XII SIGE ISSN: 1983 7402 São José dos Campos, 28 de setembro a 01 de outubro de 2010

Coordinated Employment of UAVs and WSN to Support C2 in Joint Military Operations

Edison Pignaton de Freitas[1,2], Ricardo Queiroz de Araújo Fernandes[3], Jorgito Matiuzzi Stocchero[4], Maurício Hofman da Silva[3], Armando Morado Ferreira[4], Flávio Rech Wagner[2] e Carlos Eduardo Pereira[2]
Instituto de Informática, Universidade Federal do Rio Grande do Sul, Caixa Postal 15.064, 91.501-970 – Porto Alegre/RS, Brasil.
Sektionen för Informationsvetenskap, Data– och Elektroteknik, Halmstad University, PO Box 823, SE-301 18 – Halmstad, Suécia.
Centro de Desenvolvimento de Software, QGEx, bloco G, 2º andar, Setor Militar Urbano, 70630-901 – Brailia/DF, Brasil.
1º Centro de Telematica de Área, Quartel General do Comando Militar do Sul, Rua dos Andradas 562, 90029-900 – Porto Alegre/RS, Brasil.
Programa de Pós-graduação em Engenharia de Defesa, Instituo Militar de Engenharia, Praça General Tibúrcio 80, 22290-270 – Rio de Janeiro/RJ, Brasil

Abstract — **The development of Unmanned Aerial Vehicles (UAVs) has shown promising results, especially in operations involving large UAV platforms, such as GlobalHawk, which generally operate as a single vehicle unit. However, a new trend is the use of fleets of mini-UAVs operating in coordination among them, to accomplish Intelligence, Surveillance and Reconnaissance missions (ISR) in order to support Command and Control (C2) activities. This employment of mini-UAVs gains even more strength when they work in cooperation with Wireless Sensor Networks (WSN) on the ground. The goal of this paper is to explore such combined use of UAVs and WSN supporting C2 in joint military operations. Additionally, preliminary simulation results are presented.**

Keywords — Sensor Networks, Unmanned Aerial Vehicles, Command and Control, ISR.

I. INTRODUCTION

As observed by Alberts in his book “Power to the Edge” [1], the terms command and control have many definitions, different approaches and inconsistent interpretations, even though they are familiar terms for the military language. Alberts took as the formal definition the one proposed by Pigeau e McCann [2]:

A. **Control**: those structures and processes devised by command to enable it and to manage risk;
B. **Command**: the creative expression of human will necessary to accomplish the mission.

However, Alberts [3] also recognizes that the approach over Command and Control (C2) is the result of concepts evolution of following the variables: technology; the nature of military operations; the capacity of the involved forces; and the environment where the operation takes place.

Command and Control must not be seen as final objective, but as a resource to achieve a value: the mission accomplishment. That is the reason to avoid a misinterpretation of C2 with any of the armed forces objectives.

E.P Freitas, edison.pignaton@hh.se, Tel.+46-35-167847 R.Q.A. Fernandes, ricardo@cds.eb.mil.br, Tel: +55-61-3415-3098; J.M. Stocchero stocchero@1cta.eb.mil.br; M.H. Silva, mauricio@cds.eb.mil.br; A.M. Ferreira, armando@ime.eb.br; F.R. Wagner, flavio@inf.ufrgs.br; C.E. Pereira, cprereia@ece.ufrgs.br.
Este trabalho é financiado pelo Exército Brasileiro.

In the case of Joint Operations, the focus of C2 capabilities relies on the collaboration of different partners with a shared objective, but with heterogeneous resources. In the case of a coalition, the partners may have similar resources, but different motivations.

Since each Force has its own perspective of the operational scenario, the complete coordination is only possible through shared situational awareness. It is essential for planning, resource allocation, synchronization and fratricide avoidance.

The situational awareness is built up from the information retrieved from the operational scenario. That process of information retrieval is implemented by integrating Intelligence, Surveillance, Target acquisition and Reconnaissance (ISTAR). The data acquisition and the Intelligence processing deliver the Command important resources for decision making. This is critical in the Joint Operations scenario, where each of the forces involved may have a different doctrine and use heterogeneous C2 systems. So, the shared situational awareness goal actually represents a challenge to current Joint Operations.

In order to provide relevant, trustworthy and time appropriate information, the use of autonomous computational systems for data acquisition and presentation arose with the advent of new technologies [4]. The present paper emphasizes in this context the use of C2 software integrated with Wireless Sensor Networks (WSN) [4] and of Unmanned Aerial Vehicles (UAVs) [15] working collaboratively in order to perform surveillance tasks. This collaborative usage of these technologies allows the delivery of necessary data to support intelligence for C2 in military operations. From this perspective, the goal of this paper is to present a mechanism to autonomously coordinate WSN nodes and UAVs and its applicability to support the planning of engagement and to provide a common operational picture to all forces in the military operation.

II. CONTEXT AND MOTIVATION

For a more efficient deployment of the military resources, one of the most important operational information, which any Force needs, is the awareness about the enemy’s movement in the operational scenario. This type of intelligence allows the different Forces coordinate their efforts against the enemies. There are different ways to acquire such awareness, by means of signals, human, or image intelligence, which must be combined to provide the best estimate of the real scenario to the decision makers. As examples of traditional means to gather information, it is possible to mention the interception of the enemy troops' communication (signal), the use of Special Forces behind enemy lines (human) and analysis of the enemies' previous movements on images gained from the battlefield. All this data must then be combined, or fused, to provide useful intelligence to be disseminated, in a timely manner, by the command and control system. However, the frequency of changes in current battlefield scenarios and the heterogeneous ways the forces maneuver in Joint Operations impose requirements which these traditional means cannot completely fulfill.

The advent of new technologies came to address the above mentioned problem, in which real-time information about the operational scenario can be acquired and analyzed so that the commanders are able to quickly respond to the new events. There are a number of technologies employed with this finality, in which the use of sensor networks represents an important breakthrough [4]. Another important advent in the same direction is the use to Unmanned Aerial Vehicles, which are able to carry sensors as payload, such as radars and visible light or infrared cameras [5]. An emerging trend that is gaining strength is the cooperative use of fleets of UAVs working cooperatively with sensor networks [6], which is a promising approach to support intelligence acquisition in military operations.

The reaction and adaptation to changes in the operational scenario depends on the speed of the events detection. To avoid an overload of events, the system should focus in the higher threats to the operational scenario. If the goal is to protect a border limit, the movement event in that region is expected to represent a possible threat. Thus, to catch relevant events, proper sensors have to be used in order to assess the occurrence of such events, according to their types, detecting patterns that can identify them, for instance: vibration or acoustic signature, electromagnetic waves, among others.

The best way to cover a region of interest is to spread a great number of low cost static sensors nodes that are able to provide evidences of possible events of interest and a smaller number of more sophisticated sensors mounted in mobile autonomous platforms, such as robots that can move on the ground (Unmanned Ground Vehicles - UGVs) or fly over the area of interest (Unmanned Aerial Vehicles - UAVs). A rationale for the use of both static (fixed) sensor nodes on the ground and dynamic (mobile) sensors carried by UAVs, particularly small UAVs, is to provide surveillance over large areas with minimal costs.

A reasonable assumption is that the sensors used on the ground are cheaper, but cannot provide the same meaningful data as the sensors carried by UAVs can do. So, a combination of these two types of sensors can provide an efficient and low-cost solution for surveillance in large areas. Moreover, small UAVs, such as those presented by MLB [7], are much cheaper than large conventional UAV platforms, such as Predator and Globalhawk. This makes possible the usage of a greater number of UAVs in the system, which in many ways increases the system capabilities and does enable enhanced robustness by extensive redundancy. Besides that, the preference for UAVs instead for mobile robots on the ground is the increased ability of such platforms to move over the area of interest if compared to the mobility of robots on the ground.

In relation to the rationale of the choice for small UAVs, it is possible to state that the use of conventional UAVs in defense operations is, in general, restricted to remote controlled frameworks, which need at least one operator to control the vehicle, as a remote pilot of a conventional aircraft. This model cannot evolve to a system with many UAVs, since the costs associated to each one are high. Based on that fact, the use of small autonomous UAVs represents a feasible employment of a number of such platforms in surveillance and reconnaissance missions to accomplish data acquisition to support the operational needs for C2 in Joint Operations.

Summing up the above ideas, the coordinated usage of small UAVs and WSN increases the utility of both technologies so that they are able to complement each other by offering features that covers the gaps of one another. The information provided by WSN nodes is not as rich as those provided by sensors on the UAV, but they are good enough to drive the UAVs to areas where they are needed to evaluate a given situation, maximizing the global utility of the system and optimizing its resources usage.

However, the amount of information those technologies produce are overwhelming in comparison to human cognition capabilities. For that reason, new technologies for decision making are needed to organize and correctly represent the available information. The softwares for C2 are the response to face those new realities.

The Command and Control tool used by the Brazilian Army is the software **C2 em Combate** (C2Cmb). The C2Cmb is a software the represents the operational scenario using georeferenced maps and the operational symbols defined by the Brazilian Defense Ministry for each relevant information, from units to terrain characteristics.

The C2Cmb software provides shared situation awareness through the diffusion of operational information groups (OIG) produced by each node on the C2Cmb network. It means that the perspective of each Combined Force is available to the others. The C2Cmb software follows the models of the *Multilateral Interoperability Program* (MIP) [8], specially the data models C2IEDM [9] and JC3IEDM [10] and the MIP-DEM [11] specification for communications.

The C2Cmb is able to gather georeferenced images, like aerial photos, and show them dynamically over the correct georeferenced position in the graphic interface as soon as they are available, as it is shown in Fig. 1. It means that this tool can be fed by information from the network composed by the WSN nodes and the small UAVs, in which the ground sensors detect events of interest triggered by movement, sound, heavy mass, presence of iron or electromagnetic waves, and send an alarm to the UAV-fleet in order to demand a UAV to make an aerial picture of the region of interest. After that, the UAV sends the gathered data to the C2Cmb to show the most recent view of a point where the sensors on the ground detected an event of possible interest, such as enemies crossing a borderline. All this process requires no human intervention, which lowers costs and allows faster response.

Besides the promising benefits of the combine usage of WSN and UAVs, one important aspect deserves attention: the coordination of these different types of nodes in this heterogeneous network. In order to make it possible the effective cooperation among them, mechanisms to provide the correct information exchange among the distinct nodes are required. In the context analyzed in this paper, the required coordination mechanism has to be able to guide the UAVs to the most interesting areas, using the information acquired by the ground sensors. The goal of this paper is to present a proposal of mechanism that fulfills this need, and coordinates the ground sensor nodes and the UAVs by using a bio-inspired coordination mechanism using artificial pheromones, which will be described further in the text.

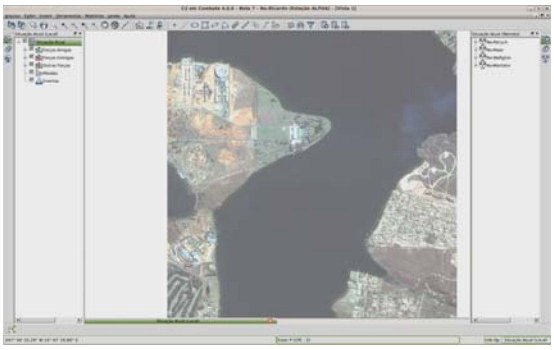

Fig. 1. C2 em Combate Graphical Interface.

III. SCENARIO PRESENTATION AND PROBLEM STATEMENT

A. Scenario Overview

The operation scenario studied in this work is a contiguous rectangular area in which each element (targets and sensors) is located by its Cartesian coordinates, x and y.

Targets are defined as non-authorized vehicles or persons, or groups of them, appearing in a non-deterministic fashion in the area. The appearance of targets is modeled as a Poisson distribution P(r), where r is the number of new targets that appear in the surveillance area at a given time t. A given target τ_i has an identifier i, which represents the order of its entrance in the surveillance area. The targets are considered to move with a constant speed $v_{\tau i}$, but different targets may have different speeds. Targets may also randomly change the direction of their movement.

The surveillance system uses heterogeneous sensor nodes equipped with 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 sensing range, which is a tunable parameter, depending on the type of sensor used and the type of the target. When a target is detected, an alarm is issued, which is heard by sensor nodes positioned within the communication range, which is also tuneable. The alarm contains a timestamp and the position of the issuer node. For the purposes of this work, the alarms indicate one target, which will lead to the use of one UAV suitable to perform a task over it. However, it is possible to generalize this approach to consider alarms indicating the occurrence of events, which may be triggered by the detection of several possible targets in a region. This situation may require more than one UAV to respond a given alarm. The exploration of this enlarged and more generic scenario is left as a future work.

1) UAV Model: The UAV instance i (denoted UAV_i) is considered to have an internal state $S_i(t)$ at a given time "t", which is composed by two components:

a) *Physical State*: including information about i:s current position $p_i(t) = (x_i(t), y_i(t))$, speed ($v_i(t)$), heading angle ($\psi_i(t)$), sensor devices type and status ($\varsigma^j_i(t)$), and energy resources ($e_i(t)$);

b) *Engagement State (ES)*: according to the detected targets in the surveillance area and to the respective alarms issued, a UAV can be in one of the following states: *idle*, *engaged*, or *busy*. The first may occur when a UAV is idle and able to engage in performing a task over a target informed about by an alarm. The second occurs when a UAV is engaged in performing a task related to a target, but it is not performing it yet. The third occurs when a UAV is handling a given target, i.e. performing a task over it. The set of states is represented by:

$$ES = \{idle, engaged, busy\}. \tag{1}$$

The kinematic model adopted in this work is similar to several others, in which the UAVs move along continuous trajectories with constant speed and with a constrained turning angle [12]. In the present work, the assumption of a constant speed is modified to allow speed adjustment needed for target tracking. An additional assumption is added to the model presented in this work, allowing the UAVs' maximum speed to be higher then the targets' maximum speed (targets of any kind k), depending on the characteristics of a given UAV. This assumption allows the system to have a high-level of responsiveness to handle new targets.

The sensors that equip the UAVs are considered to be the same for all members of the UAV-fleet. It means that all UAVs have the same sensing capabilities. This assumption is a sub-case of a more general one, in which the fleet is composed by UAVs with different sensing capabilities. However, for the sake of focus in the coordination mechanism among UAVs and ground sensor nodes, this work focuses in this sub-case.

B. Problem Statement

The studied problem is how to provide intelligent interoperability support to sensor networks composed of low-end ground sensor nodes and small UAVs applied to the surveillance of a large area scenario. The study of this problem requires, among other aspects, understanding of the constraints related to each of its components.

WSN nodes are usually known to have severe restrictions on energy consumption. This is an important characteristic that should be considered when WSN systems are being designed, as it may compromise, among other features, the overall system lifetime. The sensor nodes rely on a limited energy budget supplied by a battery, which is used to perform sensing, processing, and communication. The latter is the most energy consuming activity [13]. This implies that the nodes in a WSN should communicate as little as possible, i.e. make use of infrequent and short messages, aiming at an efficient energy usage.

Small UAVs cannot carry the same load as larger UAV platforms, and this affects directly their communication capabilities and range. Another constraint linked with the load capacity is that small UAVs must use their energy in an efficient way, since they are neither not able to carry much fuel or large batteries. This has impacts not only in the communication subsystem, but also restricts the operational range of small UAVs, limiting the cooperation possibilities needed among them and the other nodes in the system.

Given the above described scenario, an important coordination problem can be recognized: how the alarms should be delivered and assigned to the UAVs?

This problem presents an important factor that should be considered, namely the way the information about alarms should be handled, which can be done in two different ways: 1) via a central entity that collects the information about all alarms and then distributes them over the UAV network; or 2) via a decentralized handling and distribution of the information. Each option leads to different possible solutions with their particular pros and cons. The former carries all drawbacks related to single point of failure and restricting features that characterize centralized solutions. However, a centralized solution presents the benefit of the overview of the entire situation. On the other hand, a decentralized solution allows more flexibility to the system as a whole, as locality features can be explored.

IV. PHEROMONE-BASED ALARM DELIVERING

To address the above problem in the context of the desired coordination, i.e. alarm delivering, the approach proposed in this work uses a decentralized solution (using artificial pheromones) inspired by a biological mechanism used by animals to track food in the nature or to find a "partner" for reproduction.

Artificial pheromones are usually applied to distributed coordination by means of stigmergy, the indirect communication using environment cues [14]. A pheromone trail is deposited in the environment while entities are moving. The pheromone provides information to other entities when they pass over it. Artificial pheromones also loose their strength over 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 [15][16].

Differently from other existing approaches, in the present one, pheromones are used to guide the assignment of a UAV to handle an alarm issued by a ground sensor node. 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 will base their movement decisions to respond to the received alarms. This strategy is called here heuristic-P.

Following the above outlined principles, the UAVs that are not engaged in the handling of any target leave pheromone traces over the area which they cross, by means of beacon messages. These pheromone traces are represented by information collected from the ground sensor nodes that are deployed in the area through which the UAVs have passed. When a target is detected by a ground sensor node, it issues an alarm, as already mentioned. The alarm delivering will be performed by routing the alarm in the direction that points to the UAV which has the strongest pheromone trace over that area. This means that the alarm will be routed in the direction that points to the UAVs that most recently passed that location, i.e. it follows the UAV's pheromone trail composed by the pheromone traces left in the ground sensor nodes. Heuristic-P is inspired in a previous work [17], which presents a pheromone-based strategy to migrate services in a sensor network. In this referred work, 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.

Fig. 2 presents an example of how an alarm issued by a sensor node (Fig. 2-A) is routed through the network, following the pheromone traces (Fig. 2 from B to D), until it is delivered to a UAV (Fig. 2-E). The pheromone traces in the nodes are illustrated by numbers placed in the center of the circles representing ground sensor nodes. The smaller the number is, the stronger the pheromone. This translates the idea of the elapsed time past since a ground sensor node received the last pheromone beacon from a UAV. When a ground sensor node receives this pheromone beacon, it sends this information to its neighbors with a pheromone one point weaker (a number one unit greater than the one representing the node's pheromone information). This is an indirect beacon that helps the other nodes to find the traces along which to route the alarms. Nodes that receive indirect beacons do not forward them. The symbol "∞" means that the node has no pheromone trace, i.e. the last beacon (directly from a UAV or indirectly from another ground node) was received a long time ago, above a given tunable threshold (which can also so be tuned). The number representing the pheromone is periodically incremented, representing that the pheromone trace becomes weaker when time elapses, until disappearing (become ∞).

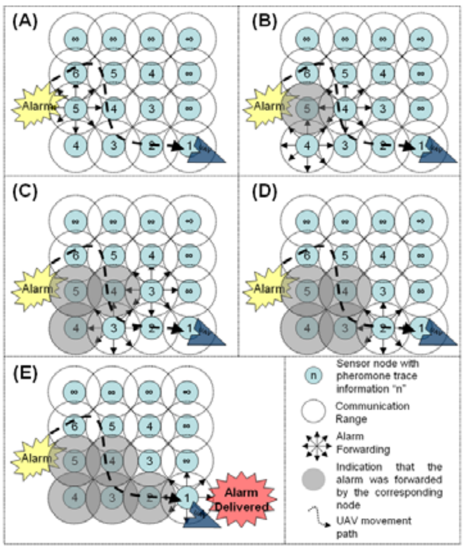

Fig. 2. Pheromone-based Alarm Delivering Example.

Aiming at the robustness of the proposal, in case an alarm is issued by a node that has no pheromone trace ("∞" pheromone mark on it), 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 in relation to the area under concern.

V. EXPERIMENTAL RESULTS

The proposed approach has been validated by means of simulations performed using ShoX [18], which is a powerful wireless ad hoc network simulator based on Java that provides easy to use mechanisms to provide extensions.

The aim of this work is to achieve a good although sub-optimal solution, as it is known that the search for optimal solutions generally has prohibitive costs. Moreover, an optimal solution for the analyzed problem would require global knowledge of the whole network, which is not practical in such systems. Moreover, this would hinder the exploration of the locality characteristic provided by the way how the alarms are delivered.

A. Simulation Setup

Three different scenarios were simulated with a different number of targets, namely, one, three, and five targets. The basic setup parameters are presented in Table I.

The choice of setup parameters was based on the characteristics of the scenario analyzed in this study, which considers Mini or Micro UAVs, which have an operational range of 10 Km and are aimed to fly at an altitude around 250 meters [19]. The UAVs fly following a random movement pattern, with collision avoidance, when they are not handling alarms. Communication ranges for both UAVs and ground sensor nodes were based on technologies such as IEEE 802.15.4 (extended range version). The ground sensor nodes are randomly deployed with an independent uniform probability (homogeneous Poisson point process in two dimensions, which generates a geometrical random graph). This distribution of 5000 nodes over a 10Km x 10Km area gives almost 100% of probability that the nodes in the network form a connected graph [20], for a communication range of 350 meters. The number of ground sensor nodes can be drastically reduced, while maintaining the network connectivity, by means of using more sophisticated sensor placement strategies, as presented in [21]. However, to keep the generality, a random distribution was used, as it well simulate the results obtained by practical methods to deploy sensors, such as dropping them from an airplane.

TABLE I SETUP PARAMETERS

Parameter	Value
Scenario Area	10Km x 10Km
Number of UAVs	6
UAVs' Communication Range	2Km
UAVs' Starting Energy Resources	90% – 100%
Number of Ground Static Nodes	5000
Ground Static Nodes Communication Range	350m
Types of Targets	1,3, 5

B. Simulation Results

The results collected from the performed simulations are expressed in terms of the utility in employing the UAV that received an alarm in handling it. In this paper, the utility is calculated by a cost function that takes as parameters the current position of the UAV, the location were the alarm was issued and the UAV's remaining energy. The utility is defined by (2):

$$U_i(t) = C(e_i(t), p_i(t), p_j)) \qquad (2)$$

where "*C*" is the cost function, $e_i(t)$ is the UAV's current energy resource status, $p_i(t)$ is the current position of the UAV, p_j is the target position reported in the alarm.

Fig. 3 presents the average results for all simulation runs for each number of targets, i.e. 1, 3, and 5, for the UAV assignment in terms of normalized utility in employing a certain UAV to handle a given alarm. It is considered that the optimal value is achieved by an "oracle" view of the system at the time instant in which an alarm was assigned to a given UAV. The oracle is a reference solution, which performs a computation having centralized "global" knowledge about all UAVs and the alarms happening in the system, thus providing the best possible solution. It is interesting to observe that the results achieved by the proposed approach are not far from the optimum one (all over 80% of the optimum, considering the 5% error margin as shown by the error bars).

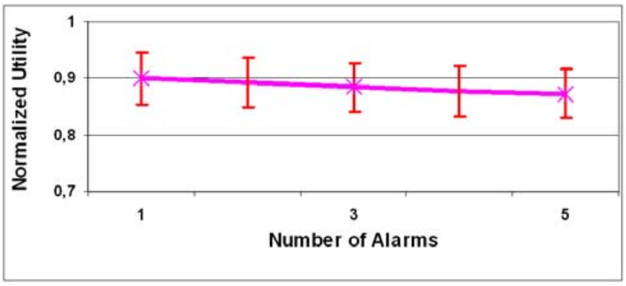

Fig. 3. Normalized Utility Results.

VI. DISCUSSION: SYSTEMATIC USAGE - SURVEILLANCE SERVICE

After the proposed solution for the coordination of the ground sensors and the UAVs in a mixed wireless network, the next step is to discuss how the surveillance service is to be organized so that it can profit of the presented technique.

First of all, the command must define the area of interest. It means that the quantitative associated area will be determined, what brings the requirement related to the necessary number of ground sensors nodes according to their communications capabilities.

The command must also select which are the events that may reveal a threat or relevant information. That definition determines which ground sensors must be selected for the task of event perception. After the deployment of the ground sensors, the area of interest will be enabled for relevant event perception.

The UAVs fleet must be chosen according to the observation capabilities determined by the command, by the area of coverage and by the estimated time for information acquisition. To keep a limited scope, first the system is considered to retrieve aerial georeferenced photos only, but the framework may be used to more sophisticated usage, such as video streaming, FLIR (forward Looking Infrared), MSS (Multi-spectral scanning) and HSS (Hyper-spectral scanning).

The C2Cmb system must be configured to receive those photos from the UAVs through the Joint Command network and to process them. The C2Cmb is able to show every georeferenced photo at the right position in the graphical interface. Moreover, the C2Cmb system is also able to order them according to the timestamps of each photo. It means that the newer photos stand visible, hiding older ones.

In other words, when the Joint Command looks to a specific position on the map, it looks into the most recent available information about that position of interest, without any human intervention.

VI. RELATED WORK

The AWARE project [6] 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. An idea that is shared and presented in both works is to use ground sensors and UAVs taking part of the same sensor network, cooperating in order to achieve surveillance mission goals. In our paper, the goal was to present how the cooperation among the UAVs and the ground sensor is performed and how this can be useful to support C2 in military operations. The first aspect is weakly handled by AWARE, while the second one is not mentioned due to focus in civilian applications that the AWARE project has.

Walter et al present an approach using digital pheromones to control a swarm of UAVs [22]. The method proposed by the authors uses digital pheromones to bias the movements of individual units within a swarm toward particular areas of interest that are attractive, from the point of view of the mission that the swarm is performing, and away from areas that are dangerous or just unattractive. In the large sense, the pheromone-based strategy used in our work has a similar goal, drive the UAVs to areas of interest, i.e. places where the alarms were issued. However, differently from their approach, we use the pheromone traces to localize the UAVs when an alarm is issued by a ground sensor node. This alarm then informs about an event of interest, which drives a suitable UAV to the location where the event happened. Moreover, an important difference is that we address cooperation among different sensor nodes, i.e. static ground sensor nodes and UAVs, while they only focus on the UAVs.

VI. CONCLUSION AND FUTURE WORK

This paper described the coordinated utilization of static sensor on the ground and mobile sensor carried by small UAVs aiming at to support the acquisition of intelligence data to support C2 in military operations, trying to stress the significance of the data that such system can provide in Joint operations. Moreover, it showed the challenge that such coordination represents, in terms of the mechanism from which the nodes cooperate. Then, a proposal of a bio-inspired coordination mechanism based on artificial pheromones is presented, along with preliminary results achieved by simulation. The obtained results are promising and provided evidences of the suitability of the proposed approach.

The directions of the future work are two fold: first denotes the systemic view of the work, which is related to the further enhancements and inclusion of additional features in the C2Cmb tool to allow the reception of data from sensors, as described in the paper; the second is related to enhancements in the pheromone-based coordination mechanism, particularly in the energy consumption issue, which was not deeply explored by the research group yet.

REFERENCES

[1] D. S. Alberts, R.E. Hayes, “Power to the Edge” DoD Command and Control Research Program. CCRP Publication Series, 2003.

[2] R. Pigeau, C. Mccann, “Reconceptualizing Command and Control”, Canadian Military Journal, volume 3, número 1, Primavera de 2002.

[3] D. S. Alberts, R.E. Hayes, “Understanding Command and Control”. DoD Command and Control Research Program. CCRP Publication Series, 2006.

[4] C-Y. Chong, S.P. Kumar, "Sensor Networks: Evolution, Opportunities, and Challenges", Proceedings of the IEEE, Vol. 91, No. 8, pp. 1247-1256, 2003.

[5] Stuart, D. M. "Sensor Design for Unmanned Aerial Vehicles", in Proceedings of IEEE Aerospace Conference, pp. 285-295, 1997.

[6] 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, pp. 38-46, 2008.

[7] MLB Co. web site. Submeter-scale aircraft, (2009), http://spyplanes.com

[8] MIP – Multilateral Interoperability Programme: http://www.mip-site.org/publicsite/03-Baseline_2.0/

[9] C2IEDM – C2 Information Exchange Data Model from MIP: http://www.mip-site.org/publicsite/03-Baseline_2.0/C2IEDM-C2_Information_Exchange_Data_Model/

[10] JC3IEDM - Joint C3 Information Exchange Data Model from MIP: http://www.mip-site.org/publicsite/04-Baseline_3.0/JC3IEDM-Joint_C3_Information_Exchange_Data_Model/

[11] NATO. MIP Technical Interface Design Plan (MITDP) – Annex A – MIP DEM Specification. 2.6 edition. Retrieved January 17, 2009, from MIP – Multilateral Interoperability Programme: http://www.mip-site.org/publicsite/03-Baseline_2.0/MTIDP-MIP_Technical_Interface_Design_Plan/ANNEXA - MIP DEM Specification/

[12] Y. Jin, Y. Liao, A.A. Minai, M.M. Polycarpou, “Balancing Search and Target Response in Cooperative Unmanned Aerial Vehicle (UAV) Teams”, IEEE Transactions on System, Man, Cybernetics-Part B: Cybernetics, vol. 36, nr. 3, p. 571-587, 2006.

[13] R. Mini, A. Loureiro, B. Nath, “The Best Energy Map of a Wireless Sensor Network”, Proc. of the 7th ACM Intl Symp on Modeling, Analysis and Sim. of Wireless and Mobile System, p. 165-169, 2004.

[14] 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.

[15] P. Gaudino, B. Schargel, E. Bonabeu, B.T Clough, “Swarm Intelligence: a New C2 paradigm with an Application to Control of Swarms of UAVs” Proceedings of 8th International Command and Control Research and Technology Symposium, 2003.

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

[17] T. Heimfarth, P. Janacik, "Experiments with Biologically-Inspired Methods for Service Assignment in Wireless Sensor Networks", IFIP Intl Federation for Information Processing, vol. 268; Biologically-Inspired Collaborative Computing; M. Hinchey, A. Pagnoni, F. J. Rammig, and H. Schmeck, Eds. Boston: Springer, 2008, p. 71–84.

[18] J. Lessmann, T. Heimfarth, P. Janacik, “ShoX: An Easy to Use Simulation Platform for Wireless Networks”, in Proc. of 10th Intern. Conference on Computer Modeling and Simulation, 2008, p. 410-415.

[19] 2009/2010 UAS-Yearbook UAS: The Global Perspective. 7th Ed., Blyenburgh & Co, 2009.

[20] 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, p. 80–91.

[21] S. N. Vecherin, D. K. Wilson, C. L. Pettit, “Optimal placement of multiple types of communicating sensors with availability and coverage redundancy constraints”, Proc. SPIE 7694, 76940U, 2010.

[22] Walter, B., Sannier, A., Reiners, D. and Oliver, J., “UAV Swarm Control: Calculating Digital Pheromone Fields with the GPU,” The Interservice/Industry Training, Simulation & Education Conference (I/ITSEC), Vol. 2005 (Conference Theme: One Team. One Fight. One Training Future), 2005.