Self-Organization of Communication in Evolving Robots

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Abstract

In this paper we present the results of an experiment in which a collection of simulated robots that are evolved for the ability to solve a collective navigation problem develop a communication system that allow them to better cooperate. The analysis of the obtained results indicates how evolving robots develop a non-trivial communication system and exploit different communication modalities.

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 et al, 2003; Quinn et al, 2003; for a review see Kirby, 2002; Steels, 2003; Wagner et al., 2003; Nolfi, in press). The objective is that 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 in other experimental researches we will not impose a restricted and predefined interaction schema and we will leave robots free to determine the modality with which they will interact. By restricted and predefined interaction schema we means the interaction modality adopted, for example, in Werner and Dyer (1992), in which females and males individuals can only play the role of the speaker and hearer, respectively. Or the interaction modality adopted in Cangelosi and Parisi (1998) and Marocco et al. (2003), in which agents alternatively assume the role of speaker or hearer and in which speakers are allowed to send to hearer robots a signal consisting of a single pattern, after having interacted for a certain amount of time with the same object that will be experienced by the hearer.

Therefore, 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).

Experimental Set-up

A team of four simulated robots that share the same environment (i.e. an arena of 270x270cm containing two target areas, Figure 2) 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 robots have a circular body with a radius of 11 cm. The robots' neural controllers consist of neural networks with 14 sensory neurons (that encode the activation states of the corresponding 8 infrared sensors, 1 ground sensor, 4 communicative sensors, and 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 internal neurons that receive connections from the sensory neurons and from themselves and send connections to the motor and communicating neurons (Figure 1). The communication sensors can detect signals produced by other robots up to a distance of 100cm from four corresponding directions (i.e. frontal [315^o-45^o], rear [135^o-225^o], left [225^o-315^o], right [45^o-135^o]).

The output of motor neurons was computed according to the logistic function (2) while the output of sensory and internal neurons was computed according to function (3) and (4), respectively (for a detailed description of these activation functions and the relation with other related models see Nolfi (2002)).

$$A_j = t_j + \sum_i w_{ij} O_i \quad (1)$$

$$O_j = \frac{1}{1+e^{-Aj}} \quad (2)$$

$$O_j = O_j^{(t-1)}\tau + I_j\left(1-\tau_j\right) \quad (3)$$

$$O_j = O_j^{(t-1)}\tau + \left(1+e^{-A_j}\right)^{-1}\left(1-\tau_j\right) \quad (4)$$

With *Aj* being the activity of the *jth* neuron, *tj* being the bias of the *jth* neuron, *wij* the weight of the incoming connection from the *ith* to the *jth* neuron, *Oi* the output of the *ith* neuron, *Oj(t-1)* being the output of the *jth* neuron at the previous time step, τj the time constant of the *jth* neuron, and *Ij* the intensity of the *jth* sensors.

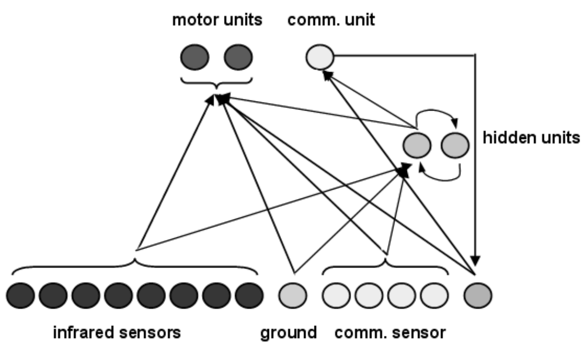

Figure 1. The neural controller of the evolving robots.

Robots 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. The initial population consisted of 100 randomly generated genotypes that encoded the connection weights of 100 corresponding neural controllers (each parameter is encoded with 8 bits and normalized in the range [–5.0, +5.0], in the case of connection weights and biases, and in the range [0.0, 1.0], in the case of time constants). Each genotype is translated into 4 identical neural controllers that are embodied in the four corresponding robots. The 20 best genotypes of each generation were allowed to reproduce by generating five copies each, with 2% of their bits replaced with a new randomly selected value. 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 experiment was replicated 10 times.

The Emergence of Communication

By analyzing the behavior of one of the best replication of the experiment 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 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.

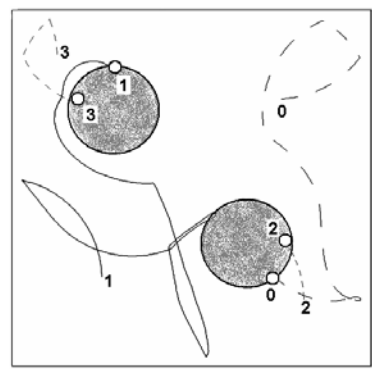

Figure 2. The environment, the robots and the behavior displayed by the team of evolved robots of one of the best replications. The square and the grey circles indicate the arena and the target area respectively. Lines inside the arena indicate the trajectory of the four robots during a trial. The numbers indicate the starting and ending position of the corresponding robot (the ending position is marked with a white circle).

To determine whether the possibility to signal and to use other robots' signals is exploited by evolving robots we tested the evolved teams 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 3). 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. The fact the performance of robots that are tested in the "Deprived" control condition are similar to those of robots evolved and tested in a "No-signal" control condition indicates that evolved robots develop an effective individual behaviour (i.e. a behaviour that maximize the performance that can be achieved without signaling) even if they have always been evaluated in a normal condition (in which signals are available). This fact can be explained by considering that the social enhancement provided by communication is not always guaranteed. Indeed, the availability of the signals is subjected to the presence of other robots in the right environmental locations that, in turn, is influenced by unpredictable variable such us the initial positions and orientations of the robots.

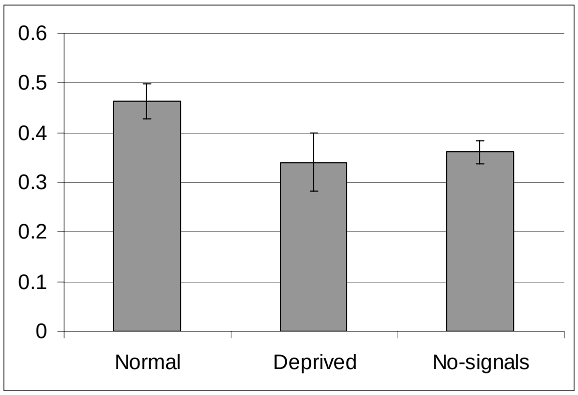

Figure 3. Average fitness of all teams of the last generations of 10 different replications of the experiment. Histograms represent the average fitness obtained by testing the robots in: a *Normal* condition (in the same condition in which they have been evolved), a *Deprived* condition in which robots are not allowed to detect other robots' signals and a *No-signals* condition in which they have been evolved and tested without the possibility to detect other robots' signals. A fitness value of 1.0 cannot be reached in practice since robots have first to locate and reach the two target areas. In all cases, individuals have been tested for 1000 trials. Bars represent standard deviations.

The Communication System

By analyzing the communication system we observed that evolved agents produce different signals and react to detected signals by modifying both their motor and signaling behavior. More precisely, robots of the best replication (the same described in Figure 2) 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 or outside 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; a signal **D** with an almost null intensity (0.07) produced by robots outside target areas that are approaching a target area and are interacting with another robot located inside the target area; 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 behavior to better explore the environment; (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 fact that signal **A** and **E** produced by robots located outside target areas allow them to explore the environment more effectively (i.e. to more quickly find the target areas) is demonstrated by the fact that the average time in which the first robot enter in one of the two target areas is 5.922s and 6.478s in normal and deprived conditions, respectively. By testing the best teams of the other replications of the experiment similar results were observed in most of the cases (result not shown). Overall, these results indicate that robots exploit their signaling behavior to produce a form of coordinated exploration that increases their ability to quickly find the target areas.

Moreover, to verify the functionality of the other signals, we tested a team consisting of a limited number of robots (2 or 3, depending of the test) placed in an environment including only a single target area in a normal condition and in a control condition in which robots were not allowed to detect signals (i.e. in which the state of the four communication sensors of all robots was always set to a null value). In all cases robots has been tested for 1000 trials lasting 100 seconds each. The results of the tests indicate:

(1) the fact that signal **B** increases the chances that other robots enter in the target area from which the signal is produced is demonstrated by the fact that the percentage of trials in which a robot randomly placed outside a target area enters in the target area that already contains a single robot is 97.2% and 75.4% in the case of robot tested in normal and control conditions, respectively;

(2) two interacting robots located in the same target area reciprocally modulate their signaling behavior so to produce signal **C** (i.e. a highly varying signal with an average intensity of 0.57). The fact that signal **C** reduces the chances that other robots enter into a target area that already contains two robots is demonstrated by the fact that the percentage of times in which a third robot randomly placed outside the target area joints the other two robots in

the same area is 2.3% and 82.6% in normal and control conditions, respectively;

(3) the fact that signal **C** increases the chances that a robot exits from a target area that contains more than two robots is demonstrated by the fact that the percentage of times in which one of three robots located in the same target area exit the area is 84.6% and 2.7% in normal and control conditions, respectively. The functionality of signal **D** and more generally the functionality of the effect that detected signals have on produced signals will be discussed in the next section.

Communication Modalities

Evolving robots might rely on mono or bi-directional communication forms. In mono-directional communication forms, the motor behavior or the signal produced by one individual affects the behavior of a second individual but the behavior of the latter individual does not alter the behavior of the former. In these forms of communication, the two robots play the role of the 'speaker' and of the 'hearer', respectively, and communication can be described as a form of information exchange (in which the 'hearer' may have access to information that is available to the 'speaker' but not to the 'hearer' by itself) or as a form of 'manipulation' (in which the 'speaker' alters the behavior of the 'hearer' in a way that is useful to the 'speaker' or both to the 'speaker' and the 'hearer'). In bi-directional communication forms instead, the motor or signaling behavior of one individual affects the second individual and vice versa. In these forms of communication each robot plays both the role of the 'speaker' and of the 'hearer' (i.e. different roles cannot be identified).

Another important aspect that characterize communication forms is whether they consists of static or dynamical processes. In static communication forms, the signal produced by an individual is only a function of the current state of the individual. In dynamic communication forms, instead, the signal produced at a given time step is also a function of the signals produced and detected previously. As an example of a static communication form we might consider the case of a robot emitting an alarm signal continuously (until the robot perceive a dangerous situation). As an example of a dynamic communication form we might consider the case of two individuals that alternatively play the role of the speaker and of the hearer by taking turns (Iizuka and Ikegami, 2002, 2003). Bi-directional and dynamical communication forms might lead to emergent properties (e.g. synchronization or shared attention) that result from the mutual interaction between two or more individuals and that cannot be explained by the sum of the individual contributions only (Di Paolo, 2000).

In the experiment reported in this paper evolved agents use different communication modalities in different circumstances.

To describe the communication modalities used, let us consider a simplified situation in which a team consisting of two robots is placed in an arena that includes only a single target area.

Figure 4 and Figure 5 show the typical motor and signaling behavior exhibited by the robots. Initially the two robots are both outside the target area and both produce a signal with an intensity of about 0.42 (signal **A**). As soon as the two robots get close enough to detect their signals, they produce a signal with a varying intensity and an average intensity of 0.33 (signal **E**) and they vary their motor trajectory by increasing their turning angle. After some time robot #0 reaches the target area and starts to produce a signal with an intensity of about 0.85 (signal **B**). Later on, once robot #1 returns close enough to robot #0 and detects the signal **B** produced by robot #0, it modifies its motor trajectory (by approaching robot #0) and its signaling behavior (by producing signal **D**, i.e. a signal with an almost null intensity, instead of signal **A**). When also robot #1 joints the area, the two robots start to produce a varying signal with an average intensity of about 0.57 (signal **C**) that reduces the probability that other robots will enter in the area and eventually, if an additional robot erroneously joints the area, increases the probability that one of the robot exits from the area.

By analyzing the functionality of the different signals and the context in which they are used, we can see how evolved robots use different communication modalities by selecting the modalities that are appropriate for each specific case.

The situation in which one robot is located inside a target area and a second robot is located outside, within the communication range, is a case in which the former robot has access to an information (related to the location of the target area) to which the second robot does not have access to. In this particular case, communication should be mono-directional, since only the latter robot should change its behavior on the basis of the signal produced by the former and not vice versa. Indeed, in this situation evolved robots rely on a mono-directional communication form in which the former robot produces the signal **B** and the latter robot switches its signaling behavior off by producing the signal **D** (i.e. a signal with an almost null intensity).

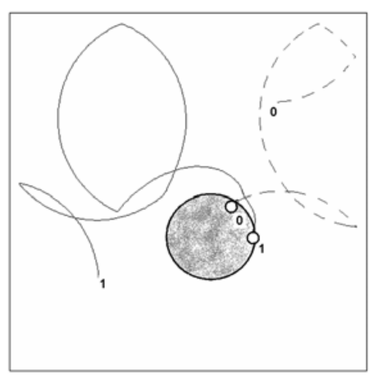

Figure 4. The behaviour of two robots tested in an arena including a single target area. The dashed and full lines represent the trajectory of robot #0 and #1, respectively.

The numbers indicate both the starting and ending positions of the corresponding robots.

This communication interaction thus can be described as an information exchange in which the former robot (the 'speaker') produces a signal that encodes information related to the location of the target area and the latter robot (the 'hearer') exploits this information to navigate toward the area. Or, alternatively, this communication interaction can be described as a form of manipulation in which the former robot (the 'speaker') 'manipulates' the motor behavior of the latter robot (the 'hearer') so to drive the robot toward the target area.

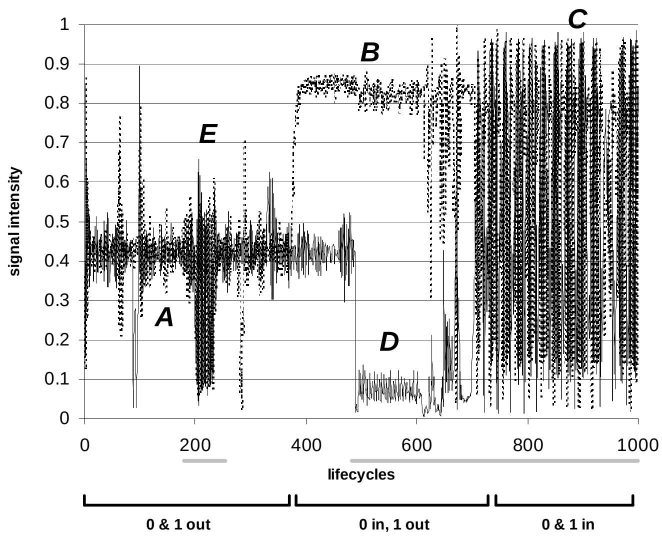

Figure 5. Intensity of the signals produced by the two robots during the behavior shown in Figure 4. Dashed and full lines indicate the intensity of the signals produced by robot #0 and #1, respectively. Letters (A, B, C, D and E) indicate the 5 classes of signals produced by the robots. The black lines in the bottom part of the figure indicate the three phases in which: (1) both robots are out the target area, (2) robot n.0 is in and robot n.1 is out, and (3) both robots are inside the target area. The grey line in the bottom part of the figure indicate the phases in which the two robots are located within the signal range. Each lifecycle lasts 100ms.

The ability of robots located outside target areas to switch their signaling behavior off (i.e. to produce the signal **D**) as soon as they detect the signal **B** plays an important function. Indeed, by testing a team of two robots, for 1000 trials, in an environment including a single target area in a normal condition and in a control condition in which robots were prevented from the ability to switch between signal **A** and **D**, we observed that the percentage of trials in which both robots were able to reach the target area within 100 seconds drop from 97.2% to 0.12% in the normal and control conditions, respectively.

On the contrary, when two robots are located in the same target area, none of the two robots have access to the relevant information (i.e. the fact that the target area contains two robots). This information, however, can be generated by the interaction between the two robots through a bi-directional communication modality. This is indeed the communication modality that is selected by evolved robots in this circumstance. The signal produced by one of the two robot affects the signal produced by the second robot, and vice versa. This bi-directional interaction allow the two robots to switch from signal **B**, that increases the chances that other robots will joint the area, to signal **C**, that decreases the chances that other robots will joint the area.

Interestingly, in this circumstance evolved robots also rely on a dynamical communication modality, since they produce signals that vary in time as a result of signals previously produced and detected by the two robots. More precisely, the signal **C** tend to vary in time as a result of the following factors: (1) the intensity of the signal detected inhibits the intensity of the signal produced, (2) the intensity of the inhibition also depends on the direction of the detected signal, (3) the signal tend to be detected by always varying relative directions since robots located inside the target area turn on the spots.

In this situation, the production of an oscillatory signal, with an average intensity of 0.57, rather then a stable non-dynamical signal play an important functional role. Indeed, we observed that evolved robots rely on oscillatory signals in all the replications of the experiment. Moreover, we observed that stable signals does not allow to reach the same level of performance. To ascertain whether the production of a stable signal could lead to the same functionally of this oscillatory signal we performed a test in which robots were forced to emit a stable signal when located in a target area that contained two robots. Robots were allowed to behave normally in all other cases. The test was repeated 10 times by using stable signals with 10 different intensities ranging from 0.1 to 1.0. The result of the test confirms that the dynamical nature of the signal is functional, in fact the obtained performances in the test were always lower than the performance obtained by allowing robots to produce the oscillatory signal.

One reason that might explain the necessity to rely on an oscillatory signal in this circumstance is the fact that the signal **C** has at least three different functions: it informs other robot located in the target area of the presence of other signaling robots, it reduces the probability that other robots joint the target area, and it increases the probability that, when the target area contain more than two robots, one of the robot will exit the area. Indeed, by analyzing the behavior of the robots in the test in which robots were forced to produce signals with a fixed intensity we observed that: (a) when the intensity of the signal is below 0.7, robots tend to erroneously exit from the target area also when the area includes only two robots, and (b) when the intensity of the signal is 0.7 or above, robots tend to erroneously enter in the target area also when the area include two or more robots. Another possible reason that might explain the necessity to produce an oscillatory signal is the fact that the signal **C** must produce the same effect (i.e. reduces the chances that other robots enter in the target area) both when the signal is produced by two or three interacting robots located into the same target area, and two different effects (i.e. increases the chances that one robot exit from the target area or not) when the signal is produced by three or two robots located in the same target area, respectively.

Conclusion

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.

By analyzing the obtained results we observed how evolving individuals developed: (a) an effective *communication system*, (b) an effective *individual behavior*, (c) an ability to rely on different *communication modalities* and to autonomously select the modality that is appropriate to the current circumstances.

The communication system that emerges in the experiment is based on 5 different signals that characterize 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 themselves, are grounded in agents' sensory-motor experiences. 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. Evolved individuals also display an ability to appropriately tune their individual and communicative behavior on the basis of the signals detected (e.g. by approaching, avoiding, or exiting a target area, by modifying their exploratory behavior, etc.). Indeed, the type of signals produced, the context in which they are produced, and the effect of signals detected constitute three interdependent aspects of the communication system that co-adapt during the evolutionary process and co-determine the 'meaning' and the efficacy of each signal and of the communication system as a whole.

Evolved robots also exploit different communication modalities (e.g. mono-directional forms in which one robot act as a 'speaker' and a second robot act as a 'hearer' or bi-directional communication forms in which two robots concurrently influence each other through their signaling and/or motor behavior) by selecting the modality that is appropriate to each specific communicative interaction. In some cases evolving individuals also engage in complex communication behaviors that involve three different robots that concurrently affect each other so to produce appropriate collective behaviors (e.g. so to push one of the three robots located inside the same target area out of the area). In some of the cases, evolved robots also exploit time varying signals that allow them to generate information that is not available to any single robot (e.g. information related to how many robot are located into a target area) and that serve different functions. In future work we plan to investigate the evolutionary origins of these communication systems. Moreover we plan to investigate further the role of bi-directional communication forms and the relation between the communication systems emerging in these experiments and natural communication forms. Finally, we plan to replicate these experiments on physical robots.

Acknowledgments

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