論 文 の 要 旨

題 目　Automatic Design of Controllers for a Multi-Legged Robotic Swarm
(多脚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 designing collective behaviors with a large number of autonomous robots. The inspirations for swarm robotics originated from social insects or animals, such as schools of fish, flocks of birds, and groups of ants or bees. As these natural swarm systems, robotic swarms are expected to show capabilities beyond a single robot. In addition, the robotic swarms are also expected to show system-level properties, such as fault tolerance, flexibility, and scalability.

In pieces of literature, many studies of swarm robotics have been conducted with mobile robots driven by wheels. By using this type of robot, the designer can reduce efforts in designing the basic motions of robots. Therefore, designers focus on developing a robot controller that generates desirable collective behaviors. On the hand, the behaviors of robotic swarms are typically discussed in relatively flat surfaces, i.e., two-dimensional spaces. To overcome this limitation, this thesis employs multi-legged robots which show vertical motions, such as climbing steps or obstacles. By using the multi-legged robotic swarm, local and physical interactions between robots or robots and the environment are expanded to three-dimensional space; multi-legged robotic swarms are expected to operate in rough terrains or to show novel collective behaviors inspired by the self-assembly of army ants. However, designing a controller becomes a challenging problem because designers have to consider not only how to coordinate a large number of robots but also how to coordinate a large number of actuators in individual robots. Therefore, the multi-legged robotic swarm raises a new problem domain as the combination of two types of large degrees of freedom controls. To solve the problem, this thesis focuses on the automatic design method in swarm robotics: evolutionary robotics and reinforcement learning. In these machine learning techniques, a huge number of trial-and-error processes seem to be effective for designing complicated controllers. This thesis aims to show the potential of the automatic design method for generating collective behaviors of a multi-legged robotic swarm.

This thesis consists of eight chapters. As described above, the objective of the thesis is to generate collective behaviors of a multi-legged robotic swarm using an automatic design method. Chapters 3 to Chapter 6 show that the evolutionary robotics approach has achieved successful results for controller designs. In addition, Chapter 7 presents a reinforcement learning approach as an alternative to evolutionary robotics. A summary of each chapter is described as follows.

Chapter 1 briefly introduces swarm robotics with the background and motivation of the thesis.

Chapter 2 describes automatic design methods in swarm robotics. The first section provides introductions to evolutionary robotics with some related topics, such as evolutionary computations, neuroevolution, and related work. Second, this chapter describes the overview of reinforcement learning with basic topics and recent trends.

Chapter 3 shows the first example of the evolutionary robotics approach for the three-dimensional collective behavior of a multi-legged robotic swarm. As mentioned above, a

combination of designing gait and collective behavior is a highly complex problem. This chapter employs both the manual design and evolutionary design as an experimental approach. The controller of a robotic swarm is developed by connecting an artificial neural network (ANN) to the hand-tuned central pattern generator (CPG). The synaptic weights of ANN are optimized by evolutionary computation to that the output of ANN affects the CPG signal and generates a collective behavior. The experimental results showed that the proposed method successfully designed three-dimensional collective behavior.

Chapter 4 summarized the pure neuroevolution approach. The proposed method in Chapter 3 could skip the evolution of basic gait; however, the tuning of CPG highly depends on the robot's specifications. This chapter proposes the approach in which the basic gait of single robots is also generated by evolutionary design: the pure neuroevolution approach. In this chapter, the neuroevolution approach shows that robot gait which has similar features to legged animals is successfully obtained by incorporating intuition-based objective function into the fitness evaluations. In addition, the neuroevolution approach successfully designed a control scheme for collective behavior, i.e., how to coordinate a large number of joints on legs based on local observations to show the coordinated motion of robots.

Chapter 5 shows the collective behavior design in a rough terrain environment. The multi-legged robotic swarm is expected to operate in fields with rugged surfaces or uneven surfaces. Based on the result of Chapter 4, this chapter aims to achieve the path formation task in not only flat but also rough terrains. In the experiment the terrain aspect is parametrized by the height of each block; the swarm performance is quantitatively discussed with the terrain settings. The experimental results showed the evolutionary robotics approach successfully achieved a path formation task in rough terrain environments. The results also showed that incremental evolution is an effective way to design a controller in a rough terrain setting.

Chapter 6 focuses on generating and analyzing the collective step-climbing behavior. The proposed approach in Chapter 4 is applied to generate a three-dimensional collective behavior. This chapter shows that the neuroevolution approach is a promising way to design a robot controller for the collective step-climbing task. Additionally, evolved controllers are analyzed to clarify what kind of behaviors are obtained. Based on the preliminary experiments, robots seem to show not only climbing of other robots or steps but also developing *helpful* stepping stones for achieving the task. In this chapter, measurement factors are designed to analyze robot behaviors. The experimental results showed that the transitions of measurement factors support the hypothesis about obtained behaviors.

Chapter 7 discusses the reinforcement learning-based approach. In former Chapters, evolutionary robotics approaches showed successful results on a multi-legged robotic swarm, similar to traditional automatic design approaches in swarm robotics. On the other hand, evolutionary computations are often denoted disadvantages with high computational costs. This chapter focuses on reinforcement learning which is a relatively minor approach of the automatic design method. Proximal policy optimization (PPO) which is one of the most popular algorithms is applied to the task of forming a line. The result showed that the PPO successfully designed the controller of a multi-legged robotic swarm.

Chapter 8 concludes the thesis and discusses future research directions.