Robot nature via robot nurture: from cognitive developmental robotics to constructive developmental science

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***Abstract*— I have been advocating cognitive developmental robotics (CDR) that aims to understand the cognitive developmental process of a human according to design principles using artificial systems, such as robots and computer simulations. CDR has already dealt with the paradigm of " nature versus nurture " discussed in the first publication on CDR [1], in which the authors declared that the dichotomy between nature and nurture was incorrect. In this paper, I reviewed CDR and propose constructive developmental science (CDS), in which robot nature is acquired in the preceding process of robot nurture in the developmental process of function differentiation. The most fundamental form of process initiation is shown, and future issues are discussed.**

I. Introduction

Cognitive developmental robotics (CDR) [1], [2] has been proposed in earlier studies, and aims to provide a new understanding on how the cognitive functions of humans develop through a synthetic approach that developmentally constructs cognitive functions. Although similar ideas have been proposed in [3], [4], [5], [6], CDR emphasizes on the cognitive development of humans and humanoids. The core ideas of CDR are "physical embodiment" and "social interaction" that allow for information structuring through interaction with the environment, as well as other agents. These ideas were instantiated according to the hypothesized development model of human cognitive functions, from body representations to social behaviors.

In the first publication on CDR [1], the authors discussed the paradigm of "nature versus nurture" as follows:

> *A fundamental controversy in cognitive science concerns the relative importance of nature and nurture in determining the structure and behavior of individuals. One extreme is that gene coding has all kinds of information necessary for development. The other extreme is that much of the information involved in the formation of a human mind comes from the environment. Both viewpoints are lacking. Neither the nature nor the nurture side address how new information emerges, as Johnson pointed out [7]. In the last decade new evidence has revealed that complicated interactions between genes, developmental processes, and the environment lead to the emergence of structural organization and behavior at many levels [8].*
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> *The view that conventional robotics methods correspond to the nature because they embedded robot behaviors explicitly while CDR corresponds to the nurture because of its dependence on learning from interactions is misguided because neither the nature nor the nurture view explains how new forms of social interaction emerge. CDR aims at a constructivist approach to realizing a mechanism that can adapt to complicated and dynamic changes in the environment based on its capacity for interaction.*

In biology, Ridley [9] claimed no more nature versus nurture but nature via nurture based on the following arguments:

> *Nurture depends on genes, and genes need nurture. Genes not only predetermine the broad structure of the brain; they also absorb formative experiences, react to social cues and even run memory, and that they are consequences as well as causes of the will.*

Although the details and complexities between biology and robotics are different, Ridley 's idea resembles that of CDR, and therefore I rephrased his claim as "robot nature via robot nurture" in constructive developmental science (CDS), an extension of CDR that focuses on more fundamental development issues. Under CDS, the robot nature (embedded structure) is a requirement for robot nurture (learning target) at the current stage and was a goal of the preceding stage in the entire developmental process.

In this study, I introduce CDS by focusing on the idea "robot nature via robot nurture," and provide its most fundamental form at the beginning of the development. Finally, future issues are discussed.

II. From CDR to CDS

A typical aspect of CDR is motor skill development, in which different robot platforms, depending on age, are prepared to study age-specific research issues instead of a single robot platform that is expected to physically grow (develop); a difficult realization. Fig. 1 shows the robot platforms and their corresponding developmental stages in infants (robots). Depending on the age, different robot platforms were used to address various research targets such as crawling and walking. An embedded structure (physical embodiment and control structure) is an assumption for a learning target (e.g., crawling and standing up), and the acquired (learned) motor skill could be an assumption for the next learning target (e.g., walking).

Fig. 1 shows only phenomenological aspects and the corresponding attempts of motor development; however, it lacks a central architecture for the development. We need a

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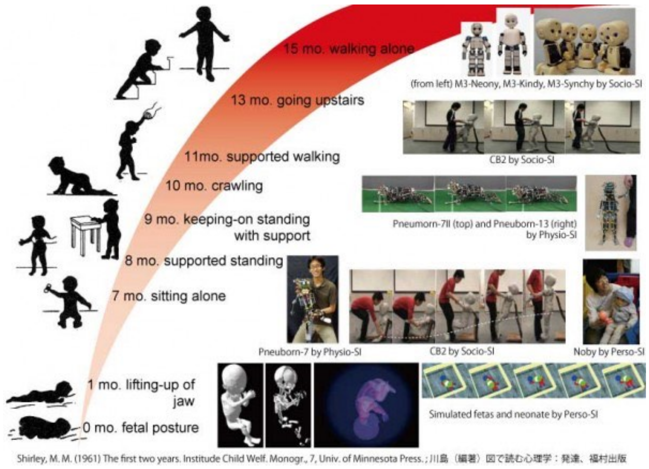

Fig. 1. Robot platforms and their corresponding developmental stages in infants (adopted from http://www.jst.go.jp/erato/asada/en/concluding-remarks/index.html)

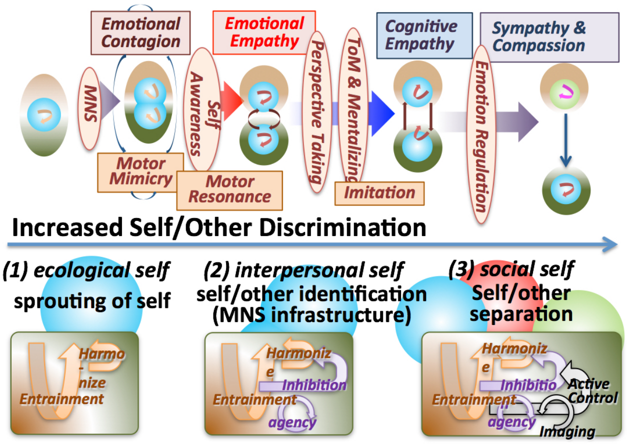

Fig. 2. An overview of the development of artificial empathy

fundamental structure that develops through the developmental process involving two constraints (physical embodiment and social interaction) and learning methods. The flow of learning processes may lead to functional differentiation.

Fig. 2 shows an overview of the development of artificial empathy (top) [10] along the developmental trajectory of self-other cognition (bottom). At the initial stage, an entrainment system (bottom left) is the most fundamental mechanism for the so-called "ecological self" to emerge (middle left) through interaction with the environment. Next, the infant interacts with its caregiver, and self/other identification is initiated through the mirror neuron system (MNS), which helps the infant to understand the actions and intentions of others. The "interpersonal self" (middle center) is established by adding agency and inhibition submechanisms to the fundamental entrainment system. Finally, the "social self" (middle right) is established, supported by more active control. In this figure, a sequence of cognitive functions are aligned along the developmental processes of artificial empathy. The relationships between these functions give rise to the idea of CDS, which resolves the concept of robot nature versus robot nurture.

Fig. 3. Conceptual model for constructive developmental science

III. Robot Nature via Robot Nurture in CDS

As Witherington mentioned [11], "The focal question facing developmental science remains the question of process: How do new forms, functions and levels of organization arise in development from precursor forms, functions, and levels?" CDS attempts to address these issues through synthetic approaches based on computer simulations and real robot experiments to obtain new insights. Fig. 3 shows a conceptual image of CDS. A fundamental neural architecture develops with "physical embodiment," through "social interactions." Both are key ideas of CDR. During the process, a function is differentiated as a result of the current learning stage, and it could be a requirement (or cause) for the next learning stage.

The dynamical systems approach [12] is not only suitable for describing the phenomena of developmental processes, but it is also a potential mechanism to replicate them, which is more important for CDS. The fundamental neural architecture in Fig. 3 could be a sort of chaos (nonlinear oscillator) network by which a variety of behaviors could emerge. Further, this network is expected to differentiate functions along the course of the development. Yamaguti and Tsuda [13] showed that heterogeneous modules emerge from homogeneous systems by applying the principle of maximizing information transmission among subsystems. This may provide a theoretical foundation for functional differentiation.

Under the basic concept of CDS (refer to Figs. 2 and 3), a function could be an assumption or a requirement (the goal of the preceding stage) or a goal (the assumption for the next stage) for each issue. For example, MNS is an assumption to acquire self-awareness, which could be an assumption to learn perspective taking, theory of mind (ToM), and mentalizing, which instead are assumptions to acquire emotion regulation as shown in Fig. 2. Function differentiation is expected to occur in each learning stage. In other words, a series of functions can be regarded as a temporal sequence of functional development.

Therefore, the robot nature versus robot nurture theory is incorrect; however, the robot nature via robot nurture theory is real. That is, robot nature is an embedded structure (assumption) for learning behaviors to achieve robot nurture (goal). Once the target behavior (robot nurture) is learned, this could be used as an assumption for the next learning stage.

As mentioned earlier, a sort of chaos network could be the most fundamental embedded structure (the first assumption) of the brain. Interaction with an environment through the body may cause diverse behavior. Before introducing any learning methods or value systems, we first discuss the behavior type and its emergence.

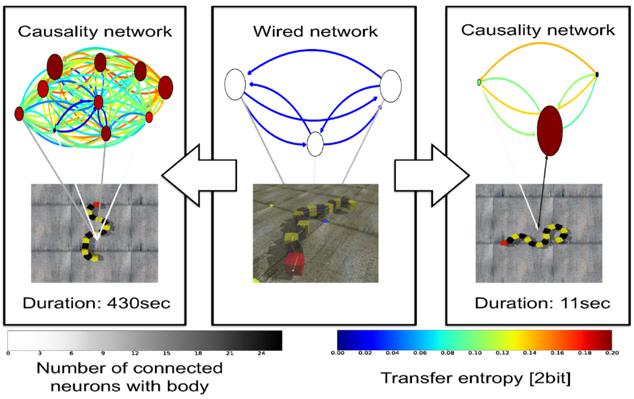

Fig. 4. Two causality networks dynamically transiting each other

IV. Neural Dynamics: the most fundamental form of the system

To understand the interactions between the body, brain and environment that generate versatile behaviors, the relationship between the emerged behaviors and network structures of the brain's neural system must be analyzed. Park et al. [14] conducted a physical simulation by using a snake-like robot with a nonlinear oscillator network and extracted the network structure according to transfer entropy for each different movement. In spite of the existence of the wired network, which is physically fixed, two kinds of network structures were found depending on the behavior, stable (attractor?) or unstable (state transition between attractors?). They are called causality networks. The stable motion is generated by locally connected several sub-networks consisting of a low complex network through weak interaction with the environment. On the other hand, the unstable motion is generated by almost a single globally connected sub-network of which complexity is high through strong connection with the environment. Figure 4 shows these two causality networks which are dynamically transiting each other (left: stable, right: unstable).

One speculation is that the unstable and stable states may correspond to the phenomena of artificial consciousness and unconsciousness, respectively, from the perspective of integrated information theory [15].

V. Conclusion

This paper provides an argument about the relationship between robot nature and robot nurture under the principle of CDS. Instead of the dichotomy of robot nature versus robot nurture, by considering the classical argument in biological evolution, I propose the idea of "robot nature via robot nurture" along the developmental process of various functions.

The beginning of this process displays the most fundamental form of a nonlinear oscillator network, with a potential of diverse behaviors. The preliminary result has been discussed in this study; however, further analysis is required to study the manner in which the network structure changes, that is, the manner in which functions differentiate according to the increase in body and/or environmental complexity.

I assume that the learning methods and value system facilitate the function differentiation, and social interaction further complicate the process. Nevertheless, the developmental processes of function differentiation may provide new insights into the relationship between structure and function.

Thus, the robot nature via robot nurture paradigm is a principle of CDS, and different developmental pathways could be considered and examined for modeling atypical development.

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