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学位の種類	博士（工学）
学位記番号	シス博　第 144 号
学位授与の日付	令和 3 年 3 月 25 日
課程・論文の別	学位規則第 4 条第 1 項該当
学位論文題名	Multi-scopic Neuro-cognitive Adaptation for Legged Locomotion Robots （多足歩行ロボットのための多視的観点からの神経認知的適応）
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【論文の内容の要旨】

Recently, various types of robots have been gradually replacing human workers in the tasks of exploring unknown, dangerous and dynamic environments. Especially, the mobility in dynamic environments is strongly required of robots. The human dynamic locomotion is realized by the simultaneous integration based on adaptability and optimality. The adaptability depends on the real-time perception as a bottom-up learning-based approach from the microscopic point of view, while the optimality depends on cognition as a top-down knowledge-based approach from the macroscopic point of view. Various cognitive architectures have been proposed in the cognitive science until now, but it is difficult for robotic researchers to apply such cognitive models to deal with adaptability and optimality simultaneously in real dynamic environments, because most of them only explain the information flow of human cognitive behaviors in the conceptual level, and the methodology to implement functions like human cognitive behaviors is not explained in detail. Therefore, I need a cognitive model that can cover and integrate the mobility from microscopic control to macroscopic planning and from short-term adaptation to long-term optimization.

This thesis proposes a neuro-cognitive model for multi-legged locomotion to realize the seamless integration from multi-modal sensing, ecological perception and cognition through the coordination of interoceptive and exteroceptive sensory information. A

cognitive model can be discussed from three different scopes: micro-, meso-, and macro-scopic, corresponding to sensing, perception, and cognition and short-, medium- and long-term of adaptation related with neuro science and ecological psychology. Basically, the multi-legged locomotion requires the intelligent functions of 1) attention module, 2) adaptive locomotion control module, 3) Object recognition module, 4) environmental map building module, and 5) optimal motion planning module, and the proposed neuro-cognitive model integrates the above intelligent functions from the multi-scopic point of view.

At the microscopic level, I build an attention mechanism for exteroceptive sensory information according to the current interoceptive sensory information, and adaptive locomotion control is done by (the lower-level of) sensorimotor coordination based on interoceptive and exteroceptive sensory information as a short-term adaptation. Furthermore, online locomotion generator is also processed in this scope. At the macroscopic level, I build environmental knowledge with higher level of behavior planning from (the collection or memory of) large scale of sensory information. The robot can conduct optimal motion planning using the built environmental knowledge. At the mesoscopic level, the proposed neuro-cognitive model integrates these two approaches of microscopic and macroscopic levels. Especially, the proposed neuro-cognitive model builds a cognitive map using the bottom-up facial environmental information and top-down map information, and generates intention towards the final goal from the macroscopic level.

The effectiveness of the proposed model has been evaluated through a series of experiments. First, I conduct experiments on locomotion learning and control based on sensorymotor coordination in the microscopic level. Next, I conduct experiments on environmental knowledge building and global path planning. Finally, I conduct experiments on the real-time re-planning and behavior coordination in the rough terrain and dynamic environments in the mesoscopic level. Through the above experiments, I showed the adaptability and optimality in the multi-legged locomotion by the proposed multi-scale neuro-cognitive model.

This thesis is organized as follows. Chapter 1 explains the social background leading to this thesis research objectives. The main contribution of the research is also discussed and highlighted in this chapter.

Chapter 2 introduces behavior coordination for multi-legged robots to better understand the challenges reflected in this thesis. Next, I explain the study on locomotion control from conventional control theory to biologically-inspired control methods in neuroscience and cognitive science. Furthermore, I review well-established findings regarding the cognitive process from interoceptive and exteroceptive sensory information to motion control in human behaviors. In addition, the background concept of multiscopic adaptation is discussed in this chapter.

In Chapter 3, I proposed the concept of sensory-motor coordination model based on perceiving-acting cycle in the microscopic level, that is a lower level control system interacting directly with the environment. The sensory-motor coordination model is composed of 1) attention mechanism module that controls the topological structure of 3D point cloud information by using Dynamic Density Growing Neural Gas (DD-GNG). DD-GNG can control the density of topological structures in specific area based on the attention, 2) object affordance detection module for the direct perception to generally identify the environmental condition based on the physical embodiment, 3) neural based locomotion module that generates dynamic gait patterns by integrating with sensorimotor coordination. The sensory-motor coordination model is optimized through a learning process in the computer simulation beforehand. The locomotion ability of real multi-legged robot and the leg malfunction evaluations are demonstrated in the experiments by several different terrains. The experimental results show that a smooth gait-pattern transition could be generated during sudden leg malfunction.

In Chapter 4, I proposed the method of building environmental knowledge by using the topological structure-based map reconstruction. Next, I proposed an optimal path planning method on the built map. Experimental results show that the proposed method can extract environmental features for multi-legged robots and build environmental knowledge for optimal path planning.

In Chapter 5, I proposed a neuro-cognitive model integrates the sensory-motor coordination model with environmental knowledge as a cognitive map using the bottom-up facial environmental information and top-down map information. The cognitive map is used to recognize a current facing situation by the topological structure information from lower level, composed as 3D vector position of nodes, edges, and 3D surface vectors of nodes. The robot generates intention towards the final goal from the macroscopic level. Furthermore, the learning process to integrate the relationship between macroscopic level of behavior commands and locomotion performance is developed as well. The proposed model has been tested for omnidirectional movement in biped and quadruped robot. Furthermore, the proposed neuro-cognitive model has also been implemented for robot climbing behavior, performing a horizontal-vertical-horizontal movement.

Concluding remarks are summarized in Chapter 6. The experimental results on multi-legged robot locomotion with the proposed neuro-cognitive model are discussed from the multi-scopic point of view. Finally, I discuss several future research directions in the interdisciplinary study on cognitive science and ecological psychology.