Abstract of the dissertation

Title Automatic Generation of Collective Behaviors for Robotic Swarms

(ロボティックスワームにおける群れ行動の自動的設計)

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In nature, social insects such as ants, bees, and wasps exhibit collective behaviors to accomplish tasks beyond the capability of a single individual. For instance, ants can transport foods far larger than themselves, and are capable of building highly complex nest involving several thousand individuals working together. This kind of intelligence implicitly shown in these social insects is also referred to as swarm intelligence. Behind these intelligent behaviors is the self-organizing process, that is, each individual of these social insects is weak and simple, yet in a swarm they are able to accomplish complex tasks through numerous local interactions between the individuals and between the individuals and the environment. Since swarm intelligence can be widely observed in natural livings, a robotic swarm can benefit in the same way. In this doctoral thesis, we study how to develop control systems for robotic swarms utilizing swarm intelligence principles. This thesis is organized as follows.

Chapter 1 introduces the research background of swarm robotics. Swarm robotics is the application of swarm intelligence to multi-robot systems. Analogous to the social insects, robots in a robotic swarm are relatively simple compared to the task they are dealing with that their communication is usually local and sensory capabilities are limited. A robotic swarm works in a distributed and self-organizing manner, that is, there is neither a super central robot dictating to the others, nor are the robots aware of global information. On the contrary, each robot only follows simple local rules and act autonomously based on its own local perception. Promoted by the properties described above, a robotic swarm is considered to be robust, flexible, and scalable.

In chapter 2, we review the design methods for robotic swarms. Designing control systems for a robotic swarm is a challenging task. The difficulty resides in

the fact that the relationship between the simple local interactions and complex collective behaviors is not straightforward. Most existing studies are based on behavior-based methods, where the human designer develops the robot controller by tuning a finite state machine by trial-and-error until expected collective behaviors are acquired. However, the design process is guided only experience and intuition, on which the performance of the system heavily relies. A promising alternative is automatic design, in which the design problem is casted into an optimization problem to reduce human intervention. Two representative automatic design approaches are evolutionary robotics and reinforcement learning. In this study, we focus on the automatic generation of collective behaviors for robotic swarms based on automatic design approaches.

Chapter 3 studies how to develop autonomous specialization behavior for a robotic swarm. While robotic swarms are expected to perform tasks more efficiently than a single high-performance robot, in situations, where multiple embodied robots gather in a limited space, a robot tends to interfere with other robots, which decreases the performance of the whole swarm. In this chapter, we investigate to use an evolutionary robotics approach to develop effective autonomous specialization strategies to manage the congestion problem in a path formation task. The results show that the emergent strategy was able to manage the congestion problem and improved the performance of the whole system.

Chapter 4 reports a case study where collective cognition behaviors are developed for the robots to distinguish between different objects. The robots used in swarm robotics are far simpler than individuals of social insects, resulting in a gap that the cognitive ability of robots is weak (e.g. in many cases, a single robot cannot recognize target objects). To fill this gap, in this chapter we adopt the covariance matrix adaptation evolution strategy to develop collective cognition behaviors for a robotic swarm in a collective foraging task with poison, in which the robots have to distinguish between foods and poisons collectively and finally only transport foods to their nest. The results show that scalable and flexible controllers with high performance (in terms of success rate) are successfully developed.

In chapter 5, we propose a new automatic design approach. Although evolutionary robotics has been applied to develop controllers for robotic swarms in various tasks, the tasks have been tackled so far are simple. The difficulty that prevents evolutionary robotics from being applied to complex tasks resides in the fact that the artificial evolution suffers from two issues: the bootstrap problem and deception. The reason behind is that designing proper fitness function could be challenging when the undertaken task is complex due to the existence of multiple components in the fitness function. To address these issues, in this chapter, we propose a two-step scheme, which takes advantages of both task partitioning and task allocation. In the first step, the original task is partitioned into simpler sub-tasks, which are easier for the robots to accomplish. In the second step, an evolutionary approach is used to synthesize a composite artificial neural network based controller to generate autonomous task allocation behaviors for the robotic swarm, which is expected to achieve the given task effectively. The proposed method is demonstrated in a complex variation of a typical collective foraging problem. The results show that the proposed method is able to develop controllers with higher performance, scalability, and flexibility compared to the conventional evolutionary approach.

Chapter 6 explores the use of deep Q-learning algorithm in developing end-to-end controllers for robotic swarms. While one of the long-term goals of automatic design is to develop controllers directly from high-dimensional raw inputs such as camera pixel images, most existing swarm robotics applications of automatic deign still require hand-crafted feature extraction of the inputs, on which the system performance heavily relies. The difficulty resides in the fact that using high-dimensional raw inputs significantly increases the parameters of the controller and therefore enlarges the search space, which requires prohibitively high computation resources. In this chapter, we explore to use the deep Q-learning algorithm to take advantages of both deep learning techniques that enable the end-to-end fashion development of robot controllers, and reinforcement learning algorithms that require less computation resources. The results show that the proposed approach is able to develop controllers using only high-dimensional raw camera pixel inputs for robotic swarms under different reward settings.

Chapter 7 concludes this doctoral thesis. In this thesis, we contributed to the swarm robotics community in the following aspects. Firstly, we adopted evolutionary robotics to develop two important collective behaviors for robotic swarms, namely autonomous specialization and collective cognition. Secondly, we proposed a new automatic design approach to address the bootstrap problem and deception. Finally, we explored the use of deep Q-learning algorithm to develop end-to-end controllers with less computation resource requirements.