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Symbol Emergence in Robotics for Long-Term Human-Robot Collaboration ⋆

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Abstract: Humans can acquire language through physical interaction with their environment and semiotic interaction with other people. It is very important to understand how humans can form a symbol system and obtain semiotic skills through their autonomous mental development from a computational point of view. A machine learning system that enables a robot to obtain and modulate its symbol system is crucially important to develop robotic systems that achieve long-term human-robot communication and collaboration. In this paper, I introduce the basis of our research field and related topics. Specifically, I describe the concept of symbol emergence systems and the recent research topics , e.g., multimodal categorization, spatial concept formation, language acquisition, and double articulation analysis, that will contribute to future human-robot communication and collaboration.

Keywords: Symbol emergence in robotics, machine learning, language acquisition, human-robot interaction, symbol grounding, multimodal learning, artificial intelligence.

1. INTRODUCTION

Mutual understanding between a human operator and an automated machine is a long-standing problem in the research area of human-machine systems. Human-robot communication and collaboration are examples of such problems. This paper focuses on studies on symbol emergence in robotics, which is an emerging research field where researchers are trying to build robots that enable long-term human-robot communications and collaborations.

In human-human communication, we usually use many kinds of symbolic systems, e.g., traffic signs, gestures, facial expressions, and language. In many studies on robotics and artificial intelligence, researchers tend to use the word "symbol" in a narrower sense, i.e., a language-based entity that can be manipulated in a logical manner (Newell, 1980; Harnad, 1990), than that in *semiotics*. If we follow the definition of a symbol and a sign that was given by Peirce, who started semiotics, language is a special case of sign systems (Chandler, 2002; Peirce, 1931-1958). The important point is that, in long-term semiotic communication, we change our vocabularies, meanings, and usages of each symbol system. The long-term adaptation is crucially important for achieving long-term human-robot and human-machine communication and collaboration. Such a capability of long-term adaptation of a semiotic system between users and machines is also a key to establishing long-term human-machine relationship and mutual understanding.

The initial key issue to develop a range of methodologies and technologies is to establish a conceptual theory about such an adaptive symbol system shared by humans and robots including humanoid robots, smart vehicles, and industrial plants involving automation. Such a conceptual theory should involve embodied interaction with a complex environment and semiotic communication by agents. The conceptual theory should provide an explanation about the dynamics of a symbol system and an explanation about how the adaptive symbol system contributes to the agents' adaptation to their complex environment. Our fundamental conceptual theory is a *symbol emergence system*.

Fig. 1 shows an illustration of a symbol emergence system that we assume to be a basis for human-human communication and that we should implement in future human-robot communication and collaboration. This is the central concept of the field of *symbol emergence in robotics*. The figure also shows several research topics in symbol emergence in robotics, which is the main subject of this paper.

In this paper, I introduce the concept of a symbol emergence system in Section 2.In Section 3, I introduce the recent research topics and achievements in symbol emergence in robotics that will contribute to the future of human-robot communication and collaboration. Finally, I conclude this paper with Section 4.

2. SYMBOL EMERGENCE SYSTEM

2.1 *From Rule-Based to Learning-Based Communication and Collaboration*

Future intelligent machines including autonomous robots and software agents should be able to communicate and collaborate with people naturally. However, it is still

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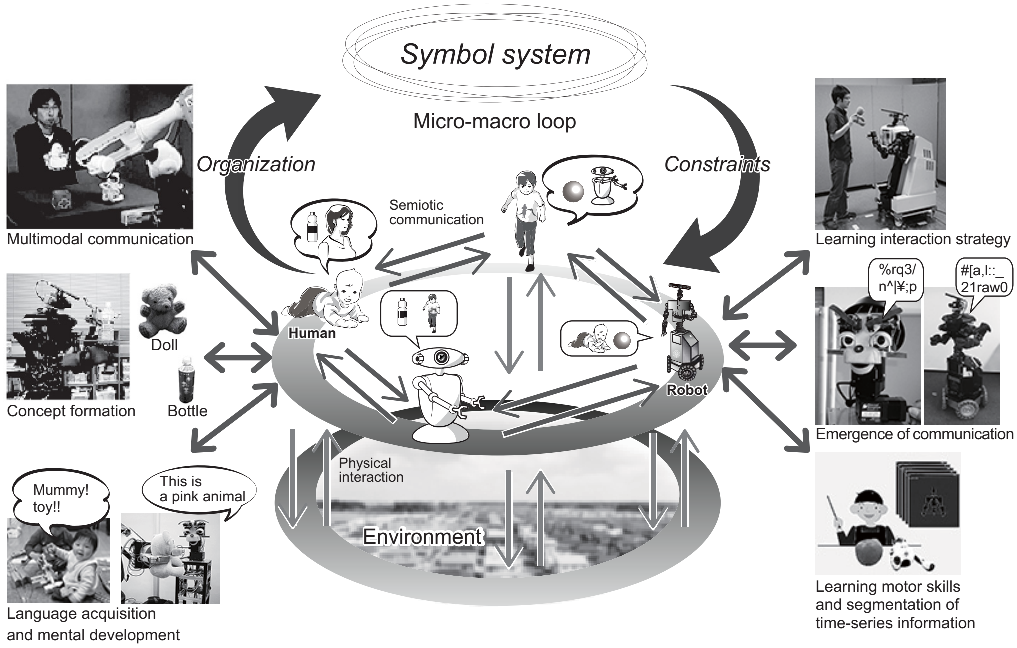

Fig. 1. Conceptual illustration of a symbol emergence system and research topics in symbol emergence in robotics (Taniguchi et al., 2016b)

tough for robots and software agents to communicate and collaborate with a human in a daily environment, e.g., office, home, museum, and factory.

Conventional studies of such human-machine communication and collaboration usually have been based on rule-based approaches. Developers are used to designing the behaviors, vocabularies, and object categories of the robots in advance. In a limited and static environment, this type of approach enables a robot to solve problems and to perform several difficult tasks successfully. However, when a machine encounters an unexpected situation, the system will stop, abruptly interrupting the human-robot communication.

However, human-human communication is not based on static rules and explicit messages, but on dynamically changing pragmatics and lexicons and implicit messages that can be inferred by referring to the contextual information and environment shared by the participants of the communication.

For example, when a human user simply says, “please clean up John’s room, my robot!” The robot should attempt to clean up the cluttered room in the house. In such case, the robot has to infer many things based on daily experiences, i.e., interactions with human users and its environment. Where is “John’s room?” To what extent should the robot clean up the room? Which robot is “my robot?” Humans can solve such problems by referring to their history, i.e., experiences, of daily interaction and local knowledge shared in their community. However, note that humans who are not familiar with the house cannot solve such problems as well. This means that humans do not have static and correct universal knowledge about their daily environment, but have the flexibility that enables them to adapt to their daily physical and semiotic environment. Our real-world environment is full of uncertainty and diversity. In addition, it changes dynamically, not only physically, but also in a semiotic sense. For example, in a house, new goods are introduced every day, and new names of things are invented so frequently. In the example shown above, “John’s room” is one of the locally invented names in the house. A robot that can communicate and collaborate with people in the daily environment has to learn such knowledge automatically through daily interactions with human users.

The long history of artificial intelligence has shown that implementing all of the knowledge about daily life to a robot in advance is almost impossible. We humans cannot know everything either before we start communicating and collaborating in our everyday life. When we encounter new situations and listen to new words, we learn them autonomously based on our real-world experiences. Future robots have to learn new words, behaviors, and concepts automatically. Sophisticated machine learning methods are indispensable to make a robot learn such things automatically. Symbol emergence in robotics is an emerging research field that attempts to solve interdisciplinary problems related to “symbols” using the constructive approach with robotic and machine learning technologies (Taniguchi et al., 2016b).

2.2 Symbol Systems in Artificial Intelligence

Symbol systems have been an important and problematic issue in both artificial intelligence and cognitive science. Human beings make use of symbol systems to recognize various phenomena in the world and to communicate and collaborate with other entities, including robots and other humans. Newell (1980); Newell and Simon (1976) proposed the physical symbol system hypothesis, and this notion has been fundamental to conventional artificial intelligence and cognitive science. The main problem with this hypoth-