論 文 の 要 旨

題 目　Automatic Design of Controllers for Robotic Swarms
(ロボティックスワームのための制御器の自動的設計)

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Swarm robotics is the study of a large group of autonomous robots that operate without relying on a centralized controller. The concept of swarm robotics originates from collective behaviors of biological systems, such as colonies of social insects, flocks of birds, and schools of fish. Similar to these biological systems, robotic swarms perform tasks beyond the capability of a single robot. In particular, a single robot in a robotic swarm is incapable or inefficient in performing a task by itself. However, the robotic swarm could achieve the task through collective behavior that emerges from local interactions between the robots and between the robots and the environment.

One of the challenges in swarm robotics focuses on designing control software for a robotic swarm. The most common approach in swarm robotics follows a trial and error process to design a controller. This method is effective if the desired collective behavior is simple enough for the designer to understand and program into the controller. However, this method is guided only by the designer's intuition and experience. As an alternative method, the automatic design method develops controllers by transforming the design problem into an optimization problem. This thesis focuses on the evolutionary robotics approach, which is the most often used automatic design method. The evolutionary robotics approach utilizes an evolutionary algorithm to optimize the parameters of the controller. The traditional evolutionary robotics approach uses artificial neural networks as robot controllers. Typically, the structure of the neural network is determined by the designer, and the synaptic weight values of the neural network are optimized by an evolutionary algorithm. So far, there has been little progress in studies using automatic design methods within the swarm robotics community. Therefore, this thesis contributes to the swarm robotics community from the following two aspects. First, this thesis presents how the evolutionary robotics approach could be applied to develop controllers for robotics swarms to perform tasks that are difficult to design controllers by hand. Second, this thesis presents novel evolutionary robotics approaches to design controllers for robotic swarms.

This thesis consists of eight chapters. As described above, the first goal is to develop controllers for robotic swarms using an evolutionary robotics approach. Based on this topic, Chapters 3 and 4 present case studies using the evolutionary robotics approach. In addition, Chapter 5 gives further analysis on collective behavior developed in Chapter 4 to provide insights into how robotic swarms should be composed. The proposal of novel evolutionary robotics approaches is described in Chapters 6 and 7. A summary of each chapter is described as follows.

Chapter 1 introduces the thesis with a background of the research.

Chapter 2 provides a brief review of automatic design methods in swarm robotics. In addition, this chapter briefly describes an introduction to evolutionary robotics, including an introduction to evolutionary computation and approaches to evolving neural networks.

Chapter 3 shows how the evolutionary robotics approach could be applied to generate collec-

tive cognition by robotic swarms in the foraging task. In biological swarms, individual cognition is enhanced by communication and cooperation with other individuals. A single individual only has a limited cognition ability; however, it could be extended beyond its cognition ability when considered as a swarm. Benefitting from collective cognition, biological swarms can exhibit sophisticated collective behavior and decision-making processes. This chapter aims to develop controllers using the evolutionary robotics approach to address a foraging task that requires collective cognition. In this task, the robotic swarm has to distinguish between two types of objects and transport one of them to the goal. A robot could not distinguish between the two types of objects because the sensory inputs are set to handle them as the same objects. The controller for the robotic swarm is successfully developed to accomplish the foraging task.

Chapter 4 aims to develop controllers to address a path-formation task with congested situations. Typically, robotic swarms are conducted to have high redundancy in the number of robots. However, in situations where multiple robots gather in a spatially limited environment, robots tend to interfere with each other. This chapter develops a controller for a robotic swarm to exhibit behavioral specialization to manage congestion in the path-formation task.

Chapter 5 further discusses the behavioral specialization within the robotic swarm that is observed in Chapter 4. More specifically, this chapter focuses on the effect of the embodiment of robots on collective behavior and specialization. The studies on swarm robotics emphasize the importance of the embodiment of robots. However, so far, only a few studies have discussed how the embodiment influences the collective behavior of robotic swarms. In this chapter, the experiments are conducted by varying the size of robots to change the degree of congestion. Additionally, the experiments are conducted with and without considering collisions among robots to discuss the effect of the robot embodiment. This chapter shows the importance of the robot embodiment that is sometimes neglected in the studies of swarm robotics.

Chapter 6 proposes an evolutionary robotics approach that applies echo state networks as controllers for a robotic swarm. The main characteristics of the echo state network are that the hidden layer is generated with sparse and random connections, and only the weight values connected to the output layer are trained. The proposed approach utilizes an evolutionary algorithm to optimize the output weight values of the echo state network. The performance of the proposed approach is compared with a typical method that uses a traditional neural network controller. This chapter shows that the echo state network could be an alternative to the recurrent neural network in the evolutionary robotics approach.

Chapter 7 focuses on the evolutionary robotics approach that evolves both the synaptic weight values and the topological structure of the neural network controller. The algorithm called Mutation-Based Evolving Artificial Neural Network (MBEANN) is employed to design the controller for the robotic swarm. The performance is compared with NeuroEvolution of Augmenting Topologies (NEAT), which is a widely used algorithm to evolve both topologies and weights. The evolved controllers are evaluated in a cooperative transportation task performed by a robotic swarm. The robot controller evolved with MBEANN outperformed the NEAT controller in the cooperative transportation task.

Chapter 8 concludes the thesis and discusses future research directions.