

EMERGENCE OF COMMUNICATION IN TEAMS OF EMBODIED AND SITUATED AGENTS

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In this paper we will describe the results of an experiment in which an effective communication system arises among a collection of initially non-communicating agents through a self-organization process based on an evolutionary process. Evolved agents communicate by producing and detecting five different signals that affect both their motor and signaling behavior. These signals identify features of the environment and of the agents/agents and agents/environmental relations that are crucial for solving the given problem. The obtained results also indicate that individual and social/communicative behaviors are tightly co-adapted.

1. Introduction

The development of embodied agents able to interact autonomously with the physical world and to communicate on the basis of a self-organizing communication system is a new exciting field of research (Steels and Vogt, 1997; Cangelosi and Parisi, 1998; Steels, 1999; Marocco, Cangelosi and Nolfi, 2003; Quinn et al, 2003; for a review see Kirby, 2002; Steels, 2003; Wagner et al., 2003; Nolfi, in press). The objective is to identify methods of how a population of agents equipped with a sensory-motor system and a cognitive apparatus can develop a grounded communication system and use their communication abilities to solve a given problem. Such communication systems may have similar characteristics to animal communication or human language.

In this paper we will describe the results of an experiment in which an effective communication system arises among a collection of initially non-communicating agents through a self-organization process based on artificial evolution. Unlike other experimental setup in which the interaction between agents or the motor behavior of agents is pre-determined and fixed (e.g. Steels, 1999; Marocco, Cangelosi, and Nolfi, 2003) evolving agents have to autonomously determine: (a) their individual behavior (i.e. how they behave on the basis of their sensory information when signals produced by other agents cannot be detected), (b) their communicative behavior (i.e. when and how many signals are produced, the context in which signals are produced, the type and

number of signals produced, the effect of signals detected on the individual motor and signaling behavior, the modalities with which agents communicate).

2. Experimental set-up

A team of four simulated robots that “live” in the same environment (i.e. a white arena of 270x270cm surrounded by white walls containing two grey target areas, Figure 1, left) are evolved for the ability to solve a collective navigation problem. Robots are provided with simple sensory-motor capabilities that allow them to move, produce signals with varying intensities, and to gather information from their physical and social environment (including signals produced by other agents). The control system of the robots is an artificial neural network.

The robots have a circular body with a radius of 11 cm and the robots’ neural controllers consist of neural networks with 14 sensory neurons (that encode the activation states of the 8 infrared sensors that allow the robots to detect obstacles, 1 ground sensor that allow robots to detect the color of the floor, 4 communicative sensors that allow robots to detect the signals emitted by nearby robots, and 1 sensor that encode the activation state of the communication actuator at times $t-1$, i.e. each robot can hear its own emitted signal at the previous time step) directly connected to the three motor neurons that control the desired speed of the two wheels and the intensity of the communication signal produced by the robot. The neural controllers also include two hidden neurons that receive connection from the sensory neurons and from themselves and send connections to the motor and communicating neurons (Figure 1, right). The communication sensors can detect signals produced by other robots up to a distance of 100cm from four corresponding directions (i.e. frontal [315°-45°], rear [135°-225°], left [225°-315°], right [45°-135°]).

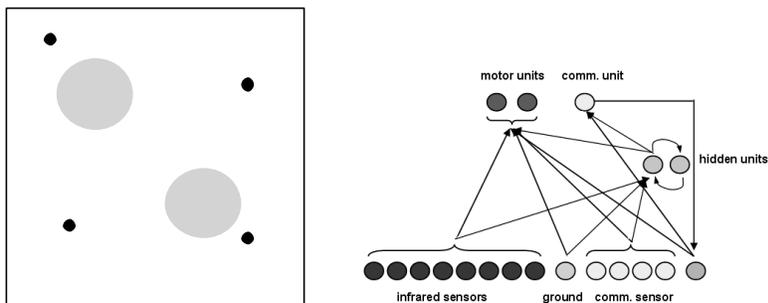


Figure 1. **Left:** The environment and the robots. The square represents the arena surrounded by walls. The two grey circles represent two target areas. The four black circles represent four robots. **Right:** The neural controller evolving robots. Internal neurons and recurrent connections are only included in one of the two experimental setting (see text).

Agents were evolved (Nolfi and Floreano, 2000) for the ability to find and remain in the target areas by subdividing themselves equally between the two areas. In particular, the fitness of the team of robots consists of the sum of 0.25 scores for each robot located in a target area and a score of -1.00 for each extra robot (i.e. each robot exceeding the maximum number of two) located in a target area. The total fitness of a team is computed by summing the fitness gathered by the four robots in each time step. The initial population consisted of 100 randomly generated genotypes that encoded the connection weights of 100 corresponding neural controllers. Each genotype is translated into 4 identical neural controllers that are embodied in the four corresponding robots. The evolutionary process lasted 100 generations. Each generation the 20 best genotypes were allowed to reproduce by generating five copies each, with 2% of their bits replaced with a new randomly selected value.

3. The evolved behaviour

By analyzing the behavior of one of the best team of evolved robots we can see that evolved robots are able to find and remain in the two target areas by equally dividing between the two. In the example shown in left side of the Figure 2, robots 2 and 3 quickly reach two different empty target areas. Later on, robot 1 and then robot 0 approach and enter in the bottom-right target area. As soon as the third robot (i.e. robot 0) enter in the area, robot 1 leaves the bottom-right target area and, after exploring the environment for a while, enters and remains in the top-left target area.

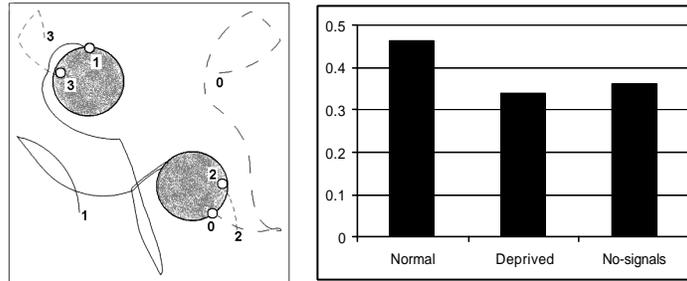


Figure 2. **Left:** The behavior displayed by the team of evolved robots of one of the best replications. The square and the gray circles indicate the arena and the target area respectively. Lines inside the arena indicate the trajectory of the four robots during a trial. The numbers indicate the starting and ending position of the corresponding robot (the ending position is marked with a white circle). **Right:** Average fitness of all teams of the last generations of 10 different replications of the experiment in a *Normal*, *Deprived*, and *No-signals* condition. In all cases, individuals have been tested for 1000 trials.

To determine whether the possibility to signal and to use other robots' signals is exploited by evolving robots we tested the evolved team in three conditions: a "Normal" condition, a "Deprived" condition in which robots evolved in a normal condition were tested in a control condition in which the state of communication sensors was always set to a null value, and a "No-signal" conditions in which robots were evolved and tested with their communication sensors always set to a null value (see Figure 2, right). The fact that performance in the "Normal" condition are better and statistically different ($p < 0.001$) from the other two control conditions indicates that communication plays a role. Performance in the "Deprived" and "No-signals" conditions are not statistically different.

4. The communication system of evolved agents

By analyzing the communication system we observed that evolved agents produce different signals (as we said above, signals consists of single values ranging between $[0,1]$) and react to detected signals by modifying both their motor and signaling behavior.

For example, in one of the best replication of the experiment, evolved agents produce and use five different signals: a signal *A* with an intensity of about 0.42 produced by robots located outside the target areas not interacting with other robots located inside target areas; a signal *B* with an intensity of about 0.85 produced by robots located alone inside a target area; a signal *C*, an oscillatory signal with an average intensity of 0.57, produced by robots located inside a target area that also contains another robot (i.e. when robots detect a

signal produced by a robot also located in a target area); a signal *D* with an almost null intensity produced by robots outside target areas that are approaching a target area and are interacting with another robot located inside the target area; and a signal *E*, an oscillatory signal with an average intensity of 0.33, emitted by robots located outside the target areas interacting with other robots also located outside target areas.

Detected signals affect the robots' motor and signaling behavior as follows: (1) robots located outside the target areas receiving signal *E* modify their motor trajectory so to reduce the time needed to reach a target area, on the average; (2) robots located outside target areas receiving signal *B* modify their motor behavior by approaching the robot emitting the signal (i.e. by approaching the target area in which the robot emitting the signal is located) and their signaling behavior (i.e. by producing signal *D* instead of signal *A*); (3) robots located outside the target areas detecting the signal *C* modify their motor behavior so as to tend to move away from the signal source; (4) robots located inside the target areas detecting the signal *C* modify their motor behavior so to increase their likeness to exit from the target area, (5) robots located outside the target areas detecting the signal *A* modify their signaling behavior by producing signal *E* instead of signal *A*. The functionality of signals have been identified and demonstrated through experimental tests that we do not report in this paper for space reasons.

5. Relation between individual and social/communicative behavior

Since robots individual and social/communicative behavior are allowed to co-evolve we might wonder what the relation between these two forms of behaviors is and how the possibility to co-adapt them is exploited by evolved individuals.

The fact that agents tested in a condition in which signals produced by other agents cannot be detected (Figure 2, right, "Deprived" condition) perform similar to agents evolved and tested in this condition (Figure 2, right, "No-Signal" condition) indicates that evolved agents tend to optimize both their individual and social/communicative behavior. The adaptive pressure toward the development of an effective individual behavior can be explained by considering that signals produced by other agents are not always available since the signals that are produced and detected depends on the current position of the other agents that is partially unpredictable since agents start from randomly initialized positions and orientations.

Indeed, the analysis of the individual behavior (i.e. the behavior of agents that are not allowed to detect other agents signals) exhibited by evolved agents indicates that they are able to solve the navigation problem to a good extent. Indeed, by avoiding walls, by exhibiting curvilinear trajectories when far from walls, and by remaining in the target areas as soon as they enter into one of them, evolved agents are able to find and remain in the two target areas most of the times even in a “Deprived” condition. Figure 3 shows how evolved agents tested in a “Deprived” condition spend about 60% of their lifetime in the conditions in which the team gathers a positive fitness.

Communication is used by evolved agents as an additional mechanism, with respect to their individual capabilities, that allow them to correct mistakes produced by their individual behaviors (e.g. to exit from target area that contains more than two agents) and to improve some of their abilities that are accomplished through their individual behavior (e.g. by reducing the time required to reach target areas, on the average or the ability to directly move toward a target area that contains a single agent by exploiting the signal produced by the agent already located in the target area). These improvements are reflected in the data shown in Figure 3 that, for example, indicates that agents spend much less time in target areas that already contains two or three other robots in a “Normal” rather than in a “Deprived” condition.

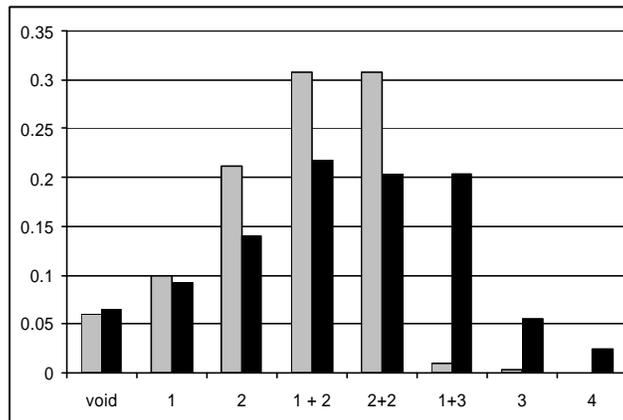


Figure 3. Percentage of lifecycles spent by a team of four agents (of the best evolved team) in the 8 possible different states tested in a “Normal” condition (gray bars) and in a “Deprived” condition in which agents are not allowed to detect other agents’ signals. “Void” indicate the case in which all the four agents are located outside target areas (fitness = 0.0). “1” indicates the case in which only a single agent is located in a target area (fitness = 0.25). “2” indicates the case in which two agents are

located in target areas (fitness = 0.5). "1+2" indicates the case in which one agent is located in a target area and two other agents are located in the other target area (fitness = 0.75). "2+2" indicates the case in which each of the two target area contains two agents (fitness = 1.0). "1+3" the case in which one target area contains one agent and the other three agents (fitness = 0.0). "3" indicates the case in which three agents are located in the same target area (fitness = -0.25). "4" indicates the case in which four agents are located in the same target area (fitness = -1.0). Average performance obtained by testing the agents for 1000 trials lasting 1000 cycles.

6. Discussion

In this paper we described the results of an experiment in which an effective communication system arises among a collection of initially non-communicating agents evolved for the ability to solve a collective navigation problem. With the methodology chosen, we observed that agents developed autonomously (i.e. without human intervention), first of all, an effective individual behavior that allow agents to cope the navigation problems without the collaboration of the other agents allowed by communication.

In addition, agents developed an effective communication system based on five different signals that correspond to crucial features of the environment, of the agents/agents relations, and agents/environmental relations (e.g. the relative location of a target area, the number of agents contained in a target area, etc.). These features, that have been autonomously discovered by the agents and that are grounded in agents' sensory-motor experiences, constitute the 'meanings' of the signals produced and detected by the agents. Used signals, therefore, do not only refer to the characteristics of the physical environment but also to those of the social environment constituted by the other agents and by their current state.

The analysis of the obtained results also indicate that individual and social/communicative behaviors are tightly co-adapted. In fact, since individual behavior in evolved agents are optimized as well as social/communicative behavior, detected signals act as a sort of additional mechanism that enhances individual behavior (when signals are available). On the other hand, individual behavior, in absence of useful signals, guarantees the maximum performance that can be achieved on the basis of the available sensory information.

The individual behavior also creates the basis for the exploitation of signaling capabilities. For example, the individual ability to reach and remain in a target area represents a pre-condition for the emergence of an ability to signal the relative position of a target area and to use that signal appropriately. Similarly the limits of the individual behavior, for instance the tendency to enter into a target area that already contains two other agents, represents a pre-

condition for the development of communication abilities that allow agents to exit from target areas that contains more than two agents.

Interestingly, one can find interesting similarities between the communication systems observed in our experiments and forms of animal communication described in the literature. For instance, signals that refer to agent/environment interactions are similar to alarm calls or food calls in birds and primates that provide information about objects or events that are external to the animal that emits the signal (Hauser, 1996). Moreover, the coordinated oscillatory signals produced by two robots located in the same target area (that allow the robots to keep additional robots away while maintaining the couple of robots in the area) are similar to the synchronized communicative interactions known as vocal duetting produced by several animals. Indeed, as in the case of the robots described in this paper, in some birds duets play an important cooperative function since they allow the members of a couple of animals to defend their territory and/or to keep the pair bond (Langmore, 1998; Slater, 1997).

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