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Engineering Human Stigmergy

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Abstract:
Discovered in the context of a research about insects, stigmergy – the indirect coordination mechanism that allows ant colonies to achieve intelligent behavior – has been extensively studied with the aim to create artificial, ant-like agents. Although stigmergic behavior has been also identified in human collectivities, there are relatively few reports about technological solutions that facilitate the emergence of such interactions between people. This paper proposes the concept of virtual pheromones, defined as engrams created by the agents not in the environment, but in a representation thereof – a map, and outlines several use cases, wherein pheromones embedded in maps are the key element for inducing stigmergic behavior in human multi-agent systems. Without proposing a theoretic generalization, this paper aims to emphasize the broad range of possible technological applications of human stigmergy, and, maybe, to mark a new starting point for a more in-depth study of this topic.

Keywords: Human stigmergy, virtual pheromones, pheromone maps, intelligent transportation systems, stigmergic shopping, stigmergic learning.

1 Introduction

Stigmergy is a process of indirect coordination in multi-agent systems, by means of traces that agents create in the environment. Upon sensing these traces, other agents are stimulated to perform similar actions, thus reinforcing the traces, in a self-catalytic process.

As a result,simple, local and unplanned actions of the agents emerge in a complex, and apparently intelligent behavior of the system as a whole.

Discovered in the context of a biological research [6], the stigmergy in biological systems relies on the capacity of the agents to deploy in the environment small amounts of chemicals, called pheromones [8].

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 finds 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. In the end, the majority of ants will choose the shortest route between the food source and the nest.

This processof finding the optimal route was called "ant colony optimization" (ACO – [4]), and attracted a great deal of interest for the emergent intelligent behavior in swarms.

Numerous researchers have studied possible uses of stigmergy in robotics [19], for military applications [12], for routing data packets in computer networks [18], web mining [1], mobile sensor networks [7], or in cognitive sciences [9].

A variety of solutions have been proposed for the implementation of the artificial pheromones, including automatic deployment of chemicals in the environment [16], storing special data structures in RFID tags [19], exchanging short range messages between agents [15], or by creating dedicated software entities [10]. All the implementations of stigmergic systems with artificial agents are based on a set of concepts and principles that have been formulated in [13]. 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 dictates 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*).

In this approach, a MAS presents the following features:

- agents are simple, identical entities;
- the environment is seen as a shared memory for all the agents;
- agents communicate with each other indirectly, by creating and sensing changes in the state of the environment.

Obviously, this model of interaction, which describes well multi-agent systems with simple, "lightweight" agents [13] is not suitable to describe interactions between so-called BDI agents (BDI stands for Beliefs, Desires, Intentions [17]). The decision making, and the final behavior of such agents are governed by mechanisms far more complex than the simple, reactive response to environmental stimuli.

However, there are many situations when human behavior is stigmergic [5], and it seems that the technological progress, which facilitates indirect communication between people, is likely to create more opportunities for human stigmergy. Notable examples in this direction are: the market system, intelligent transportation systems, web page ranking (Google), recommender systems (e.g. Amazon ranking, IMDB rating) online auctions (eBay), and many others.

The present paper aims to facilitate the understanding of human stigmergy by presenting several examples of technological solutions to induce stigmergic behavior in human collectivities. Without having the intention to propose theoretical generalizations, this may be the starting point for other interesting research in this direction.

Beyond this introduction, this work is structured as follows:

Section 2 discusses the concept of "virtual pheromones", and proposes a simple model for it.

Section 3 presents several use cases wherein virtual pheromones are used to create stigmergic interactions between human agents, and Section 4 is reserved for discussion and conclusions.

2 Virtual Pheromones as Pheromones Embedded in Maps

In an application of robotics [20], we proposed a solution for the implementation of artificial pheromones, wherein the agents leave traces not in the environment, but in a representation thereof – a map. 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 1). 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,

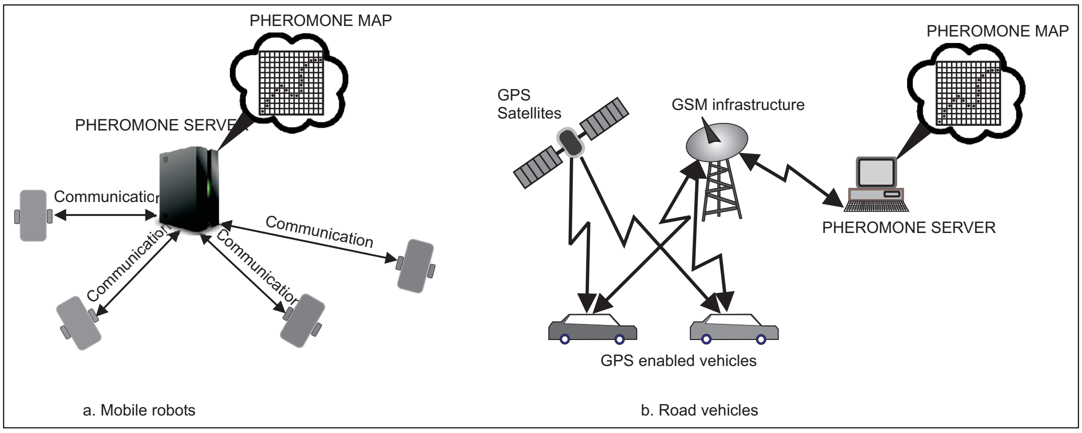

Figure 1: An illustration of the implementation of virtual pheromones

- 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. With the notations in figure 2:

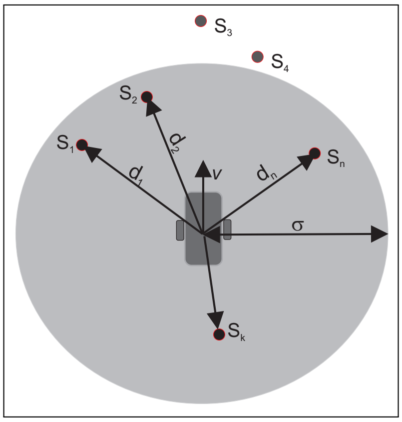

Figure 2: Notations used to describe virtual pheromones aggregation and diffusion

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

where $p(x)$ is the intensity of the pheromones source S_k, sensed at the distance d_k, due to diffusion. Due to the superposition of the effects (aggregation) of all N pheromone sources located within the sensitivity range σ, the resulting pheromone intensity, sensed in an arbitrary location is:

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

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

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

where t_k is the time of creation for the source S_k, and 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.

3 Applications of Virtual Pheromones

The concept of virtual pheromones as described in Section 3 of this article was initially developed in a research aiming to reduce cost of some service robots. By manipulating the pheromone maps it is possible to define easy-to-follow robot paths, by means of virtual pheromone gradients, as shown in figure 3.

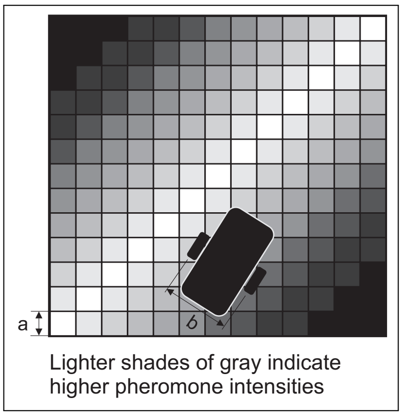

Figure 3: Defining Robot paths by means of pheromone gradients

The idea was later used in an experiment for creating mixed robot formations with physical and virtual agents [21]. In this experiment, a real robot was programmed to follow a software simulated leader robot.

Though interesting, the experiments described in [20] and [21] are limited to controlling individual agents, and do not make use of the capability of pheromones to mediate stigmergic interactions. The following use cases focus on human stigmergy.

3.1 Use case 1: Real-Time Ant Colony Optimization 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. [14]) 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 these solutions usually offer just an estimate of the traffic conditions, based on previously collected data, or they rely on measuring the average speed of individual vehicles by means of GPS data collected via smartphones.

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

A possible implementation of an improved GPS navigation system for vehicles based on stigmergy would have the general structure presented in figure 1b. A fragment of the pheromone map, is transmitted by the server in response to queries sent by individual agents and superposed over the existing GPS navigation maps as a transparent layer. Since the pheromone map is created and maintained by the agents themselves, no additional operation costs are required for this system.

3.2 Use case 2: In-Store Recommender Systems

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 relatively easy to set up a network like the one presented in figure 4, 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.

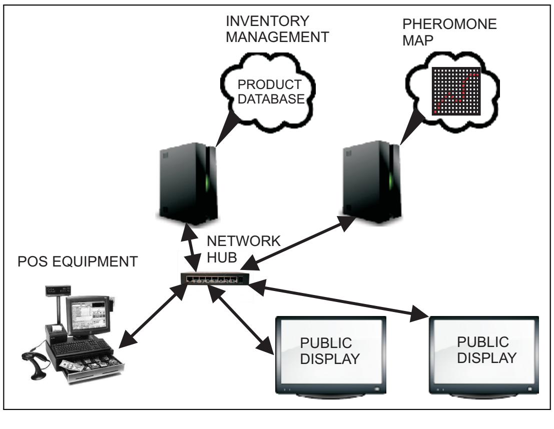

Figure 4: The structure of a stigmergic in-store recommender system

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 (at least, this happens in the case of e-commerce - see amazon.com)

3.3 Use case 3: Self-Organization of the Educational Objects

In certain conditions, the emergence does not affect the agent's behavior, but the environment shared by the agents. Consider, for example, a database of "educational objects" [23] used by a (large) community of students, or researchers. Each object is described by a set of metadata, 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

Every time a user accesses an object in the database, the pheromone intensity associated with that object increases. Besides that, the pheromone intensity of all objects that share the same keywords with the object directly accessed is also increased, but with a lesser ratio (diffusion).

On the other hand, the pheromone intensity of all objects in the database is automatically decreased by software at regular time intervals, so that, if an object is not accessed for a long time, its pheromone intensity eventually drops to zero (through evaporation).

This simple scheme, automatically creates some metadata describing the "educational value" of the objects in the database, so that any user can immediately select educational objects (filtered by tags) with the highest value.

Though very simple, this approach, combined with a P2P environment, may be the starting point for a serious attempt to overcome the "teacher-student" learning paradigm, and replace it with a new "teach while you learn" paradigm. Further research in this direction might be beneficial.

4 Discussion and Future Work

There are several aspects of the concept of virtual pheromones, as defined in this paper, worth to discuss:

a. Built this way, the pheromone maps can be seen as a special type of cognitive maps [24], having a very interesting feature: they create a link between the behavior implicit communication messages, generated by the agents [11] and certain geographical places.

If somebody buys a product, chooses to watch an item in an exhibition, or visits a certain web page, he involuntarily sends a message carrying information about a personal decision. Fusing the information from a plurality of such messages in a unique map, and making this map available for all the agents is the key element that can trigger stigmergic interactions.

The idea that there is a connection between what we call swarm intelligence and the concept of cognitive maps has been suggested back in 1995 by Chialvo and Millonas in [2].

A closer look at the examples outlined in the above paragraphs (see also [22]), suggests that the concept of virtual pheromones as defined here offers the means to create such cognitive maps in just a few simple steps:

- Automatic identification of Behavior Implicit Communication (BIC) signals. It is worth to note that the problem of automatic detection of certain behaviors has been extensively studied under the name activity recognition in various contexts (e.g. human - robot interaction, ambient intelligence, pervasive healthcare etc.), but there are no signs of capitalization of the results of the research on activity recognition from the perspective of capturing BIC messages;
- Localization - Linking the BIC messages to specific places within the environment. This can be done either by enabling agents with a certain degree of location awareness, as in the above examples, or by creating a number of place agents [3] (i.e. active places in the environment), capable to recognize and keep record of certain behaviors of the agents;

- Creating a dynamic cognitive map of the environment based on the place-activity information provided by the virtual pheromones;

- Sharing the resulting map (or parts of it) with all agents.

b. The model of the virtual pheromones described by (3) does not require the absolute position of the agents to compute the pheromone intensity associated with a certain place. It only needs the relative distances between the specific place considered and the pheromone sources. This means that the proposed model can be used - in principle - in any metric space, whenever we can define a distance function. This leaves room for some interesting applications, where the intelligent agents operate in more abstract spaces, like databases, or social networks (see also [23]).

c. 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.

To conclude, we will note that, 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, may be useful.

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