Stigmergic Algorithms for Simple Robotic Devices
(Extended Abstract)

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Abstract— This position paper is meant to discuss the use of stigmergy in minimalist robotic systems, and to argue for a methodological approach based on the combination of formal analysis and empirical evaluation. In the full paper we will illustrate this approach in three case studies: building a globally optimal navigation map, building a gas concentration gradient map, and updating the above maps dynamically. All case studies have been implemented in a real environment with inexpensive robots, using an RFID floor as the stigmergic medium.

I. STIGMERGY IN ROBOTICS

One of the many fascinating phenomena which can be observed in nature is *stigmergy* [1]. Stigmergy is a mechanism by which agents organize their individual or collective work through the bias of traces left in the environment. Traces are typically made of volatile chemicals called pheromones [2] that are released and detected by organisms of the same species. These traces can be seen as an external memory whose contents are written by an agent and then read by a different agent, or by the same one at a late time, who uses this information to decide its behavior. Stigmergy allows a simple agent, or a collection of simple agents, to exhibit complex behavior without the need for internal memory, planning, or direct communication. Stigmergy is the principle at the basis of the seemingly intelligent behavior of many social insects [1].

Stigmergy is a very interesting phenomenon to study in robotics and computer science [3], [4]. By stigmergy, many simple robotic devices could, via indirect communication through the environment, exhibit a collective behavior which is significantly more complex than the one of each individual robot. Consider for instance an environment where robots can write and read "traces" in the floor, in the form of bytes of information. A cleaning robot could use these traces to leave a last-cleaned timestamp in each part of the floor, and so it can develop a very simple but effective cleaning strategy ("go to the areas with the older stamps"). The practical beauty of this strategy is that the robot may end up solving its task in a globally optimal way by only looking at local information (the marks at its current location). A second interesting point is that multiple robots could clean the same place using this strategy, and automatically distribute optimally in the environment without the need for explicit communication of for global maps and memories.

In general, *stigmergic algorithms* can be used to realize complex behaviors with global properties using computation-ally simple robotic systems with a local view, by leveraging the spatial memory provided by the stigmergic medium [3]. More complex examples of what could be achieved by stigmergy include "ant colony optimization" [5], [6], a family of stigmergic optimization algorithms inspired by the behavior of ants, and its physical robotic realizations [7].

II. THE STUDY OF STIGMERGY IN ROBOTICS

The claim in this position paper is that stigmergic algorithms in robotics should be studied by a combination of theoretical investigation and empirical experimentation. The theoretical investigation should be aimed at defining a robotic stigmergic system, as a function of the type of robots and of the type of stigmergic medium in which they operate; and at studying the formal properties of such a system, e.g., what global algorithms can be implemented in a distributed way through stigmergy, and what are the properties of this implementation (e.g., completeness, soundness, convergence, computational complexity). The empirical investigation should be aimed at verifying the hypotheses generated by the theoretical investigation in real, physical systems. It should also be aimed at assessing the application potential of stigmergic algorithms, possibly looking at specific application domains.

To support this claim, we will analyze three case studies:

1) A stigmergic algorithm by which one or multiple robots can find optimal paths to a target position, even when the robots have no sense of global location and the target is outside from the range of the robot's sensor. This algorithm was first presented in [8].
2) A stigmergic algorithm by which one or multiple robots equipped with gas sensors can generate a gradient map leading to the areas of highest gas concentration, again with no use of global localization. This algorithm was first presented in [9].
3) The extension of the previous two algorithms to the case of dynamic environments, in which obstacles may be added and removed, by adding a time dimension to the stigmergic medium. These results are novel contributions of this position paper.

Formal analyses are proposed in each case study that state general properties of the algorithms. In order to support these formal properties with empirical evaluation, All the test cases have been implemented on a physical test-bed. This testbed consists of a set of simple ePuck robots [10], which navigate
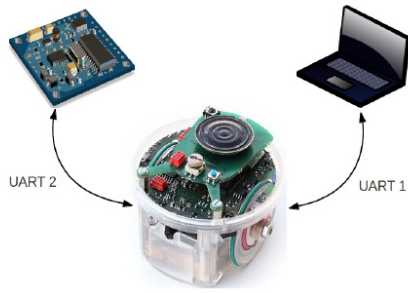
Fig. 1. Testbed used for the empirical study of stigmergy. Left: an ePuck robot equipped with a M1-mini RFID tag reader. Right: the RFID tags placed under the apartment's floor.

in a large apartment-like environment whose floor hides an hexagonal grid of RFID tags [11]. Each robot is equipped with an RFID tag reader, so it can read and write bytes of information in the tags while it moves over them. This mechanism mimics the pheromone trails left by ants in one of the most famous example of stigmergy found in nature.

The third case is worth a few comments. The algorithm for optimal path planning in [8], outlined in sort format below, lets the robot(s) build a distance map to the target location by running a variant of Bellman-Ford algorithm [12].

Algorithm 1 BuildDistanceMap()

Require: All tags initialized to ∞, robot starts at goal
1: distance_count $\leftarrow$ 0
2: **while** *Explore* **do**
3:    $x \leftarrow$ ReadTag()
4:    **if** NextTag(x) **then**
5:       distance_count $\leftarrow$ distance_count + 1
6:       **if** distance_count > $val(x)$ **then**
7:          distance_count $\leftarrow val(x)$
8:       **else**
9:          WriteTag(x, distance_count)
10:      **end if**
11:   **end if**
12: **end while**

The time dimension can be introduced through an *evaporation* mechanism that mimics the decay of pheromone intensity with time, which is observed in nature [2] and used in ant colony optimization [6]. This, however, would require that the amount $v(x)$ of virtual pheromone in each tag x is updated at each time step, something which cannot be done with passive tags. We have therefore developed a local version of pheromone evaporation, in which pheromone values are associated with a time stamp and discounted accordingly to an evaporation function f whenever the tag is visited. The resulting algorithm is outlined below.

III. Summary

With this position paper we offer three main contributions to the discussion on unconventional computing methods for robotic systems. First, to discuss the use of stigmergy in physical robotic systems as a paradigms to realize algorithms that compute solutions with global properties using only local computation; second, to discuss the methodological issue of

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Algorithm 2 BuildDistanceMapDynamic()

Require: All tags initialized with $val = \infty, t = 0$
1: distance_count $\leftarrow$ 0
2: **while** *Explore* **do**
3:    $x \leftarrow$ ReadTag()
4:    **if** NextTag(x) **then**
5:       $v \leftarrow f(val(x), \text{current\_time} -t(x))$
6:       distance_count $\leftarrow$ distance_count + 1
7:       **if** distance_count > v **then**
8:          distance_count $\leftarrow v$
9:       **else**
10:         WriteTag(x, distance_count, current_time)
11:      **end if**
12:   **end if**
13: **end while**

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the relation between formal analysis and empirical validation, and the need to have both; third, to illustrate these points with concrete, tangible case studies.

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