Synergistic Intelligence: approach to human intelligence through understanding and design of cognitive development

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Abstract—**Introduction of a JST ERATO Asada Synergistic Intelligence Project (hereafter, SI) that aims at understanding cognitive developmental natural agents (humans), building artificial agents (humanoids), and their mutual feedbacks is given. The project consists of four groups: (1) Physio-SI: dynamic motions such as walking, running, and jumping, and their seamless connections based on pneumatic muscle actuators, (2) Perso-SI: cognitive developmental robotics including body image, imitation, and language communication. (3) Socio-SI: emergence of communication and society by androids, and (4) SI-mechanism: neuroscientific supports for Physio, Perso, and Socio-SIs. The purpose, plan, and goal are given.**

Index Terms—**Synergistic Intelligence, Cognitive Developmental Robotics, Humanoid Science**

I. Introduction

Advanced technologies of hardware and its control enable us to build humanoid robots that have a large number of DoFs and various kinds of many sensors. Human-like motions are realized on these robots, and the shape and appearance have come close to us.

The current robotics lacks the faculties of language communication with ordinary people and of intelligent behavior generation in various situations such as at home. The fundamental relationship between humans and robots would become more important since these robots would be introduced into our lives in near future, and therefore the mechanisms of adaptation and development of both humans and robots should be taken into account in order to find the correct direction of the technology in future.

"Synergistic Intelligence (hereafter, SI)," the title of our project, emerges intelligent behaviours through the interaction with environment including humans. Synergistic effects with brain science, neuroscience, cognitive science, and developmental psychology are expected. SI is one approach to a new discipline called "Humanoid Science" that aims at providing a new way of understanding ourselves and a new design theory of humanoids through mutual feedback between the design of human-like robots and human-related science.

"Humanoid Science" under which a variety of researchers from robotics, AI, brain science, cognitive science, psychology and so on are seeking for new understanding of ourselves by constructivist approaches, that is expected to produce many applications.

SI adopts a methodology called "Cognitive Developmental Robotics" (hereafter, CDR) [1] that consists of the design of self-developing structures inside the robot's brain, and the environmental design: how to set up the environment so that the robots embedded therein can gradually adapt themselves to more complex tasks in more dynamic situations. Unstructured terrains are opponents for adaptive walkers to negotiate with in order to generate dynamic motions. The caregiver's behaviour to a robot is one environmental design issue since parents, teachers, and other adults adapt themselves to the needs of children according to each child's level of maturity and the particular relationship they have developed with that child.

One of the most formidable issues in SI is "Nature vs. Nurture": to what extent should we embed the structure, and to what extent should we expect the development triggered by the environment? A symbolic issue is " Language Acquisition. " How can robots emerge the symbol in the social context? What is the essential element in this process?

The goal of SI is to understand the fundamental developing process of three-years old human child for robot realization of this cognitive developmental process, and the topics we are going to attack are (1) emergence of dynamic, elastic motions by artificial muscles, (2) cognitive developmental experiments on baby robots, (3) realization and understanding of communication by android, and (4) understanding neuro-infrastructures for the above processes based on brain functional imaging and animal experiments.

II. Physically Synergistic Intelligence

Physio-SI in short, aims at understanding emergence of human intelligence from dynamic connection between body structure and environment with artificial muscles.

The agent behavior is determined by not only its dynamics but also environmental one if its compliance is comparable to that of the environment. This interaction may help the agent to be adaptive and robust against changes of the environment, which cannot be taken for the rigid agents with high-ratio geared motors. In this project, we utilize such physical interactions to realize dynamic skills such as walking, jumping,

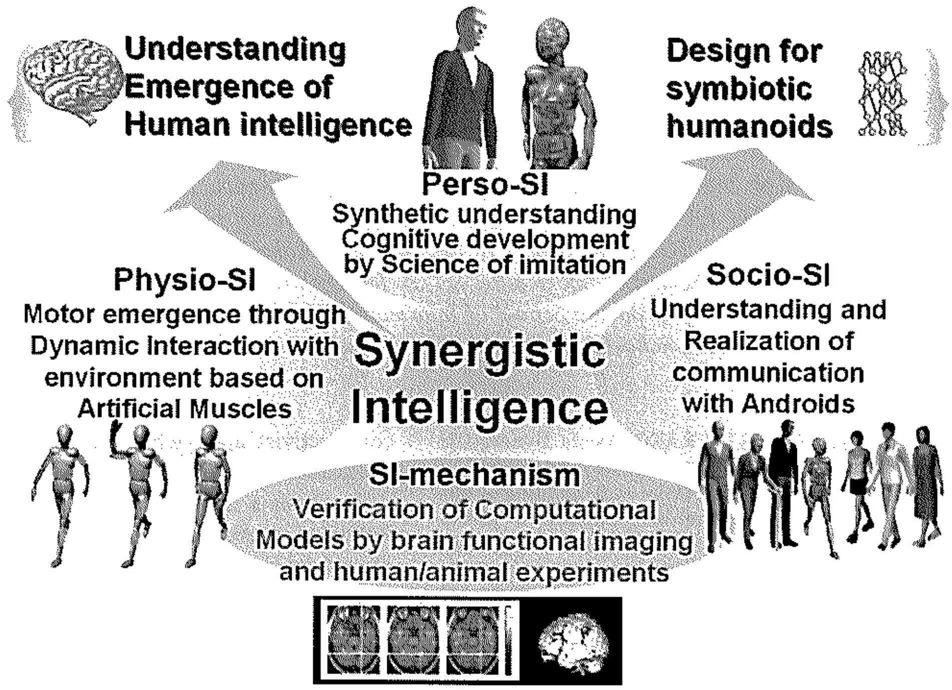

Fig. 1. An overview of Synergistic Intelligence Project

and running, and try to figure out the methodology to emerge synergistic intelligence:

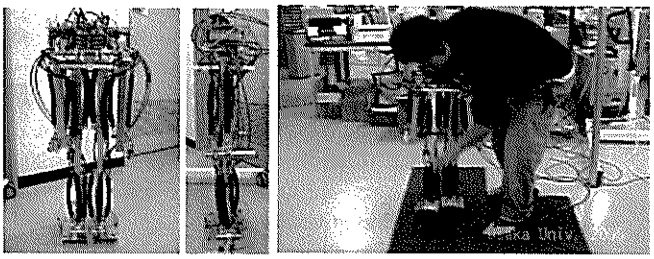

Fig. 2. A 3D biped robot actuated by antaginistic pairs of pneumatic muscles [2]

- **Walking on uneven terrains utlizing antagonistic driven legs:** By utilizing flexibility provided by antagonistic driven legs and ballistics of the body, we will derive a methodology to realize adaptive walking on uneven terrains Preliminary results are shown in [2].
- **Realization of dynamic behaviors:** We will realize dynamic behaviors such as jumping and running by utlizing compliance and dymamic power provided by the antagonistic drive.
- **Smooth transition between dynamic behaviors:** We will propose a framework to deal with different modes of locomotion, walking and running, and develop a "Motor Skill Emerging Humanoid" that can realize these locomotion modes.
- **Cognitive approach to locomotion:** From the standpoint of building a Motor SKill Emerging Humanoid, we approach to the synergistic intelligence mechanisms and will understand the foundation of emergence of dynamic behaviors.

III. Interpersonally-Synergistic Intelligence

Fusing together the capabilities of real world behavior and communication will be the critical step towards the truly humanoid robot intelligence. Interpersonally-Synergistic Intelligence group (Perso-SI in short) aims at constructing synthetic robotic models that account for the process of cognitive development starting from bodily movements of fetuses and reaching rich meaningful communication of infants. This w[illegible] bridge the research of the other two groups, namely, Physio-Synergistic Intelligence and Socio-Synergistic Intelligence.

Our developmental cognitive model would account for (but not limited to) the following cognitive functionalities:

1) Acquisition of brain internal representation of self body through whole body sensory-motor learning,
2) Learning about objects and tools,
3) Emergence and development of behavior imitation,
4) Concept/imagery formation by abstraction of behaviors, and
5) Fusing together the behavior concepts/imitation with interactions through gestures, vocalizations, and facial expressions.

Some of our models will be based on the neuroscientific models provided by the Synergistic Intelligence Mechanisms group; The model of object manipulation for topic 2, imitation learning for topic 3, and motor imagery for topic 4.

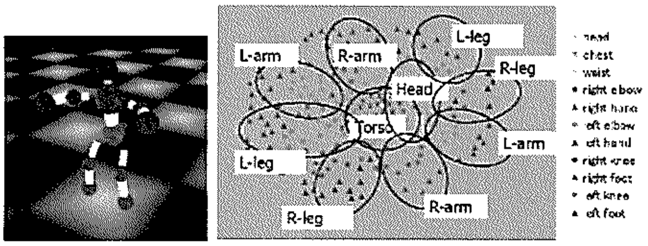

Fig. 3. A body representation: simulated baby body (left) and topographic somatosensory cluster map (right) [3]

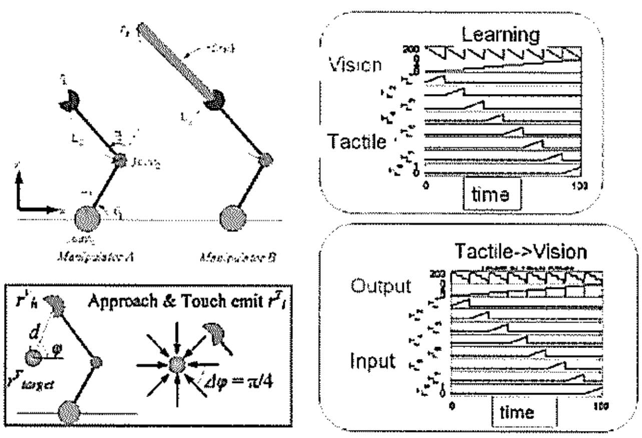

Fig. 4. Adaptation of body representation in tool use [4]

Early stages of research on the above topics are already in progress. Figure 3 shows the somato-sensory topographic map (related to topic 1)self-organized based on temporal correlations of tactile signals from the skin of the simulated baby body under random motion in a liquid medium [3]. Figure 4 shows the result of learning to use a stick as an extension of self body [4]. The model is based on recent findings in neuroscience [5].

Two of the hardware platforms required for the above research are; (a) whole-body sensory-motor learning robot, and (b) behavior imitation learning robot. We will develop these robots and use them for the above described research on cognitive models. Robot (a) will have a whole body tactile sensing skin and whole body motion capabilities, and will be used for experiments such as body image acquisition by sensory integration learning. Robot (b) will emphasize object manipulation capabilities and their integration with audio-visual sensing, and will be used for experiments on imitation learning, concept acquisition, and fusing with communication. In addition, we will construct (c) a computer simulation of sensory-motor learning of fetuses, in order to carry out learning experiments and model validation for very early stages of sensory-motor learning.

Another preliminary work on imitation is vowel acquisition based on mutual imitation between an infant vocal robot and a caregiver. A pioneering constructivist approach to building a robot that reproduces a developmental process of infants' vowel acquisition has been conducted by Yoshikawa et al. [6] inspired by the observation in infant study. They have constructed a mother-infant interaction model with robot learning capability and parrot-like teaching by caregiver. However, the robot has not listened his/her own voice, therefore nor actively explored more natural vowels similar to the caregiver. Miura et al. [7] extended the previous work in the following manners seeking for more natural interaction. First, a lip is added to the robot to imitate the lip shape of the caregiver in order to accelerate the learning process by constraining the initial exploration area in the formant space. Second, the pentagon the caregiver's vowels construct in the formant space is utilized as the desired vowels for the robot. Third, mutual imitation between the robot and the caregiver is introduced in order to obtain more natural vowels hypothesizing that the caregiver imitates the robot voice but unconsciously the imitated voice is close to one of his/her own vowels. Through this process, the desired positions specified at the second step is gradually shifted, expecting to more natural ones.

Fig.5 shows the formant distribution of the robot utterances when the lip shape is imitated. The top row indicates the formant distributions of utterances when the lip shape is fixed to imitate that of human's vowel utterances /a/, /i/, /u/, /e/, and /o/, respectively. The bottom row shows the lip shapes of human and the robot, respectively.

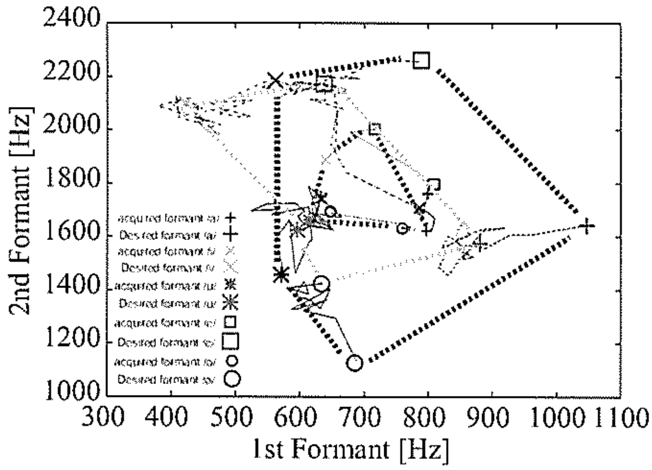

Fig. 6. Desired and acquired vowels by a robot at the learning step 500

Fig.6 shows the results of all vowels where thin folded lines indicate how robot's vowels are modified according to the mutual imitation. The initial ones are shown as nodes of a pentagon connected by dotted black lines and the final ones as nodes of a pentagon connected by dotted yellow-green lines. The acquired vowels are shown as nodes of a pentagon connected by dotted sky-blue lines. The initial nodes are black

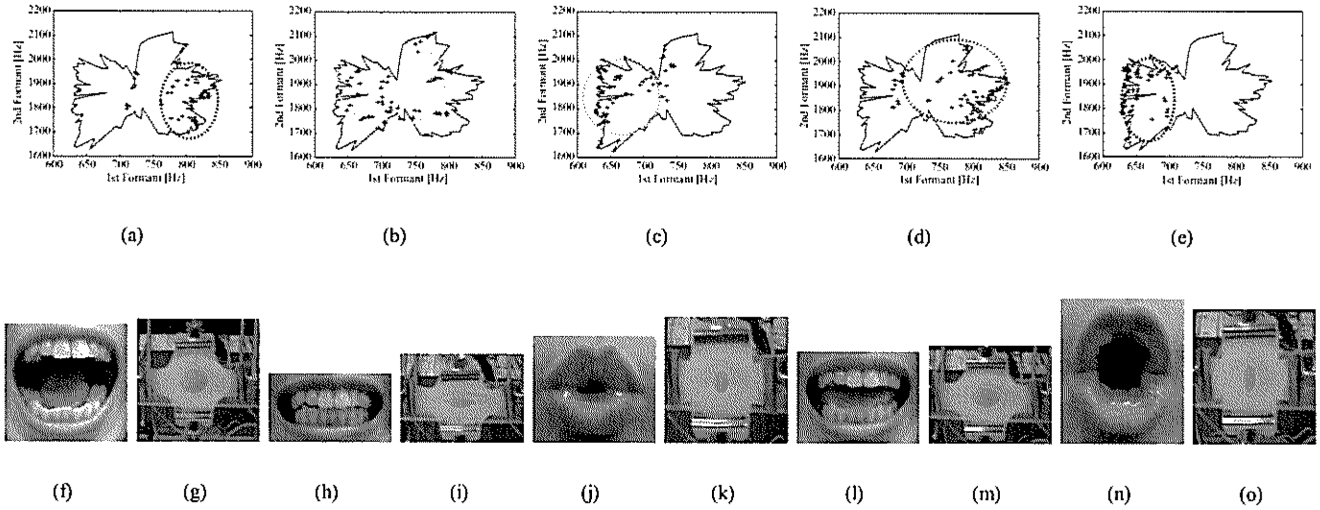

Fig. 5. Formant distribution of the utterances (top: /a/, /i/, /u/, /e/, /o/) from lip shape imitation (bottom)

and the final ones colored. The human vowels are shown as larger marks such as +, *, and so on, while the robot ones as smaller ones. We asked about 40 subjects which is more natural between robot's vowels with and without mutual imitation, and more than 70% subjects agreed with mutual imitation.

IV. Socially Syngenetic Intelligence

This group studies developmental mechanisms of communication and evaluations of intelligence based on human subjects and the human society. We, humans, anthropomorphize the object for conversation. This is an essential human ability and a hint for investigating principles of communicative and intelligent machines by engineering and scientific approaches. This idea guides us to a new cross-interdisciplinary framework called Android Science [8]. In this framework, we tackle the following issues

- Development of Man-Made Man (M3: M cube): In order to realize robots that can be accepted by the human society, we need to develop a human-like robot. The robot developed in this project is different from other robot-like humanoids and very humanlike androids. The robot M3 is going to have about 50 pneumatic actuators, soft skin covering the whole body, and various humanlike sensors with a child size.
- Mechanisms for establishing social relationships with humans: We, humans, have various interactive behaviors for establishing fundamental relationships with others as humans, for example eye movement while looking at each other, personal distance, shard attention, synchronized movement while interacting, and reactions with tactile sensation. These human behaviors are precisely measured and the numerical models are developed [9]. Then, these programmable models of the behaviors are going to be implemented into M3.
- Constructive approach for understanding social mechanisms of humans and robots: We are going to implement more complicated and social behaviors to the robot that has the fundamental relationships with humans. This is the constructive approach [10] that starts from the basic elements and gradationally implements more complex behaviors. Finally, we acquire knowledge on what is a human and what is the human society by using the develop robot.

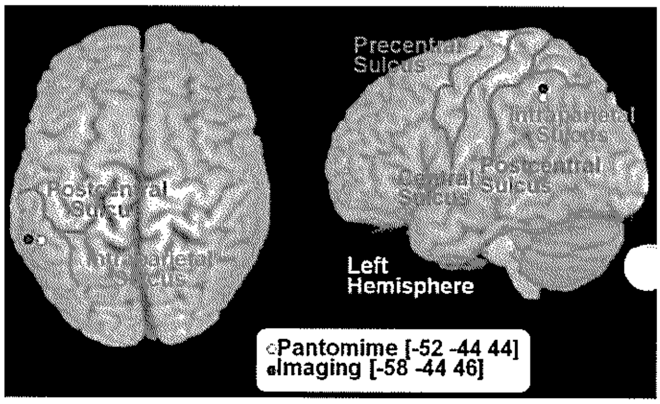

Fig. 7. Almost the same region was activated in the condition of pantomiming and imaging of chopstick use [11]

V. Synergistic Intelligence Mechanism

SI-Mech in short, will conduct the following three issues:

1) study of neural correlates of interactive control mechanism between hands and objects,
2) investigation of the brain mechanism of imitation and imaging, and

3) construction of an acquisition model for fundamental functions of communication.

In study of neural correlates of interactive control mechanism between hands and objects, we will use tracing of line drawing tasks under various conditions to identify the neural circuits involved in smooth manipulation of hands and objects. We will also clarify the relationship between some motor and mental disorders and the neural substrates. Furthermore, Nagai et al. [12] indicated that patients with Williams syndrome can trace the drawings of objects, but can not copy them. To investigate this dissociation between tracing and copying, we will use functional imaging and neuropsychological methods to clarify the difference in brain regions involved in these behaviors.

On the other hand, mechanisms of prediction and imitation play important roles in acquiring functions of communication. Imazu et al. [11] studied neural correlates of tool (chopstick) use with functional neuroimaging and revealed the following finding: actual use of chopstick activates the right cerebellum, whereas pantomiming and imagery of chopstick use activate the left inferior parietal lobule (7). This result suggests that different neural networks are involved in actual use, and pantomime and imagery of tool use. This could explain the dissociation observed in patients with ideomotor apraxia: they unable to pantomime with tools, despite their ability to manipulate tools actually.

For the purpose of 'the investigation of the brain mechanism of imitation and imaging', we will first examine those of action in the human brain with functional MRI. Second we will make a research on both the deficit and the learning process of action imitation of autistic children who have communication deficits, modeling the relationship between action imitation and communication function. In addition, we are going to compare the aforesaid study of William's syndrome with that of the autism and clarify the essence of communication function.

Furthermore, the 'motor sequence prediction learning hypothesis' on the basis of the brain imaging studies as well as the anatomical ones has been proposed. There are two main assumptions in the hypothesis. First, it is assumed that the functions of left BA44 and BA45 in Broca's area differ from each other; left BA45 is involved in motor sequence prediction and left BA44 is implicated in motor sequence generation, interacting with the basal ganglia respectively. Second, left BA45 makes contact with the temporal lobe through long-distance association fibers to integrate semantic and syntactic information. Finally, in terms of 'the construction of an acquisition model for fundamental functions of communication', we plan to construct an acquisition model through brain imaging studies based on the 'motor sequence prediction learning hypothesis'.

VI. What's expected?

In this project, we will establish a new discipline that explains the essential relationship between humans and robots in future symbiotic society. Systematic and continuous modelling of "embodiment," "autonomy," and "sociality" from a viewpoint of emergence and development will be performed, and constructivism will be shown by realizing these models on real robots. Fundamental principles for adaptive and developable robots will be revealed and may contribute to human society.

An expected goal is realization of three years old humanoid that can show the capabilities of 1) seamless transition among running, jumping, walking, and stop, and whole body motion such as rope skipping, 2) naming game with toy playing and novel behavior generation from imitation, and 3) self-expression, attention, and conversation.

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