

# Interactive Surface for Bio-inspired Robotics, Re-examining Foraging Models

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**Abstract**—In this paper we propose a new experimental device for defining and studying self-organized systems, especially those including physical or chemical interactions such as those encountered in collective natural phenomena. We want to be able to reproduce with real robots several paradigms such as stigmergy. In these phenomena the environment stores, diffuses, evaporates chemical substances (pheromones) that drive the behavior of each entity. The proposed device is a smart surface which relies on a graphical environment on top of which robots can move but also read/write information thanks to colorimetric sensors and infrared emitters. The surface itself is able to perform some computation, implementing e.g. diffusion/evaporation mechanisms. More generally, the proposed robotic system allows to re-examine theoretical/simulated models in the perspective of defining self-organized robots. We consider in this paper the foraging problem as a case study. In particular we re-examine the expression of the model proposed by Drogoul&Ferber [1] to implement pheromone-based exploration and transport with robots. We then analyze self-organized behaviors, as emergence of chains of robots, and their robustness.

**Keywords**-Digital Pheromones; Swarm robotics; Foraging; Mobile robots; Self-organization; Experimental device

## I. INTRODUCTION

In the perspective of defining and studying bio-inspired self-organized systems, especially physical ones as mobile robots, we propose a new experimental device allowing real robots to read and write information in the environment.

As envisioned by R. Brooks in [2] and [3], collective intelligence should be deployed with myriads of simple “ant-robots”, presenting self-organized properties similar to the ones in nature.

Many models have been proposed to simulate social insects and to measure their robustness or performances in problems such as foraging (eg. [4]), sorting (eg. [5]) or task allocation (eg. [6]). In particular, many models rely on the stigmergic principle, which consists for agents to mark/modify their environment to perform indirect communication and cooperation [7]. However, few robotics implementations have been proposed to date. Indeed, in nature, marks laid by insects are generally pheromones, i.e. a chemical substance, which are difficult to sense and manipulate

by mobile robots. Recent works show that chemical signals like odor or pheromones can be used for robot localization [8] and simple communication [9] but their use is sensitive to environmental conditions. For this reason, we investigate the design of active environments, i.e. with perception and computational abilities, in order to study the implementation of the stigmergic principles with robots.

In this paper, we define a physical and digital surface which can be marked and read by robots. This environment is a graphical surface where it is possible to display any color images, to put objects/robots on top of it and which can interact with. Robots can locally perform interactions with the environment, directly dropping colored traces and measuring color of the area under their body (thanks to seven colorimetric sensors).

Such a device allows to focus on interactions between robots and an active environment before to envisage their deployment on “real” large environments. Such environments holding a sensor network or smart tiles as proposed in [10].

To perform and analyze self-organized behaviors with this new experimental device, we consider as case-study: the foraging problem (collective exploration and transport of resources). Foraging has been studied with simulated models but rarely with real robots. In particular, we re-examine the model proposed by Drogoul&Ferber in [1] as it envisages a deployment with robots and presents emergent behaviors. Foraging is also examined to study path emergence and path following, when paths are continuous trails of digital pheromones built by robots.

The paper is organized as follows. Section 2 presents the experimental device, called “Interactive surface for robots”. In section 3 we revisit the foraging model proposed by Drogoul & Ferber [1] in the perspective of a robotics implementation and some evolutions. Then in Section 4 we present and analyze some experiments with robots and discuss the robustness of the self-organized behaviors reached by the system. We conclude the paper in Section 5 by summarizing the possibility of this new experimental device and how we envision its exploitation for future experiments.

## II. INTERACTIVE SURFACE FOR ROBOTS

### A. Existing approaches

Few studies have been conducted where robots drop and perceive pheromone-like information directly in the environment. We can mention the experimental devices of T. Kazama [11] and G. Theraulaz [12] using image projection over the robots. In such approaches, robots let their trace through their tracking by a CCD camera over the system. A video projector projects an image standing for a potential field (pheromone for example) which can be perceived by light sensors situated on top of the robots. However, let us note, that this reading can be disturbed by the natural ambient light and shadow phenomena. At the opposite, Svennebring and Koenig equipped robots with a black pen to mark trails on the floor, leading to validate a covering ant-algorithm [13], but not providing active processes such as pheromone evaporation or diffusion.

Our idea consists in getting the best of these two approaches, which can be summarized as writing and reading information on the floor while being displayed underneath it.

### B. A new experimental device

*The environment:* It is composed of a table with a transparent surface (220cm x 160cm). Under the table there are two projectors for graphical display and two infrared cameras to track robots' movements or active markers on the surface. Fig. 1 shows a general view of the table.

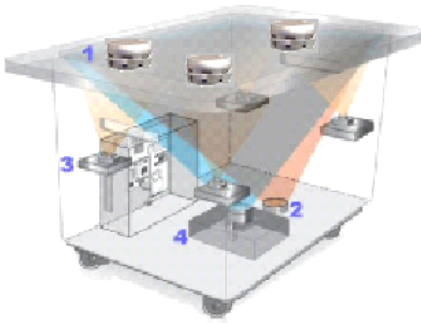


Figure 1. Principle of the Interactive Table

*The Robots:* We use Kheperas III autonomous mobile robots from the K-Team Corporation (cf. figure 2). To allow their interaction with the table we developed and embedded an electronic board for perception. Each robot is provided with the following abilities :

- Colors reading in 7 points by using colorimetric sensors, located under the robot frame, in the front. Fig. 3 shows the location of these points, they are located on a virtual grid of 2cm side. Each sensor allows to measure the values of the primary colours and the luminous intensity  $(r, g, b, i)$ .



Figure 2. Khepera III robot

- Emission of infrared signals by 3 emitters allowing the table to track the robots position and orientation (emitters form a triangle, see red points in fig. 3).
- Each robot has a WIFI card for communication and proximity sensors to avoid obstacles.

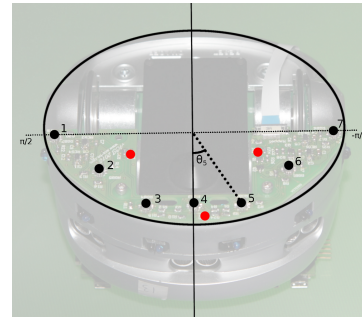


Figure 3. Embedded board on Khepera III : 7 colorimetric sensors (black points) and 3 IR emitters (red points) on the frame of the robots

This system allows the robots to write directly in their environment, i.e. without communication nor localization, thanks to the emission of infrared signals towards a CCD camera under the table. A PC, connected to this camera, can display such a perception on the surface or can compute more complex effects. More generally, the environment's activity is computed in a process which uses graphics card (GPU) abilities.

### C. Behaviors definition

The robots and the environment previously presented allow to define robot's behaviors and active environments as a set of simple rules.

On robots, a reactive behavior can be defined with rules of the form :

$$\wedge (Sensor_i \in Color_j) \rightarrow Action_k$$

where  $Color_j \in R \times G \times B$  with R,G,B into  $[0 - 255]$  and  $Sensor_i$  is one of the seven colorimetric sensors

To define objects in the environment we set :

$$\forall p \in Object_i : Color(p) = Color_i$$

where  $p$  is a position on the surface and  $Color_i$  the color of the  $Object_i$ .

Dynamical evolution of chemical substances is given by:

$$\forall p \in Substance_i : Color(p) = F(neighbourhood(p))$$

$F$  is the evolution function of the current color of the considered position  $p$ . For instance, the evaporation process of a pheromone is computed as :

$$Color(p) = \rho \cdot Color(p)$$

in which  $\rho$  is the evaporation factor.

In order to study the transition from simulated models to real robotic systems, we consider the foraging task as case-study.

### III. RE-EXAMINING FORAGING MODELS

#### A. The Foraging Problem

Foraging is a well-known task in collective intelligence [7]. It is the task for ants to look for food that they transport back to the nest. The problem has been generalized with mobile robots/agents that have to explore an unknown environment to find and transport back some resources [14]. Ants provide an efficient approach to solve this problem [15]. They lay when moving pheromones, which are a chemical marker and a way of communication. Ants accumulate pheromones between food sources and their nest through a positive reinforcement mechanism. The accumulation of pheromone leads to the emergence of trails that other ants can follow and to find out food too. As pheromones are volatile, a trail disappears when the available food is exhausted (evaporation process is the negative reinforcement mechanism [16]).

Several simulation models of ant foraging have been proposed to reproduce and study pheromone trails construction. We remind the reader about the model of the “Dockers”, introduced by Drogoul & Ferber [1], as it is defined in the perspective of a robotic implementation. This is the starting point of our study for a robotics implementation of a pheromone-based foraging.

#### B. Dockers Model



Figure 4. Illustration of Dockers robots (from [17])

The foraging model introduced by Ferber and Drogoul in [1] is called “dockers robots”. Two face-to-face robots can interact and exchange their transported resources while trying to avoid collisions (see illustration Fig. 4). As a

consequence, an interesting self-organized process arises when numerous robots are along a trail, chains of robots emerge. In a chain, robots transfer from one to another their resources, while keeping motionless (blockages, due to spatial competition, are avoided).

Simulated robots also build trails from resources to their base following the ant approach. For this, authors propose to replace the pheromones by attractive “crumbs” which can be put down and picked up. Robots put down two crumbs every step on moving back to the base if resources (called samples) have been found. To emulate the evaporation of pheromones, when robots are following a path, they pick up only one crumb per step (removing trails less quickly than they build them).

The model details the interaction process used to perform the resource transfer. Dockers robots can detect samples carried by others and pick them up. For this, a robot carrying a sample switches on a light. This signal will trigger in close robots the same behavior as a sample detection, i.e. pick-up resources.

The whole algorithm of dockers robots is given in figure 5. In next section we revisit and extend such a model to study its robotics implementation.

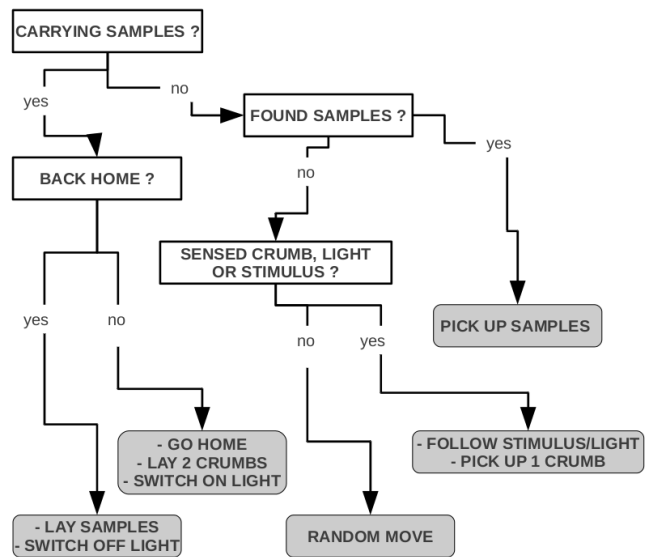


Figure 5. Foraging with Dockers agents (from [1])

### IV. DEFINING FORAGING ROBOTS

In the dockers models [1], robots are supposed to manipulate crumbs to emulate trails of pheromones. In this paper we aim to explore a more bio-inspired approach, i.e. robots able to drop and read a volatile information in the environment. For this purpose, the interactive surface is used to compute dynamic colored fields which are generated and perceived by the robots.

The environment, including resources, is represented by colored shapes on the surface. Even if physical objects can be put on the table, we use in this first study only a graphical representation of them. Anyway, the table can track objects and add a graphical representation/information.

Before examining robots' behaviors we define the environment. Then we details the programming of robots' behaviors which take colored-sensory input and return the appropriate motor action.

#### A. Environment

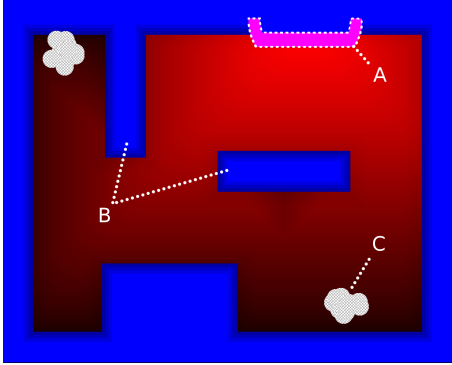


Figure 6. One foraging environment composed of a base (A), obstacles (B) and samples to collect (C). In red the gradient propagated from the base.

1) *Objects*: Figure 6 illustrates one of the environment we defined as follows :

- Robot base : pink shape - Fig. 6(A)
- Obstacles : blue shapes - Fig. 6(B)
- Resources : white pucks - Fig. 6(C)

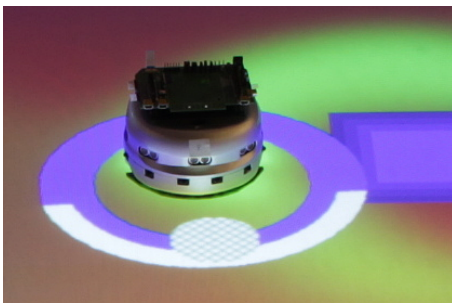


Figure 7. A robot carrying a resource

2) *To be back in the base*: In order to make robots capable to return to the base we suppose it emits a signal. This is translated on the table by displaying a colored gradient continuously descending from the base. This gradient, red-colored (see Fig. 6), propagates from the base (called WaveFront in [18]). By descending the gradient, robots follow a shortest path, avoiding obstacles, until the base.

#### B. Robots' behaviors

1) *Obstacle avoidance*: Obstacles can be sensed by blue color detection. We add a thin blue gradient surrounding each obstacle to obtain a more accurate avoidance. The obstacle avoidance behavior is as simple as fleeing blue color, which is done by descending the blue gradient. Note that robots are also surrounded by a blue disk, in order to avoid robots collisions.

2) *Resource exchange*: Similarly to dockers robots, we allow robots to transfer resources. A carried puck is displayed in front of the robot (see Fig. 7). So another robot can detect a carried resource as any other puck. If this robot is free, and closer to the base, it picks up the puck.

3) *Pheromone deposit and use*: Robots can read and deposit a pheromone, which is expressed by the green color. As green color is a value in  $[0..255]$ , pheromone quantity in a position (of a sensor) is given directly by the perceived green value (note this coding limits to a gradient of 256 values, by mixing with another primary color we go up to  $256^2$ ).

We use this pheromone for two tasks, depending on the perceived quantity. As robots laid small quantities of pheromones when exploring, they try to avoid it to visit un-explored areas. At the opposite, as they mark their path with a high quantity of pheromone when discovering resources, robots follow these high pheromone paths to reach sources. We can abstract this behavior by :

$$\text{deposit} \begin{cases} \text{MaxQ value} & | \text{back home} \\ \text{LowQ value} & | \text{else} \end{cases}$$

$$\text{exploring} \begin{cases} \text{Fleeing green gradient} \\ | \forall i G_i < \text{Phero} \\ \text{Ascending green gradient} \\ | \exists i G_i > \text{Phero} \end{cases}$$

where  $i \in [1..n]$ ,  $G_i$  the green value of sensor  $i$ .  $\text{Phero}$ ,  $\text{LowQ}$  and  $\text{MaxQ}$  are constants :  $0 < \text{LowQ} < \text{MaxQ} \leq 255$  and  $\text{Phero} \in [0..255]$  is close to  $\text{LowQ}$ .

Note that the strategy of exploration based on the descend of a pheromone drop on visited areas is similar to the multi-agent patrolling model proposed in [19].

Pheromones quantities evolve in function of two parameters: the evaporation rate  $\rho$  and the diffusion rate  $\delta$ .

The full behavior of our foraging robots is given by the diagram of the Fig. 8. When compared to the dockers robots, it is useful to highlight some differences. For one, an obstacle avoidance method have been established. For another robots, with the help of using digital pheromones, do not need to lay crumbs, and much less to pick up them.

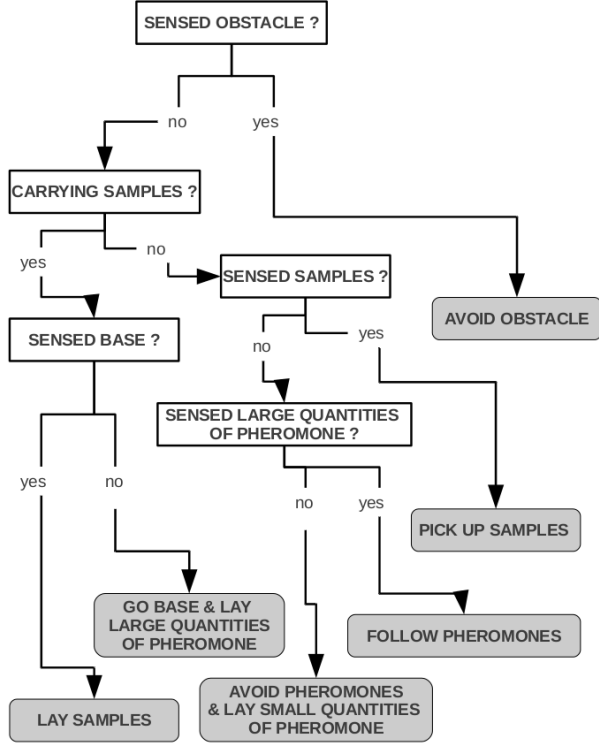


Figure 8. Behavioral diagram of our foraging robots

### C. Robotic implementation

Robot's motion is performed by updating the speed of wheels, which is done as

$$\begin{aligned} sl &\leftarrow SPEED - \Delta \\ sr &\leftarrow SPEED + \Delta \end{aligned}$$

$SPEED$  represents the average speed of the robot.  $\Delta \neq 0$  produces a difference more or less important between the wheels and then makes the robot to turn.

Robots behaviors consist in climbing and descending color gradients. For a specific color  $C$ , the behavior and its programming are :

$$\begin{array}{l|l} \text{If } C \text{ detected} & \exists i \in [1..n] \ C_i > Th \\ \text{Then descend } C \text{ gradient} & j = \operatorname{argmin}_i(C_i) \\ \text{or climb } C \text{ gradient} & \text{or } j = \operatorname{argmax}_i(C_i) \\ & \Delta \leftarrow \theta_j * GAIN_C \end{array}$$

where

$C_i$  are the sensors value of the  $C$  color and  $Th$  is a constant threshold for color  $C$  detection.

$\theta_j$  is the direction (angle) of the  $j^{th}$  sensor to the front direction of the robot, which is multiplied by  $GAIN_C$  constant to compute  $\Delta$ .

This approach is used to avoid obstacles (blue gradients), to return to the base (red gradient), and to follow or to flee pheromones (green gradients) following their quantities (see section IV-B).

We can also define behaviors combining several reactions to different colors. For instance, following pheromone trails while fleeing the base is defined as :

$$\begin{array}{l|l} \text{If detection of a} & \exists i \in [1..n] \\ \text{high level of green} & G_i > Phero \\ \text{Then follow green grad} & j = \operatorname{argmax}_i(G_i - R_i) \\ \text{and avoid the red} & \Delta \leftarrow \theta_j * GAIN_{phero} \end{array}$$

Robots need also to detect the samples and their base, it is basically performed as color detection on the different colorimetric sensors (white for samples, pink for the base).

Experiments have shown the necessity of defining a function  $\Phi$  to denoise the color perceptions. In practical terms, the detected amount of the three primary colors is never nil because sensors are distorted. We also use perceptions of black to quantify the noise during a calibration stage. The function  $\Phi$  is a simple subtraction between the input and this value. The antennal morphology among some insects play a similar role [20].

## V. EXPERIMENTS

To evaluate this foraging model, we conducted experiments using four Khepera III robots on the interactive surface. Thresholds for colors perception and gains for wheels control were empirically tuned.

Evaporation $\rho$	Diffusion $\delta$
0.000015	0.2

Table I  
PHEROMONE PARAMETERS USED ABOVE THE TABLE

Table I gives the evaporation and diffusion rates, applied at frequency 20Hz in the environment.

### A. Observations

This section presents experimental observations. A movie can be seen at [21].

1) *Start*: Robots begin the exploration by dropping small quantities of pheromone (one pheromone deposit covers the disk situated under the robot). Figure 9 illustrates this behavior. The evaporation process builds gradients from recent visited areas to others. As a consequence robots which arrive in an impasse will quickly escape by following the pheromone gradient.

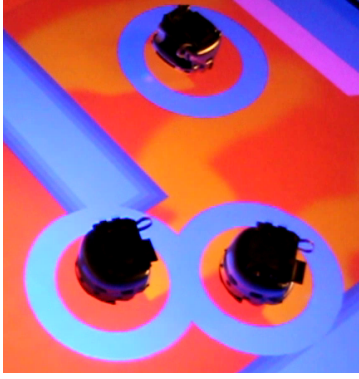


Figure 9. Three foraging robots explore their environment

2) *Emergence of trails and resources transport*: As expected, pheromone trails appear when robots transport resources to the base. When discovering one of these trails, a robot follows it and reinforces it. A robot arriving to the base, drops its sample and switch to exploration state. He detect therefore his own trail and start following it to return to the heap. Figure 10.a illustrates such a process with two robots.

When a heap of pucks becomes empty, robots will stay for a while in the heap area until quantities of pheromone decrease under the threshold  $P_{hero}$ . Then, robots escape this zone to continue exploring the environment.

3) *Emergence of chains*: When several robots are on the same trail, resource exchange naturally splits the transport on several sub-paths. Each robot carries samples on a sub-trail because another robot takes its sample before it arrives at the base. As shown in figure 10, chains emerge when a path between a heap and the base is crowded of robots. In this case, robots almost do not move and samples go from one robot to another until the base.

### B. Collective Behavior Evaluation

To evaluate the global behavior of the system and its robustness (next section), we compute on each robot the percentage of time spent in each of these behaviors : Avoid (obstacles), Explore, Follow (pheromones) and Return (to the base). The X-axis of diagrams is the number of triggered behaviors, and the Y-axis gives the percentage of each one. We calculate  $P_b$  the percentage for the behavior  $b$  as follow:

$$P_b = \frac{\text{card}(\forall e \in \text{Behav} \mid e = b)}{\text{card}(\text{Behav})} \times 100$$

where  $\text{Behav}$  is the set of triggered behaviors since the beginning of the experiment.

Let us now examine a full foraging task realization (all samples of all heaps collected) with four robots in the environment of figure 6. Figure 11 plots the average

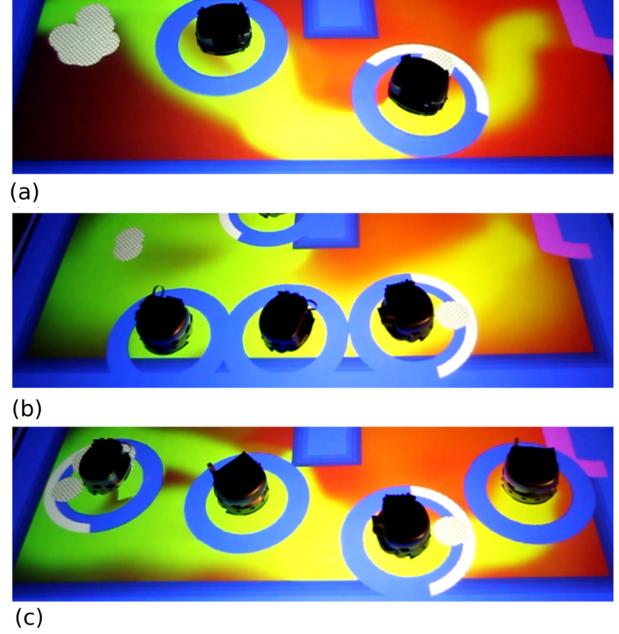


Figure 10. Foraging robots in action - Emergence of chains

percentage of the time spent in each behavior from the four robots, denoted  $\bar{P}$ .

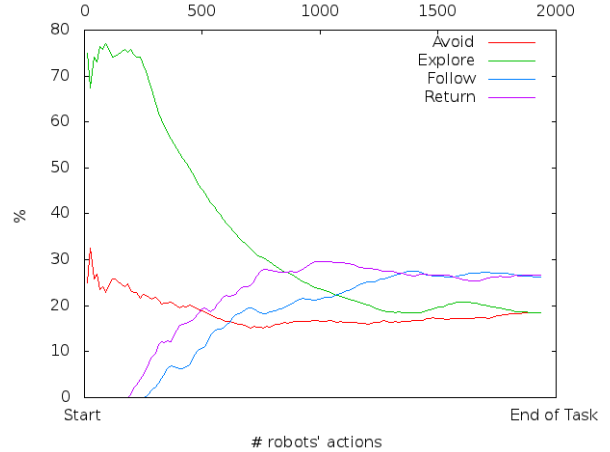


Figure 11. Foraging with four robots - Average percentage of time spent in each behavior

One can see, at first, a strong decrease of  $\bar{P}_{Explore}$ , as soon as robots start to discover resources. As a consequence, we can observe that  $\bar{P}_{Avoid}$  slowly decreases as robots start to build and use trails of pheromones ( $x > 300$ ). Indeed robots do not need to go around each other when carrying resources.

The increase of  $\bar{P}_{Explore}$  at 1300 corresponds to a search of samples as a heap was just exhausted.

More generally, the system progresses to equalize  $\bar{P}_{Return}$

and  $\bar{P}_{Follow}$  values. That reveals the system tends to involve all robots in resource transports, while resource exchange allows to balance the average time spent on returning to the base with following a trail.

### C. Study of Robustness

In order to evaluate the robustness of this robotic model, we examine how the whole system behavior changes when we reduce the robots perception. For a better readability we consider experiments with only one robot.

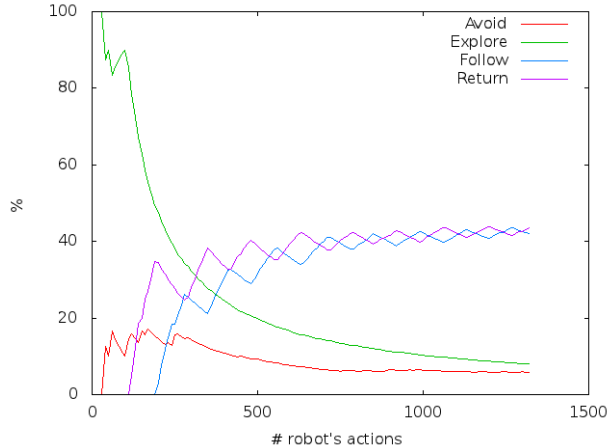


Figure 12. Foraging with one robot that uses all colorimetric sensors - Percentage of time spent in each behavior

First of all, we focus on the ideal case of a fully-functional single robot. Its behavioral progress is shown in Fig. 12. This experiment is used as a reference afterwards. In the considered experiments, we stop the measures before the first discovered heap becomes empty.

One can see there is a logic phase-opposition oscillation between  $P_{Return}$  and  $P_{Follow}$  explained by the round-trips between an heap and the base.

Concerning  $P_{Avoid}$ , its curve is similar in shape to  $P_{Explore}$ . That can be easily explained by a best indirect-knowledge of the environment obtained thanks to the pheromone trails.

In order to test the robustness of this model, we switch off some colorimetric sensors of the robot. Then we observe the resulting behavior and study the time spent in each of its activities.

The experimental results show us that the robot continues to solve the task with one or more inactive sensors if there is at least one activate sensor on each side of the robot. Of course, the more we activate sensors, the more robot's movements are accurate.

By using only the two sensors situated on the extrema positions (Fig. 3 : sensors 1 and 7), the robot moves with a lot of oscillations and consequently have difficulties to follow trails. It is visible on Fig. 13, the curve of  $P_{Follow}$

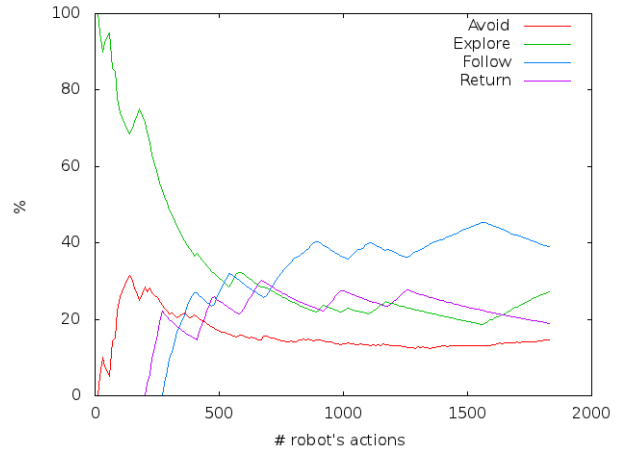


Figure 13. Foraging with one robot that uses only two colorimetric sensors - Percentage of time spent in each behavior

becomes higher than others behaviors. Furthermore, the robot sometimes lost the trail, explaining that  $P_{Explore}$  can increase for a while.

## VI. CONCLUSION

This paper introduces a new experimental device designed to study bio-inspired self-organization paradigms as stigmergy. The proposed interactive surface provides an active environment, which implements and displays dynamic information and which allows robots to interact with. We presented and formalized a set of reactive behaviors based on the local marking and reading of color information in the environment.

We have shown, through the implementation of foraging robots, that pheromones-like substances can be deposit and read by robots as ants done in nature. Thus we implemented and evaluated the simulated model, proposed by [1], of the dockers robots. Our robotics implementation replaced the deposit and pick up of physical crumbs by pheromone trails. We shown that such a continuous information allows the emergence of global behaviors such as path construction and chains of robots transferring resources towards the base.

We extended the model by introducing an exploration behavior based on the descent of low level of pheromones while ascending high levels to follow trails. We also re-examined other behaviors through color marking and sensing, such as obstacle avoidance and signals diffusion to return to the base. Finally, we shown that these robots behaviors were robust to the reduction of robot's perceptions.

## ACKNOWLEDGMENT

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