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APPLICATIONS OF THE EMERGENCE IN COGNITIVE MAS

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Abstract: The emergence and self-organization have been extensively studied in Multi-Agent Systems comprising simple, ant-like agents. When it comes to human multi-agent systems, the inter-agent, and agent-environment interactions are much more complex, and difficult to model. This paper presents several use cases wherein the indirect coordination mechanisms based on behavior implicit communication between cognitive agents lead to interesting practical applications. Without aiming to propose any theoretical generalization, the examples outlined here may contribute to a better understanding of human multi-agent systems.

Keywords: Multi-Agent Systems, Stigmergy, Cognitive MAS, Virtual Pheromones, Intelligent Transportation Systems, Stigmergic Recommender Systems.

1. INTRODUCTION. BRIEF REVIEW OF THE STATE OF THE ART

The concept of "emergence" (Deguet (2006)), initially introduced in philosophy, was later widely explored in connection with the concept of "complex systems" (Standish (2008)). In a very general sense, emergence is the key element that makes complex systems irreducible to their parts. From an engineering perspective, these concepts have been successfully studied using the multi-agent systems (MAS) model (Ferber (1999)), defined as a large number of simple (reactive) identical agents that share a common environment.

An important step in understanding emergence was the discovery of stigmergy (Grassé (1959)) – the indirect coordination mechanism by means of chemical markers (called pheromones Karlson (1959)) deployed by the agents in the environment, which allows ant colonies to exhibit global intelligent behavior.

Pheromones diffuse in space, so that a local source can be detected from within a certain range, and at the same time they evaporate, which makes unreinforced traces to decay and eventually disappear.

A typical example of stigmergic interaction is the ant foraging behavior. When a searcher ant discovers a food source, it starts leaving a pheromone trail on its way back to the nest. Other ants tend to follow the path created by the searcher, reinforcing the initial trail. Due to evaporation, longer trails that require more time for the ants to walk along become less attractive and, in the absence of reinforcement, they eventually disappear.

Eventually, the majority of ants will choose the shortest route between the food source and the nest (see figure 1). This process of finding the optimal route was called "ant colony optimization" (ACO – Dorigo (1992)), and attracted a great deal of interest for the emergent intelligent behavior in swarms.

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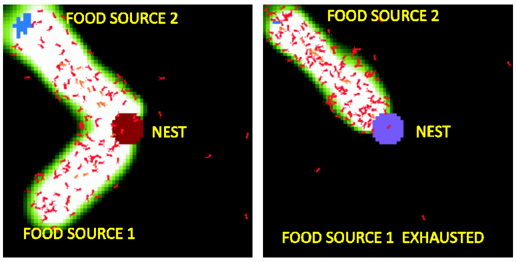

Fig.1. A simulation of ant colony activity using Netlogo. Lighter shades of green indicate higher pheromone concentrations

The actual concept of "swarm intelligence" was coined by Beni & Wang (Beni (1989)).

Numerous researchers have studied possible uses of stigmergy in robotics (Sauter (2005), Susnea (2008)), for military applications (Parunak (2001)), for routing data packets in computer networks (Gunes (2002), Kwang Mong Sim (2003)), web mining (Ajith (2003)), mobile sensor networks (Howard (2002)), and even in cognitive sciences (Marsh (2007), Heylighen (2007)).

In what concerns the actual implementation of the artificial pheromones, the proposed solutions range from automatic deployment of chemicals in the environment (Purnamadjaja (2007)), recording special data structures in RFID tags (Mamei (2005), Susnea (2008)), to exchanging short range messages between agents (Payon (2001)), or simply creating special software entities (Gunes (2002)).

The general principles for the implementation of stigmergic systems with artificial agents are have been formulated in Parunak (1997). According to Parunak, a multi-agent system (MAS) is a three-tuple:

MAS = <Agents, Environment, Coupling>

wherein the agents are characterized by a set of states, a number of inputs and outputs, and a program that governs the transitions between internal states. The agent's program runs autonomously (i.e. without being invoked by an external entity).

The environment also has a set of states and a "dynamics" (program) that controls the transitions between states.

By means of their inputs and outputs, the agents interact with the environment by spreading pheromones, in certain conditions, according to their own program (coupling).

From this perspective, a MAS has the following features:

- agents are simple, identical entities;
- the environment acts as a shared memory for all the agents;
- the communication between agents is indirect, mediated by the changes in the state of the environment.

Although stigmergy proved to be an exceptional tool for the study of MAS composed of simple, ant-like agents, there are much fewer studies that explore the use of stigmergy in societies composed by cognitive/rational agents. This type of stigmergy was called "cognitive stigmergy" (Ricci (2007)), and the rational agents were also called "BDI agents" (Parunak (2006)) (BDI stands for Beliefs, Desires and Intentions).

According to Omicini and Ricci (Ricci (2004), Ricci (2007)) the main solution to enable stigmergic interactions between BDI agents is to make use of the "behavior implicit communication" (BIC). A typical example of BIC is that of a person (i.e. a BDI agent) who buys a product, or chooses to watch an exhibit in a museum, or visits a web page, and thus involuntarily sending a signal containing information about a personal decision.

The conclusion is that designing artifacts capable to capture and display BIC signals is the key element for enabling stigmergy in cognitive MAS.

This paper contains a brief analysis of several examples of emergence in human multi agent systems in an attempt to facilitate the understanding of the mechanisms that may induce self-organization processes in such systems.

Based on these examples, the emergence in cognitive MAS may fall under one of the following categories:

- emergent behavior of the agents (e.g. intelligent transportation systems, stigmergic evacuation systems);
- self-organization of the environment shared by the agents (e.g. web page ranking);
- emergent knowledge (e.g. recommender systems, web usage mining systems)

Beyond this introduction, this work is structured as follows:

Section II proposes the concept of "virtual pheromones" and describes a means for the implementation thereof.

Section III presents several use cases wherein virtual pheromones are used to create stigmergic interactions between BDI agents, and Section IV is reserved for discussion and conclusions.

Without having the aim of proposing any theoretical generalization, the examples analysed in this paper may contribute to a better understanding of emergence in cognitive MAS.

2. A CENTRALIZED APPROACH ON CREATING ARTIFICIAL PHEROMONES

In practice, all the solutions based on creating no matter what type of markers (chemicals, temperature gradients, RFID tags storing some particular data structures) deployed in the environment by humans, or man-made agents have limited applicability, mainly for economic reasons.

In an application of robotics (Susnea (2009)), we proposed a solution for the implementation of artificial pheromones, wherein the *agents leave engrams not in the environment, but in a representation thereof – a map*. (We prefer the term *"engram"* rather than *"trace"* because of its cognitive connotations.)

In this approach, a number of agents, equipped with their own localization system and wireless communication periodically communicate with a "pheromone server".

The "pheromone server" is a computer, running a special application software that creates and maintains a data structure called "pheromone map" " (see figure 2).

Basically, the pheromone map is a 2D grid array, wherein each cell is associated with the following data:

- the coordinates of the corresponding geographic space,
- an integer representing the resultant pheromone intensity of all the pheromone sources located in the respective cell

Periodically, each agent sends queries to the pheromone server, and includes in the query packet position information, as reported by its own localization system.

Upon reception of a query packet, the server locates the agent on the internal map and computes for the respective position the resultant pheromone intensity, by means of a potential field model (Khatib (1986)).

With the notations in figure 3, the effect of diffusion is that a pheromone source S_k can be sensed at the distance *x* with the intensity *p(x)* according to (1).

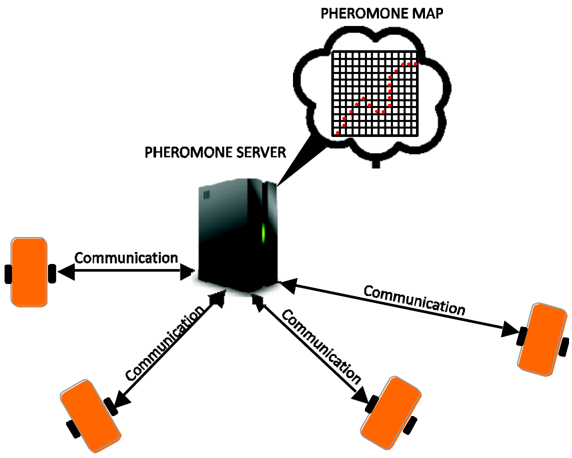

Fig.2. Implementation of the virtual pheromones

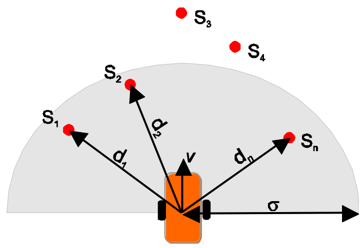

Fig.3. Notations used to describe virtual pheromones aggregation and diffusion

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

Due to the superposition of the effects of all *N* pheromone sources located within the sensitivity range σ (aggregation), the resulting pheromone intensity, sensed in an arbitrary location is:

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

and, assuming that the evaporation produces a linear decrease of the pheromone intensity, it is possible to write:

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

where τ is an evaporation constant.

This simple, linear model was selected in order to reduce the computational load of the server, because the pheromone intensity (3) must be computed repeatedly, at regular time intervals, for every cell of the grid map, and this can be cumbersome in applications operating with very large maps.

The value P_R, computed by the server is returned to the querying agent in the response packet, and thereafter the agent acts as if it had its own pheromone sensing system.

This centralized approach on implementing artificial pheromones may e criticized for the following drawbacks:

- it leads to the loss of the intrinsic robustness of MAS against system failures;

- it limits the scalability of the system, due to the bandwidth constraints of the communication channel between the agents and the pheromone server.

In practice, however, none of the above mentioned drawbacks is a real issue. Backup servers ensure reasonable downtime for millions of computer networks, and certainly would do the same for a pheromone server.

In what concerns the scalability, considering the fact that the data volume exchanged between the agents and the server is very low, and the time between communication sessions is not critical, it results that systems comprising thousands of agents are perfectly feasible. This seems to be enough for most practical applications.

There are also some important advantages of centralized virtual pheromones:

- Since most of the work is done by the server, the hardware required for sensing the actions of the agents is reduced, and can be implemented with existing technology (RFID, barcodes, smartphones).

- "Snapshots" of convenient pheromone distribution maps, (e.g. those obtained in an Ant Colony Optimization process), can be saved for later use. In fact, the entire pheromone map can be easily manipulated to influence the behavior of the agents in a desired direction.

- The system allows the simultaneous use of multiple pheromone types, which increases the overall flexibility of the system.

- Software simulated agents can interact in real time with physical agents (Susnea (2011)

It is easy to notice that the number and the weight of advantages are far more significant than the drawbacks of this approach. The following section presents several interesting practical applications of this concept.

3. FOSTERING EMERGENCE IN COGNITIVE MAS

3.1. Use case 1. An improved GPS navigation system for road vehicles

Common GPS navigation systems for vehicles comprise a GPS locator, which provides the information about the current position to a microcontroller that extracts from a local memory a predefined map of the geographic area, corresponding to the actual location of the vehicle. This map is displayed on a local screen, and serves for orientation.

The main drawback of this solution derives from the fact that it uses static maps. No matter how often these maps are updated, they still do not include information about how fluent is the traffic at present time on a particular road segment, or whether there is a traffic congestion or a traffic jam.

There are numerous attempts to overcome this limitation, (e.g. Dowling (2006), Adam (2007)) mainly based on providing an additional communication channel between the on-vehicle navigation assistant and an external device, which can be an Internet server, or a roadside equipment designed to store an updated knowledge base about traffic conditions, actual practicability of the roads, etc.

Some web mapping services (e.g. Google maps) include –for limited geographical areas - color coded traffic information in maps, but all they can offer is an estimate of the traffic conditions, based on previously collected data.

Even so, the problem of updating the additional knowledge base still remains open, and can only be solved with substantial operation costs.

We proposed (Susnea (2010)) an improved GPS navigation system for vehicles based on stigmergy would have the general structure presented in figure 2, wherein the wireless link between agents and the pheromone server can be a mobile Internet connection. A fragment of the pheromone map, corresponding to the geographic area surrounding the location of the querying agent can be transmitted by the server in response to queries sent by individual agents and superposed over the existing GPS navigation maps as a transparent layer.

Pheromone trails can be visually represented with different colors, (or shades of gray) depending on the pheromone intensity, as illustrated in figure 4.

Since the pheromone map is created and maintained by the agents themselves, no additional operation costs are required for this system.

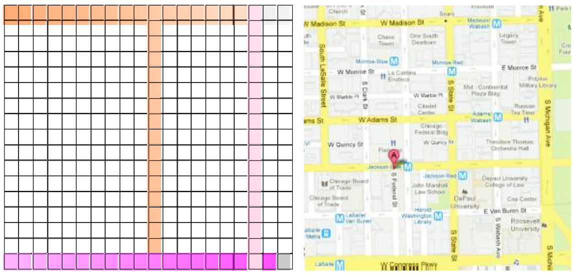

Fig.4. Layering pheromone information over GPS navigation maps

In an alternative implementation, the agents use GPS enabled smartphones and a mobile Internet connection to report their current position to a server, which mixes GIS data obtained from a web mapping service with pheromone information, and delivers the results as a web page, just like Google maps does.

3.2. Use case 2: Stigmergic Shopping in Supermarkets

Most department stores and supermarkets use powerful inventory management software, which uses data from the POS equipment to keep a detailed database of the goods offered for sale. Every item in this database has an unique barcode identifier, which is associated with substantial additional information (price, lot number, expiry date etc.) including the geographic position on the shelf where the respective item is located. Having this information, it is relative easy to set up a network like in figure 6, wherein a pheromone server maintains a map of the store and updates the pheromone distribution every time the POS reports the sale of an item. The resulting map is displayed for public on TV screens deployed throughout the store.

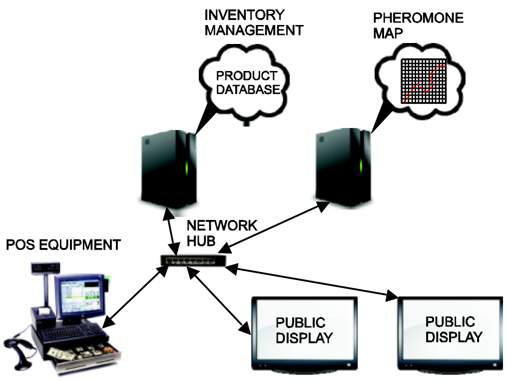

Fig.5. Ranking products in supermarkets

The shelves with frequently sold products are displayed on the map as "hot spots", thus creating on the customers an effect similar – to a certain degree – with the Amazon sales rank.

The underlying idea of "value" associated with a high sales rank is likely to produce a stigmergic effect on the shopper's behavior: some shoppers will visit the places indicated as holding highly ranked products and eventually will buy those products, contributing to a further increase of their sales rank.

3.3. Use case 3 – Guiding visitors in museums and exhibitions

RFID tags are now very cheap, so they can be included or simply temporarily attached to the access tickets in museums and exhibitions.

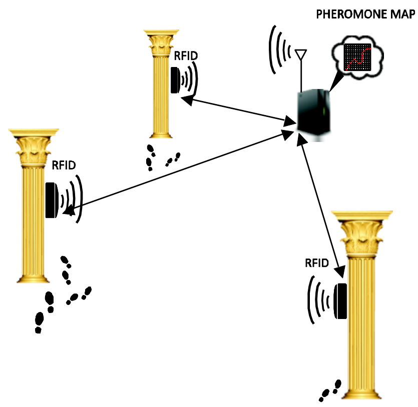

Fig.6. Using RFID tags to track visitors in museums

A number of RFID readers deployed throughout the premises can count the visitors approaching the readers, and report the results to a computer that builds a pheromone map indicating the points that attract most visitors (see figure 6).

This map can be displayed on TV screens, or broadcast locally for smart phones, along with additional "cultural" information about the respective items.

A variant of this solution, using RFID badges, can be used to design stigmergic evacuation systems for buildings, capable to display real-time information about practicable exit pathways.

3.4. Use case 4: Automatic generation of reports about the geographic distribution of emergency calls

The number of emergency calls (911/112) generated from a specific geographic area is an interesting demographic indicator, which may contain information about zones with higher criminality rate, the debut of an epidemics, or other morbidity factors. This can be of interest for authorities that allocate resources for emergency situations, for real estate agents, or for tourists that could avoid this way the zones with high criminality.

Since most modern smartphones are equipped with GPS locators, it is easy to write a software application to intercept emergency calls and automatically send a digital message to a server, reporting the geographic coordinates of the location where the call was generated. (Susnea (2011b). The server creates and maintains a pheromone map and generates graphic reports about the distribution of emergency calls. These reports can be made available for authorities and for individual subscribers.

A variant of this solution can be used for real-time monitoring of military combat areas. A simple electronic device mounted on military vehicles can automatically detect the use of weapons in the vicinity of the vehicle, and send reports containing the coordinates of the current location to a base station. The pheromone maps created this way contain real-time information about military operations in a specific geographic area and may be a valuable decision tool for the commanders. In certain situations, these maps can also be made available for civilians (e.g. for coordinating the operations of evacuation in certain exposed areas) .

3.5. Use case 5: Stigmergic learning networks

In Susnea (2013) we proposed a method to create self-organization of the educational content in large anonymous learning networks.

Consider a database of "educational objects" (Friesen (2001)) used by a (large) community of students, and/or researchers. Each "object" is described by a set of properties, including:

- an unique identifier,
- a set of tags (keywords) describing the educational content of the object,
- a means to detect that the object has been accessed by some user,
- a means to store virtual pheromone information

Assuming that every item *x* in the database is associated with metadata consisting in a set of keyword tags:

(4) $$K_x = \{k_1, k_2, .., k_{\mu x}\}$$

where

(5) $$\mu_x = |K_x|$$

is the cardinal of the set K_x.

For any two items *i, j* in the database, it is possible to compute the co-presence CP_{ij}:

(6) $$CP_{ij} = |K_i \cap K_j|$$

And the Jaccard similarity index:

(7) $$S_{ij} = \frac{|K_i \cap K_j|}{|K_i \cup K_j|}$$

and, finally, the distance between elements i and j, d_{ij}:

(8) $$d_{ij} = 1 - S_{ij}$$

Having a distance, it is possible to associate pheromone information with all the items in the database, according to the following algorithm:

- Every time a user accesses an object *k* in the database, the pheromone intensity associated with that object increases with a constant ratio p_k;
- Compute the distances d_{ik} between the object k and all other objects with (8);
- Diffuse the effect of the new pheromone source S_k over the entire space, and increase the pheromone intensity of all items i with

(9) $$\delta p_i = p_k \left(1 - \frac{d_{ik}}{\sigma}\right)$$

- At regular time intervals, decrease the pheromone intensity associated with all the objects in the database with a constant ratio to reflect evaporation.

As a result, the pheromone intensity field in the database can be used along with other metadata to filter the items most "valued" by the community.

This simple scheme implements a rudimentary recommender system based on stigmergy, which actually allows self-organization in learning networks with very low user accountability. Multiple variations and improvements are possible.

4. DISCUSSION AND CONCLUSIONS

Although stigmergy was intensely studied over the past decades, the above mentioned use cases suggest that there is still plenty of room for interesting research and applications, mainly in what concerns the coordination mechanisms between complex, intelligent agents. In this context, the centralized approach on implementing virtual pheromones, presented here, proved to be useful.

It is also important to note that designing systems that treat humans as simple "agents", certainly may raise some ethical issues. For example, a stigmergic evacuation system designed to save lives in case of fire, involves RFID badges and readers deployed throughout the building, which can easily be used to monitor the movements of individuals. And this is not always ethical, and sometimes not even legal.

Creating systems that allow tracking and recording these involuntary messages can leave room for abuse.

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