CB^2: A Child Robot with Biomimetic Body for Cognitive Developmental Robotics

Takashi Minato #[1], Yuichiro Yoshikawa #[2], Tomoyuki Noda *[3], Shuhei Ikemoto *[4],
Hiroshi Ishiguro #*[5], and Minoru Asada #*[6]

#*Asada Project, ERATO, Japan Science and Technology Agency*
Graduate School of Engineering, Osaka University
2–1 Yamada-oka, Suita, Osaka 565–0871, Japan
[1 2]`{minato,yoshikawa}@jeap.org`
[5 6]`{ishiguro,asada}@ams.eng.osaka-u.ac.jp`

**Dept. of Adaptive Machine Systems, Graduate School of Engineering, Osaka University*
2–1 Yamada-oka, Suita, Osaka 565–0871, Japan
[3 4]`{tomoyuki.noda,shuhei.ikemoto}@ams.eng.osaka-u.ac.jp`

***Abstract*— This paper presents a new research platform, CB^2, a child robot with biomimetic body for cognitive developmental robotics [1] developed by the Socially-Synergistic Intelligence (Hereafter, Socio-SI) group of JST ERATO Asada Project. The Socio-SI group has focused on the design principles of communicative and intelligent machines and human social development through building a humanoid robot that has physical and perceptual structures close to us, that enables safe and close interactions with humans. For this purpose, CB^2 was designed, especially in order to establish and maintain a long-term social interaction between human and robot. The most significant features of CB^2 are a whole-body soft skin (silicon surface with many tactile sensors underneath) and flexible joints (51 pneumatic actuators). The fundamental capabilities and the preliminary experiments are shown, and the future work is discussed.**

Fig. 1. The developed humanoid robot CB^2.

I. INTRODUCTION

This paper presents a new research platform, "CB^2", a **C**hild-robot with **B**iomimetic **B**ody for cognitive developmental robotics [1] developed by the Socially-Synergistic Intelligence (Hereafter, Socio-SI) group of JST ERATO Asada Project. Based on the cognitive developmental robotics, the Asada project aims at understanding the human developmental process of cognitive functions through mutual feedback between scientific and synthetic approaches by building a humanoid robot in which a computational model of the development is embedded. Among four different groups [2], the Socio-SI group has focused on the design principles of communicative and intelligent machines and human social development through building a humanoid robot that has physical and perceptual structures close to us, that enables safe and close interactions with humans. For this purpose, CB^2 was designed, especially in order to establish and maintain a long-term social interaction between human and robot.

We focus on a development of timing control and temporal concepts which may be required for a development of communication skill. Here the timing control basically means to create a temporal condition which is most effective for a response [14]. To enable to control action timing toward others and surrounding environments is a necessary developmental process for robots or infants to establish a communication with others. The sense of time is not associated with a specific sensory organ unlike the vision or audition; it is induced by other perceptions. In other words, the sense of time is strongly relevant to other different perceptions. It is, therefore, possible to discover not only a factor to induce a function development but also interactions between developments of various functions through studying the development of timing control. We perform the preliminary studies on the developmental mechanism of timing control in terms of sensory-motor organization, interpersonal responsive behaviors, and motion capabilities in order to construct developmental models of both

TABLE I

COMPARISON OF HARDWARE SPECIFICATION.

	Joint flexibility	Soft and sensitive skin	Actuators mounted throughout whole-body	Humanlike appearance	Child size
Robovie-II [3]	No (Electrical motors)	No	No (Upper body)	No	No
Infanoid [4] BARTHOC [5]	No (Electrical motors)	No	No (Upper body)	No	**Yes**
iCub [6]	No (Electrical motors)	No	**Yes**	No	**Yes**
Robovie-IIF [7]	No (Electrical motors)	**Yes**	No (Upper body)	No	No
ASIMO [8] QRIO [9]	No (Electrical motors)	No	**Yes**	No	**Yes**
SAYA [10]	**Yes** (Pneumatic actuators)	No (No tactile sensor)	No (Head)	**Yes**	No
Repliee R1 [11]	No (Electrical motors)	No (No tactile sensor)	No (Head)	**Yes**	**Yes**
Repliee Q2 [12] Geminoid [13]	**Yes** (Pneumatic actuators)	**Yes**	No (Upper body)	**Yes**	No
CB^2	**Yes** (Pneumatic actuators)	**Yes**	**Yes**	**Yes**	**Yes**

human and robot.

The ability to communicate and establish relationships with humans cannot simply be programmed into a robot. The robot must develop these skills much as humans do from early childhood on. Moreover, just as in childhood, other humans' help is necessary to aid normal development. To this end, it is necessary to develop a robot which is able to elicit others' help and to interact safely and tightly with persons in many ways, such as "help the robot stand up by holding it" and "teach a body motion by directly moving its limbs." In other words, it is necessary that assistive behaviors of human helper naturally appear during the developmental process of the robot's behaviors. We therefore have designed and built a new humanoid robot CB^2 that is able to tightly and safely interact with persons in daily life in advance of constructing the developmental models. CB^2 has a humanlike appearance similar to a child-sized boy. It also has much more actuators throughout its body to make human-like motions than the existing human-size humanoid robots. To make the interaction more natural and safer, we use flexible pneumatic actuators, and the body is covered in soft silicone skin. Various sensory organs are also necessary. CB^2 has two cameras inside its eyes, two microphones in the ears, and tactile sensors beneath the silicone skin. Table I compares CB^2 with the typical humanoid robots for studying human-robot communication and human development with respect to the presence of several features which are required for natural and tight human-robot interaction. The joint flexibility and the soft and sensitive skin provide tight interaction with humans. The humanlike motion owing to the actuators mounted throughout whole-body and the childlike appearance invite child-directed behaviors from humans. Only CB^2 provides all the features and therefore it can be said that CB^2 is a novel research platform for studying a developmental mechanism through human-robot interaction.

The next section shows the specifications of CB^2, and three preliminary but essential studies using CB^2 are introduced with their future works.

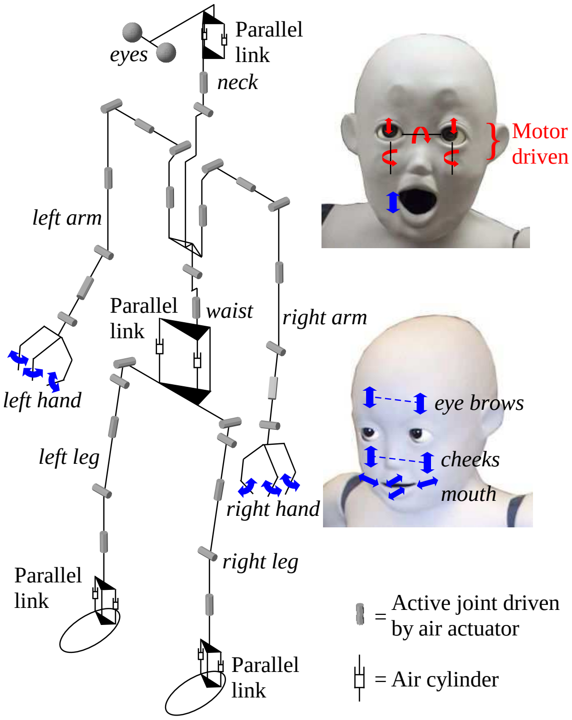


Fig. 2. The kinematic structure of CB^2.

II. THE DEVELOPMENT OF CB^2 AS A NEW RESEARCH PLATFORM

CB^2 (Fig.1) is a new research platform for studying a developmental mechanism through human-robot interaction in that CB^2 has all of the following features.

- It has a humanlike appearance similar to a child-sized boy. It is about 130cm high and weights about 33kg.
- It has fifty-six actuators (Fig.2).

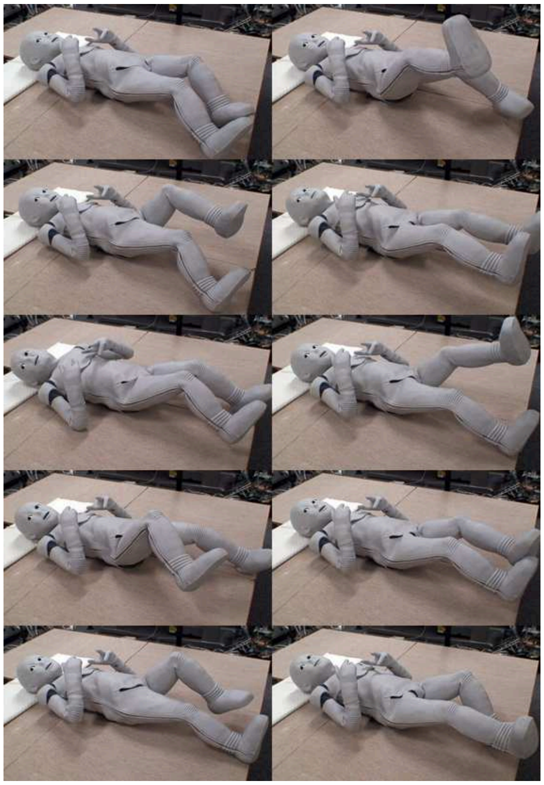


Fig. 3. An example of flexible whole-body movement: an infant's general movement.

- It has flexibly controlled joints thanks to pneumatic actuators.
- The whole-body is covered in soft silicone skin (Fig.5).
- It has many tactile sensors throughout its body (Fig.6).

As shown in the kinematic structure of Fig.2, CB^2 has totally fifty-six actuators; the eyeballs and eyelids are driven by electrical motors since quick movements are required for these parts while the other body parts are driven by pneumatic actuators. The joint driven by the pneumatic actuator has mechanical flexibility in the control thanks to the high compressibility of air. The pneumatic actuators mounted throughout the whole-body enables CB^2 to generate flexible whole-body movements. Although the mechanism is different from a human, it can generate humanlike behavior (although it has a more limited range of movements than that of humans). Fig.3 shows an example of baby-like motion in the similitude of an infant's general movement. Taga et al. have shown that the chaotic dynamics of the neural system is a source of variability of the general movements [15]. In order to generate chaotic movements, the joint angle trajectories in the lower half of the body were generated from a trajectory on the Lorenz attractor in this example. CB^2 can generate not only a fidgety motion but also a dynamic whole-body motion. Fig.4 shows such an example motion. CB^2 turns over onto its left side by making use of the inertia forces of the legs. It is difficult to stand up, walk, and run by itself because the power of these actuators is not sufficient. These motions are however possible, if a person helps it. In addition to gross body movements, CB^2 can also make facial expressions although these are not as rich as those of a person. Existing robots typically use powerful electrical motors, which make it dangerous for us to tightly interact with them. The soft skin and flexible actuators (which do not strongly fight against an external force) increase the safety and promote feelings of security, inviting tighter interaction from people. Moreover, we can expect that the childish appearance and humanlike movement elicit interpersonal behaviors toward CB2^2 from people.

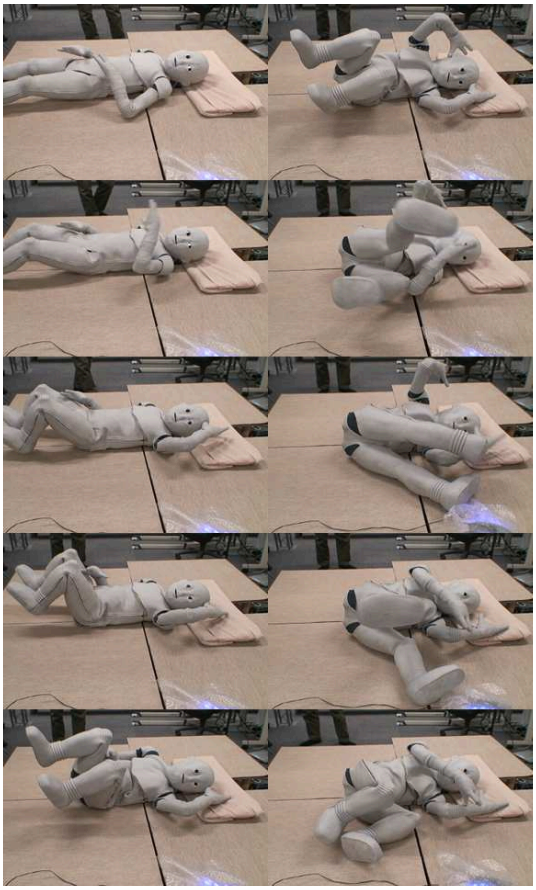
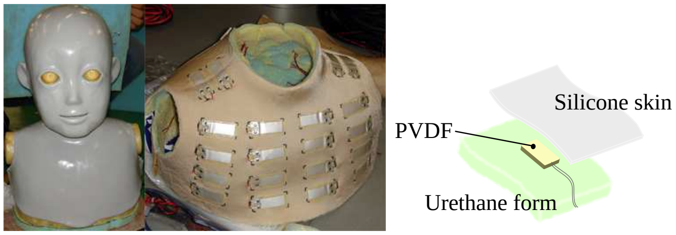


Fig. 4. An example of dynamic whole-body movement: rolling over.

The pneumatic actuator is controlled by an air flow control valve (the operating pressure is constant (0.7 MPa)). Although the output torque of the pneumatic actuator cannot be controlled, the response characteristic varies owing to the flow rate. The joint driven by the pneumatic actuator can be passively moved by releasing the compressed air. CB^2 has also an artificial vocal tract (rather than a simple speaker) and can produce a voice quite similar to human vowel sounds using the flexible vocalization mechanism [16].

The vision is realized by two cameras mounted inside the eyeballs, and the audition is realized by two microphones mounted both on the head, and located externally, around CB^2. The tactile sensation is realized by the tactile sensors using PVDF films embedded beneath the skin. The sensor output



(a) The silicone skin and tactile sensors.

(b) The skin structure.

Fig. 5. The tactile sensor.

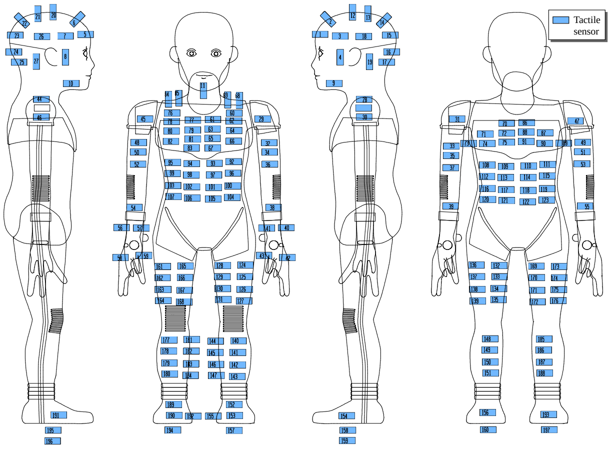


Fig. 6. The tactile sensor layout.

is proportional to the rate of change of bending (deformation rate). The information equivalent to a contact force is obtained by temporal integration of the sensor output. The tactile sensors are put between urethane foam covering the mechanical parts and the silicone skin. A touch on the skin where no sensor is located can be detected because the deformation of urethane foam is spatially spread. 197 tactile sensors cover the whole body as shown in Fig.6 and realize a whole-body tactile sensation. All sensor outputs can be read in 100 Hz.

CB^2 is not a stand-alone system: the control valves, air compressor, and computers for controlling actuators and sensor information processing are placed outside the body. In spite of this, it can continuously work for a long period (for all the day).

III. PRELIMINARY STUDY WITH CB^2 – SELF-ORGANIZED SENSORY-MOTOR INTEGRATION

As robots become more ubiquitous in our daily lives, the physical distances between humans and robots decreases. This increases the potential for robots to inadvertently harm users. Moreover, it becomes increasingly important for robots to be able to interpret the meaning of touch (or haptic) feedback from humans. Covering the whole robot body with malleable tactile sensors addresses both of these concerns. First, soft and compliant surfaces are less dangerous in the event of accidental human impact. Second, flexible sensors are capable of distinguishing many different types of touch (e.g., hard v.s. gentle stroking). The soft skin has the additional advantage of inviting more natural types of touch interaction from humans. Unfortunately, the processing information from these types of sensors presents a difficult challenge. To get a better understanding of this domain, we have constructed a database of recorded interactions between humans and a robot equipped with tactile sensors covering the whole body (Robovie-IIF [7]), and performed several classification and visualization tasks. Using a novel feature space based on cross-correlation between tactile sensors, we have found that interaction scenarios in which we can expect subject's touch could be successfully classified simple k-nearest neighbors, achieving performance of 60% in a 13-way forced choice task [17]. We have also found that many categories of touch interactions can be easily visualized by arranging sensors into a "Somatosensory Map" using multidimensional scaling (MDS) applied to this feature space as a similarity measure. On the other hand, the maps visualized from categories without touch interactions showed a same distribution of sensors. This means that the cross correlations in a short time window are stable except during touch interaction. Fig.7 shows the "Somatosensory Map" derived from tactile sensor signals obtained when CB^2 is touched at the head, the hands, and the body during a interaction with a person. This map is different from the self-organized somatosensory map shown in [18] in that a structure of the actual task (haptic interactions with a person) is reflected in the map. The interactions are also visualized in the map showing distinctive clusters consisting of the touched parts of sensors. These promising results suggest that this feature space can be effectively used for automatic analysis of touch behaviors in more complex tasks and in various types of robots.

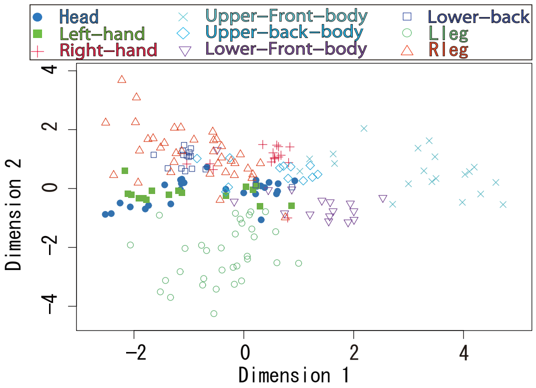


Fig. 7. The somatosensory map of CB^2. In this map the sensors which have a high correlation with each other are closely placed. The map is generated a cross-correlation between 197 sensor outputs obtained when a person touches CB^2's hand, head, torso and so on.

While Robovie-IIF has built-up constructed skins separated at the joints, CB^2 has a seamless skin in terms that the materials embedding tactile sensors are not separated at the multiple joints. This feature always causes various self-touches which are tactile senses caused by own movements, and requires self movement information for classifying tactile sensor signals. If it is possible to assume that the robot knows a tactile sense caused only by self movement in advance, it can be removed from the total tactile senses. However, this assumption is not satisfied because a part of the robot's body is always in contact with something in the real world (e.g., robot's feet are always in contact with a floor). Furthermore, a problem to discriminate a factor caused by self movement from other actors can be seen in the human development process. This kind of problem is supposed to be solved by introducing a temporal concept. In the future, we explore a mechanism to discriminate self from others through developing a method to associate a tactile sense with a body movement based on the classification method we have developed.

IV. PRELIMINARY STUDY WITH CB^2 – DEVELOPMENT OF MULTIMODAL COMMUNICATION

In addition to the childlike properties, CB^2 is provided with multimodal sensing capabilities, such as vision, audition, and touch, to capture what humans usually perceive. They are supposed to be a basis of the CB^2's potential to exhibit responding behaviors in a way how a person usually anticipates in other persons' responding behaviors. Furthermore, it is thereby expected to derive human's interpersonal perceptions and behaviors in the interaction with CB^2, which are originally supposed to be shown in human-human interaction.

Such responsiveness is regarded as an important element with which a person gives others an impression that the person is a communicative being for the others [19]. To reveal feasible mechanisms for such responsiveness, we have started an experiment with an interactive anthropomorphic on-screen agent by focusing on the effects of the response timing. In the experimental setup, a participant was asked to sit across from an on-screen agent that was designed to blink in response to the participant's blinking, and then answer on a question, "did she feel that the on-screen agent looked at her?". Yoshikawa et al. reported that the agent could give participants stronger feeling of being looked at by it if it responded with not too rapid but not too slow latencies [20]. This result implies that controlling the timing of response even with a subtle channel of communication such as blinking could change the participants' impression on an interactive agent. In the future, we expect that we can model how a person anticipates in other's responses through revealing the relationship between multimodal channels and the timing of them in the experiments with CB^2.

Furthermore, it is a formidable issue to answer on a developmental question, how a robot or infant can acquire such response timing of multimodal channels and the mechanism to recognize others based on such timing. Since persons might unconsciously anticipate CB^2 to respond in a childlike way due to its childlike properties, it could be a promising experimental tool to model on which ways of responding persons forms impression of child-likeness and exhibits child-directed behaviors for CB^2. Through such experiments, we also plan to approach to the mysteries on the infant/robot cognitive development of 'others' concepts from the viewpoint of what kinds of robot's responses can derive a caregiver's child-directed behaviors and how these behaviors can help or guide the development.

V. PRELIMINARY STUDY WITH CB^2 – SOCIALLY MOTOR DEVELOPMENT

The flexible joint driven by the pneumatic actuator provides high safety and robustness against breakdown caused by an external force. This fact promotes that people physically interact with a robot movement and enables physical human-robot interaction with a simple control method. This can be advantage against existing robots driven by powerful electrical motors. We then focus on the physical interaction between a person and CB^2 owing to its flexibility. As the example, we have implemented that a person helps CB^2 up by holding its arms (hereafter, raising up interaction). This section describes the implementation and studies on motor development through physical human-robot interaction.

In order to implement the raising up interaction, CB^2 needs to actively and passively change its posture in accordance with an external force applied by a person. We have implemented a method to control the angles of all joints driven by the pneumatic actuators by gain scheduling control. If the control gain is small, CB^2 passively changes the posture in accordance with the applied force. On the other hand, CB^2 keeps the joint angles in the desired positions against the applied force if the gain is large. The applied force can be detected by measuring the angular error on the actively driven joint.

The raising up interaction is implemented in the following procedure.

1) Define the CB^2's initial posture.
2) Define the final desired posture and gain to keep a standing position without an external disturbance.
3) Define the intermediate desired posture.
4) Turn the timing to switch the desired posture.

The resultant interaction is shown in Fig.8. The desired postures, gain, and switching timing were experimentally determined.

In the figure 8, the postures 1, 2, and 3 denote the initial, intermediate, and final desired postures, respectively. The robot switches the desired position from position 2 to 3 during the interaction. Although the desired posture discontinuously changed, the actual joint angles smoothly changed thanks to the joint flexibility. The result shows that the flexibility not only contributes to safety and robustness but also facilitates the design of control system.

The raising up interaction shown in Fig.8 can be interpreted as a kind of communication between the human helper and robot in which the physical forces are transmitted to each other. We think of the physical instruction as a physical communication which can be quantitatively analyzed and study the motor development of the robot with a person's physical help. During the motor development with physical help, the robot

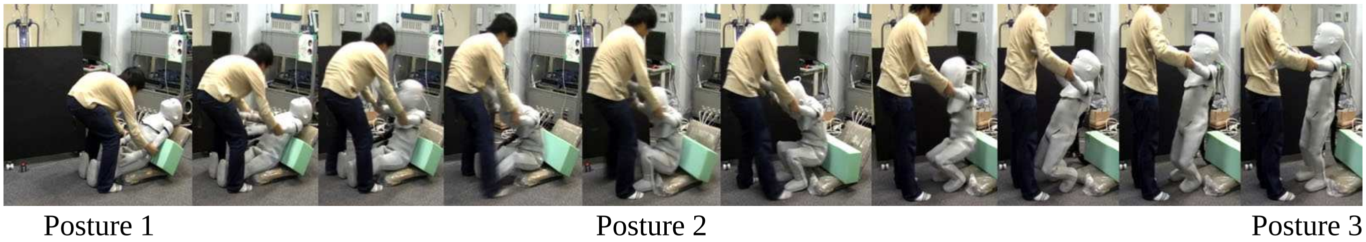


Fig. 8. CB^2 is standing up with a person's help.

(learner) is supposed to acquire how to minimize the supporting effort given by the person (teacher) while learning the desired motion. Meanwhile, a development of communication ability involves a maximization of information gained from other's physical expression (e.g., language and gesture), that is, a minimization of the other's physical expression to gain information. In other words, a learner acquires how to interpret the other's intention as much as possible from the physical expression. From the analogy between two developments, a process to minimize the teacher's effort corresponds the process of communication development. We then study a mechanism to promote a social motor development in the viewpoint that decreasing a teacher's supporting force in the motion learning is relevant to a development of ability to interpret other's intention, that is, to communicate with others. Viewed in the light that the timing tuning was important in the implementation of the raising up interaction, we especially focus on a relation between the motor development and a development of timing control.

VI. CONCLUSION

This paper reported the development of a new humanoid robot CB^2 that has a soft skin and flexible actuators and described studies on developmental mechanisms thanks to the characteristic of CB^2. These studies associate with each other in elucidation of the mechanism of human development. CB^2 enables long-term and tight interaction with people, and, therefore, it can be a research platform to study a developmental mechanism in which various factors are combined in a complicated way. It contributes not only to a development of communicative and intelligent robots but also to understanding the development of human intelligence.

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