Socially Developmental Robot based on Self-Induced Contingency with Multi Latencies

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Summary

Early social development is a process that a human infant and his/her caregiver adapt to each other. This paper presents a learning mechanism to find the contingency of human-robot interaction in the real world, which is intended to enable similar process to the mutual adaptation in the infant-caregiver interactions. A contingency measure based on information theory is applied not only to acquire behavior rules but also to find suitable latency to observe the found contingency. Experimental results show that a robot can acquire a series of social behavior such as gaze following and utterance to a human subject through 20 minutes interaction. Mutual adaptation between them is discussed in terms of transition and synchronization of their behavior, based on the analysis of the interaction data.

1 Introduction

Human infants acquire a variety of social behavior and gradually socialize through various interactions with their caregivers [1]. For example, they become to follow the gaze of an adult and then begin to show gaze alternation, i.e., successive looking between a caregiver and an object, and pointing. However, it remains unclear how these abilities are acquired through multimodal sensorimotor association with their caregivers.

When we try to understand such a learning process, we need to consider not only the information processing for learning in an infant but also dynamics of the interaction with a caregiver because the caregiver adapts himself/herself to infant development. In other words, it is necessary to model mutual adaptation of dynamics among cognition and actions of both an infant and a caregiver. However, it seems difficult to study such adaptation and to understand how an infant adapts itself to its caregiver. A simple computational model might miss key elements such as response time to a caregiver.

We approach to reveal a basic mechanism underlying the dynamics of early social development from a viewpoint of the cognitive developmental robotics [2]. As a learning principle of an infant, we focus on contingency that refers to a rule of environmental changes caused by a certain action given a certain context. Finding contingencies in the interaction with another person is supposed to be the most fundamental for early social development [3]. Synthetic studies have reported that such ability allows a robot to acquire a social skill such as gaze following [4] and detection of responses from another person [5]. Although some mechanisms based on contingency or similar principles have been proposed for learning several motor skills

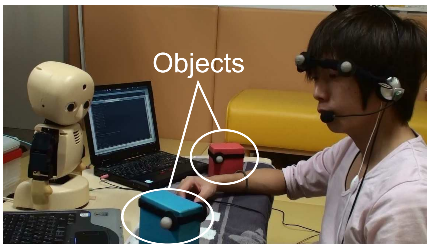

Figure 1: An experimental setup

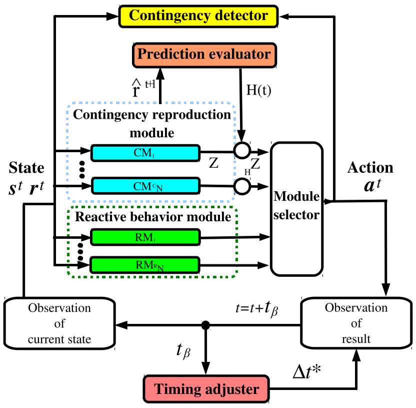

Figure 2: The proposed mechanism.

or social ones [6, 7, 8], computation time was unrealistic [8] or time interval to find contingencies in the interactions was fixed [6, 7, 8].

In this paper, we build and examine a robot that extracts contingencies from the interaction with a person and utilizes them as behavior rules for realizing mutual adaptation with the person. A contingency measure proposed in [8] is applied not only to find the behavior rules but also to improve them online in order to refine the robot's behavior during the interaction. It is also used to find suitable time intervals between robot's actions to highlight the found rules. Experimental results show that a robot can acquire a series of social behavior such as gaze following and utterance to the human subject through 20 minutes interaction.

2 Methods

We assume a scene of human-robot interaction where a person sits across from a robot and tries to teach it colors of objects on a table between them (see Fig.1). We also assume that the robot detects the following information: locations of objects, orientation of the human's head, human's utterance, and its own posture. The robot executes actions such as gaze shift and vowel utterance. These senses and actions are represented and processed in a discrete manner. The robot has no knowledge about relations among them at the beginning.

Let s_i^t and a_j^t be a state of sense S_i and a motor command for act A_j at time t, respectively. Contingency among s_k^t, a_j^t, s_i^t, and $s_k^{t+t_\beta}$, is measured as the reliability of the transition rule from s_k^t to $s_k^{t+t_\beta}$ caused by a_j^t given s_i^t. We refer to a combination $(S_k|S_i, A_j)$ as an *event*. The task of the robot is to find several events with larger expected values of contingencies than other possible ones. The found values are then exploited for learning behavior rules and for tuning time interval t_β between its actions so as to highlight the contingencies.

We use the information theoretic measure proposed by Sumioka *et al.* [8], called C-saliency, to evaluate contingencies in each event. C-saliency of an event $(S_k|S_i, A_j)$ is given by:

$$\begin{aligned} C_{i,k}^j &= T_{(S_i,A_j)\to S_k} - \left(T_{S_i\to S_k} + T_{A_j\to S_k}\right) \\ &= \sum_{s_i^t, s_k^t} p\left(s_k^t, s_i^t\right) \sum_{s_k^{t+t_\beta}, a_j^t} e\left(s_k^{t+t_\beta}, a_j^t \mid s_k^t, s_i^t\right), \end{aligned}$$

where $T_{Y\to X}$ shows transfer entropy [9] representing the dependency of a process X on a process Y, and $e(s_k^{t+t_\beta}, a_j^t \mid s_k^t, s_i^t)$, called an element of C-saliency, indicates the reliability of the contingency among $s_k^{t+t_\beta}$, s_k^t, a_j^t, and s_i^t. A behavior rule is defined as selecting an action with the highest element of C-saliency.

The robot incrementally acquires behavior rules based on the extended mechanism of the previous method proposed in [8] (Fig.2). The mechanism includes a prediction evaluator to ignore doubtful behavior rules and a timing adjuster to tune time interval for each rule to highlight the found contingencies, in addition to four existing modules: 1) a contingency detector; 2) contingency reproduction modules (CMs) that output motor commands according to behavior rules; 3) reactive behavior modules (RMs) that output ones according to predefined rules; and 4) a module selector.

RMs and CMs output motor commands to be executed and the reliability values that are computed based on elements of C-saliency. The reliabilities are used by the module selector to decide robot's actions after they are modified by the prediction evaluator. The history of the current state and the selected motor command are stored with the resultant state in the contingency detector to find a contingent event and to generate subsequent CM based on it. A behavior rule in the CM is updated online so that the C-saliency of the contingent event increases, while it was fixed in [8].

Although a robot and its caregiver were assumed to alternately act at a fixed time interval in the previous model [8], it is not likely in the real world interaction. The timing adjuster finds an appropriate time interval to observe contingent change caused by the last action of the robot, based on the prediction of the change. This module allows the robot to take its next action at different interval.

3 Results

We implemented the proposed mechanism into a humanoid robot and observed its interaction with a person during about 20 minutes. In the interaction, the person responded to its behavior and tried to draw its attention to an object. Its senses and acts were given and represented by six sensory variables, allowing the duplicated definitions for the same property, and two action ones: orientation of person's head (S_1), a state of an object (S_2), person's utterance (S_3), person's frontal face (S_4), person's profile (S_5), own posture (S_6), gaze shift (A_1), vowel utterance (A_2).

The robot was able to acquire various behavior rules with different time intervals, although their types, orders, and intervals depended on the history of the interaction. We pick up and analyze a case where it acquired some social skills. Fig. 3 shows the change of its behavior through the interaction with a person. It found a rule in $(S_3|S_2, A_2)$ that its utterance to an object causes human's utterance (U-1) and then often chose to utter a vowel when looking at an object (green line in Fig. 3-B). Then, it become to often keep its gaze on an object due to the next rule found in $(S_2|S_6, A_1)$ at G-1 (cyan line in Fig. 3-A). After that, the utterance during looking at the person (red line in Fig. 3-B) and shifting its gaze to the person given human utterance (magenta line in Fig. 3-A) increased from U-2 and G-2, respectively. Finally, it became to follow the person's gaze by using the rule found in $(S_2|S_1, A_1)$ at G-3 (red line in Fig. 3-A).

An analysis of time intervals found by the robot revealed different tendencies between events concerning objects and those concerning the person (Fig. 4). The time interval for objects had a peak immediately after the last robot's action while one for the person was observed a few seconds later which is considered to correspond to the duration between a robot's action and a human response. As a result, longer interval was observed when a contingent change concerning the person was expected, compared to one concerning an object.

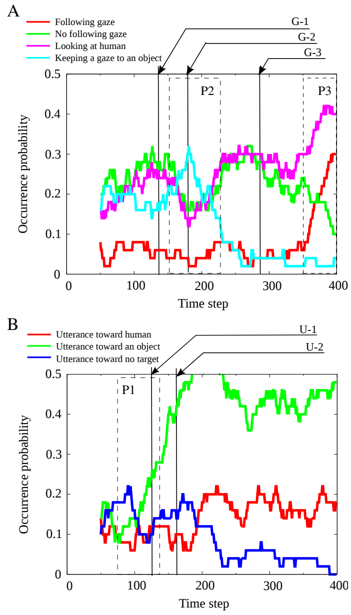

Figure 3: Change of robot's behavior in face-to-face interaction. (A) change in gaze shift (B) change in utterance. One step in the horizontal axis indicates action selection of the robot. The vertical one indicates the moving average of the occurrence rate of each behavior among the last 50 steps. The timing of generating new CMs is shown as arrows at the top of the graphs.

4 Discussion

We observed changes of the dynamics of person's behavior as well as ones of the robot even during 20 minutes interaction (see Fig.5). The person increased the utterance to an object (blue line in P1 of Fig.5-B) as the robot increased its utterance to an object (green line in P1 of Fig.3-B). The person's utterance to the robot was often observed when the robot kept its gaze on an object (aqua line in P2 of Fig.3-A and red one in P2 of Fig.5-B). When the robot became to follow the person's head (red line in P3 of Fig.3-A), the person often uttered a vowel to an object (blue line in P3 of Fig.5-B). Since the changes in the person seem to synchronize with ones in the robot, these results might show that mutual adaptation between them creates new interaction patterns.

We also observed the synchronization between the person and the robot in terms of the timing of their actions. The robot and the person took ac-

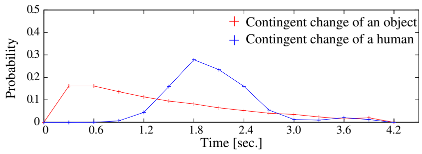

Figure 4: Examples of probability distributions of the contingent changes observed during 4.5 seconds after the last robot's action. The red and blue lines show the case of contingent change for an object (G-1) and one for a human (U-1), respectively.

tions alternatively as the interaction develops: the ratio in Fig. 5-C approached to one, Moreover, the time interval between their actions seemed to get shorter (data not shown). This might imply that mutual adaptation between an infant and a caregiver shapes temporal structures of the interaction.

Although similar tendencies were observed among some of persons, there was a diversity of their behavior patterns. Further analysis on the influence of person's behavior on learning of the robot will shed light on how the behavior of a caregiver facilitates early social development.

We built a robot that could acquire a series of social behavior through the 20 minutes interaction with a person. By virtue of the shorter time scale necessary for mutual adaptation, the proposed system is expected to provide a new research field where early social development can be synthesized and examined through human-robot interaction.

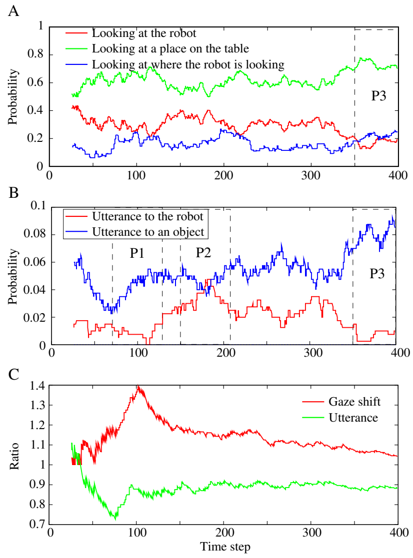

Figure 5: Changes of human's behavior. (A) change in gaze shift of the human. (B) change in human's utterance. (C) transition of the ratio of the number of actions to a robot's action. A step in the horizontal axis shows the robot's action selection. The vertical one shows the moving average among the last two minutes before robot's action.

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