論 文 の 要 旨

題 目　Designing Controllers for Robotic Swarms with Deep Reinforcement Learning
(深層強化学習によるロボティックスワームのコントローラーの設計)

氏 名　金 伯胤

Swarm robotics studies how systems composed of many homogeneous robots can be used to accomplish tasks. The robots only have limited local sensory capabilities, yet in a swarm, they can accomplish tasks beyond the capability of a single robot.

Robots in a swarm robotics system can only perceive limited local information from the environment. However, robots can cooperatively accomplish a task that a single agent could not achieve. The SR system has three desirable properties, i.e., fault tolerance, scalability, and flexibility. Fault tolerance is the property to accomplish the task even with the loss of robots. Scalability is the property to achieve the given task with different group sizes. Flexibility is the property that a robotic swarm should still be able to cope with changes in tasks. Due to these characteristics, a robotic swarm has various potential applications, such as searching and transporting objects. One of the promising approaches in designing a controller for a robotic swarm is Reinforcement Learning (RL). Recently, RL has achieved considerable success in applications, such as games and controlling robots. In addition, RL is known to work well in both single-agent and multi-agent applications.

This thesis introduces two case of studies that designing controllers for robotic swarms with deep reinforcement learning. The first case explore the generation of collective behaviors with raw camera images as the primary information input. The second case proposes a hierarchical training method for reinforcement learning to train the swarm robotics controller.

In this thesis, we contributed to the swarm robotics community in three aspects.

Firstly, in chapter 3, we explore the generation of collective behaviors with raw camera images as the primary information input. Spatial information has always been a necessity in generating collective transport behavior. The rise of deep neural network technology makes it possible for a robot to perceive the environment from its visual input. This chapter shows the use of deep reinforcement learning in training a robotic swarm to generate collective foraging behavior. The collective foraging behavior is evaluated in a transportation task, where robots need to learn to process image information while cooperatively transporting foods to the nest. We applied a deep Q-Learning algorithm and several improved versions to develop controllers for robotic swarms. The results of computer simulations show that using images as the primary information input can successfully generate collective foraging behavior. Besides, we also combine the advantages of several algorithms to improve performance and perform experiments to examine the flexibility of the developed controllers.

Secondly, in chapter 4, we discuss how to design a controller for another form of swarm robotics, a swarm of drones. By applying the deep reinforcement learning techniques explored in Chapter 3, we propose using visual information to replace the position information. We created an artificial neural network with convolutional layers and trained the network with Deep Reinforcement Learning algorithms. We showed that our robots could learn and use

visual information for the replacement of position information. Deep Q-Network as a subset of the reinforcement learning algorithm is used. We compared the performance of standard DQN, 2- step Q-learning, 3-step Q-learning, DQN with freeze target network, and 3-step Q-learning with the freeze target network. 3-step Q-learning with freeze target network showed the highest performance compared to others, and we assessed the scalability of this controller. We found that this controller is relatively scalable up to 48 agents.

Thirdly, Chapter 5 proposes a hierarchical training method for reinforcement learning to train the swarm robotics controller. Firstly, the original task is partitioned into simpler sub-tasks, which are easier for the robots. Then, train sub-controllers to complete each sub-task separately. After that, a strategy for selecting sub-controllers is trained to solve the multi-objective task, which is expected to achieve the given task effectively. We expect that this hierarchical training method can overcome the drawbacks in the complex rewards shaping. We demonstrate the proposed method in a complex variation of a typical collective foraging problem. For comparison, a conventional reinforcement learning method is employed with two different reward settings; sparse rewards and reward shaping. We demonstrate that the proposed method trained with sparse rewards outperforms the conventional approach. We further examine the scalability, fault tolerance, and flexibility of the controllers developed by the proposed method.

This thesis consists of six chapters. A summary of each chapter is described as follows.

In chapter 1, the research background of swarm robotics is described.

In chapter 2, we first give a brief review of deep reinforcement learning. Then, we describe the development of deep reinforcement learning, its applications, and related techniques, including reinforcement learning, deep learning, artificial neural networks, convolutional neural networks, etc.

Chapter 3 investigates the generation of collective behaviors with raw camera images as the primary information input.

Chapter 4 describes the generation of flocking behavior in a flying swarm with deep reinforcement learning.

Chapter 5 describes applying a hierarchical training method for the reinforcement learning training process to address the multi-objective task with sparse rewards. A comparison between the proposed method and the conventional approach is also presented.

Finally, we conclude this thesis in chapter 6.