Minimal Agency Detection of Embodied Agents

Hiroyuki Iizuka[1,2] and Ezequiel Di Paolo[1]

[1] Centre for Computational Neuroscience and Robotics,
Department of Informatics, University of Sussex
Brighton, BN1 9QH, UK
[2] Department of Media Architecture, Future University-Hakodate
116-2 Kamedanakano-cho, Hakodate, Hokkaido, 041-8655, Japan
ezca@sacral.c.u-tokyo.ac.jp, ezequiel@sussex.ac.uk

Abstract. Agency detection is studied in a simple simulated model with embodied agents. Psychological experiments such as double TV-monitor experiments and perceptual crossing show the central role of dynamic mutuality and contingency in social interactions. This paper explores the ongoing dynamical aspects of minimal agency detection in terms of the mutuality and contingency. It is investigated how the embodied agents can establish a live interaction and discriminate this from interactions from recorded motions that are identical to the live interaction but cannot react contingently. Our results suggest that the recognition of the presence of another's agency need not lie on complex cognitive individual mechanisms able to integrate past information, but rather on the situated ongoingness of the interaction process itself, on its dynamic properties, and its robustness to noise.

1 Introduction

Social interaction may lead to coordinated behaviours when mutual anticipations are formed dynamically. This mutuality of influences is a key property of the interaction process but its dynamical characteristics have not been sufficiently investigated from a theoretical perspective. In contrast, important empirical evidence points to the central role of dynamic mutuality, or contingency, in sustaining and forming several aspects of an ongoing interaction. This is clearly shown in Trevarthen's double TV-monitor experiments with infants [6,9], Nadel's extensions to these experiments [7], and in the perceptual crossing experiments by the GSP group at UTC Compiègne [1]. In Trevarthen's experiment, a mother and her baby are placed in separate rooms and allowed to interact only through video screens that display their faces to each other. During 'live' interaction, mother and infant engage in coordinated utterances and affective expressions. However, if a delayed video recording of the mother is displayed to the baby, the baby becomes withdrawn and depressed. This shows that it is not sufficient for the baby to sustain interaction that the mother's expressive actions be displayed on the monitor, but the mother is required to react 'live' to the baby's own motions in order for the interaction to continue. It can be assumed that

F. Almeida e Costa et al. (Eds.): ECAL 2007, LNAI 4648, pp. 485–494, 2007.

a most important clue during interactions is its ongoingness which has to be shared between the subjects and is therefore a property of the dyadic system.

Auvray et al. [1] have studied social interaction by means of a minimal perceptual crossing paradigm. In their experiments, two blindfolded subjects interact in a virtual one-dimensional space. Each subject moves a receptor field using a computer mouse and can get all-or-nothing tactile sensation when the receptor crosses an object or the other subject's receptor. Subjects are constantly 'followed' by a shadow object that mimics their movement and, from their partner's perspective, is indistinguishable from their receptor. Their task is to find each other without becoming fixated on static objects or on the partner's objectively identical shadow. Subjects can achieve this goal thanks to how mutuality influences the global dynamics of the task since becoming fixated on a shadow that does not respond to one's own movements does not cause one's partner to stop the search and the interaction breaks down. Thus, mutual searching behaviour produces one globally stable dynamical situation when both subjects are directly touching each other.

The common idea in these experiments is that subjects are exposed to behaviours that are identical in motion to a 'live' interaction but do not have a subjective control to respond to the subject's own motions. Human subjects (even infants) easily discriminate the two conditions by engaging in interaction and thus investigating whether a partner has a contingent control of their motion. This dynamical enquiry produces an experience of confronting another subject, *an agency*. This suggests that the presence of another subjectivity is not located anywhere in the quality of the motion themselves but it is rather in the ongoingness of interactions shared between subjects.

The aim of our study is to explore ongoing dynamical aspects of minimal interaction between embodied agents. We investigate how embodied agents can establish a live interaction and discriminate this from interactions with dummy agents, which have the same motions but can not react live. The issue we want to test is *whether such a discrimination requires a complex perceptual strategy on the part of the discriminating agent or whether simpler solutions emerge from the interaction process itself.*

2 Model

Agents are required to discriminate whether another agent is a live interaction partner or a recording of the agent's behaviour by using minimally restricted sensor and motors. The two agents, top and bottom, face each other in an unlimited 1-D space. Each agent can move only left and right horizontally. One on-off sensor is attached on the centre of the agent and it is activated, i.e. set to 1 when it crosses the partner, while it is set to 0 otherwise. With a certain probability the sensory information is flipped into a different state (the probability is set to 0.05) at each Euler time step as sensory noise. The presence of noise will play an important role for agents to achieve the task, as will be explained later. The schematic view is illustrated in Fig. 1.

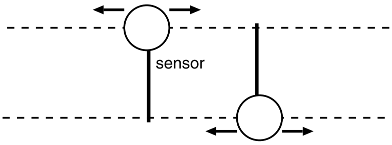

Fig. 1. A schematic view of the simulation settings. Two agents equipped with single on/off sensor are facing each other in a unlimited 1-D space.

The task is for an agent to cross its partner if it is interacting live (contingently) and to stay away from a recorded motion that replays the partner's previous motions as in the double TV-monitor experiments. The behaviours of original and recorded motions are identical but sensory noise is introduced independently.

2.1 Agents

Agents are controlled with a continuous-time recurrent neural network (CTRNN, [2]), which consists of fully-connected 8 nodes in our model. The time evolution of the states of neurons is expressed by:

$$\tau_i \dot{y_i} = -y_i + \sum_{j=1}^{N} w_{ji} z_j(y_j) + I_i, \quad z_i(x) = 1/(1 + e^{-x-b_i}), \tag{1}$$

where y_i represents the cell potential of neuron i, z_i is the firing rate, τ_i (range $[1, 100]$) is its time constant, b_i (range $[-3, 3]$) is a bias term, and w_{ji} (range $[-8, 8]$) is the strength of the connection from the neuron, j, to i. I_i represents the sensory input, which is given to only one sensory neuron. The number of neurons, N, is set to 8. The sensory input is calculated by multiplying 1/0 (on/off) signal by a gain parameter (range $[1, 100]$), which is genetically encoded. There are two effector neurons for controlling the motor activity. Similarly, the motor output is calculated from the difference of the firing rates of the effector neurons, which is mapped into a range $[-1, 1]$ and is then multiplied by a gain parameter (range $[1, 100]$)

The time evolution of the agents' movement and neurocontrollers are calculated using an Euler method with a time step of 0.1.

2.2 Evolutionary Setup

Agents are evolved using a rank-based genetic algorithm with elitism. We differentiate agents into two groups: those represented at the top and the bottom of Fig. 1. In order to allow each group of agents to have different behavioural strategies, a co-evolutionary approach with two populations is used. Each population has 20 agents, which are evaluated by interacting with the best 5 agents from another population. In each population, all network parameters, w_{ji}, τ_i, b_i,,

η_{ji} and the gains are represented by a real-valued vector ([0,1]) which is decoded linearly to the range corresponding to the parameters (with the exception of gain values which are exponentially scaled). Crossover and vector mutation operators [3], which adds a small random vector to the real-valued genotype, are used. The best 5 agents of the population are retained and 10 agents are replaced by the agents with mutation which are selected from the original populations based on a fitness and the rest 10 agents are replaced by mating with crossover between selected two agents.

The fitness is calculated on the basis of two factors. One is how many times the agent can cross its central position with that of a live interacting agent (live interaction). The other is how much the agent can stay away from a dummy agent which only replays the motions of their partner as recorded in the first stage (one-way interaction). It should be clear that both conditions start from the same initial configurations such as positions, speeds, and neural states and then, at a certain point, the top agent is replaced with the recorded motions. It means that the bottom agent has a exactly same states as those being taken in the live condition when the top being replaced. This is schematically shown in Fig. 2. Therefore, agents need to discriminate the two conditions through ongoing interaction while somehow exploiting the presence of noise. This way of modelling contingent and non-contingent motion reproduces the analogous conditions of the double TV-monitor and the perceptual crossing experiments.

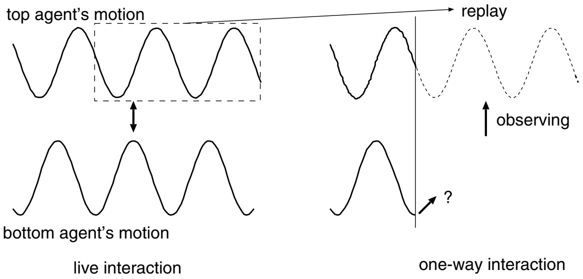

Fig. 2. Live and one-way interactions. Both agents can react to the current situation to establish coordinated behaviour in the live interaction while the only bottom agent can behave reactively while the top agent just replay the previous motions that are recorded in the live condition.

In this paper, only the bottom agents are evolved to discriminate live from recorded interactions. This means that each population has a different fitness function. The population for the bottom agents is evaluated by both factors explained above while the only first factor (crossing under live interaction) is applied to the top agents. In order to measure how many times an agent does not cross the dummy during a trial, the maximum times of crossing is arbitrarily set to 20 (a number estimated from pilot runs) and not-crossing is counted by subtracting the crossing times from it.

3 Results

Evolved agents successfully acquired the capacity to discriminate between the two conditions. Here we analyse one such pair of agents in detail in an attempt to derive some general lessons. Figure 3 shows trajectories of both agents under the live interaction and the trajectory of the bottom agent when interacting with the recorded motion of the top agent (one-way interaction); the differences in position between top and bottom agents are shown on the right. The crossing coordination is established while the two agents move to one direction and control their speeds up and down in order to cross each other without losing track of each other. Under the condition of one-way interaction, the collapse of the coordination is observed. Although there is no big difference at the beginning of the interaction, eventually the bottom agent moves away from the recorded motions. Since the one-way interaction starts the same way as the live interaction, i.e., both conditions have same internal and physical states at the time of switching, a distortion of the ongoing interaction by accumulation of sensory noise must cause the differentiation of behaviours.

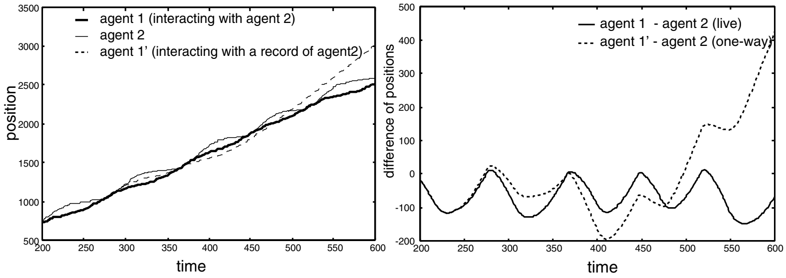

Fig. 3. Left: The agents' trajectories of live and one-way interactions. Thin (top agent) and thick (bottom agent) solid lines show the results of coordinated behaviours under the live interaction. The dashed line shows the trajectory of the bottom agent interacting with the replay of the thin solid line (top agent). Right: The difference between the two trajectories under each condition. When the line crosses 0 it means that two agents cross each other.

3.1 Noise Stability

Without noise in our current settings, there is no way to tell whether the partner is reactive or non-reactive. In other words, the bottom agent needs to exploit the effect of noise to achieve the task. Figure 4 shows the noise effect in the coordinated behaviours. The coordination established by two adaptive agents can be maintained without being destroyed by the increasing noise. Although the stronger noise breaks the coordination more, the coordination shows a robustness against noise perturbations. However, if the top agent is replaced with non-reactive recording, the coordination is not established any more. It means that the bottom agent exploits the presence of noise to detect that the partner is nonreactive and avoids it. Despite the fact that behaviours of the top agent are identical in motion under live and one-way interactions, the bottom agent does not coordinate with the recording. It means that only mutual coupled dynamics can maintain the coordination while suppressing disruptions induced by sensory noise.

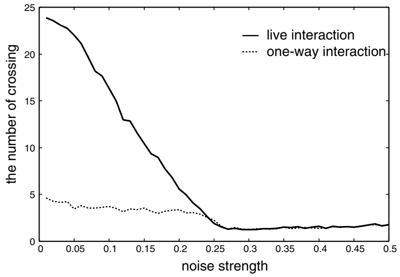

Fig. 4. The average number of crossing by the evolved agents against the noise strength that is investigated at intervals of 0.01. To take the averages, 100 trials are used at each noise strength. The noise strength during evolution is 0.05.

3.2 Ongoing Behaviours of Agents

How do the agents create this ongoing interaction? Typically, the top agent keeps its position on the right hand side (positive in the space) of the bottom agent and control the speed up and down. If the top agents receives sensory stimulation, then it increases the speed to the right. After moving away from the bottom agent, it decreases the speed and waits for the bottom to catch up and make sensor contact. This process is repeated periodically (Fig. 3). By contrast, the bottom agent keeps its position on the left hand side (negative in the space) of the top agent. Without any sensory stimulus, it accelerates to the right to catch up with the partner and decreases the speed after making contact.

Figure 5 shows the neural dynamics of both agents during the coordinations as well as the attractor states constituted when the input is forced to be constantly activated (1) or deactivated (0). The top agent often uses the edges of neural activations and the dynamics (plotting 3 representative neurons) changes sharply which means that the neural activities behave as in a discrete system. The internal dynamics changes quickly depending on the sensory inputs so that the resulting behaviours are reactive. In contrast, the internal dynamics of the bottom agent tends to take place in the transient dynamics between the attractors (indicated as the points with constant input 0 and 1). Before an attractor state is reached, the input changes and the transient trajectory is redirected to the new attractor. During the coordination, the agent alternates between mak-

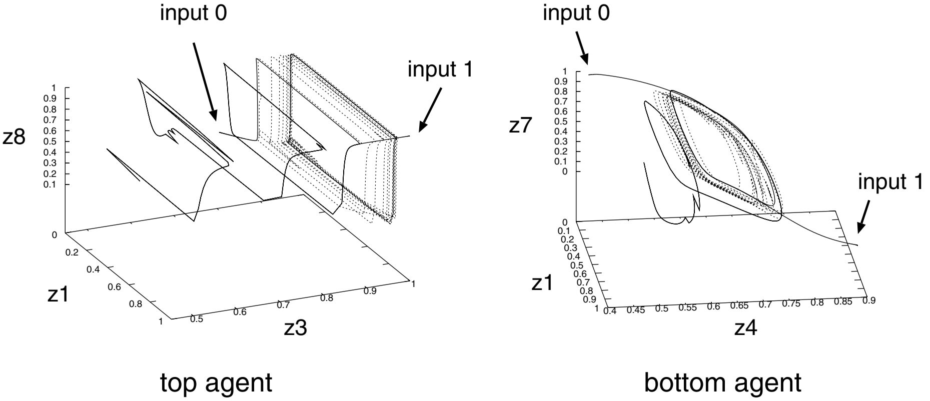

Fig. 5. The internal dynamics of agents. Each axis indicates the firing rate, z_i. The choice of neural activations is representative for visual clarity. The dashed line shows the dynamics constituted by interaction between agents and the solid line shows the dynamics when the sensory input is fixed to be always deactivated (0) or activated (1). Input 0 and 1 are attractors constituted under the fixed sensor.

ing contact and staying away from its partner. The permanence of the system in its transient dynamics is a reflection of the agent's embodied interactions.

In order to see how the transient dynamics is generated and modulated by the inputs, controlled sensory inputs are given to the bottom agent. As seen in Fig. 6, if the controlled inputs which have a close frequency to the average over the actual interactions are given to the bottom agent, it can reproduce similar dynamics to the actual one. However, reducing the length of the stimulations of the sensory input and increasing the gaps generate the internal dynamics falling into the attractors, which can hardly adjust the agent's behaviour. A sufficient length of the consecutive activations is necessary to stay away from the attractor and to show the transient dynamics. Actually, when the body size of agents are reduced, they cannot achieve coordinated crossing even in the live interaction because the smaller bodies do not produce inputs that are sustained for long enough. It means that the bottom agent uses the duration of the sensory stimulus to tell if the interaction is live or one-way by using the transient dynamics.

What factors affect the duration of the sensory input intervals during interaction? The duration is affected by the relative speeds of the two agents as they cross. In the live interaction, at the crossing, the top agent "catches" the movement of the bottom agent and provokes a return to the left by reacting to the partner to fit the moving speed (Fig. 7). The reactive response makes the duration of contact longer. In other words, the duration of the contact and the intervals between contacts are *co-regulated by both agents*. However, a small difference of the timing of start crossing is enough for the recorded trajectory of the top agent not to be able to "respond" in time to catch the bottom agent. This non-responding behaviour cannot make sufficiently long sensory contacts

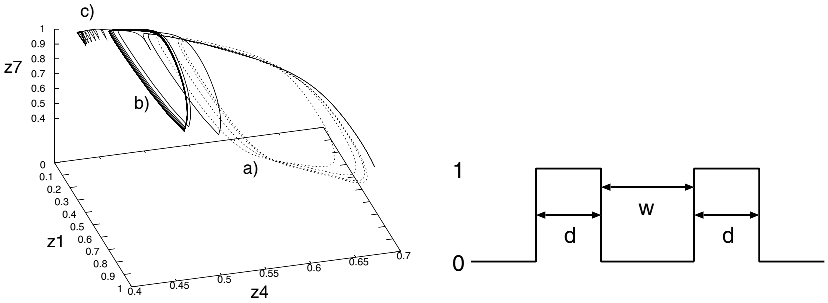

Fig. 6. The internal dynamics of the bottom agent corresponding to different periodic stimulus patterns: a) $d = 20, w = 63$, b)$d = 14, w = 69$, and c)$d = 10, w = 73$ where d and w represent the length of activations and deactivations of controlled sensory inputs.

and the bottom agent passes through and moves away. Therefore, the presence of noise causes a breakdown of the coordination and the lack of co-regulation makes this breakdown irrecoverable.

This co-regulated behaviour happens between the agents. A single agent cannot control the duration of the contact interval to make it last the right time in order to produce the cyclic transient dynamics in the bottom agent. It means that there is a kind of agreement between agents that cannot be determined individually. Only the precise timing and interdependency of dynamics can produce co-regulation in this case.

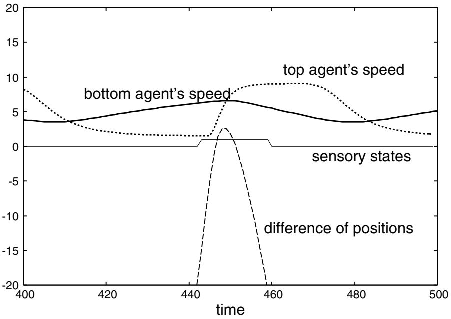

Fig. 7. Co-regulations of agents' speeds for the duration of contacts. The top agent starts "catching" behaviour at the beginning of contacts and that works the bottom agent to "give up" passing through and it eventually slows down. Both these behaviours make the sufficient duration of contacts.

4 Discussion

This simple model explores the agency detection observed in minimal social interaction. In order for agents to produce a different behaviour in the case of a one-way interaction, it is sufficient to rely on properties of the mutuality of the live interaction, such as increased robustness to noise and timing differences. This suggests that, at least in some cases, the recognition of the presence of another's subjectivity need not lie in complex cognitive individual mechanisms able to integrate past information, but rather on the ongoingness of the interaction process itself and its robustness to noise. These simulation results show the possibility of embodied modelling to deal with matters as complex as agency detection and co-regulation of interaction without the models themselves being complex.

In our model, social coordination is realized through contingent co-regulation, which gives rise to the detection of live agency. Contingency is a relational condition and its perception must rely on how the patterns of expressive action of a partner relate to our own actions rather than on the patterns themselves. The interrelated structure of social coordination has the global stability of the mutual feedback against perturbations of noise and the active co-construction of precise contact timing.

Our results also shed light on the ongoingness in social interactions. This kind of ongoingness has been less investigated in the simulation studies so far (some can be seen in [4,5]). The dynamical structure of ongoingness could be very different from the simple attractors views in which the timing issue is removed due to a convergence of the dynamics to stable structures. In our results, one of the agents behaves reactively and another uses the transient dynamics and those behaviours are interrelated in the sense that both agents are meant to behave in a way of making the time of contact longer when crossing. In the presence of non-reactive recorded motions, this co-regulation cannot occur. It is a kind of agreement between agents that can be seen in our daily social interactions. As discussed above, this agreement cannot be attributed to a single individual. It arises from a relational view of coupled dynamics. In order to understand social interaction, however, we are highlighting not only the importance of the coupled dynamics but also an aspect of the ongoingness under the coupling. If the interaction had a pre-established harmony, there would be no reason to regard the agents as separate and it all could be described by a single whole dynamics where we don't have to call any behaviour an "agreement". But the interaction that our evolved agents establish is not like this. It is rather based on the ongoing co-regulation that they establish by constantly responding to the abrupt breakdowns induced by the presence of noise. Agreement is constantly renewed – as opposed to pre-established – by this ongoing and transient dynamics.

The embodiment of agents is rather minimal and the minimalism will allow us to formulate hypotheses for more sophisticated forms of embodied interaction in both simulations and experiments with real robots [3,8]. In order to better understand the role of embodiment, future work will compare these results with interaction in disembodied agents that are not situated in an environment but are directly coupled with each other as well as agents capable of different ways of regulating their mode of coupling. In our model, the agents' capacities such as sensors and motors are very limited but they make use of the environmental space that produces the gap between their bodies. Agent are not in constant coupling with a partner. Coordination consists on regulating the presence (or more generally the quality) of the coupling. In the experimental situation, the mother or baby can attract the other into an interaction by "actively" moving and observing the response of the other. Such active engagement can only work if the existence of some sort of a "gap" in coupling is possible. The environment can thus be considered as a buffer and implicitly work in our current simulation as it is. Modifying such a buffer, or even removing in the case of disembodied agents, will result in a family of models shedding light on how embodiment lies at the root of social coordination.

Acknowledgments. This research was partially supported by the Japanese Ministry of Education, Science, Sports and Culture, Grant-in-Aid for JSPS Fellows, 17-04443.

References

1. Auvray, M., Lenay, C., Stewart, J.: The attribution of intentionality in a simulated environment: the case of minimalist devices. In: Tenth Meeting of the Association for the Scientific Study of Consciousness, Oxford, UK, 23-26 June (2006)
2. Beer, R.D.: Intelligence as adaptive behavior: An experiment in computational neuroscience. Academic Press, San Diego (1990)
3. Beer, R.D.: Toward the evolution of dynamical neural networks for minimally cognitive behavior. In: Maes, P., Mataric, M.J., Meyer, J.-A., Pollack, J.B., Wilson, S.W. (eds.) From Animals to Animats 4: Proceedings of the 4th International Conference on Simulation of Adaptive Behavior, pp. 421–429. MIT Press, Cambridge (1996)
4. Paolo, E. A, D.: Behavioral coordination, structural congruence and entrainment in a simulation of acoustically coupled agents. Adaptive Behavior 8:25-46. MIT Press, Cambridge (2000)
5. Iizuka, H., Ikegami, T.: Adaptability and diversity in simulated turn-taking behavior. Artificial Life 10, 361–378 (2004)
6. Murray, L., Trevarthen, C.: Emotional regulations of interactions between two-month-olds and their mothers. In: Field, T.M., Fox, N.A. (eds.) Social perception in infants, pp. 177–197. Ablex, Norwood (1985)
7. Nadel, J., Carchon, I., Kervella, C., Marcelli, D., Réserbat-Plantey, D.: Expectancies for social contingency in 2-month-olds. Developmental Science 2, 164–174 (1999)
8. Robins, B., Dautenhahn, K., te Boekhorst, R., Billard, A.: Robotic assistants in therapy and education of children with autism: Can a small humanoid robot help encourage social interaction skills? Universal Access in the Information Society 4(2), 105–120 (2005)
9. Trevarthen, C.: The self born in intersubjectivity: The psychology of an infant communicating. In: Neisser, U. (ed.) The perceived Self, pp. 121–173. Cambridge University Press, Cambridge (1993)