.

[12] J. Lessmann, T. Heimfarth, P. Janacik, "ShoX: An Easy to Use Simulation Platform for Wireless Networks,"

in Proceedings of 10th International Conference on Computer Modeling and Simulation, 2008, pp. 410-415.

[13] K. Fodor, A. Vidács, "Efficient Routing to Mobile Sinks in Wireless Sensor Networks," in Proceedings of 3rd international conference on Wireless internet, Austin, USA, 2007.

[14] M. Demirbas, O. Soysal, A. S. Tosun, "Data salmon: A greedy mobile basestation protocol for eficient data collection in wireless sensor networks," in Proc. IEEE Int. Conf. on Dist. Comp. in Sensor Sys., 2007.

[15] K. Hwang, J. In, D. Eom, "Distributed dynamic shared tree for minimum energy data aggregation of multiple mobile sinks in wireless sensor networks," in Proc. 3 rd European Workshop on Wireless Sensor Networks, 2006.

[16] S. Jain, R. C. Shah, W. Brunette, G. Borriello, S. Roy, "Exploiting mobility for energy eficient data collection in wireless sensor networks," Mobile Networks. Applications, vol. 11, is. 3, 2006, pp. 327-339.