5th International Conference on Cognitive Systems 2012

Cognitive Developmental Robotics as Embodied Cognitive Systems

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February 23, 2012
@TU Vienna in the Kuppelsaal

CogSys 2012
February 22 - 23, 2012, TU Vienna, Austria
Introduction of myself: Minoru Asada

• Professor of Graduate School of Engineering, Osaka University, JAPAN.  
  www.er.ams.eng.osaka-u.ac.jp

• Research director of JST ERATO (Exploratory Research for Advanced Technology) Asada Project  
  www.jeap.jp

• The former president of RoboCup Federation  
  www.robocup.org
Thank you for your kind words!

- Still very hard to recover physically and economically!
- We appreciate everything you have done so far!
- Japanese robotics researchers built a community to help any kinds of activities. [roboticstaskforce.wordpress.com]
Major Projects on Robotics in Osaka

- **JST ERATO** Asada Synergistic Project (2005.09-2011.03, 2011.04-2012.03 (one year extension) **16,000K + 500K** (Euro))
  - Profs. Asada (research director), Hosoda, and Ishiguro (group leaders)

- **JST CREST** Ishiguro Studies on cellphone-type tele-operated androids transmitting human presence (2010.10-2016.03) **5,000K?**

- **JSPS Global COE Program:** Cognitive Neuroscience Robotics (2009.04-2014.03) **Profs. Ishiguro (leader), Asada (sub-leader), Arai, Miyazaki, Hosoda 6,000K**

- **JSPS grant-in-aid scientific research: Fundamental Structure (S):**
  - Prof. Asada (2010.04-2015.03) **1,600K**
  - Prof. Hosoda (2011.04-2016.03) **1,300K**

- **MEXT:** Establishment of a new area of Hyper Bio Assembler for 3D Cellular Systems Prof. Tatsuo Arai (2011.10-2016.03) about **25,000K?**
RoboCup

- A grand challenge: to build a team of 11 humanoids that can get a win against FIFA world-cup champion team
RoboCup 2011 Istanbul
Welcome to RoboCup 2012

The RoboCup Federation and the Mexican Robotics Federation are pleased to invite you to RoboCup 2012 to be held in Mexico City from Monday 18th through Sunday 24th June 2012.

RoboCup objective:
It is our intention to use RoboCup as a vehicle to promote robotics and AI research, by offering publicly appealing, but formidable challenge. One of the effective ways to promote engineering research, apart from specific application developments, is to set a significant long term goal. When the accomplishment of such a goal has significant social impact, it is called the grand challenge project. Building a robot to play soccer game itself do not generate significant social and economic impact, but the accomplishment will certainly considered as a major achievement of the field. We call this kind of project as a landmark project. RoboCup is a landmark project as well as a standard problem.

The Dream
We proposed that the ultimate goal of the RoboCup Initiative to be stated as follows:
By mid-21st century, a team of fully autonomous humanoid robot soccer players shall win the soccer game, comply with the official rule of the FIFA, against the winner of the most recent World Cup.

We propose that this goal to be the one of the grand challenges shared by robotics and AI community for next 50 years.
Outline of my talk

1. How do humans and humanoids develop?
2. What’s cognitive developmental robotics?
3. How do the concept of self and mirror neuron system develop?
4. How do infants vocalize vowels?
5. Future issues
What's human development?

When I was a baby...

Elementary school

Junior high school

High school

1986-1987 @ UM

1997.8.28 @ 1st RoboCup

2009.6.5 @ Shanghai
Early Brain Development (1)

[Neuroscience: Dale Purves et al., 2008]
Emergence of fetal movements and sense (Brain figures on the top are from Figure 22.5 in [Purves et al., 08], emergence of movements is from Figure 1 in [Vries et al., 84], and fetal senses are from [http://www.birthpsychology.com/lifebefore/fetalsense.html])
36 weeks
Infant development and learning targets

M / behaviors / learning targets

5 / hand regard / forward and inverse models of the hand

6 / finger the other’s face / integration of visuo-tactile sensation of the face

7 / drop objects and observe the result / causality and permanency of objects
Infant development and learning targets

M / behaviors / learning targets
---------------------------------------
8 / hit objects / dynamics model of objects
9 / drum or bring a cup to mouth / tool use
10 / imitate movements / imitation of unseen movements
11 / grasp and carry objects to others / action recognition and generation, cooperation
12 / pretend / mental simulation
Ridley presents a history of the long debate over genes versus the environment as the dominant influence on human behavior. He asserts that "versus" is wrong. His point of departure is the recent identification of the full sequence of the human genome. "The discovery of how genes actually influence human behaviour, and how human behaviour influences genes, is about to recast the debate entirely. No longer is it nature-versus-nurture, but nature-via-nurture."
Why such baby robots?

• Because, we’d like to understand how humans can be intelligent by building such robots that develop like humans.

• Why not other approaches such as brain science or psychology?

• Because, it seems difficult for only one discipline but interdisciplinary approach seems promising:
  – Brain science → tends to microscopic (see next slide)
  – Psychology → macroscopic (based on observation)
“A huge crowd of brain researchers work like ants on a gigantic brain: This is the view of the graphic designer Uwe Brandi from Göttingen, about how scientists try to unravel details of the thinking organ. **But how do the details fit together in a realistic way?**”

Basic idea: Humanoid Science

A new understanding of ourselves

Hint to new design theory

Humanoids?
Machines
Robots
Humans
Animals
Mammals
Primates

"Humanoid Science"
1. How do humans and humanoids develop?

2. What’s cognitive developmental robotics?

3. How do the concept of self and mirror neuron system develop?

4. How do infants vocalize vowels?

5. Future issues
What is cognitive developmental robotics?

• Cognitive developmental robotics aims at understanding human cognitive developmental process by synthetic or constructive approaches.

• Its core idea is "physical embodiment" and “social interaction” that enable information structuring through interactions with the environment including other agents.

What’s cognitive developmental robotics?
What’s cognitive developmental robotics?

Robots are:

- reliable agents as *controllable* *(reproducible)* ones for psychological and social experiments,
- *computational models* to verify the hypotheses (constructive approaches), and
- *social agents* in our future society.
JST ERATO Asada Synergistic Intelligence P

Understanding Emergence of Human Intelligence

Design for Symbiotic Humanoids

Perso-SI

Physio-SI

Synergistic Intelligence

Socio-SI

SI-mechanism

www.jeap.jp

2005.09-2012.03
Our robots

• We (JST ERATO Asada Project) have developed several kinds of robot platforms with different mechanisms, supposing different ages and research purposes.

Platforms for Cognitive Developmental Approaches

15M walk alone

13M go up stairs

11M walk led by the hand

10M crawl

9M stand supported by furniture

8M stand with help

7M sit by itself

1M jaw up

0M fetal posture

Robots in action
From physical interaction to cognitive one

Dynamic Motion

- standing with support, early
- whole body motion & assist
- crawling
- holding during neonate & infant
- rolling over
- intersubjectivity

Self/other discrimination

From emergence of social behavior through interactions with caregiver to development of communication
Some examples of physical embodiment

1. Fetus and Neonate simulation (extension from the last CogSys10 talk by Yasuo Kuniyoshi [Mori & Kuniyoshi 10])

2. Repetitive grasping with anthropomorphic skin-covered hand enables robust haptic recognition (Hosoda G. [Takamuku et al., 08])

3. Visual attention by saliency leads cross-modal body representation [Hikita et al., 07]

Physical embodiment changes the way to think about!
More realistic bodies have been simulated such as ones with soft skin.
Anthropomorphic skin-covered hand

(Hosoda G. [Takamuku et al., 08])
**Dynamic body representation (1)**

- **Bimodal neuron**: body image extension by tool use. [Iriki et al., 96, 01]

- **Body scheme** → unconscious, dynamic process of body control.
- **Body image** → conscious representation of self body.
- Interaction between external environment (vision) and body scheme. [Stamenov, 2005]

[Stamenov, 2005]
The activities of bimodal neurons change after training of tool-use.

Before tool-use

After tool-use

The receptive field was extended to the tool.

How such representation is acquired?
Proposed model

The model consists of 3 modules.

1. Arm posture module
   Represents the current arm posture by Self-Organizing Map

2. Attention module
   Detects the visual attention point based on Saliency Map

3. Integration module
   Associates the arm posture map with the attention map by Hebbian Learning using a tactile sensation as a trigger

[Hikita et al., 07]
Dynamic body representation (3)

Results: Experiment with a real robot

The connection weights

With hand

With a tool

The activation of the integration map

[Minato et al., 2007]
Outline of my talk

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5. Future issues
Social development: the concept of self and mirror neuron system

- Symbolic goals of CDR are language and mind
- The development process of the concepts of self and others \(\rightarrow\) from nonverbal communication to verbal one [Arbib, 2006]
- Memory and the concept of time.
- Research platform to promote CDR studies.

http://courses.umass.edu/ling394/index.html
MNS Connects Physical Embodiment and Social Entrainment (1)

- **Mirror neuron system may have an important role** in the process of social behavior emergence.
- Observation and action execution $\rightarrow$ others’ behavior understanding.
- Monkey $\rightarrow$ Goal oriented (actions of transitive verbs)
- Human $\rightarrow$ plus actions of intransitive verbs

1. Sharing self and other’s body representation
2. The difference between efference copy and sensory feedback $\rightarrow$ self motor perception or other’s body.
MNS Connects Physical Embodiment and Social Entrainment (2)

• *Mirror neuron system may have an important role* in the process of social behavior emergence.  

1) Self/others indifferenciation  
2) Self/Non-self discrimination $\rightarrow$ *ecological self*  
3) Self-other-object relation $\rightarrow$ *interpersonal self*  
4) Self-caregiver (others)-object relationship $\rightarrow$ *conceptual self*  
5) Concept of time $\rightarrow$ *temporally extended self*

- *Mechanism for the seamless emergence of the above representation from 1) to 4) or 5). It is not necessary to have explicit representation.*
MNS Connects Physical Embodiment and Social Entrainment (3)

• Be careful for too much expectation of the roles of MNS [Hickok, 2009]

• A more general and fundamental structure might be needed. → synchronization of oscillations [Yamaguchi, 2008, Taga’s group, 2007, 2008, 2009]

1. Synchronization with environment through rhythmic motions such as beating, hitting, knocking and/or reaching behavior


3. Desynchronization with others
MNS Connects Physical Embodiment and Social Entrainment (4)

1. ecological self
2. interpersonal self
3. social self

Synchronization with environment
sprouting of self

self/other identification (MNS infrastructure)

Self/other separation
desynchronization from others

Physical body in synchronization → self/other identification
Desynchronization → self/other separation
Early Development of Mirror Neuron System [Nagai et al., 2011, Kawai et al., 2011]

MNS [Rizzolatti & Craighero, ‘04] activates both when
- executing an action
- observing the same action by others

Self-other correspondence

A movie of the robot's imitation
Under construction!!
Model for emergence of the early MNS

Matured vision

Immature vision

Visual image

Visual space

Motor space

Hebbian learning

MNS

[Nagai et al., 2011, Kawai et al., 2011]
Result (1) Self-other differentiation

Principal component analysis of the visual space in the each stage of development

First
Non-differentiation

Second
Some clusters differentiated

Last
Differentiation

[Nagai et al., 2011, Kawai et al., 2011]
Result (2) Self-other correspondence

Motor command

Self-motion

Other-motion

w/ visual dev.

w/o visual dev.

[Nagai et al., 2011, Kawai et al., 2011]
Result (3) Imitation after learning

Human

Robot

[Nagai et al., 2011, Kawai et al., 2011]
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Vowel Acquisition by Maternal Imitation

- Vowel Imitation between Agents with Different Articulation Parameters by Parrot-like Teaching
  - Infants seem to acquire (imitate) phonemes:
    - without any explicit knowledge about the relationship between their sensorimotor system and phonemes, and
    - without a capability to reproduce the adult’s sound as they are.
- How can robots do that?

[Yoshikawa et al., 03]
Human Vocalization [Deacon 98]

- Vocalization → the interaction of the oral and respiratory tracts → special association with midbrain systems.
- To organize vocalization → coordinated activation of the cluster of motor neurons that control the muscle of breathing, the tension of the larynx, and the movement of the oral and facial muscles. → the motor neurons controlling all of these are located in the upper brain stem.
Two evolutionary shifts producing increasing cortical control over motor output from brain stem articulatory and vocal systems. These shifts were produced by an increase in the proportions of the cerebral cortex in comparison to these brain stem structures.

Cortex-brain stem projection
A constructivist approach

• The purpose → To build a robot that acquires the vowels of a human caregiver
• Design issues:
  – What kind of mechanism should be embedded?
  – What should be the behavior of the caregiver?

[Yoshikawa et al., 03]
Observations in human infants

- Infant’s speech-like cooing tends to make its mother utter [Masataka and Bloom’94].
- **Maternal imitation of infant's cooing** (i.e., parrot-like vocalization) increases vocalization rates of a three-month-infant [Pelaez-Noqueras ’96].

Conjectures

- It reinforces infants’ speech-like cooing.
- It helps to find the correspondence between cooing and phonemes.

[Yoshikawa et al., 03]
The robot

Output sound

Sound source

Silicon tube
deforming

5 Motors

Microphone

Formant extractor

F1 F2 F3 F4

Frequency [Hz]

[Yoshikawa et al., 03]
What’s Formant Space?

- Resonant frequency changes depending on the shape of vocal tract.
- Vocal feature for vowel discrimination.
- Non-human primates and birds utilize as perceptual cues [Fitch 2000]

Formant distribution of Japanese average female [Yoshikawa et al., 03]
A model of interaction

The caregiver

Randomly cooing

The robot

Parrot-like teaching

Random articulator

Articulation layer

Auditory layer

Learning module

motors

microphone

[Yoshikawa et al., 03]
Learning mechanism

- Clustering the articulation parameters and the formant vectors by the SOM algorithm.
- Connections are updated based on Hebbian learning.

[Yoshikawa et al., 03]
Experiment

One Japanese caregiver

[Yoshikawa et al., 03]
Result: how does it acquire vowels?

[Yoshikawa et al., 03]

The articulation vectors corresponding to the variation of the caregiver’s vowels

- The vowel /o/ is not acquired due to the difference in shape of vocal tracts.
- There is “arbitrariness” in correspondence.
Introducing subjective criteria

• A “subjective” criterion: more facile articulation is better.
  – less torque \( c_{trq} \)
  – less deformation change \( c_{idc} \)

Articulation layer

Basic Hebbian rule
\[
\Delta w_{ij} \propto a^f_i a^m_j
\]

Modified Hebbian rule
\[
\Delta w_{ij} \propto \eta(c_{trq}, c_{idc}) a^f_i a^m_j
\]

Auditory layer
Result: effect of subjective criteria

[Yoshikawa et al., 03]

Comparing the distribution of the articulation vectors corresponding to the variation of the caregiver’s vowels

Subjective criteria can reduce arbitrariness.
Acquired vowels

- The acquired vowels can be interpreted as Japanese vowels.

[Yoshikawa et al., 03]
Childlike voice?

[Yoshikawa et al., 03]
Lip shape imitation

[Miura et al., 2006]
Visual imitation, too!

[Miura et al., 2006]
Why not using a speaker?

• Physical embodiment enables to introduce subjective criterion such as less torque and less deformation (easy to vocalize).

• We introduce respiration to realize turn taking with caregiver towards natural interaction → now we are designing more realistic infant vocal robot with artificial lung.
**Infant’s Vowel Development**

- Sharing process of perceptual & behavioral primitives between a caregiver and her infant across their different bodies
  - Physical quantities of their producible vowels are different [Vorperian & Kent.’07]
- Dynamic process including intrapersonal interaction & social interaction [Kuhl et al.’08]
Caregiver’s Sensorimotor Magnets Lead Infant’s Vowel Acquisition through Auto Mirroring

A method that aids unconscious guidance in mutual imitation for infant development based on a biasing element with two different kinds of modules.

1. The normal magnet effect in perceiving heard vocal sounds as the listener’s own vowels (perceptual magnet) and also includes another magnet effect for imitating vocal sounds that resemble the imitator’s vowels (articulatory magnet).

2. What we call “auto mirroring bias,” by which the heard vowel is much closer to the expected vowel because the other’s utterance is an imitation of the listener’s own utterance.
Caregiver’s Sensorimotor Magnets Lead Infant’s Vowel Acquisition through Auto Mirroring

How humans imitate the sound?

Synthesized Voices → Imitated Voices

![Formant Graphs](image)

[Imitation Graphs](image)

[Ishihara et al., 08.09]
Psychological experiment for auto-mirroring bias

Imi (Cnt) < Imi (Exp)

Auto-Mirroring bias

[Wakasa et al., unpublished]
Psychological experiment for auto-mirroring bias

[Wakasa et al., unpublished]

Significant difference
Auto-mirroring bias exists!

※significant level 5%

<table>
<thead>
<tr>
<th>Voice Feature [Hz]</th>
<th>1st set</th>
<th>2nd set</th>
<th>3rd set</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Cnt. G</td>
<td>Exp. G</td>
<td>Cnt. G</td>
</tr>
<tr>
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<td>11</td>
<td>15</td>
</tr>
<tr>
<td>p-value</td>
<td>0.036</td>
<td>0.014</td>
<td>0.454</td>
</tr>
</tbody>
</table>

Concentration level down

Auto-mirroring bias exists!
Automirroring and magnet biases

[Ishihara et al., 08, 09]

- Automirroring Bias Module: Other’s voice $s(t)$ is biased to automirroring anticipation $s_g(t-1)$ and converted to $s^b(t)$ that is given by:

$$s^b(t) = s(t) + \alpha (s_g(t-1) - s^b(t)) \quad (0.0 \leq \alpha \leq 1.0)$$

- Sensorimotor Map Module: We use the normalized Gaussian network (NGnet) to map the other’s utterable vowel region onto the listener’s own.

![Diagram of NGnet](image)
Proposed imitation mechanism with biases

[Ishihara et al., 08, 09]
Caregiver’s Sensorimotor Magnets Lead Infant’s Vowel Acquisition through Auto Mirroring

[Ishihara et al., 08, 09]
Caregiver’s Sensorimotor Magnets Lead Infant’s Vowel Acquisition through Auto Mirroring

[Ishihara et al., 08, 09]

With both biases
Caregiver’s Sensorimotor Magnets Lead Infant’s Vowel Acquisition through Auto Mirroring

[Ishihara et al., 08, 09]
Outline of my talk

1. How do humans and humanoids develop?
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5. Future issues
   1. Theoretical foundation
   2. Connection/interaction in infants and robots
   3. More realistic infant robot
**Conjecture**

**Computational capabilities of a dynamical system are maximized at the order-chaos phase transition** (Wolfram, 1984), (Langton, 1990), or (Kauffman, 1993)

- Transfer entropy maximized at the edge of chaos
- Active information storage maximized at the edge of chaos
How are different systems connected and how do they interact?

• "Distance errors" and "Scale errors" are examples showing disintegration of perception-action systems at 12 months and at 18 months.

• Such errors in infants' development reveal how different systems are connected and how they interact, and give the hints for their constructive models. We propose a general model to explain the developmental process considering these errors.

• Please visit the poster by Beata J. Grzyb et al.!
Mutual attachment in caregiver-child relationship (1) [Ishihara et al., 2011]

- A number of theoretical models to understand developmental of caregiver-child attachment
- Several child robots no realistic
- What kinds of treatment robots could receive from the “caregivers” appears to depend on what kinds of impression the robots give to their caregivers.
- Therefore, more realistic robots more close to a real children are needed. **Affetto, that has realistic appearance of 1- to 2-year-old child**
Mutual attachment in caregiver-child relationship (2) [Ishihara et al., 2011]

- Affetto: a child robot with realistic facial expressions
Mutual attachment in caregiver-child relationship (3)

AFFETTO:
A child robot with realistic facial expressions that develops based on affective attachment with a caregiver

Hisashi Ishihara
Yuichiro Yoshikawa
Minoru Asada
Osaka Univ., Japan/JST ERATO Asada Project
/Japan Society for the Promotion of Science

www.youtube.com/watch?v=VXgKNFQE-4I

www.youtube.com/watch?v=Quai3SpKD08
Summary

• Cognitive developmental robotics is a promising approach to new science of human cognition with design theory.

• Physical embodiment and social interaction are keys for robots (infants) to develop their cognitive functions.

• Designing robots and their environments as close as humans’ produces new research issues to be attacked.
Acknowledgement

• Group Leaders of SI project
  – Prof. Hiroshi Ishiguro (Osaka Univ.)
  – Prof. Koh Hosoda (Osaka Univ.)
  – Prof. Yasuo Kuniyoshi (Univ. of Tokyo)
  – Prof. Toshiro Inui (Kyoto Univ.)

• Early MNS development
  – Assoc. Prof. Yukie Nagai
  – Yuji Kawai (M1)

• Future issues: Beata J. Grzyb and Joschka Boedecker

• Affetto Project:
  – Ph.D candidate Hisahi Ishihara (JSPS, Osaka Univ.)
  – Dr. Yuichiro Yochikawa (Osaka Univ.)
Thank you for your attention!