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A Brief History of Virtual Pheromones in Engineering applications

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ABSTRACT: *In the past decades, numerous engineering designs attempted to imitate the operation mode of the natural pheromones, in applications ranging from robotics to packet routing in communication networks, and coordination in large human teams. This paper is a brief review – from an engineering perspective - of the state of the art in what concerns the implementations of the concept of "virtual pheromones" – the man-made counterpart of the biological pheromones. We provide an overview of the most significant solutions found in the vast literature dedicated to the means of coordination in multi agent systems, and try to identify the trends of evolution of the research in this field.*

Keywords : *Multi Agent Systems, virtual pheromones, stigmergy, Robotics, Behavioural Implicit Communication*

I. INTRODUCTION

The concept of *pheromones* is essential for understanding many fundamental biologic processes. Coined by Karlson & Luescher ([1]) in 1959, the term pheromones designates a class of chemical substances used by many animal species for intraspecific chemical communication. Animals often use pheromones to transmit chemical signals that serve for social organization (recognition of the members of the same family, kin, or colony), territorial behavior, finding and choosing mates, sending alarm messages, and for coordinating complex collective behaviors.

Etymologically, the term is derived from the Greek words *pherein* (to carry), and *hormon* (to stimulate, to excite) ([2]).

When perceived by other members of the same species, pheromones elicit specific reactions e.g. certain behavior patterns, or sometimes even developmental changes. The probability of the specific reaction is proportional with the pheromone intensity.

Once released in the environment, pheromones are subject to the following processes that describe their spatio-temporal evolution:

- spatial diffusion: this allows other agents to sense the pheromone at a certain distance from the source. Also, pheromone diffusion creates spatial intensity gradients, which contain important orientation clues for the sensing agents.
- aggregation: multiple sources of pheromones superpose their effects.
- evaporation: the intensity of a pheromone source decreases with time, thus eliminating obsolete information.

These simple processes, linked with certain behavior patterns, are the key for understanding the paradox of coordination in some insect colonies, capable of intelligent complex behavior, without the need of a central coordination mechanism, which intrigued the entomologists for over a century. A typical example of such coordination is the ant foraging behavior. When carrying food from a source to the nest, ants leave a trail of pheromones to indicate the path to the food to the other ants.

The pheromone scent determines the other ants to adjust their behavior and to follow the existing trail, reinforcing it by depositing additional pheromone along the path, in a self-catalytic process. On the other hand, the pheromone evaporation creates a negative feedback loop in this process, making longer or less used paths to decay and eventually disappear.

As a result the majority of the ants will follow the best path between the food source and the nest. This mechanism of indirect coordination between the agents by means of traces created in a shared environment was first described by Grassé ([3]), who called it "stigmergy" (from the Greek words "stigma" – sign, mark, and ergon – work, action).

The biological stigmergy has been extensively studied ([4]), and the mechanism through which the ants eventually find the shortest path between the food source and the nest was formalized in what Dorigo called the "Ant Colony Optimization" algorithm ACO ([5]).

But the processes of decentralized self-organization in multi-agent systems composed of simple, ant-like agents go far beyond the ACO. These processes have been called with the generic name "swarm intelligence" ([6]), and later included a variety of other optimization algorithms (see [7]).

There are now thousands of research articles dedicated to the study of the processes related to swarm intelligence. This paper is only concerned with the engineering applications relying on the implementation of "virtual pheromones", sometimes also called "digital pheromones" or just "synthetic pheromones".

The reminder of this paper is structured as follows:

Section 2 contains a selection of the most interesting solutions involving virtual pheromones from a historical perspective, and in Section 3 we try to identify the trends of evolution of the research in this field, and formulate conclusions.

II. AN OVERVIEW OF THE STATE OF THE ART FROM A HISTORICAL PERSPECTIVE

The idea to create simple, ant-like robotic agents capable of decentralized coordination dates back to 1980s, though the actual term of artificial, or virtual pheromones was used much later. In 1989, Steels ([8]) noted that the spatial propagation of sound creates a gradient field that can emulate the process of diffusion, and explored the possibility use this principle for creating robotic systems capable of self-organization.

In 1993 Drogoul & Ferber ([9]) suggested two possible ways to implement decentralized coordination in multi-agent systems composed of simple robots: by leaving "crumbs" along their path (like Tom Thumb, and other fairy tale characters used to do), or by creating chains, like dockers used to do between the ship and the wharves.

Parunak in [10] (1997) attempted to extract some general engineering principles from the analysis of the natural multi-agent systems. He emphasized the importance of the environment and proposed a structure of the multi-agents systems (MAS) as a three-tuple:

$$MAS=<Agents, Environment, Coupling>$$

where "coupling" defines the interactions between the agents and the environment.

A variety of other studies from the same period (e.g. [11],[12]) reflect the growing interest in the study of "collective robotics", and "robot colonies", but the term "virtual pheromones" was not explicitly mentioned until 2001 ([13]). In this study, Payton et al. propose a solution wherein the "virtual pheromones" are short range infrared communication messages passed from one robot to another in a multi-hop communication network. The intrinsic directionality of the infrared communication was used to emulate spatial pheromone gradients, and relative distances between robots were estimated by counting the number of hops for each message.

Obviously, according to this model, the pheromones are tied to the robots, rather than being deployed in the environment, and the pheromone gradients change as the robots move.

To overcome this drawback, O'Hara et al. proposed in [14] a solution wherein the environment is pre-populated with a grid of beacons capable to store information and to communicate with the robots. A variant of this idea can be found in [15], where Hoff et al. assume that "during the execution of the algorithm [...], some robots will decide to stop their normal search behavior and become 'pheromone robots', also known as beacons, which means they stop moving and act as locations on which virtual pheromone can be stored."

An interesting variation of the idea of deploying a sort of digital beacons throughout the environment can be found in [16], where Mamei & Zambonelli use RFID tags to store pheromone information. They also found an elegant solution to emulate the process of pheromone evaporation: the pheromone data structure stored in the RFID tags includes a time stamp indicating the moment of the most recent update of the pheromone. Assuming that the robots are equipped with a real-time clock, they can easily evaluate the pheromone decay through evaporation by comparing this time stamp with the current time.

Though the idea of using proximity RFID tags as physical support for digital pheromones has multiple advantages, it still has some drawbacks: RFID tags can be read one at a time (see fig. 1), so that the robot can only sense pheromone gradients by (randomly) moving from one tag to another.

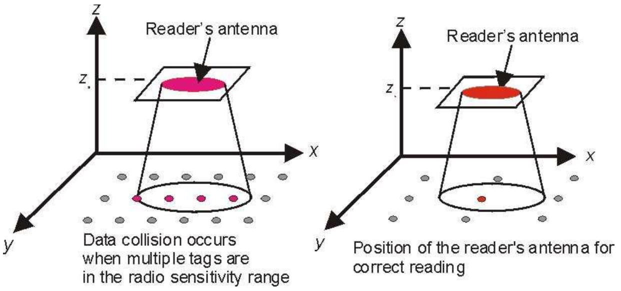

Figure 1: RFID readers can only access one tag at a time

We proposed a simple and efficient solution for this problem in [17], by using two reader antennas, located to a certain distance apart from one another, just like ants and other insects do to sense the pheromones (see fig. 2)

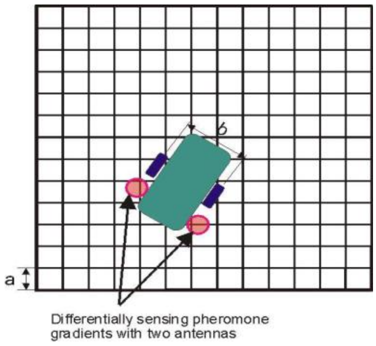

Figure 2: A better emulation of the process of pheromone diffusion with RFID technology by using differential sensing with two antennas

However, none of the above mentioned implementations emulate all of the transformations of biological pheromones (diffusion, aggregation, evaporation). Therefore, the quest for improving the model of the virtual pheromones continued to produce new solutions. An apparently good idea would be to instruct the robots to leave thermal traces by locally heating the ground along their path ([18]), but – considering the limited amount of energy available for the mobile robots – this solution is not feasible in practice.

In another implementation, described in [19], robots draw marks on the floor using a special disappearing ink. In [20] the marks on the floor are not drawn but projected by a computer that communicates with the robots and controls a video projector.

Other researchers tried to directly imitate the biological pheromones, by enabling robots to disperse and sense some chemical substances in the environment ([21],[22]), but it seems that there is still a long way to go for creating a reliable and cost effective artificial nose.

Considering the above examples, it becomes obvious that it is impractical for the agents to leave physical or chemical marks in the environment. It would be much more convenient to create a virtual environment for storing and manipulating the virtual pheromones. Therefore, Vaughan et al. ([23]) studied a scenario wherein the robots have their own localization means (odometry) and share a common *localization space*, defined as “any consistent spatial or topological representation of position. Such a space is shared if there is some [...] correlation between the representations maintained by two or more individuals. A prime example is the Global Positioning System (GPS). Two systems equipped with GPS share a metric localization space in planetary coordinates”.

In this approach, each robot periodically “drops crumbs” in this localization space by keeping a list of records of its coordinates and heading estimates as provided by the odometric system. In a subsequent communication process, these individual “private crumb lists” are fused into a “global crumb list” that guide the robots in their navigation tasks.

However, the task of creating and updating a global representation (or “map”) of the environment is quite complex and not really compatible with the idea of ant-like agents, capable only of local interactions with the environment. Therefore, in [24], we proposed a solution wherein the task of maintaining a global map of the environment is allocated to a central computer, called “pheromone server”. In this approach, the process of “dropping crumbs” is equivalent to sending a data packet to the pheromone server, containing the agent’s ID and current position. This creates a discrete pheromone source *Sk*, in a 2D map of the environment (see fig. 3)

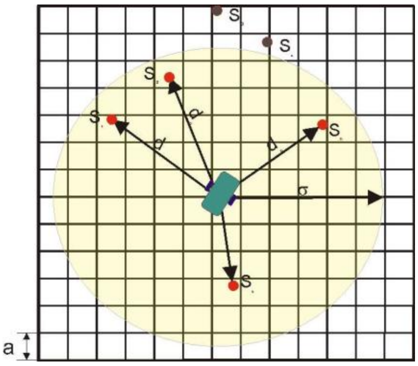

Figure 3: Notations used to describe the virtual pheromone model used in [24]

The major advantage of this scenario is that it allows a complete model of virtual pheromones, i.e. a model that reflects all the processes specific to the biological pheromones: dispersion aggregation, and evaporation.

Assuming a linear model, with the notations in fig. 3, the diffusion of the pheromone source *Sk* at the distance x can be described by:

$$p(x) = \begin{cases} p_k\left(1 - \dfrac{x}{\sigma}\right) & 0 < x < \sigma \\ 0 & x \geq \sigma \end{cases} \qquad (1)$$

the aggregation of all the N sources:

$$P_R = \sum_{k=1}^{N} p_k\left(1 - \frac{d_k}{\sigma}\right) \qquad (2)$$

and the evaporation:

$$P_R(t) = \sum_{k=1}^{N} p_k\left(1 - \frac{d_k}{\sigma}\right)\left(1 - \frac{t - t_k}{\tau}\right) \qquad (3)$$

where t_k is the moment of creation of the source S_k, and, τ is an evaporation constant, and σ is the sensitivity range (i.e. the maximum distance from a pheromone source where the “scent” of the source can still be sensed).

All the examples described above can be included in the general category of applications called “swarm robotics”, but of course, swarm robotics is not limited to pheromone-based interactions. A recent comprehensive survey of the literature dedicated to swarm robotics is available in [25]. On the other side, the domain of possible applications of the virtual pheromones is not limited to robotics.

When both the agents and the environment are virtual (i.e. software simulated or implemented) there is plenty of room for applications involving stigmergy and virtual pheromones. Such application range from optimal routing in communication networks ([26], [27]), modeling and simulation of the crowd behavior, and smart evacuation systems ([28],[29],[30]), task allocation in flexible manufacturing systems ([31],[32]), to intelligent traffic control and congestion avoidance systems ([33],[34],[35]).

The solutions aimed to elicit stigmergic self-organization in multi-agent systems with human agents (e.g. [36],[37],[38]) rely on creating a virtual environment capable to capture and broadcast the Behavioural Implicit Communication (BIC) messages of the individual agents in the form of a shared global cognitive map that reflects the activity of all agents (see fig. 4).

Unlike the simple, ant-like agents, whose interactions with the environment are direct and local, human agents tend to use some technological means to interact with the environment, and build complex cognitive maps before taking actions. If these cognitive maps reflect the actions of the other agents, this may result in stigmergic behavior of the whole MAS ([38]).

Typical examples of applications built according to this model are the collaborative filtering systems used for data mining (39]), or for the optimization of the educational paths in e-learning ([40],[41]).

Finally, it is worth to mention another class of applications involving virtual pheromones: those involving both human and robotic agents, or physical and virtual agents. A comprehensive survey regarding Finally, it is worth to mention another class of applications involving virtual pheromones: those involving both human and robotic agents, or physical and virtual agents. A comprehensive survey regarding the human interactions with robot swarms is available in [42], and an attempt to define a framework for creating hybrid systems with interacting physical and virtual agents is described in [43].

III. DISCUSSION AND CONCLUSION

The diversity of applications involving virtual pheromones illustrated in the previous paragraph, explains the interest of the researchers in defining a unified model for them.

One of the first unifying perspectives treats virtual pheromones as potential fields (see [44]), since the potential field is the closest physical concept that describes well the processes diffusion and superposition of effects.

In another approach, the process of sensing a spatial distribution of virtual pheromones is equivalent to a neural network. We suggested this in [24] (see fig. 5).

This analogy is investigated in depth in [45], where Mora et al. describe the implementation of a Kohonen Self Organizing Map (SOM) based on the concept of virtual pheromones.

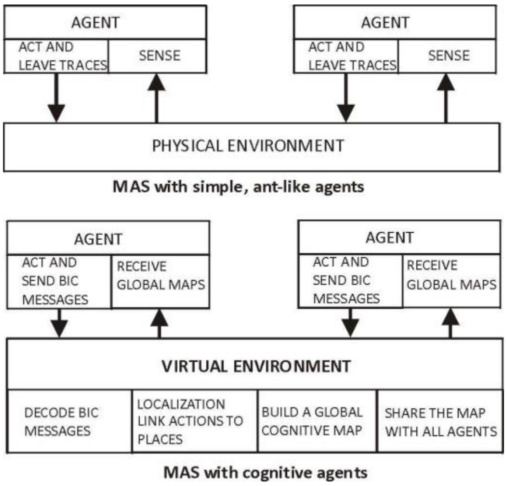

Figure 4: Capturing and broadcasting BIC messages may foster stigmergic interactions between intelligent agents (see [35]).

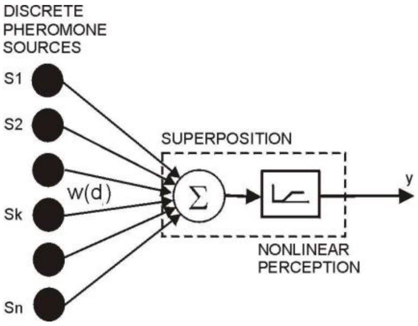

Figure 5: Sensing multiple pheromone sources is equivalent to the operation of a neuron

Parunak (in [46]) suggest an interpretation of the pheromone distributions as “probability fields”. A more rigorous study of the stochastic behavior of the ant system is available in [47], but the work on defining an ultimate mathematical model of the virtual pheromone is still in progress.

After reviewing the vast literature available on topics related to stigmergy and virtual pheromones, we believe that the most promising research direction remains the study of the so-called “cognitive stigmergy” ([48]) and the self-organization in MAS with intelligent agents.

The model of stigmergic interactions we proposed in [38] based on the automatic identification of the Bevavioural Implicit Communication (BIC) messages, creates a strong link between the extremely fertile research field of activity recognition (see [49], [50]) and the equally rich in results field of the study of self-organization in MAS.

REFERENCES

[1] Karlson P. & Luescher M. ‘Pheromones’: a new term for a class of biologically active substances. *Nature*, 183, 1959, pp:155–156.

[2] Wyatt, T. D. (2003). Pheromones and animal behaviour: communication by smell and taste. Cambridge University Press.

[3] Grassé, P. P. La reconstruction du nid et les coordinations interindividuelles chez Bellicositermes natalensis et Cubitermes sp. la théorie de la stigmergie: Essai d'interprétation du comportement des termites constructeurs. *Insectes sociaux*, 6(1), 1959 : 41-80.

[4] Theraulaz, G., & Bonabeau, E. (1999). A brief history of stigmergy. *Artificial life*, *5*(2), 97-116.

[5] Dorigo, M., Maniezzo, V., & Colorni, A. Ant system: optimization by a colony of cooperating agents. *Systems, Man, and Cybernetics, Part B: Cybernetics, IEEE Transactions on*, *26*(1), 1996: 29-41.

[6] Beni, G., & Wang, J. Swarm intelligence in cellular robotic systems. In *Robots and Biological Systems: Towards a New Bionics?* 1993 :703-712. Springer Berlin Heidelberg.

[7] Yang, X. S., Cui, Z., Xiao, R., Gandomi, A. H., & Karamanoglu, M. (Eds.). *Swarm intelligence and bio-inspired computation: theory and applications*. 2013, Newnes.

[8] Steels, L. Cooperation between distributed agents through self-organization. In Y. Demazeau, & J. P. Müller (Eds.), Decentralized AI: proceedings of the First European Workshop on Modelling Autonomous Agents in a Multi-Agent World, Cambridge, England, August 16–18, 1989.

[9] Drogoul, A., & Ferber, J. Some Experiments with Foraging Robots. In From Animals to Animats 2: Proceedings of the Second International Conference on Simulation of Adaptive Behavior (Vol. 2, 1993). MIT Press.

[10] Parunak, H. V. D. " Go to the ant": Engineering principles from natural multi-agent systems. *Annals of Operations Research*, *75*, 1997: 69-101.

[11] Arkin, R.C. and Bekey, G.A. (editors). Robot Colonies. Kluwer Academic Publishers, 1997.

[12] Holland, O., & Melhuish, C. Stigmergy, self-organization, and sorting in collective robotics. *Artificial life*, *5*(2), 1999 :173-202.

[13] Payton, D. W., Daily, M. J., Hoff, B., Howard, M. D., & Lee, C. L. Pheromone robotics. In *Intelligent Systems and Smart Manufacturing* 2001 :67-75. International Society for Optics and Photonics.

[14] O'Hara, K. J., Walker, D. B., & Balch, T. R.. The GNATs—Low-cost Embedded Networks for Supporting Mobile Robots. In *Multi-Robot Systems. From Swarms to Intelligent Automata Volume III* 2005 (:277-282). Springer Netherlands.

[15] Hoff , N. R., Sagoff, A., Wood, R. J., & Nagpal, R. Two foraging algorithms for robot swarms using only local communication. In *Robotics and Biomimetics (ROBIO), 2010 IEEE International Conference on* (pp. 123-130). IEEE.

[16] Mamei, M., & Zambonelli, F. Physical deployment of digital pheromones through RFID technology. In *Swarm Intelligence Symposium, 2005. SIS 2005. Proceedings 2005 IEEE* (pp. 281-288). IEEE.

[17] Susnea, I., & Vasiliu, G. On defining and following robot paths in an RFID augmented environment. In *15th International Conference on System Theory, Control and Computing. 2011*

[18] Russell, R. A.. Heat trails as short-lived navigational markers for mobile robots. In *Robotics and Automation, 1997. Proceedings., 1997 IEEE International Conference on* (Vol. 4, pp. 3534-3539). IEEE.

[19] Mayet, R., Roberz, J., Schmickl, T., & Crailsheim, K. Antbots: A feasible visual emulation of pheromone trails for swarm robots. In *Swarm Intelligence* 2010 (pp. 84-94). Springer Berlin Heidelberg.

[20] Sugawara, K., Kazama, T., & Watanabe, T. Foraging behavior of interacting robots with virtual pheromone. In *Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on* (Vol. 3, pp. 3074-3079). IEEE.

[21] Purnamadjaja, A. H., & Russell, R. A. Guiding robots' behaviors using pheromone communication. *Autonomous Robots*, *23*(2), 2007 :113-130.

[22] Ishida, H., Wada, Y., & Matsukura, H. Chemical sensing in robotic applications: A review. *Sensors Journal, IEEE*, *12*(11), 2012 :3163-3173.

[23] Vaughan, R. T., Støy, K., Sukhatme, G. S., & Matarić, M. J. Blazing a trail: insect-inspired resource transportation by a robot team. In *Distributed autonomous robotic systems 4 2010* (pp. 111-120). Springer Japan.

[24] Susnea, I., Vasiliu, G., Filipescu, A., & Radaschin, A. Virtual pheromones for real-time control of autonomous mobile robots. *Studies in Informatics and Control*, *18*(3), 2009:233-240.

[25] Brambilla, M., Ferrante, E., Birattari, M., & Dorigo, M. Swarm robotics: a review from the swarm engineering perspective. *Swarm Intelligence*, 2013 *7*(1), :1-41.

[26] Ducatelle, F., Di Caro, G., & Gambardella, L. M. Using ant agents to combine reactive and proactive strategies for routing in mobile ad-hoc networks. *International Journal of Computational Intelligence and Applications*, *5*(02), 2005:169-184.

[27] Roth, M., & Wicker, S. Termite: Ad-hoc networking with stigmergy. In *Global Telecommunications Conference, 2003. GLOBECOM'03. IEEE* (Vol. 5, pp. 2937-2941). IEEE.

[28] Gaud, N., Galland, S., Gechter, F., Hilaire, V., & Koukam, A. Holonic multilevel simulation of complex systems: Application to real-time pedestrians simulation in virtual urban environment. *Simulation Modelling Practice and Theory*, *16*(10), 2008: 1659-1676.

[29] Henein, C. M., & White, T. Macroscopic effects of microscopic forces between agents in crowd models. *Physica A: statistical mechanics and its applications*, *373*, 2007:694-712.

[30] Rahman, A., Mahmood, A. K., & Schneider, E. (2008). Using agent-based simulation of human behavior to reduce evacuation time. In *Intelligent Agents and Multi-Agent Systems* (pp. 357-369). Springer Berlin Heidelberg.

[31] Peeters, P., Van Brussel, H., Valckenaers, P., Wyns, J., Bongaerts, L., Kollingbaum, M., & Heikkilä, T. Pheromone based emergent shop floor control system for flexible flow shops. *Artificial Intelligence in Engineering*, *15*(4), 2001:343-352.

[32] Xiang, W., & Lee, H. P. Ant colony intelligence in multi-agent dynamic manufacturing scheduling. *Engineering Applications of Artificial Intelligence*, *21*(1), 2008:73-85.

[33] Ando, Y., Fukazawa, Y., Masutani, O., Iwasaki, H., & Honiden, S. Performance of pheromone model for predicting traffic congestion. In *Proceedings of the fifth international joint conference on Autonomous agents and multiagent systems* 2006 (:73-80). ACM.

[34] Narzt, W., Wilflingseder, U., Pomberger, G., Kolb, D., & Hortner, H. (2010). Self-organising congestion evasion strategies using ant-based pheromones. *Intelligent Transport Systems, IET*, *4*(1), 93-102.

[35] Susnea, I; Vasiliu G. Patent application „Vehicle Navigation System", Romanian National Patent Office OSIM Application number A00960/11.10.2010.

[36] Parunak, H. V. D. A survey of environments and mechanisms for human-human stigmergy. In *Environments for Multi-Agent Systems II* (2006: 163-186). Springer Berlin Heidelberg.

[37] Susnea, I. Engineering Human Stigmergy. International Journal of Computers Communications & Control, 10(3), 2015:420-427.

[38] Susnea, I., & Axenie, C. Cognitive Maps for Indirect Coordination of Intelligent Agents. *STUDIES IN INFORMATICS AND CONTROL*, *21*(1), 2015:111-118.

[39] Grosan, C., Abraham, A., & Chis, M. *Swarm intelligence in data mining* 2006:1-20. Springer Berlin Heidelberg.

[40] Semet, Y., Yamont, Y., Biojout, R., Luton, E., & Collet, P. Artificial ant colonies and e-learning: An optimisation of pedagogical paths. In *10th International Conference on Human-Computer Interaction*. 2003

[41] Susnea, I., Vasiliu, G., & Mitu, D. E. Enabling Self-Organization of the Educational Content in Ad Hoc Learning Networks. *Studies in Informatics and Control*, *22*(2), 2013:143-152.

[42] Kolling, A., Walker, P., Chakraborty, N., Sycara, K., & Lewis, M. Human Interaction With Robot Swarms: A Survey. In press, to appear in IEEE TRANSACTIONS ON HUMAN-MACHINE SYSTEMS.

[43] Susnea, I. Vasiliu, G. "A framework for creating mixed robot formations with physical and virtual agents" *International Conference of the Air Force Academy —Henri Coanda, AFASES2011*, Brasov, 2011.

[44] Van Dyke Parunak, H., Brueckner, S., & Sauter, J. Digital pheromone mechanisms for coordination of unmanned vehicles. In *Proceedings of the first international joint conference on Autonomous agents and multiagent systems: part 1* 2002: 449-450. ACM.

[45] Mora, A. M., Fernandes, C. M., Merelo, J. J., Ramos, V., Laredo, J. L. J., & Rosa, A. C. KohonAnts: A Self-Organizing Ant Algorithm for Clustering and Pattern Classification. *Artificial Life*, *11*, 2008:428.

[46] Van Dyke Parunak, H. Interpreting digital pheromones as probability fields. In *Winter Simulation Conference* 2009: 1059-1068. Winter Simulation Conference.

[47] Chialvo, D. R., & Millonas, M. M. How swarms build cognitive maps. In *The biology and technology of intelligent autonomous agents* 1995:439-450. Springer Berlin Heidelberg.

[48] Ricci, A., Omicini, A., Viroli, M., Gardelli, L., & Oliva, E. Cognitive stigmergy: Towards a framework based on agents and artifacts. In *Environments for Multi-Agent Systems III* 2007*:* 124-140. Springer Berlin Heidelberg.

[49] Turaga, P., Chellappa, R., Subrahmanian, V. S., & Udrea, O.. Machine recognition of human activities: A survey. *Circuits and Systems for Video Technology, IEEE Transactions on*, *18*(11), 2008:1473-1488.

[50] Liao, L.. *Location-based activity recognition* (Doctoral dissertation, University of Washington, 2006)