Collective emergent robotics: Towards a design methodology

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Abstract. Building collective behaviors from local individual interactions is one of the most challenging problems in robotics control. An emergence approach is necessary as long as we want to synthesize collective systems producing at the collective (macro)-level more than the sum of the micro-level individual capabilities or exhibiting new behaviors and structures. This work aims to set some basic concepts in the design of emergent collective systems and to introduce the methodology *Cirta* leading this process of design. The construction of this methodology is based on the idea of overlapping micro-dynamics that could be grasped by a designer when considering an interplay of structure, environment and organization. In particular, collective behaviors are mapped into invariant and spatio-temporal patterns of interactions between the robots and their local environment.

The methodology *Cirta* consists (1) in analyzing a collective phenomenon (task) to deduce collective actions to be held by the robots' group, (2) in specifying the conditions under which the desired macro-level behavior is realized by micro-level interactions, and formalizing patterns of interactions yielding the collective actions, (3) in instanciating the generic conditions in concrete interactions and (4) in evaluating the probabilities of occurrences of the supposed behaviors, using a stochastic model by Markov's chains. The different stages of *Cirta* are illustrated with a collective foraging behavior, where we prove, under well established conditions, the emergence of new structures embodied in chains' formation of robots connecting the nest to a food source.

keywords: Emergence, Collective robotics systems, Design methodology, Adaptive behaviors.

1 Introduction

How to build complex and adaptive behaviors in collective artificial systems ? Nature seems to have solved similar problems by emergence of global and collective behaviors. So simple insects like ants, termites or flies become the ideal metaphors in designing intelligent and autonomous systems. The joint strength of several miniature robots can handle the lack of robustness and flexibility encountered with a single sophisticated machine. But which rules are governing these behaviors? Facing the complexity and misunderstanding of emergent phenomena, it seems natural to call for bottom-up approaches [14, 5, 21]. Based on intuition and experiments, they proceed by endowing the robots with a set of simple behaviors and according to what happens in the real world, they fit the behaviors to obtain a desired task. These approaches apply to small groups of robots and do not bring any lighting on the process of design of collective systems. Some works [19, 7, 20, 1] are inspired from observation of natural social insects or birds and try to reproduce a part of their patterns of organization in simulation and sometimes in experimental environments.

Few top-down attempts exist in robotics systems like [3] proposes a methodological framework (*Cassiopee*) using role assignment to implement soccer behaviors on simulated robots. It is generally admitted that there is no obvious way to derive individual properties from global behaviors, nor to ensure coherent and efficient collective behaviors from individual ones. Given individual properties, some authors like Kelly [8], Parunak [17] and Holland [6] propose a set of principles that a collective multi-agent system must match to exhibit interesting emergent behaviors. Ferber [4] proposes the effectiveness in working in groups and the existence of conflicts' resolution mechanisms as minimal criteria in the evaluation of groups' performance. Balch [2] also adopts a diversity metric to evaluate collective robots' performance inspired by the concept of Shannon's information entropy.

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It is therefore not surprising that there are relatively few attempts in the design methodologies if we realize that the main problem is to understand the mechanisms underlying collective phenomena. In this paper, we point out two major difficulties that should be taken into account in the design process:

- Overlapping and layering multi-levels of dynamics,
- Misunderstanding of emergent phenomena;

and give elements of response when building a methodological framework to handle the design of emergent collective behaviors in robotics colonies.

In the first part of the paper (section 2), we define the process of emergence and introduce some fundamental concepts on which the methodology *Cirta* is based. The second part (section 3) focuses on the construction of the collective system design methodology (*Cirta*) to establish a connection between individual behaviors of robots and collective ones. This methodology, illustrated in this paper with a collective foraging behavior, entails four stages and tries to give answers to the following questions: How to design and specify the individual skills and their interactions (the micro level), giving a desired collective behavior? And how to evaluate the performance of the global macro system, giving the micro world of its constituents?

2 Fundamental concepts and the *Cirta* methodological approach

To build our design methodology, we firstly introduce basic definitions and relevant concepts on which our emergence approach is based.

2.1 Emergence definition

Emergent phenomena are generally qualified as "side effects" behaviors. Consequently, they are not defined or with unusable concepts like unpredictability. We propose an operational definition of emergence inspired by Bunge, Forrest and Lenay ([13, 16]) works. We suppose:

- We have a set of interacting entities that can be expressed in a *micro level theory (submitted to local and fast dynamics)*;
- The interaction dynamics produces a global phenomenon that could be a regularity, a stable state or a process *(with global and slow dynamics)*;
- This phenomenon is observed by an external observer or by the system itself, and expressed in a *macro level theory.*

The observation condition requires a trace of the phenomenon (which is globally produced and the only concrete and observable element) and an interpretation of this trace as describing coherent behavioral structures or functionalities. The interactions of these traces (e.g. pheromone traces) with the system (e.g. the ants colony) could produce new structures (e.g. pheromone paths). If the produced phenomenon is stabilized, it becomes a structural emergence (traces and paths) and a dynamic emergence (process of stabilization) (see [16] and [12] for more detailed account of emergence).

2.2 Basic concepts of the *Cirta* design methodology

The main problem resides in defining the right level of description of collective behaviors in order to understand or derive them from individual behaviors and conversely. In fact, these different levels correspond to different scales of sizes concerning *space* and *time*. The micro level elements are very *limited in space* and exerts *high speed dynamics* on their local environment. The macro level however results from a dynamic composition and stabilization of the micro-dynamics, covers *larger spaces* and possesses *slower dynamics*. So each level is bordered by the velocity of its dynamics and the space of influence of the latter.

A consequence of this idea is that emergent phenomena are *recursive* ones that could be overlapped (in a spiral-like way) as we change scales of sizes. Therefore, collective behaviors of groups result from the micro-dynamics of individual behaviors of robots, that in turn, result from the micro-dynamics of elementary sensory-motor behaviors, and so on. In this study, we consider the process of emergence occurring through two cycles:

- first connecting collective behaviors of the group (*macro level*) to individual behaviors of robots (*micro level*);
- and second, deriving sensory-motor loops (*β-micro level*) of robots from their individual behaviors (*β-macro level*). Note that in our study, the *β-micro level* contains the only concrete and implementable elements of the system.

The methodological framework *Cirta* covers the problem of transition and connects the different levels.

An other consequence is that we clearly distinguish between two domains of existence of a robotics system: The domain of its internal and structural dynamics (which describes the interaction capabilities in terms of stimulus-response (or sensory-motor) loops corresponding to the micro level); and the domain of behavior where the system arises as a totality in recursive interactions because it results from its encounters with the medium. In the latter, an observer or the designer observes and interprets the environment in terms of coherent structures corresponding to the macro level. Maturana [18] states that it is only the observer that conserves a double look by attending simultaneously, or in succession, to the structural dynamics of the system and to its relation as a whole, who can speak of a generative relation between the processes of the structural dynamics of the system and the phenomena of its domain of behavior.

From Maturana's point of view [15], the observer that sees both a system and its medium, sees that the system slides in the medium through its continuous structural changes following a path in which it conserves its living organization (autopoiesis) and its dynamic structural congruence with the medium (adaptation), or it disintegrates. We extend this postulate to collective systems and suggest that the designer should keep a *triple* look by attending simultaneously, or in succession, to the structural dynamics of the system elements *(structure)*, to its relations as a whole *(organization)* and to the *environment* in order to create dynamic correlations and reciprocal generative relations between the processes of the micro dynamics and the macro one. Figure 1 shows a pyramidal model that includes these perpetual changing points $< Structure, Environment, Organization >$.

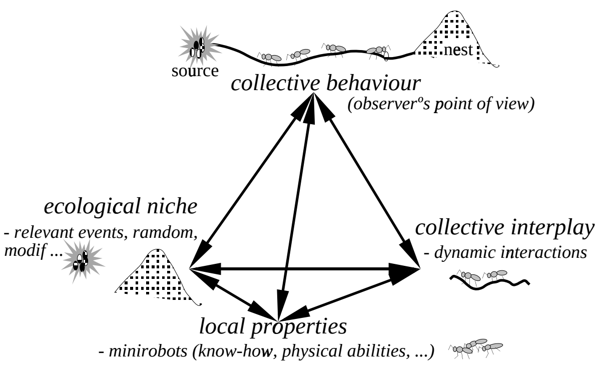

Fig. 1. Different contributions to a phenomenon emergence: *Structure, Ecological niche and Organization*

As defined by Maturana [9], *Structure* refers to the actual components and the actual relations that realize a particular composite unity. It fully determines its interactions by specifying the variety of interactions it can undertake (what it will accept as an interaction and! what will be ignored). *Organization* refers to the manner of composition that defines the unity. The configuration of relations and interactions of the system should be systematically conserved through the same system's interactions in the medium, in a process that Maturana [15] qualified as spontaneous organization. All systems (space, objects, other robots ...) that interact with a particular robot (or group of robots) constitute its *Environment*. It has a structural dynamics independent of the structural dynamics of the systems that it contains, although it is modulated through its encounters with them. So, the organization sought after in this study appears as a particular dynamic configuration *(homeostatic equilibrium)* of structural changes occurring in the micro world and that is conserved through the system's interactions with its medium.

3 The different stages of the *Cirta* methodology

Giving the previous statements, the *Cirta* methodology is organized in the following stages:

1. A *preliminary stage* analyzes the global phenomenon (collective task) to deduce collective actions to be performed by the collective system *(macro level)*;
2. A *specification stage* where collective actions are linked to (invariant) spatio-temporal patterns of interactions. It leads to derive the robots and the environment properties *(micro level)*;
3. An *instanciation stage* where the elementary stimuli and responses of the robots, the physical environment properties and associated patterns of perception *(β-micro level)* are concretely specified;
4. An *evaluation and validation stage* where the conditions of occurrence of the supposed global behaviors are validated using a stochastic model by Markov's chains.

Through the two first stages we apply a *first cycle* of the emergence process to connect the macro organization to generic micro (robots and environment) properties. The third stage constrains the generic properties and then applies the *second cycle* of the emergence process to yield the β-micro dynamics (elementary sensory-motor loops). The last stage goes up these overlapping cycles to ensure the effectiveness of the process of emergence and so, the observation of the supposed collective behavior.

In the following sections, *Cirta* is illustrated using a simplified example of collective foraging behavior. The ecological niche of the robots contains a nest and potential food sources (Fig. 2). The robots' group has to explore the environment and to exploit food sources. We suppose the robots have limited physical abilities and are endowed with an adaptive behavior-based architecture [12]. The latter is based on a set of sensory-motor loops and an adaptive module that reacts to sensory inputs, defines the sign-stimuli[2] and computes a motivation field to select local behaviors. In this way, the behavior of a robot is emergent from its local interactions according to its past experiments and encounters with the medium.

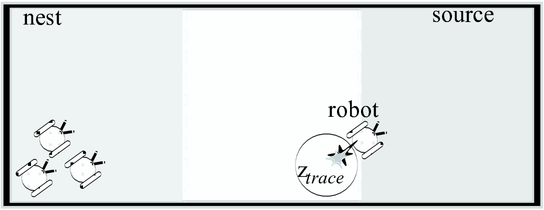

Fig. 2. Schema of the ecological niche

3.1 The preliminary step: Analyzing collective behaviors

The preliminary step aims to analyze global actions needed to emerge the global collective phenomenon. The latter results from a macro organization of the system's entities (robots, environment's objects ...). The idea is then to map the collective organization into sub-macro organizational states (attractors) where each state will correspond to a collective action. The latter (e.g. identification or localization of objects) is considered as an attractor of the system and at this step, we only specify the attractors needed to achieve the macro organization and so the global behavior. This analysis could rely on a functional decomposition or a systemic one in terms of components and is deduced from a rough definition of the collective phenomenon and the ecological niche. In our case study, from the global foraging behavior, we define two main collective actions: The collective identification and the collective localization of the environment objects.

Under these considerations, the design issue becomes a process that ensures the convergence of the system (the robots' group) to the sub-macro organizational states (local attractors) and articulates the transitions between them by adequately constraining the environment and the robots' behaviors (see Fig. 3). Note that several organizational states may be simultaneously held by the collective system, but will correspond in this case to a division of labor by different groups of robots.

3.2 The specification step: Formalizing organizational patterns

Throughout this step, we aim to describe collective actions as organized spatio-temporal patterns of interactions, involving the dynamics of the robots and the environment. We use first order calculus formulas to

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[2] A *sign-stimulus* is a relevant combination or selection of elementary stimuli. Actually, we suppose that only few aspects of the world are relevant for the robot's behavior.

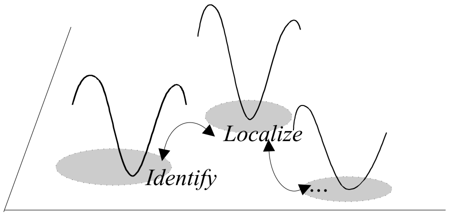

Fig. 3. An example of sub-macro organizational states

formalize the interactions patterns. The choice of formal methods is facilitated by the power of symbolic formalism to cover large variety of interactions schemes. This step will lead to the description of possible patterns leading to the described collective actions.

Before proceeding, we make the following conventions to establish the formalism. We denote by $\mathcal{C}$ the collective system ($\mathcal{C} =< \mathcal{S}, \mathcal{E}, \mathcal{O} >$) including the structure $\mathcal{S}$, the environment $\mathcal{E}$ and the organization $\mathcal{O}$.

The structure $\mathcal{S}$ is composed of potentially heterogeneous groups $\mathcal{G}$ of robots. We assume that the robots abilities are described in terms of stimulus-response pairs, and that each robot is only sensitive to the stimuli for which it has a response. We introduce the predicate $sensitive(mr, s, z(i, e))$ to state that the robot mr is sensitive to the stimulus s in the spatio-temporal zone of influence z (i.e. time interval i and subspace e). In the same way, we express that a robot mr has a response r for the stimulus s by: $response(mr, s, r)$. This predicate does not mean that the robot will necessarily choose the response r in presence of s, but only that this response is available.

To describe the environment's $\mathcal{E}$ properties including the robots ones, we introduce a set of propositions $p_i(c_1, \ldots, c_k)$ where p_i is a property or a relationship and c_i are variables or constants naming among others, the objects and the robots of the environment. We introduce further the predicate $hold(prop, z)$ to state that the proposition $prop$ is true over z; the predicate $produce(prop, s, z)$ to state that $prop$ produces the stimulus s in z. The formula $effect(r, (prop, s), z)$ states that the response r produces a property $prop$ over z or even a direct stimulus s (direct robot-robot interaction). The organization $\mathcal{O}$ is held by the generic patterns of interactions, actions and perception, formalized in the following sections.

Formalizing collective actions As suggested in the preliminary analysis step, to achieve the foraging task, the collective system needs to identify and localize relevant objects of the environment. Collective actions[3] are formalized in terms of robots' interactions and are described by introducing *tasks* and the operator $Can_c T$ to express that the collective system can perform the task T. We consider the term $Identify(obj, z(i, e))$ (resp. $Localize(obj, z(i, e)))$ describing the task of identifying (resp. localizing in a near field) the object obj in the influence field z (within the time interval i and the subspace -e.g. a sphere- of detection e) associated to the object.

We state in most cases (and in particular for the identification and localization abilities) that a collective system can perform a task if and only if at least a group of robots can perform the task:

$$Can_{\mathcal{C}} T \overset{def}{=} \exists\, \mathcal{G} \subseteq \mathcal{C} \;\; s.t. \;\; Can_{\mathcal{G}} T$$

Consequently, the following formalism describes how a group of robots can perform a task. A group of robots identifies the object in any time interval and subspace where the object's identifying property can be perceived by mean of a stimulus:

$$\begin{aligned} Can_{\mathcal{G} \subseteq \mathcal{C}}\, Identify(obj, z) \overset{def}{=} \; & \exists\, (p, s)\, s.t. \;\; characterize(p, obj, z_i) \\ & \wedge\, perceive((\mathcal{C}, \mathcal{G}), (p, s), z_p) \;\wedge\; z_p \subseteq (z \subseteq z_i) \end{aligned}$$

In addition to the ability of identifying the object, the robots' group should be in its neighborhood and so should have a notion of proximity to localize the object. We must have a stimulus s related to the proximity relation $p(\mathcal{G}, obj)$. For example, p can be expressed as a distance relationship ($\forall mr \in$

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[3] More complete formalism for others actions could be found in [10] and [12].

$\mathcal{G}$, $w.h.\ distance(mr, obj) < \delta$):

$$\begin{aligned} Can_{\mathcal{G}\subseteq\mathcal{C}}\, Localize(obj, z) \overset{def}{=}\ & Can_{\mathcal{G}\subseteq\mathcal{C}}\, Identify(obj, z) \\ & \wedge \exists\ (p, s)\ s.t.\ characterize(p, (\mathcal{G}, obj), z_i) \\ & \wedge\ perceive((\mathcal{C}, \mathcal{G}), (p, s), z_p)\ \wedge\ z_p \subseteq (z \subseteq z_i) \end{aligned}$$

The $characterize(p, obj, z_p)$ conditions ensure the properties to be locally non ambiguous. We shall now make explicit the perception of the environment properties and conditions by groups of robots.

Formalizing perception of an environment condition In this section, we establish and formalize the connection between the collective actions and the interactions patterns, achieved through the predicate *perceive* of perception of environment's properties and conditions. The construction of this predicate is based on the idea of analyzing the different schemes involved in the perception of an environment's condition *prop* by a group of robots $\mathcal{G}$ and by mean of a stimulus s. This perception could be achieved by:

1. Detecting a stimulus that is directly tied to the property (e.g. by seeing directly a food source) or,
2. an effect of a response to another stimulus produced by the same property (e.g. when the robots detect a pheromone trail that leads to the source, in which case s' is the perception of the trail) or,
3. an effect of a response to anything which happens to produce this stimulus if and only if this property holds (e.g. following an obstacle as a response to a proximity stimulus can compute a curvature which is an internal stimulus linked to an object category),
4. it can further be produced when different teams of robots reacting to different aspects of the property *prop*, create collectively a state of the world that leads to the presence of the stimulus s which is detected by the specific group of robots.

$$\begin{aligned} perceive((\mathcal{C}, \mathcal{G}), (p, s), z) \overset{def}{=}\ & \forall\ mr \in \mathcal{G}, sensitive(mr, s, z_{mr})\ \wedge\ z_{mr} \subseteq z & (1) \\ & \vee\ \exists\ \mathcal{G}' \subseteq \mathcal{C}, (p', s')\ \ s.t.\ \ (p \rightarrow p') \\ & \quad \wedge\ perceive((\mathcal{C}, \mathcal{G}'), (p, s), z_p)\ \wedge\ influence((\mathcal{C}, \mathcal{G}'), (p', s'), z_i) \\ & \quad \wedge\ \forall\ mr \in \mathcal{G}, sensitive(mr, s', z_{mr}) \wedge z_{mr} \subseteq (z \subseteq z_i) & (2) \\ & \vee\ \exists\ \mathcal{G}' \subseteq \mathcal{C}, (p', s')\ \ s.t. \\ & \quad perceive((\mathcal{C}, \mathcal{G}'), (p', s'), z_p)\ \wedge\ hold(p) \rightarrow influence((\mathcal{C}, \mathcal{G}'), (p, s), z_i) \\ & \quad \wedge\ \forall\ mr \in \mathcal{G}, sensitive(mr, s, z_{mr}) \wedge z_{mr} \subseteq (z \subseteq z_i) & (3) \\ & \vee\ \exists\ \mathcal{G}_j \subseteq \mathcal{C}, (p_j, s_j), j = 1 \ldots k\ \ s.t.\ \ (\sum_j p_j \rightarrow p) \\ & \quad \wedge\ perceive((\mathcal{C}, \mathcal{G}_j), (p_j, s_j), z_{p_j})\ \wedge\ influence((\mathcal{C}, \mathcal{G}_j), (p'_j, s'_j), z_{i_j}) \\ & \quad \wedge\ produce(\sum_j (p'_j, s'_j), s, z_s) \\ & \quad \wedge\ \forall\ mr \in \mathcal{G}, sensitive(mr, s, z_{mr}) \wedge z_{mr} \subseteq (z \subseteq z_s) & (4) \end{aligned}$$

where the predicate $influence$ is defined by:

$$influence((\mathcal{C}, \mathcal{G}), (p, s), z_i)\ \overset{def}{=}\ \exists\ r,\ \ s.t.\ \forall mr \in \mathcal{G},\ response(mr, r)\ \wedge\ effect(r, (p, s), z_i)$$

Finally, note that the above-mentioned responses can be produced by any robot of the team including the same one and also by any coalition of the robots' team. Perception includes here more dimension than purchasing sensory stimuli. Actually, the recursive definition of the predicate *perceive* allows various patterns of activities in achieving collective actions, and constrains them in order to connect the local attractors and so, to support the system's organization.

3.3 The instanciation step: Instanciating the patterns of interactions

We specify at this stage, how the generic properties could be concretely achieved in our case study at the *β-micro level*. The idea is to select particular stimuli and strategies so to minimize the robots' abilities in terms of physical sensory-motor capacities and primitive behaviors. Technological constraints may also contribute to this selection but are not discussed here.

In our case study, we defined the ecological niche containing food sources, a nest and robots. According to the previous formalism, we suggest that:

- For the *generic identification properties*, we associate to food sources a modulated infrared signal as an identification property distinguishing in a non-ambiguous way a food source. This property is perceived directly by mean of the stimulus S_s or also by seeing a trace (S_{tr}, an infrared signal) produced by an other robot in response to the stimulus S_s or S_{tr}. In the same way, we associate to the nest an other modulated infrared signal that identifies it. This property is perceived directly by mean of the stimulus S_n. Finally, we suggest that there is no need to specifically identify a robot by a congener. The infrared signal emitted by a robot in case of direct or indirect source identification is the only direct robot-robot interaction used in this study.
- For the *generic localization properties*, we suppose that these properties could be confused with the identification ones. In particular, we suppose that a suitable threshold of the infrared signal intensity related to a source determines the sufficient relation proximity of the robot to the food.

Sign-stimuli	*Responses*
S_n	flee from the nest,
$(S_{ex} \wedge \overline{S_{tr}})$	explore the environment,
S_{tr}	pursue the trace signal (S_{tr}) and propagate it,
$S_{\overline{tr}}$	try to trace down a lost signal,
$(S_s \wedge \overline{S_{tr}})$	go towards the food source and create a trace.

Fig. 4. Sign-stimuli and potential associated responses for a robot

Furthermore, the perception of a trace (an infrared signal emitted by a robot) has priority over direct exploration or source identification stimuli, which will favor the tracking behaviors. The sign-stimuli that could be perceived by a robot and the corresponding responses are summed up in the table (Fig. 4). It is clear that only the observer can express these descriptions and associations in such a way.

3.4 The effective occurrence step: Validating global behaviors occurrence

The last step of the methodology aims to theoretically execute the emergence process in order to ensure that the selected patterns will be sufficient to cover the relevant space trajectories, leading to the supposed attractors. We use a stochastic model by Markov's chains to study the dynamics of the collective system and the effects of some crucial parameters such as the number of robots and the fields of influence[4] of relevant features (nest, sources ...). This study is based on experimental results on the range of sensors, the efficiency of tracking behaviors ...

Preliminary definitions The environment dynamics being too complex and partially unknown to model, we have decided to model the dynamics of the robot's interactions (essentially of their perception). The relevant percepts are composed from the stimuli and called *sign-stimuli*. The dynamics is then expressed by the percepts dynamic vector $V_{mr}(t)$ supposed to verify a Markov's process (discrete in time and homogeneous[5]):

$$V_{mr}(t) = \mathcal{P}_{mr} \cdot V_{mr}(t-1)$$

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[4] An *influence field* of an object, a property or a stimulus is defined as the spatio-temporal field of interactions involving it.

[5] The transition probabilities are independent of time.

where $\mathcal{P}_{mr}$ is the transition matrix corresponding to the probabilities of transition of sign-stimuli perception and will capture generic features of the environment and the robot strategy. The transition matrix could be written as a graph of transitions, which enables us to use the theory of graphs. In particular, it will be sufficient to verify the strong connectivity and the non periodicity of the graph of transitions to ensure the convergence of the system modelled as a Markov's process. This property will be used here to prove the convergence of the robots behaviors and the collective system.

Under these preliminary considerations, characterizing the evolution of a robot amounts to specify its transition matrix. To do this, we will start from the β-micro level where the stimuli to be perceived by a robot are described. According to these stimuli, we will then analyze the transitions of their perception and specify the corresponding graph of transitions (and from which the transition matrix is directly derived). Finally, we will evaluate the probabilities of transition to characterize the limit observed regularities.

To simplify the probabilities expressions, we assume that the robots are homogeneous, i.e., they initially possess equivalent sensory-motor abilities. Because of the motivation field, they could evolve differently according to their spatial position and sensory-motor past experiments. In the next sections, we will respectively describe the models of the dynamics of the robots and the dynamics of the traces created in the environment.

The model of the robots dynamics In our case study, the percepts dynamic vector $V_{mr}(t)$ stands for the probabilities of perception of each sign-stimulus in the robot's stimuli space. The robot's evolution is then characterized by a set of trajectories in the space of the sign-stimuli[6] perceived by the robot.

$$V_{mr}(t) = \begin{bmatrix} P\left(S_n, t\right) \\ P\left((S_{ex} \wedge \overline{S_{tr}}), t\right) \\ P\left(S_{\overline{tr}}, t\right) \\ P\left(S_{tr}, t\right) \\ P\left((S_s \wedge \overline{S_{tr}}), t\right) \end{bmatrix}$$

In order to specify the transition matrix ($\mathcal{P}_{mr}$), we propose to represent the graph of the possible transitions between the sign-stimuli depending both on the environment and the robot's responses. The resulting graph from a recursive analysis of the perception of the related stimuli is given in figure (5).

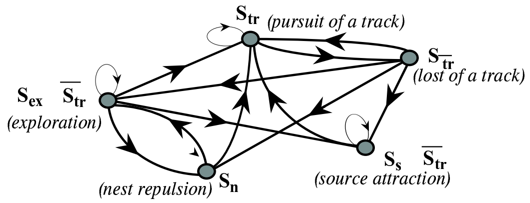

Fig. 5. The graph of perceptible sign-stimuli for a robot. For example, from an initial state of perception of the nest stimulus (S_n), a robot could perceive in the next state the exploration area (S_{ex}), a trace (S_{tr}) leading to a food source, or even the nest (S_n).

From the graph of transitions (Fig. 5), we derive the general form of the matrix $\mathcal{P}_{mr}$ where the signs ($\bullet$) and ($\times$) denote respectively the transition probabilities $P(Ss_i; Ss_i)$ (diagonal elements) and $P(Ss_j; Ss_i)$, $i \neq j$:

$$\mathcal{P}_{mr} = [p_{ij} = P(Ss_j; Ss_i)] = \begin{bmatrix} \bullet & \times & \times & 0 & 0 \\ \times & \bullet & \times & 0 & 0 \\ 0 & 0 & 0 & \times & 0 \\ \times & \times & \times & \bullet & \times \\ 0 & \times & \times & 0 & \bullet \end{bmatrix}$$

Note that the probability of transition $P\left(S_{\overline{tr}}; S_{\overline{tr}}\right)$ vanishes since the lost of a trace is only memorized on one step.

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[6] These sign-stimuli are chosen each other exclusive to allow a stochastic model. To simplify the notations we omit here the exclusive writing. For instance, by S_n we mean $S_n \wedge \overline{S_k}$ with S_k denoting the others sign-stimuli.

We verify the *strong connectivity* and the *non periodicity* of the graph (5) associated to the transition matrix, which ensures the convergence of the robot behavior to a limit vector $V_{mr}(t = \infty)$. In addition and because of these conditions, the Markov's process is regular, i.e. the limit vector is independent of the initial state $V_{mr}(t = 0)$ (and so, of the spatial distribution) of the robot:

$$V_{mr}(t = \infty) = \mathcal{P}_{mr}^{\infty} \cdot V_{mr}(t = 0)$$

To evaluate the transition matrix elements, we study the probabilities of perception of a stimulus as formalized in the section (3.2). These probabilities include geometrical constraints as the overlapping of objects influence fields (nest, source and traces), dynamic effects of responses and design choices as the number of robots and the distribution of sign-stimuli on the robots. A numerical evaluation of the probabilities of transition is then completed by considering the condition of a stochastic matrix[7] on $\mathcal{P}_{mr}$. In our case study schemed by figure (2), the matrix of transition of sign-stimuli perception for each robot mr_i (index i) of the ecological niche is formulated by:

$$\mathcal{P}_{mr_i} = \begin{bmatrix} \frac{1}{2+3\alpha} & \frac{1}{3(1+\alpha)} & \frac{1}{3(1+\alpha)} & 0 & 0 \\ \frac{1}{2+3\alpha} & \frac{1}{3(1+\alpha)} & \frac{1}{3(1+\alpha)} & 0 & 0 \\ 0 & 0 & 0 & \frac{1-\alpha}{1+8\alpha} & 0 \\ \frac{3\alpha}{2+3\alpha} & \frac{\alpha}{1+\alpha} & \frac{\alpha}{1+\alpha} & \frac{9\alpha}{1+8\alpha} & \frac{3\alpha}{1+3\alpha} \\ 0 & \frac{1}{3(1+\alpha)} & \frac{1}{3(1+\alpha)} & 0 & \frac{1}{1+3\alpha} \end{bmatrix}$$

where $\alpha = (M - i)/27$ is a parameter depending on the total number of the robots M and the index i of the robot mr_i entering the chain of traces regardless of its identity. The factors 1/3 and 1/27 are respectively related to the subdivision of space (nest, source, exploration field) in figure (2) and the ratio of the influence field of a trace on the total surface. The limit behavior is then related to the asymptotic behavior of the powers of the transition matrix.

The results The study of the *kth* powers of the transition matrix shows that $\mathcal{P}_{mr_i}^{\infty}$ is stabilized for an order of approximately ($k \approx 10$) for different robots indexes and total numbers of robots. The limit vector corresponding to the limit behavior of the robot $mr_{i=1}$ is illustrated in figure (6) for different values of the total number of robots.

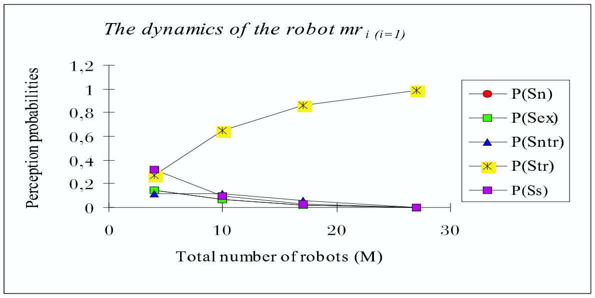

Fig. 6. The limit dynamic state vector of the robot $mr_{i=1}$ versus the total number of robots (M)

This graphic shows that for small total numbers M of robots, the probabilities of perception of a source or a trace are equivalent and dominate the other probabilities. However, where increasing the total number of robots, the probability of direct perception of a source decreases and the probability of perception of a trace is reinforced. Note that the total number of robots is here limited by the available space possibly covered with robots. These results let foretell that the global stable regularity observed at the collective scale is a behavior of formation of robots' chains connecting the nest to food sources. This result will be confirmed when studying the dynamics of the created traces in the environment.

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[7] The sum of each column's elements is equal to 1.

The model of the traces' dynamics In this section, we consider the dynamics of creation and discrete propagation of traces in the environment. A trace is an infrared signal created by a robot when identifying a food source or when perceiving a trace that leads to a source. The dynamics of the traces' evolution is formulated by the dynamic state vector $V_{tr}(t)$ standing for the probabilities of perception of a trace by each robot mr_i of the collective system (M) at the time $t-i+1$.

$$V_{tr}(t) = \ ^{T}[P(mr_i, S_{tr}, t-i+1),\ i = 1 \dots M-1]$$

We prove that this dynamic vector verifies a fixed point equation of the form:

$$[V_{tr}(t)] = [\mathcal{A}] + [\mathcal{B}] \cdot [V_{tr}(t)]$$

where the matrix parameters $\mathcal{A}(mr_i, mr_{i+1}),\ i \leq M-1$ and $\mathcal{B}(mr_i),\ i \leq M-2$ are deduced from the robots dynamics (section 3.4):

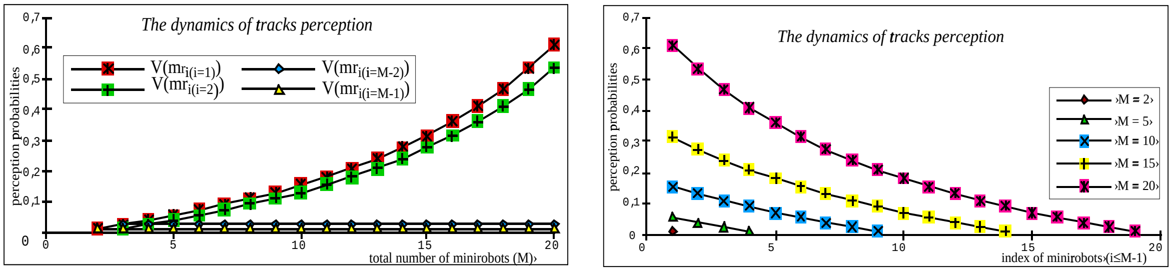
$$\begin{cases} \mathcal{A}(mr_i, mr_{i+1}) = P\left(mr_{i+1}, (S_s \wedge \overline{S_{tr}}), t-i\right) \ \cdot\ Pr\{z_{mr_i} \subseteq z_{trace_{i+1}}\} \\ \mathcal{B}(mr_i) = Pr\{z_{mr_i} \subseteq z_{trace_{i+1}}\} \end{cases}$$

expressing that the robot mr_i is pursuing a trace created by a team mate mr_{i+1} that directly found a food source or pursued an other trace. The boundary condition is given by $P(mr_M, S_{tr}, t-M+1) = 0$ saying that at least one robot mr_M of the collective system has directly seen a food source and not a trace related to the latter, which forbids the formation of cyclic chains of robots. Finally, a recursive resolution of the fixed point equation gives:

$$\begin{cases} V_{tr}(t) = [v_{tr}(mr_i, t-i+1),\ i = 1, \dots M-1] \\ \text{with } v_{tr}(mr_i, t-i+1) = pp_s \cdot pp_{tr}^{M-i} \cdot (M-i)! \ \cdot\ \sum\limits_{k=0}^{M-1-i} \left(\dfrac{1}{pp_{tr}}\right)^k /k! \end{cases}$$

with $pp_s = 1/3$ and $pp_{tr} = 1/27$ describing respectively the probability of perception of a source (given by the robot's dynamics) and the ratio of the influence field z_{trace} of a trace on the total surface.

The results Some components of the traces dynamic vector are represented for the first robots $mr_i, i = M-2, M-1$ and the last ones $mr_j, j = 1, 2$ constituting a chain of traces on the graph (7(a)) versus the total number of the robots present in the ecological niche. Note that these indexes are defined for the modelling needs independently of any potential identities of the robots.



(a) (b)

Fig. 7. Probabilities of a trace perception versus the total number of robots and the index of the robots

The probabilities of perception of a trace by each robot of the collective system (the whole vector components) are represented on the graphic (7(b)) for different values of the total number of robots ($M = 2, 5, 10, 15$ and 20).

These graphics show that the probabilities of a trace perception increase with the number of robots, that in turns create more traces in the environment. However, these probabilities decrease with the index of the robots. The robots with high indices, corresponding to the first elements of the group forming a chain of traces, directly perceive a food source and so have less chance to pursue a trace.

The results also reveal that emergent phenomena have critical mass behaviors. On the graphics, we can observe a stabilization of the global behavior with sufficient probabilities beyond fifteen robots present in the ecological niche. Although the linear stochastic models applied in this validation stage do not consider the possibility of non linear and cyclic chains' formation, they give an appropriate approximation of the regularities and the limit behaviors.

4 Conclusions

Collective robotics do clearly lack for structured design methodologies. In this paper, we have presented the emergence methodology *Cirta* to design and evaluate emergent collective behaviors of robots' groups, where the *micro* world of individual properties and the *macro* world of global and collective structures are naturally articulated. It leads on the one hand to derive the micro world (robots and environment) properties in order to observe a given collective behavior. On the other hand, it leads to an evaluation of the observability conditions of the desired collective behavior.

Cirta relies on a positive definition of emergence and on an analysis of some relevant features of the mechanisms underlying the process of emergence. We suggest that the emergence problematic gets close if we take into account the major role of $< Structure, Environment, Organization >$ and their interactions to stabilize a global and slow dynamics phenomenon from the local and fast dynamics of the micro world. The case study considered in this paper is limited to a simplified example of foraging behavior, but is sufficient to reveal the basic concepts of the *Cirta* methodology. We have shown that the limit regularity observed at the collective scale is a chain formation of robots connecting the nest to food sources. To extend to other collective robotics applications [8], it needs a *rough* definition of the phenomenon to emerge and a *prior* knowledge of some elements of the micro world dynamics. The first analysis step of *Cirta* may then show new collective actions that could be formalized and derived in new properties and conditions, to be perceived and realized by the collective system.

The theoretical results presented in this paper are based on isolated experiments with two robots equipped with a ring of IR sensors and a set of behaviors (wandering, obstacle avoidance, and tracking behaviors). Experiments with large populations of real robots still have to be done [9] and will likely reveal additional properties and mechanisms of interactions in collective systems, and thus contribute to our understanding of how the *micro* and the *macro* dynamics are articulated in the genesis of new emergent structures. Current work aims to deepen our emergence approach and focuses on the emergence of *perception* as a result of the robots activities and interactions with the medium. *Perception* covers different dimensions including large varieties of patterns of interactions in achieving an environment condition. In particular, it does not appear as building any representation in the robot's head; but appears to be the result of the activity of the group which can, by interaction only, make present to one robot, conditions which are distant in space and time.

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[8] See [11] for an other application to a collective object extraction behavior.

[9] At this state of work and due to limited technical means, we could not dispose of large number of robots to make experiments and validate our theoretical models.

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