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A coupled-oscillator model of human attachment dynamics evaluated in a robot dyadic interaction

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Abstract. A better understanding of the nature of human relationships can aid the design of effective and appropriate social behaviour for robots. The investigation of human bonding via robotic modelling can also serve to test psychological theories in an embodied setting. In this work we present a robotic model of "attachment"—the primary bond between child and caregiver that shapes relationship behaviour throughout our lives. Following a dynamical systems approach, we model attachment as a behavioural coupling between motivational oscillators and show, by means of a dynamical analysis, that coupled robot dyads generate dynamical patterns that resemble caregiver-child interactions. By demonstrating coupling in an embodied model, we also show that measures of physical and emotional distance (a psychological variable), inferred from sensory data, can serve as effective control parameters for attachment behaviour. We find that this oscillator framework generates rich patterns of robot behaviours that can be associated with quantitative and qualitative observations of the "strange situation" procedure, an experimental paradigm that is widely studied in human relationship science, and of human avoidant and ambivalent attachment styles. The ability to estimate human attachment style and to generate appropriately-matched robot behaviours could be useful in social and companion robotics.

Keywords: Attachment · Human-Robot interaction · Dynamical systems.

1 Introduction

People can form emotional bonds with intelligent artefacts, such as social and companion robots, that are complex and can be personally meaningful [1]. Some forms of bonding could be beneficial in situations where the robot provides a valued service such as being physically or socially- assistive, at the same time, concerns have been raised that inappropriate bonding with a robot could cause harm (e.g. [2]). The nature of the behavioural interaction between human and robot is likely to be a determining factor in establishing any long-term bond. We have previously analysed human-robot relationships through the lens of social psychology and relationship science, proposing that there can be similarities between human-robot bonds and some forms of human-human and human-other bond [3, 1]. In the current contribution, we present a dynamical systems account of the human attachment bond and explore its potential for understanding caregiver-child relationships through an embodied robotic model. We consider that this approach can both advance the understanding of human relationships and provide insights that could aid the future design of social and companion robots.

1.1 Attachment as a motivational system

Attachment theory, developed by John Bowlby in the 1950s and 1960s [5] and expanded by Mary Ainsworth [6], highlights the importance of foundational relationships, particularly that between a child and its primary caregiver (typically the mother), as being critical in establishing ways of relating to others that persist through life. The classical theoretical approach uses different categories to classify attachment styles in children, as revealed by a laboratory procedure termed the "strange situation" procedure (SSP) [6, 7]. In a typical experiment, a child and their caregiver are observed during multiple short episodes during which the caregiver is either absent, present alone, or present with a stranger. In the SSP, a child that is observed to have a weak emotional bond with the caregiver is characterised as having an *avoidant* attachment style and one that appears preoccupied about the caregiver's availability is characterized as *ambivalent*. A key dependent variable is the physical distance between child and caregiver, as illustrated in figure 1—a securely attached child typically shows bouts of exploratory behaviour, that involve moving away from, then returning to, the caregiver, on a quasi-periodic basis. In contrast the ambivalent child will typically stay close to the caregiver while the avoidant child will explore while paying little attention to the caregiver.

More recent work has proposed that the attachment styles identified by Bowlby and Ainsworth are best considered as emerging from a multi-dimensional motivational system [9, 10]. For instance, Gagliardi [10], describes a 7-dimensional framework with three basic dimensions—avoidance, ambivalence and disorganisation—viewed as emerging during an early "imprinting" period (6 to 24 months). According to this approach, avoidance has an essentially emotional nature, meaning that it is primarily concerned with the affective bond between child and caregiver. Ambivalence, on the other hand, has a more situational or physical nature, meaning that it is concerned with the caregiver's availability. Gagliardi [11] recently described an information-theoretic model in which the child and caregiver were modelled as point agents in a two-dimensional space inspired by the SSP. The child's behaviour, derived from its attachment motivational system, was modelled as situated in the two-dimension avoidance-ambivalence space. The caregiver, whose behaviour was the manifestation of a caregiving motivational

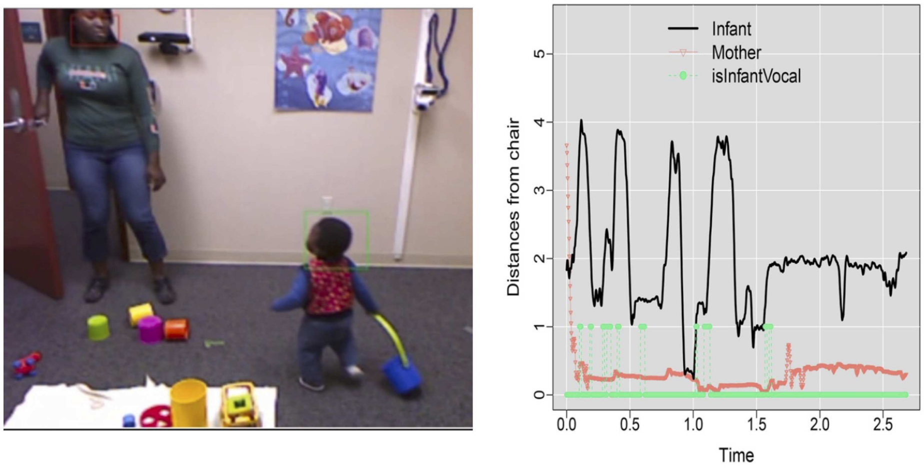


Fig. 1. Left: an SSP room with a mother (caregiver) and her child. Reprinted from [7] with permission from Elsevier. Right: Example behavior patterns displayed in the SSP, plots show distance of the child (black line) and mother (red line) from the chair during a reunion episode and illustrate the oscillatory movement patterns often seen with securely attached children. Reproduced from [8] with permission from Springer Nature.

system, was modelled as situated in a two-dimensional sensitivity-responsiveness space. Robotic experiments with this model generated alternating patterns of exploration and approach behavior that were aligned with the attachment literature confirming the utility of the dimensional framework.

1.2 A dynamical systems approach

In the current work, we propose a model of attachment that builds more directly on the dynamical system perspective in developmental psychology [12, 13], modelling the child-caregiver relationship, as manifested in the SSP, as a system of coupled oscillators. This model builds on the dimensional view of avoidance and ambivalence, and the emphasis within the Gagliardi model [11] on physical and emotional distance, whilst more directly exploring the dynamical behaviour of the two coupled systems—a child that is motivated to attach and a caregiver that is motivated to provide care—both seeking to balance other motivations such as to explore. We adopt a novel approach that simplifies the information-theoretic model of Gagliardi into a set of differential equations that are more amenable to dynamical analysis while still capturing key characteristics of attachment phenomena. We also extend the approach from modelling point agents in a two-dimensional world, to a robotic implementation that operationalizes some of the elements of the Gagliardi model that assume the capacity of the two agents to infer each other's attachment state.

Our dynamical model stems from the motivated-behaviour-as-an-oscillation framework [14] in which the internal needs of the agents shape a dynamical landscape in a manner that can generate or extinguish attractors in the phase space. From this point of view, different motivational systems are activated depending upon the location of the agent's internal state in such a phase space by using attractor-centered readout functions. The results presented here are a natural corollary of such approach—if motivation is an oscillation, interaction becomes coupling. The coupling of dynamical oscillators has been widely studied. In the current work we use attractive and repulsive coupling to simulate ambivalent and avoidant tendencies. This kind of coupling generates a wide range of behaviours including inhomogenous steady states (IHSS), oscillation death, synchrony, anti-synchrony and bi-stability [15]. Helm et al. [16] have previously used a couple-oscillator model to understand interpersonal synchrony with respect to physiological signals such as heartbeat and respiration (see [17]), the current work extends this methodology to the domain of interpersonal behavior.

1.3 Related work

In originating attachment theory, Bowlby [5] was concerned with applying insights from both ethology and cybernetics—–key scientific movements at the time he was working—to the understanding of human personality and relationships. A number of subsequent models have built on Bowlby's enthusiasm for computational accounts (see [18]), most notably, Petters [18], who developed a cognitive architecture for agents to implement and test aspects of attachment theory, and Gagliardi [11], who recently developed the information-theoretic account described above motivated by the emerging dimensional view. The current study complements this work by focusing on the dynamics of attachment behaviour, through a relatively minimal coupled oscillator model, an emphasis that might have appealed to Bowlby's search for concise explanations that can capture regularities underlying observable human behaviour. A previous dynamical account provided by Stevens [19], sought to cast attachment within the framework of homeostasis and modelled the development of attachment as a long-term process of adaptation. In contrast, the focus here is on short-term adaptation of caregiver-child dyad within timeframes comparable to the rich behavioural databases generated by the strange situation. The oscillator model developed here is particularly useful in capturing this kind of interaction. The use of robotics creates a focus on operationalising theories of coupling between agents while also generating a behavioural richness that can be absent in disembodied models. There are interesting parallels here with earlier work by Canamero et al. [22] who developed a model of imprinting in a physical robot. The robot we have used is animal-like rather than human-like, partly as our broader aim is understand the mammalian brain architecture for emotional and social behaviour. From this perspective human attachment can be seen as the expression of an underlying layered motivational control system that is present in all mammals [23, 24]. We are also interested to explore similarities between attachment and other mammalian social behaviours such as filial huddling [25, 24].

1.4 Model Overview

In the first part of this contribution, we present our model, followed by an overview of the different attachment styles emerging as phenomena of synchronization and anti-synchronization. Finally, to test our model, we use the MiRo-e robotic platform [26]. In previous studies, we have demonstrated control of this platform with brain-inspired layered cognitive architecture [27], and have explored the robot's capabilities in affective communication [28]. In the current paper, we use a pair of MiRo-es to investigate the emergence of attachment-like behavior in a robot dyad modelling the caregiver-child character of the SSP.

2 The Model System

In previous work [14] we modelled motivational dynamics as a particle, here denoted x, moving within a one-dimensional motivational space so as to minimise energy. For two motivations, we define the potential $\Psi(x)$ such that:

$$\Psi(x,u,v) = \frac{1}{2}\left((x+1)^2(x-1)^2 + (x+1)^2\frac{(1-u)}{2} + (x-1)^2\frac{(1-v)}{2}\right), \quad (1)$$

Here u and v are two needs corresponding to the two motivations, these could relate to physiological variables, such as hydration or blood sugar level, or to more psychological constructs such as emotional needs. Equation (1) models an interaction between a fast gradient dynamics for the motivational state, x, and a slower accumulation of the needs. This system will evolve over time to minimise energy by following the negative gradient of the potential.

To model attachment, we assume each robot has two motivations: to receive or give care, and to explore. To simplify the model, we assume that both motivations are encoded by the same underlying need $u = -y$ and $v = y$. This remodels attachment as an approach-avoid conflict. Replacing in equation (1) we get:

$$\Psi(x,y) = \frac{x^4}{2} - \frac{x^2}{2} + xy + \frac{1}{2}.$$

Note that when $y = 0$, this potential has two minima (point attractors), however, as y becomes positive or negative, one of the minima disappears allowing the system to settle on the other one as illustrated in Figure 2).

The slow need accumulation is modelled as

$$\dot{y} = bx + \text{coupling terms.}$$

We showed previously [14] that such a system generates relaxation oscillations therefore we obtain two coupled Van der Pol oscillators represented by the system:

$$\begin{aligned}
\dot{x}_c &= -\frac{\partial \Psi}{\partial x_c}(x_c, y_c) = x_c - 2x_c^3 - y_c, \\
\dot{y}_c &= bx_c - \varepsilon_{Am} f(y_p, y_c) - k_0(\varepsilon_{Av} g(y_p, y_c) + \delta), \\
\dot{x}_p &= -\frac{\partial \Psi}{\partial x_p}(x_p, y_p) = x_p - 2x_p^3 - y_p, \\
\dot{y}_p &= bx_p + \varepsilon_{Am} f(y_p, y_c) - k_0(\varepsilon_{Av} g(y_p, y_c) + \delta).
\end{aligned} \tag{2}$$

Here x_i, where $i \in \{c, p\}$ (c representing child and p representing parent/caregiver), is the current motivational state based on receiving or giving care, and the variable y_i, where $i \in \{c, p\}$, is the accumulated need. ε_{Am} and ε_{Av}, referred to below as the *ambivalence* and *avoidance* terms respectively, are parameters that weight the contributions of the two coupling functions and that link the accumulated needs of the two agents. These are defined as:

$$\begin{aligned}
f(y_p, y_c) &= y_c + y_p \\
g(y_p, y_c) &= y_c - y_p.
\end{aligned} \tag{3}$$

The functions f and g are inspired by the "repulsive" and "attractive“ coupling used in [15]. The rationale behind that choice is explained in the following section. Note that ε_{Am} and ε_{Av} are parameters of the caregiver-child dyad. k_0 and δ are chosen so that the parameters change in the interval $[0, 1]$ in an interpretable way. The dynamics of these caregiver-child dyad parameters and how the model behaves will be explained further below.

3 Dynamics of the Disembodied Model

Figure 2 shows the phase space geometry under different coupling regimes for the caregiver and the child. In all the figures, we show the nullclines for each oscillator (a nullcline is a curve in the phase plane where one of the variables undergoes no change). In the absence of any coupling, the two nullclines intersect in a unstable fixed point and a relaxation oscillation emerges as an attractor for the system (figure 2, left).

In the fully ambivalent scenario, the ambivalence term will push the two oscillators apart by the repulsion mechanism (figure 2, center). On the other hand, the avoidance term will draw them together towards a common fixed point which corresponds to a state of perpetual exploration (figure 2, right).

We now proceed to analyze the full system as the ambivalence and avoidance parameters change.

3.1 Ambivalent regime

When $\varepsilon_{Av} = 0$, we are in the ambivalent regime. The system has 3 fixed points, the trivial one at the point $(0, 0, 0, 0)$ an in-homogenous steady state (IHSS) at

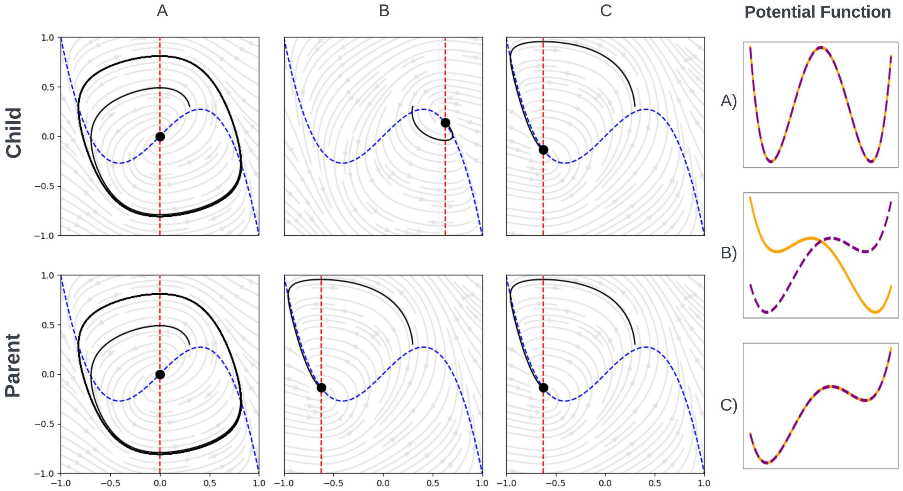


Fig. 2. Illustration of the mechanisms of attachment in the coupled oscillator model. We assume $f(x,y) = g(x,y) \equiv k$ to illustrate the attraction and repulsion effects for illustration purposes. We show the solution to (2) as a closed trajectory in the xy phase space for the child (top row) and for the caregiver (bottom row). The blue curve corresponds to the nullcline $\dot{x} = 0$, th red line is $\dot{y} = 0$. The black dot is a fixed point of the system. A. The first column shows the behaviour of the uncoupled oscillators and illustrates the existence of closed trajectories (i.e. relaxation oscillations). B. Shows the putative ambivalent behaviour with $\epsilon_{Am} = 1$ and $\epsilon_{Av} = 0$. Notice that the system is attracted to opposite fixed points that correspond to perpetual exploration and approach. C. Putative avoidant behaviour, with $\epsilon_{Av} = 1$ and $\epsilon_{Am} = 0$, showing how both agents are attracted to an exploration fixed point. Right column shows the corresponding potential functions $\Psi(x)$ for the child (purple) and for the parent/caregiver (yellow) at the fixed points.

$FP = (\bar{x}, \bar{y}, -\bar{x}, -\bar{y})$, with

$$\bar{x} = \sqrt{\frac{\varepsilon_{Am} - b}{2\varepsilon_{Am}}} \tag{4}$$

$$\bar{y} = \frac{b}{\varepsilon_{Am}} \sqrt{\frac{\varepsilon_{Am} - b}{2\varepsilon_{Am}}}, \tag{5}$$

which are obtained by setting $\dot{x}_i = 0$ and $\dot{y}_i = 0$, and solving he resulting quadratic equation. The later is of interest to us. It can be observed that, as ε_{Am} increases, there is a sub-critical Hopf bifurcation (a transition in the behavior of the system) such that the existing limit cycle loses stability at $\varepsilon_{Am} = b$ and the system settles in an ambivalent steady state in which the needs are opposite to each other. Figure (3) shows the dynamics of the model as the ambivalence parameter increases in the interval $[0, 1]$, (3b) shows the sub-critical Hopf bifurcation.

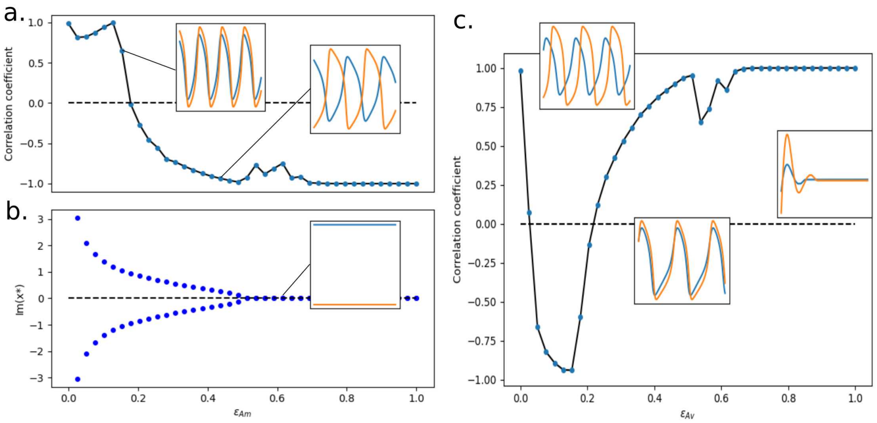


Fig. 3. a. Correlation coefficient of the needs of the parent and the child as the ambivalence parameter ϵ_{Am} increases. For lower values, the dyad is synchronized (inset). As the parameter increases, it becomes quickly uncorrelated until it collapses in an inhomogenous steady state in which the parent is not able to satisfy the needs of the child. b. Subcritical Hopf bifurcation. A limit cycle loses stability and a steady state appears as the parameter increases. Shown in the graph is the imaginary part of the roots in 5. c. The correlation coefficient in the avoidant regime drops quickly for small values of the parameter. This region is characterized by the needs of the child tracking the needs of the parent. Half way through the interval, the system becomes synchronized just before settling into the only steady state: one of continuous exploration or complete avoidance.

In order to understand the interaction between the needs of the caregiver-child dyad, we compute correlation coefficient between the two needs:

$$r(x_c, x_p) = \frac{\sum_i (x_c^i - \bar{x_c})(x_p^i - \bar{x_p})}{\sqrt{\sum_i (x_c^i - \bar{x_c})^2}\sqrt{\sum_i (x_p^i - \bar{x_p})^2}}. \tag{6}$$

The dyad starts synchronized but promptly becomes desynchronized and then antisynchronized as the parameter increases in the oscillatory regime; when the child needs care, the parent is not available to provide it.

3.2 Avoidant regime

When $\varepsilon_{Am} = 0$ we are in the avoidance regime. The system has a unique fixed point at $(\bar{x}, \bar{x}, \bar{y}, \bar{y})$; the dyad tend towards the same steady state. This state is given by the solutions of the cubic equation:

$$x^3 + \frac{1-q}{2q}x + \frac{\delta}{2} = 0,$$

with $q = \frac{k_0 \epsilon_{Av}}{b}$. We have chosen k_0 and δ such that

$$-\Delta = -4\left(\frac{1-q}{2q}\right)^3 - 27\left(\frac{\delta}{2}\right)^2 < 0,$$

for all $\epsilon_{Av} \in [0,1]$, so that there is only one fixed point. Δ is the discriminant obtained from solving the depressed cubic equation. Similar to the ambivalent case, this fixed point becomes stable as the parameter increases, however, in this case, it is shared by both agents in the system. Figure (3c) shows the dynamics of the correlations in the avoidant dyad.

4 Robotic implementation

We implement the attachment dynamical model in a robot-robot dyad, where one robot assumes the role of the parent/caregiver and the other the role of the child.

4.1 Action selection

To select actions, we use readout functions that indicate whether the approach or explore behavioural systems should be activated. When the motivational state is positive, the approach behavioural system controls the robot, and when it is negative, the exploration system takes over. Mathematically, we express the activation level of each system as:

$$A_{\text{approach}}(x_i) = \Theta(x_i), \tag{7}$$

$$A_{\text{explore}}(x_i) = \Theta(-x_i), \tag{8}$$

where $\Theta(\cdot)$ is the Heaviside function (a form of step discontinuity). Following [11], we define a way of influencing the other agent's motivational state by the perceived physical (d_p) and emotional distances (d_e) between them. To achieve this, we modify equations in (9) to include those behavioural estimates:

$$\begin{aligned} f(y_p, y_c) &= y_c + y_p \pm d_p \\ g(y_p, y_c) &= y_c - y_p - d_e. \end{aligned} \tag{9}$$

Therefore, the physical distance influences the ambivalent coupling while the emotional distance influences the avoidant coupling. The emotional distance (d_e) increases over time following the first order equation:

$$\dot{d_e} = \kappa_e(1 - d_e), \tag{10}$$

when there is no care being given, and is reset to $d_e = 0$ once a care-giving interactions is successful. κ_e is the rate of accumulation of the emotional distance. The emotional distance here is considered as emotional connectivity, which we treat here as similar to physiological needs such as thirst or hunger. This need is considered to be satisfied through interactions such as care-giving interactions.

The physical distance is the normalized euclidean distances from the parent:

$$d_p = \min\left(1, \frac{d_x(p_c, p_p)}{L}\right), \tag{11}$$

where $d_x = \|p_c - p_p\|_2$, p_c and p_p are the position vectors of the child and the parent, estimated from odometry data, and L is the size of the arena.

In this work, both agents have access to the internal accumulated needs of the other agent as required for the coupling of the oscillators, therefore the effects of d_p and d_e are only modulatory. Future work will focus on the estimation of these variables from behaviour. Here, we consider responsiveness and availability to the other agent as a measure of physical distance, thus we base this calculation on the caregiver and child's respective positions.

4.2 Giving care

The caregiving interaction happens by means of vocalizations performed using MiRo's biomimetic voice synthesis [30]. Each agent accumulates evidence about the interaction using a simple drift diffusion process (see figure 4):

$$dX_i = (-aX_i + I) + \sqrt{\sigma} dW, \tag{12}$$

where a is the rate of accumulation and σ the variance of the random process. The parameters of the stochastic equation are chosen empirically to match the rates and time scale of the oscillation. The input I is defined through a simple template matching algorithm: each robot's audio input is continuously sampled by the approach motivational system for energy peaks in the preferred frequency bands of each agent. Those bands correspond to the bands and harmonics where the biomimetic vocalization is more likely to occur depending upon the mass of the animal being simulated [30].

Because both the vocalization and the environment are noisy, the caregiving interaction is only complete after enough evidence is accumulated following the procedure described in figure 4 (right).

The caregiving interaction for the caregiver has been designed to start from the first threshold where it simultaneously makes and expects audio responses until it crosses a threshold where it deems the child's responses satisfactory. In the case of the child, it will begin from below the first threshold, and either randomly drifts towards it or cross over it when it receives enough stimulation from the caregiver. The architecture of the system along with the dynamics of the caregiving interactions are shown in figure (4).

5 RESULTS

5.1 Robot implementation

The two MiRo-e robots [26]—one representing the parent/childgiver and other the child——were placed in a enclosed square arena with wide field camera record-

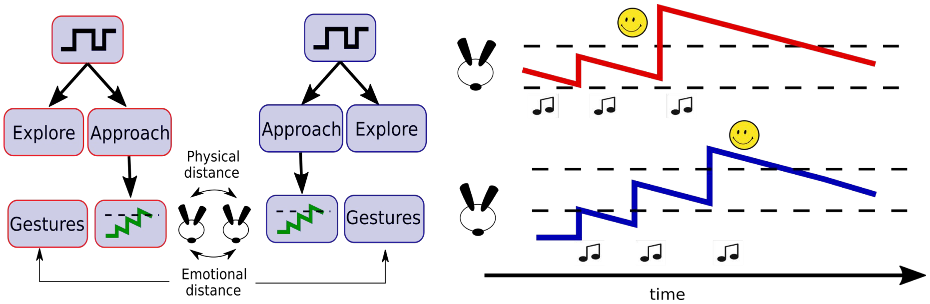


Fig. 4. Left. Cognitive architecture of the child and caregiver robots. The oscillator controller acts as a motivational switch that activates one of the two parallel behavioural systems—approach and explore (see figure 5)—depending on need state. Right. Evidence accumulation for the caregiving interaction. The process has two thresholds. The first one initiates vocalizations for each agent. Once the accumulation is above the first threshold, the agent will respond with a new vocalization each time it detects a potential response. The process finishes after crossing the second threshold at which point the emotional distance is reset to 0.

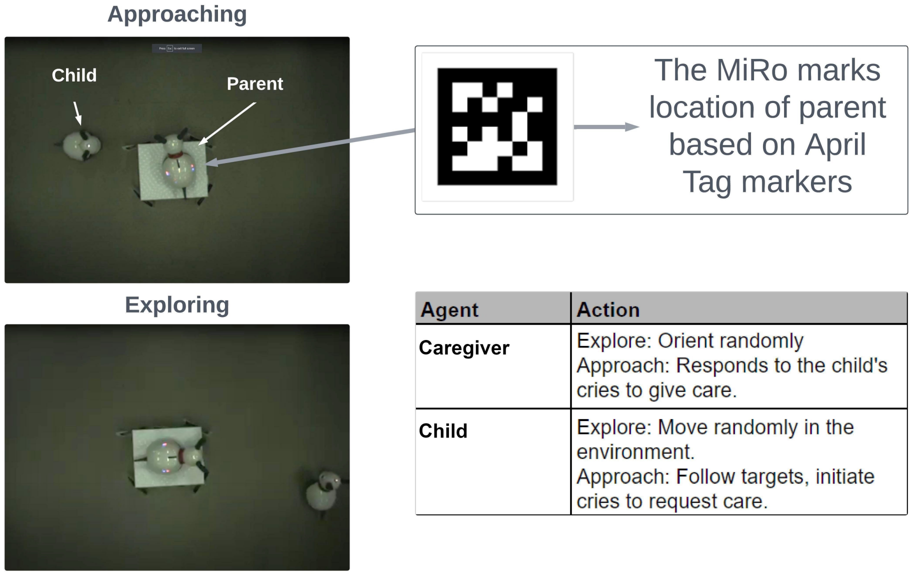
ing their interaction and with a reflective marker on the head of the child robot for tracking (see figure 5). The caregiver robot was located in a box surrounded by april tags that the child could easily detect. The parent/caregiver attends to the child as part of its exploration routine but giving/receiving of care was based solely on vocalizations (as explained above).

We tested the model system over multiple episodes of X minute duration, initialising the model each time, and using appropriate parameter values to generate behavior patterns relating to the different attachment regimes——secure, avoidant and ambivalent (See figures below and supplementary videos). Based on our disembodied model (specifically, the correlations between oscillators shown in figure 3), we identified three regions of parameter space corresponding to putative secure, ambivalent and avoidant regimes.

For lower values of the parameters (secure regime), the child explores the arena and uses the caregiver as a secure base. Each caregiving interaction is successfully completed (figure 6). Note that interactions tend to be short and happen only when the infant is close to the caregiver.

A putative avoidant attachment is achieved for mid-range parameter values $\epsilon_{Av} \approx 0.6$ where the two oscillators are synchronized but the avoidant state dominates. The child spends more time away from the parent having short bouts of vocalizations before switching back to exploration (figure 7, left).

Finally, an ambivalent dyad is observed for higher values of the parameter $\epsilon_{Am} > 0.6$, where the oscillators are anti-synchronized. Calls for care are not reciprocated by the caregiver and the child spends increasing amounts of time close to the base, in need of care, while the caregiver ignores its calls (figure 7 right).



Agent	Action
Caregiver	Explore: Orient randomly Approach: Responds to the child's cries to give care.
Child	Explore: Move randomly in the environment. Approach: Follow targets, initiate cries to request care.

Fig. 5. Experimental setup of the robot-robot SSP. The arena is an enclosed region in the robotics lab with a box in the middle, on top of which sits the caregiver. The child is tracked with a reflective marker. The box is surrounded with April tag markers that serve as targets for the child's approach behaviour. Once the child is close to an April tag it starts asking for care by vocalising. The approach routine of the caregiver consists of orienting towards the child and responding to care requests. The exploration routine of the child consists of choosing random points in the arena to explore; for the caregiver, it consists of random orientations withing the box. The table in the figure shows the different actions available to the caregiver and child robots.

6 Conclusions and future work

This research advances the understanding of human relationships by presenting a novel dynamical model of human attachment viewed as the behavioural coupling of two oscillators. Moreover, we have demonstrated, in an embodied implementation using a robot dyad, that clear patterns of attachment can be detected for different parameters values that resemble the results of quantitative studies on human attachment [8]. For instance, we show in Figure 6, a pattern of oscillatory behavior, for the secure attachment scenario, with alternating bouts of exploration and care-seeking, that resembles that illustrated in figure 1 for the SSP. Interestingly, the patterns of distances and vocalizations, in our robot model, vary greatly for different parameter regimes, with episodes of low and high proportions of vocalizations as observed in human dyads when placed in the strange situation. Our dynamical model predicts clear regions of synchronicity, antisynchronicity, and steady states in the phase space. Additionally, just before the transition to a steady state, we observe non-periodic regimes (crit-

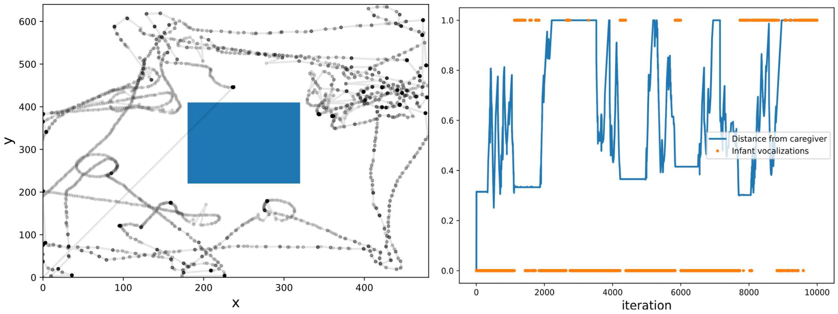


Fig. 6. Left. Trajectory of the child relative to the caregiver located at the blue square in a secure scenario $\epsilon_{Am} = 0.1$ corresponding to a parameter regime in which both oscillators are synchronized. The child explores the space safely and returns to base regularly. Right. Distance from the base (center of the arena) normalized and plotted in blue, higher values indicate exploration bouts. Vocalizations are indicated in orange, where a value of 1 indicates a request for care. In the secure regime, vocalizations occur close to the caregiver and are attended to immediately (as indicated by their length).

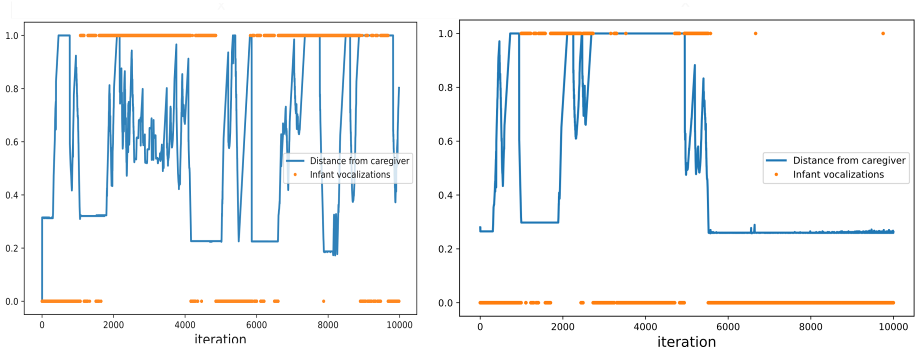


Fig. 7. Distance and vocalizations as in figure (6) for avoidant and ambivalent regimes. Left. Avoidance—the child spends most of the time far from the parent and the exploration bouts are punctuated by short care request attempts before switching back to exploration. Right. Ambivalence—the calls for care are usually unattended. The child spends increasing time close to the base while the parent ignores the care requests.

ical fluctuations). Future work could test these predictions directly by careful tracking of parent-child interactions.

A limitation of the current model, that we are working to understand, is that the bifurcation in the original dynamical model is not reproduced in our robotic implementation. Future work will also focus on improving the estimation of the physical and emotional distances based on observed behaviour and care received. This aspect relies on an accurate estimate of the robots' physical location relative to each other, the detection of each other and their gestures, and the capacity to learn the correct parameter values over time. Improvements in coupling between the agents may help in matching the dynamics of the theoretical model, alternatively, the theoretical model could be modified in recognition that coupling will always be noisy and imperfect.

The results of studies also show that a coupled oscillator model of attachment can generate visually-appealing and temporally-rich patterns of human-robot interaction that could be useful in developing application of social and companion robots, whose behavior can otherwise appear stereotyped (leading to loss of interest). Robillard and Hoey [4] have proposed that assistive technologies, such as robots, can usefully align their emotional expression with the emotional state of the user; our study suggests methods for implementing alignment in robot behavior, which could lead to advances in the development of therapeutic robots.

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