Graduate School of Creative Science and Engineering
Waseda University

博 士 論 文 概 要
Doctoral Thesis Synopsis

論 文 題 目
Thesis Theme
Acquisition and Extension of the Robot Body Model Using Motor Babbling through Deep Learning

申 請 者
(Applicant Name)

Kuniyuki	TAKAHASHI
高橋	城志

Department of Modern Mechanical Engineering,
Research on Intelligent Machines

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Today, intelligent robots are expected to play an important role in supporting humans in their daily activities. Conventional robots such as industrial robots are primarily designed to perform designated tasks with high speed and precision and would require extra modifications to perform other tasks. In addition, these robots are typically applicable only in highly controlled environments that have no or negligible uncertainty and are free of human movement. Recently, there has been a growing interest in the development of robots working closely with humans. In real environments, where humans exist, it is essential that robots would be required to adapt to dynamic and uncertain environments and cope with new tasks and situations in a short duration. Robot with tool use skills would be particularly useful in human society, as this would enable the robot to expand its capabilities in performing tasks. To perform various tasks, robots should have complex structure such as large numbers of applicable sensors and degrees of freedom (DOFs). Designing robot models manually has become difficult because of the above reasons. To address this challenge, I developed a model in which the robot body and environment is based on experiences the robot acquires through physical (embodied) interactions as opposed to models in which the robot body and environment is pre-designed; that is, the robot learns sensorimotor relationships from experience using machine learning, particularly deep learning. The focus of this approach is embodiment. In this thesis, I focus specifically on the body model acquired from interaction with the environment through embodiment.
Enabling robots to act intelligently is usually referred to as artificial intelligence. Symbolic AI is based on the manipulation of symbols, an assumption defined as the physical symbol systems hypothesis. These approaches are only valid if all possible situations are described. However, it is difficult to describe all possible situations in the real world. In contrast, Brooks proposed a subsumption architecture in which the system and environment are connected using a connection between the sensor and motor without a description of the symbols. This approach is referred to as embodied AI. It is hypothesized that for complex intelligence, in particular for human-like intelligence, a human-like body is necessary for the robot to interact with the environment. To consider the complex relationship between the sensor and motor, machine-learning, particularly by using deep learning, has been proven effective. Deep learning has desirable characteristics, such as the ability to obtain individual features from data. The term deep learning refers to the use of deep neural networks (DNNs) and recurrent neural networks (RNNs). DNNs are feed-forward neural networks, whereas RNNs are recurrent connections.
When considering a robot body, body schema is an important concept used to explain the body model. Body schema involves mapping between the motor and the sensors located on the body and includes information about the size and shape of the body. In addition, body schema is not fixed after acquisition but is, instead, a plastic model. In particular, when humans are proficient in using a tool, they behave as if their bodies extend to the edge of the tool that they use. The phenomenon is referred to as tool-body assimilation. Owing to body schema, humans have the capability of recognizing the tool tip posture, position, and motion because their body schema is plastic with respect to their body and the tool. Hence, body schema can connect the body and tool easily; that is, it is possible to describe the tool using the model to extend the body schema. When a body schema is considered from an engineering perspective, it is a multi-modal association of motion and sensors. In my research, I added the concept of the forward/inverse model (In this study, the forward model predicts the next

state of the arm-tip position from the current state of the joint angles, and the inverse model predicts the next state of the joint angles from the current state of the arm-tip position). I refer to it as the body model, and in particular, I refer to it when considering the dynamics as body dynamics.

The objective of my thesis is to propose a machine learning framework that the robot acquires its body model from the experiences it gains through embodiment without pre-designed robot-environment model to adapt to dynamic and uncertain environments and cope with new tasks and situations in a short duration. Specifically, I focus on the acquisition and extension of the robot body model using motor babbling through deep learning to realize dynamic motion learning for flexible-joint robots and tool use with a tool-body assimilation model.

This thesis is organized into four chapters. Chapter 1 provides the background, research objective, related work, and overview of the proposed approach as an introduction of the current study about acquisition and extension of the robot body model using motor babbling through deep learning.

In chapter 2, I propose a learning strategy for robots with flexible joints having multi-DOFs in order to achieve dynamic motion tasks. In spite of there being several potential benefits of flexible-joint robots such as exploitation of intrinsic dynamics and passive adaptation to environmental changes with mechanical compliance, controlling such robots is challenging because of their increasingly complex dynamics. To achieve dynamic movements exploiting such benefits of flexible-joint dynamics, I introduce a two-phase learning framework of the body dynamics of the robot using a RNN motivated by a recent deep learning strategy consisting of pre-training and fine-tuning. This two-phase learning methodology comprises a pre-training phase with motor babbling and a fine-tuning phase with additional learning of dynamic motion tasks. In the pre-training phase with motor babbling, I consider active and passive exploratory motions in order to efficiently learn body dynamics. In the fine-tuning phase, the learned body dynamics are adjusted for specific tasks. I demonstrate the effectiveness of the proposed methodology in achieving dynamic tasks involving constrained movement requiring interactions with the environment on a simulated flexible joint robot model as well as in hardware experiments using a PR2 robot both of which have a seven DOF redundant arm. The results illustrate a reduction in the required number of training iterations for task learning as well as generalization capabilities for untrained situations with the learned body dynamics through motor babbling. In addition, I discuss the issues regarding the trade-off between task training iterations and the success rate of task execution. Furthermore, I discuss the small number of exploratory motor-babbling motions for body dynamics.

In chapter 3, I propose a tool-body assimilation model that considers grasping during motor babbling for using tools. A robot with tool-use skills could be useful in a human--robot symbiosis situation because this allows the robot to expand its task performing abilities. In the existing tool-use model, the body and tool models are separated. Therefore, the motions during tool use are expressed by each tool. To address these issues, I adopted tool-body assimilation. In a tool-body assimilation model, the tool model is expressed as a body with a tool. Therefore, the motions during tool use are expressed by the body model, and the robot effectively learns the tool functions. Almost all existing studies for robots to use tools require predetermined motions and tool features; the motion patterns are limited and the robots cannot use novel tools. Some of the other past studies fully search for all available parameters for novel tools, but this leads to massive amounts of calculations. Other past studies

approaches were mainly focused on obtaining the functions of the tools, and showed the robot starting its motions with a tool pre-attached to the robot. This implies that the robot would not be able to decide whether and where to grasp the tool. In real life environments, robots would need to consider the possibilities of tool-grasping positions, then grasp the tool. To address these issues, the robot performs motor babbling by grasping and nongrasping the tools to learn both tool functions and the robot's body model. In addition, the robot grasps various parts of the tools to learn the different tool functions from the different grasping positions. These rich motion experiences are learned using deep learning. Tool features were self-organized in parametric bias, modulating the body model according to the tool in use. Finally, I designed a neural network for the robot to generate motion only from the target image. To evaluate the model, I have the robot manipulate an object task without any tools or with several tools of different shapes. I have the robot generate motions after showing the initial and target states by deciding whether and where to grasp the tool. Therefore, the robot is capable of generating the correct motion and grasping decision when the initial and target states are provided to the robot.
In Chapter 4, the achievements of a series of both numerical and robot experiments of acquisition and extension of the robot body model. Finally, reviews on the remaining research topics and future directions conclude this thesis.

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氏 名　髙橋　城志　　　　　　　　　　印

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種 類 別 (By Type)	題名、　発表・発行掲載誌名、　発表・発行年月、　連名者（申請者含む）(theme, journal name, date & year of publication, name of authors inc. yourself)
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