Human-Machine interaction as a model of Machine-Machine interaction: how to make machines interact as humans do

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Abstract

Turn-taking is one of the main features of communicative systems. In particular it is one of the basis allowing robust interactions in imitation, thanks to its two intricate aspects, communication and learning. In this article, we propose a simple model based on the interaction of 2 oscillators which will explain how “turn-taking” may emerge dynamically between two agents. An implementation of the model on the ADRIANA robotics platform is given and results showing the robustness of the model are discussed.

keywords: turn-taking, synchrony, imitation, coupled oscillators

1 Introduction

Our aim is to use the simple format of human communication in order to make machines interact. In this context, turn-taking, which is one of the main features of human communication, must be taken into account in robotics models. In this article, we propose a simple model based on the interaction of 2 oscillators which will explain how “turn-taking” may emerge dynamically between two agents. An implementation of the model on the ADRIANA robotics platform is given and results showing the robustness of the model are discussed.

In the rest of the paper, we first give the physical and psychological theoretical context. We then detail our conceptual model. In section 4, the implementation on a real robot is given. Then, extensive simulations and results are discussed before concluding.

2 Theoretical context

Huygens discovered in 1665 that the pendulums of two clocks hung together anti-synchronize after a while ([1]). The model of the pendulums anti-synchronization has been given three hundred years later
when the two pendulum oscillate, they make the support move. These movements of the support provide little exchanges and loss of energy between the two oscillators. The furthest from anti-synchrony the pendulum are, the larger the movement is and thus the highest the exchange and loss of energy is. The anti-synchronisation is the unique stable attraction basin of this dynamic system. This explain the Huygens’ observations.

The more general issue of coupling between non-periodic oscillators such as chaotic oscillators has been studied by ([3, 4, 5, 6, 7]) following the pioneer model of Synchronization in Chaotic Systems from Pecora and Carroll ([8]). Emerging from these studies, three important aspects should be underlined. First, the coupling between the oscillators is obtained under very few constraints on these two oscillators: they should exchange information (a signal related to each of the internal state of the oscillators must be transmitted to and influence the other oscillator); the global system must be dissipative, and of course, the oscillators should oscillate. Second, the coupled oscillators stabilise in anti-synchronized oscillations (anti-phase synchronization). Third, these experiments permit a synchronization (same frequency and constant phase gap) between the coupled oscillators even if their own frequencies are quite different.

These two last points also appear in the domain of psychological studies of dyadic interactions between humans. Synchrony between partners has been shown to be a necessary condition to enable interaction between an infant and her mother: the infant stop interacting and imitating her mother when the mother stop being synchronous with her, all other parameters staying equal [9, 10, 11]. Moreover, synchrony has been shown to be a premise of the interaction: in Nadel’s Still Face experiment, the experimenter faces an autistic child which first ignores her. She then forces the synchrony with the child by imitating him, and the child enters in interaction with the experimenter. They finish taking turns and imitating each other [12]. This synchronous imitation takes advantage of the two facets of imitation (communication and learning) which provides two roles: the role of imitator and the role of model. By alternating the two roles, they take turn: reciprocal imitation is used as a genuine communicative system where there is no need of an arbitrary set of symbols to interact [13].

Until recently, roboticists have mainly been interested in the learning function of imitation since it is a simple way for a robot to learn from another, and since it has “social” effects by boosting the learning speed in a population of robots [14, 15, 16]. Moga has shown that a robot can “learn” a sequence of action from another agent (human or robot) but has noticed that while the learning procedure works quite well during an interaction with a human being, it almost does not work in an interaction between two robots [17]. In fact, the human participating to the interaction naturally formats the interaction by ensuring the synchronisation and coupling with the robot.

The limits of imitative robots concerns how far the interactions between two autonomous robots can go or how far the interactions between an autonomous robot and a naive human can go: the problem rises from the fact that a robot, acting as a model for the imitator, is controlled by an open loop that does not integrate this very imitator! Thus, the dynamics of interaction, intrinsically taken into account by a human teacher, is the unique way for the imitator to learn something.

Taking inspiration from both the physical theoretical framework on oscillators and psychological
observations and concepts, we propose a model of the coupling between robotics systems having oscillatory dynamics. The main idea is that each robot could have an internal propensity to “interact” with someone else and thus to be either “sensitive” to the other’s behaviour or, conversely, urged on proposing its own behaviour to another. In our model, each agent propensity to “interact” is controlled by a simple oscillator accorded to a frequency $f$. When the oscillator is up, the agent acts whereas when the oscillator is down the oscillator stands by. Besides, to model the interaction, each oscillator of each agent may partly be inhibited by the actions of the other agent. Our goal is then to study if synchrony and turn-taking, may emerge from the dynamics of such a simple model.

Practically, each robotic agent is equipped to demonstrate basic movements: an arm with one joint, the shoulder. Besides, each agent has an oscillatory dynamic: the movements of its arm is controlled by an internal oscillator (the agent’s “propensity to interact”). When the oscillator is up, the agent moves its arm as much as it can, and conversely, when the oscillator is down the agent stands by. This results in an alternation of moving vs standing periods. Considering this oscillatory dynamic, our model gives the two agents the ability to exchange and loose energy: both agents are equipped with a camera pointing at the other agent and when an agent sees the other agent moving, this inhibits its internal oscillator. As in the Huygens’ clocks experiments, this may result in an important evolution of the two-agents system dynamics. The inhibition of one oscillator by the other always tends to increase the delay between their highest activations. That makes the system converge toward an anti-synchrony dynamic.

### 3 Conceptual model

The oscillator is made of three neurons ($N_i$), powered by a constant signal ($cte$), which activities are bounded between $-1$ and $1$. These four neurons activate and inhibit each other proportionally to the parameter $\alpha$. This model fits the set of equation 2 (see also fig.1-left).

\[
\begin{align*}
N_1(n+1) &= f(N_1(n) - \alpha.N_2(n) + \alpha/2) \\
N_2(n+1) &= f(N_2(n) + \alpha.N_1(n) - \alpha.N_3(n) - \alpha/2) \\
N_3(n+1) &= f(N_3(n) + \alpha.N_2(n) - \alpha/2)
\end{align*}
\]

\[
f(x) = \begin{cases} 
0 & \text{if } x < 0 \\
1 & \text{if } x > 1 \\
x & \text{if } 0 < x < 1
\end{cases}
\]

This oscillator produces the sinusoidal signal plotted on fig.1-right.

We tested this model of oscillator when it is submitted to a brief perturbation. The oscillator keeps the phase forced by the external perturbation. Conversely the frequency of the oscillator even after having been modified by an external influence retrieves its default value when the influence stops (see fig.2).
Figure 1: The oscillator is made of three neurons, $N_1$, $N_2$ and $N_3$, with a self-connection weighted to 1. Links which weights are $+\alpha$ connect $N_2$ to $N_1$ and $N_3$ to $N_2$, and links which weights are $-\alpha$ connect $N_1$ to $N_2$ and $N_2$ to $N_3$. A constant input $cte$ activates $N_1$ with weight $+\alpha/2$, and inhibits $N_2$ and $N_3$ with weight $-\alpha/2$.

Figure 2: After perturbation happening on neuron $N_1$, the phase of the oscillator differs from its initial phase, and if there is no other perturbation it remains constant.
4 Implementation

In order to shift from the conceptual model to a robotics implementation, we must consider how the oscillators and their interaction could be embodied in a concrete robot. The main issue is that the reciprocal influence between the two oscillators has to be mediated by the environment. We must thus think about how each robot could act in the environment and how it can perceive it.

In a previous work, Andry and Gaussier [18], following Daunehahn [19], have proposed to use a simple homeostatic architecture as a bootstrap for interaction and imitation. The key idea was that a perceptual ‘misunderstanding’ can serve the function of communication between systems. The interaction was mediated by the vision (in particular the detection of movements) on the perception side, and the movements of a robotic arm on the action side.

In our robotic platform ADRIANA (ADaptable Robotics for Interaction ANAlysis), the detection of movements and a moving arm are also used to interact (see fig.3).

![Image](image-url)

Figure 3: In the present experiment ADRIANA is customized with a single arm for each robot and a webcam which enables the robot to see the other robot but not to see its own arm. The two robots move their arms according to their own dynamic. They influence each other by seeing the movement of the other robot.

Yet, this platform is a more general set of construction especially dedicated to the study of interaction and communication features such as synchrony, rhythm, turn taking, role switching and imitation... In this platform several robots arms with simple joints can be added and arrange at will. The resulting robot can thus have one or multiple degrees of freedom (up to 8), and can demonstrate various motor patterns or dynamical sequences to the agent it interacts with. A webcam can be added behind the arms so as to enable the agent to see its own arms and thus to learn a correspondence between what it does and what it sees. But it can also be added in front of the arms so as not to see them but being able to see another’s movements instead (making possible the correspondence between what is performed and what is perceived). Both the arm and the camera are controlled by our neural networks simulator *Prometheus* ([20]).

In this paper, the platform is simplified: each robot has only one arm and the camera is put in front
of the arm. Each robot faces the other robot in order to perceive its arm movements. The architecture controlling each robot is composed of two parts: the oscillator (the same as in the previous section) which controls the single arm, and the image processing system which computes the inhibitory signal.

The activation of the oscillator is directly transformed in motor activation. For that purpose, the oscillator controls the arm movements through an integrate and fire neuron (see fig.4). Each time the integrate and fire neuron fires, the arm moves up and down once. Thus, the frequency of the arm movements directly depends on the activation of the oscillator: the higher the activation of $N_1$ is, the more frequent the arm movements are. The vision system of the robot should enable to detect the motor activity of the other robot. The webcam we use captures 25 frames per second. The movement detection function of our architecture compares two images every 4 frames. Due to the setup, the movement detected directly depends on the motor actions of the other agent. We then have a sort of frequency coding of the signal: the integrate and fire encodes the oscillator activation whereas the movement detection decodes this signal considering only binary categories (movement vs no-movement).

![Figure 4: The upper neuron $N_1$ of the oscillator is directly connected to an integrate and fire neuron. Each time the integrate and fire neuron fires, the arm moves up and down once.](image)

5 Robotic experiments

We have tested these architecture and setup with two robots having the same oscillator’s parameter ($\alpha = \beta$). As shown on figure 6, after a transition period, the two oscillators of the two robots stabilise in anti-synchronization: when one robot moves the other stops and conversely, the two robots take turns.

We want this model to be robust enough to support variability between the agents’ frequencies or changing environment, as it can happen in real life communication and imitation and as it is the case in coupled chaotic oscillators ([3, 4, 5, 6, 7]). Thus, we have tested the three parameters which might modify the robots capability to enter in a stable dynamic of anti-synchrony:

First, we have tested the reciprocal influence of the two agents (which can change if the attention of the agents to each other changes or if the environment become noisy). This influence is here modulated by the inhibition due to the perception of movement. This parameter is explicitly given by the weight
Figure 5: Architecture of the two agents influencing each other. Each agent is driven by an internal oscillator and produces actions depending on this oscillator. A noise due to the environment and the hardware devices appears on the signal between the two oscillators. Note that in simulation this noise has to be simulated to enable the agent to anti-synchronize (see section 5.1).

Figure 6: Activation evolution over time of each oscillator of the two systems. The two systems start in the same state: at time $t = 0$ the activation of their oscillator is 0. When the oscillators start to activate, the two robots start to move together, but they inhibit each other and one (here the agent 1) takes the advantage. After a transition period, the oscillators are stabilised in phase opposition: when one robot moves the other stops and conversely, they take turns.
inhibit of the link between movements detection and $N_1$ described in the paragraph concerning the implementation (section 4, fig.4).

Second, we have tested the ratio between the frequencies of the oscillators controlling the two agents (two agents may have different internal rhythms, or not the same propensity to interact). The frequencies ratio depends on the two parameters $\alpha$ and $\beta$ which control each agent oscillator (see figure 1).

Third, we have tested the influence of the noise in the system: this noise is mainly due to the signal of inhibition transmitted from one agent to the other by the mean of action and visual perception. In the robotic experiment, the noise is due to the environment and the hardware devices: the arms and the cameras.

In order to evaluate the propensity of the two-agents system to anti-synchronize, we recorded the activations of each agent’s neuron $N_1$ at each time-step. We characterise the anti-synchronisation state by the fact that it fits two conditions:

First, the two agents must have the same fundamental frequency. We test this property calculating the fast Fourier Transform (FFT) of each signal and extracting its maximum value (different from zero) so as to obtain the fundamental frequency of each agent.

Second, the two agents must take turns. We test this property plotting a “Lissajou” graph of the two signals $N_{1,1}$ and $N_{1,2}$, i.e. for each time step $t$ we plotted in $\mathbb{R}^2$ the couple $(N_{1,1}(t), N_{1,2}(t))$. The Lissajou plot points out the temporal relations between the two oscillators: a periodic cycle accounts for a stable relations between the oscillators, and if the main component of this cycle is parallel to the second bisector then the oscillators are in phase opposition.

32 experiments were conducted with the robots in order to test the following set of parameters: the frequency ratio $\frac{\beta}{\alpha}$ took the values 1, 1.2, 1.4, 1.6, 1.8, 2, 4 and 6, (only $\beta$ varies, $\alpha = 0.1$) the reciprocal inhibition inhibit took the values 0, 0.1, 0.3 and 0.5. The noise could not be controlled in those robotics experiments since it was due to the environment and the hardware devices. Each experiment was 3000 time steps long and thus took around 12 minutes for a given set of parameters.

The “FFT” analysis show a wide range of phase lock between the two oscillators: for high values of the reciprocal influence (inhibit in 0.3, 0.5) the two agents lock on the same frequency (fig.7, middle and right graph) whereas for the lowest value of the reciprocal influence (inhibit = 0.1) they do not lock for frequencies ratio higher than 4 (fig.7, left).

The Lissajou patterns show that the frequency lock of the two agents is associated with a turn taking between the two systems (see figures 8): the two oscillators start with the same initial value ($(N_{1,1}(0), N_{1,2}(0)) = (0,0)$) and after a transition phase (fig.8-left) stabilise on an cycle which principal component orientation is parallel to the second bisector (fig.8-middle, fig.8-right). That characterizes the fact that when one agent acts, the other stands by, and that they alternate.

Even for high differences of frequencies, the Lissajou pattern takes values alternatively in the left upper part and in the right lower part of the Lissajou graph (see fig.9).
Figure 7: Three graphs representing the frequencies observed of both agents when they interact: on the upper graph the reciprocal influence \( \text{inhib} = 0.1 \), on the middle one \( \text{inhib} = 0.3 \), on the lower one \( \text{inhib} = 0.5 \). The abscissa axis shows the ratio, \( \frac{\beta}{\alpha} \), between the frequencies of the two agents: \( \beta \) varies while \( \alpha = 0.1 \). Agent1’s frequencies are plotted with cross and Agent2’s frequencies are plotted with circles.

5.1 Complementary simulations

Due to the technical complexity of experiments with real robots, we have only been able to test a few set of parameters (see above). To test more exhaustively the conditions, the robustness and the limits of the anti-synchronization between the two systems, we designed a simulation of the 2 systems in interaction. The noise which naturally appears in the real implementation had to be introduced into the simulation. We then tested a wider range of values of the parameters with a thinner sampling. The frequencies ratio \( \frac{\alpha}{\beta} \) was taken between 0.1 and 0.6 with a step of 0.001. The inhibition between the two systems was still varied between 0.1 and 0.5. Since the system is not deterministic due to the noise added in the simulation, we performed these experiments 100 times so as to obtain mean results for each set of parameters. The simulation enables us to limit the duration and the material cost of the experiment: with the robots, each of the \( 600 \times 3 \times 100 \) sets of parameters would have taken 12 min to test and the motors should have been replaced every 25 tests. That means about 1500 days non-stop (\( \approx 4 \) years), and 7000 replacement of the motors.

The results on simulation for the values of parameters used in the robotics experiments \( (\beta = 0.10.12...0.180.20.40.6) \) were almost equivalent. Yet, surprisingly, for some of the values (see figures 11 and 12), the results were discontinuous and seem even “chaotic” (the system is both deterministic and very sensitive to initial condition, see the Standard deviations of figs. ??). In fact, this phenomenon is similar to the “phase locking of periodic oscillators in the presence of noise” described by Stratonovich’s equations in 1963 [21]. In simulation the noise is clearly added whereas in robotic experiment it is induced by sensors, effectors and environment. The regions of synchronization observed in simulation are
Figure 8: The three graphics show the evolution of the “Lissajou” patterns of the two-agents system through time (Agent1 on X-axis and Agent2 on Y-axis): from the upper graph to the right graph we have the “Lissajou” patterns during respectively, the begining \( t \in [1, 100] \), the middle \( t \in [101, 300] \) and the end \( t \in [301, 2000] \) of the experiment. The two oscillators which drive the robots have the same frequency \( \alpha = \beta \) and the reciprocal influence between the robots is medial \( \text{inhib} = 0.3 \).

Figure 9: Left: “Lissajo” patterns for a medial ratio of the frequencies of the two agents \( \frac{\alpha}{\beta} = 2 \) and a high reciprocal influence \( \text{inhib} = 0.5 \). Right: “Lissajou” patterns for a high ratio of the frequencies of the two agents \( \frac{\alpha}{\beta} = 6 \) and a high reciprocal influence \( \text{inhib} = 0.5 \).
Figure 10: Architecture of the two simulated agents influencing each other. Each agent is driven by an internal oscillator and produces actions depending on this oscillator. Note that, in the robotic experiment, a noise appeared on the signal between the two oscillators, due to the environment and the hardware devices. In simulation this noise has to be simulated to enable the agents to anti-synchronize. The weight value (0.047) between the Noise and the neurons N1 has been determined experimentally from the mean value of the signal detected by the movement detection mechanism during the robotic experiments.

Figure 11: Means of the observed frequencies of the two systems (interacting with a low reciprocal inhibition, 0.1), plotted as a function of the ratio between the agents’own frequencies (α/β): the X axis indicates the ratio α/β, the Y axis indicates the mean frequencies observed on the 100 tests performed with these parameters α and β. The third curve indicates the standard deviation, for the 100 trials, for the observed frequency of system 2.

analogous to the “phase locking domain” described as “tongues” by Arnold in 1983: when two periodic oscillators are coupled together there are parameter regions called “Arnold tongues” where they mode lock and their motion is periodic with a common frequency [22].
Figure 12: Means of the observed frequencies of the two systems (left: interacting with a mean reciprocal inhibition, 0.3. Right: interacting with a high reciprocal inhibition, 0.5), plotted as a function of the ratio between the agents' own frequencies ($\alpha/\beta$): the X axis indicates the ratio $\alpha/\beta$, the Y axis indicates the mean frequencies observed on the 100 tests performed with these parameters $\alpha$ and $\beta$. The third curve indicates the standard deviation, for the 100 trials, for the observed frequency of system 2.

6 Concluding comments

The results of our experiments suggest that a “turn-taking” behaviour may naturally emerge from the dynamical interaction between 2 oscillating systems. This emerging dynamics have been shown to tolerate a wide range of parameters. This robustness allows the 2 systems to remain in interaction even if the condition are not ideal: the agent’s dynamics and the environment around the agent may be modified along time. It suggests that the emergence of turn taking between two systems is a very robust dynamical attractor that can be trusted in order to develop further functionalities upon it (learning of motor repertoires, imitation, role-switching...). Furthermore the simplicity of our implementation (detection of movement and coding of the activation of the oscillator in motor activation) make it easily implementable on various robotics: the robot just needs a camera and an arm.

Even if the “turn-taking” behavior appeared in the major part of our results, some of the values tested, in simulation only, show a variability of results and no anti-synchronization between the two systems. We propose to come back to the robotics experiment with the values obtained in simulation in order to confirm whether or not such discontinuities exists in a “real” interaction and how they can be overridden. A formal mathematical description of the interaction may give a basis to understand the convergence of the system. Experiments of psychology can also be a way to investigate the dynamic of the interaction and to inspire our imitative robots: recent results of psychology indicate that a bottom-up model of exchange of energy between dynamic systems may account for the interaction between a child and her mother ([23]). The child and her mother can be seen as two agents which attempt to minimize their internal energy cost, especially minimizing the difference between what they do and what they perceive. When the child and her mother interact they are synchronous and thus the energy cost of the mother-infant system is minimized and the information they exchange is maximized. This view
also fits physics results on chaotic oscillators which support the idea that the more chaotic oscillators are synchronized, the more information they exchange ([24]). It must be noticed that, even if “turn taking” has not been embedded within the architecture directly, its emergence is basically linked with the existence of an “ad hoc” oscillator within the architecture. If the motor activity of a robot is modulated by an internal oscillator, the state of this oscillator can influence an external observer such as another robot and reciprocally. In our opinion, an equivalent oscillatory behavior could emerge from the robot internal dynamics as it seems to emerge in humans, for instance oscillations could emerge from the competition between contrasting motivations. This emerging oscillatory behavior could account for a propensity to communicate with others: for instance there may be oscillation between two state, a “receptive” one and an “active” one.

REFERENCES


