博士論文(要約)

Study on Intelligence of Heterogeneous Robotic Team for Exploration Tasks
(探査タスクにおける異種群ロボットの知能化に関する研究)

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In recent years, manufacturing small and light weight robots at low cost has become much easier than it was in the past. Therefore, research on the Multi-Robot Systems (MRS) are actively pursued toward industrial applications. The MRS technology is expected to be applied in many fields such as disaster relief, security, environmental monitoring, and planetary exploration. From an operational point of view, the simultaneous operation of multiple robots is much more difficult compared with the case of a single robot operation. From such a perspective, the automation algorithm for MRS is an important factor for the maturity and the future spread of the technology. The automation algorithm for MRS has been actively studied for a long time as the Multi-Robot Task Assignment (MRTA) problem. A large part of previous studies focuses on homogeneous MRS in which every robot has the same ability. Relatively few studies focus on heterogeneous MRS in which robot members have different abilities in the system. Since heterogeneous MRS can distribute resources such as sensors, they are expected to achieve excellent mass and economic efficiency compared with redundant homogeneous MRS robots. Therefore, making use of heterogeneous MRS is an attractive solution for resource-constrained applications such as disaster relief and planetary exploration.

However, taking heterogeneity into account greatly complicate the automation algorithms. In this study, a type of robot is defined as a group of robots with the same capability set and the number of types of robots that make up the whole system is considered as the heterogeneity of the system. From this point of view, it can be said that conventional heterogeneous MRS research such as cooperative exploration between UGV (Unmanned Ground Vehicle) and UAV (Unmanned Aerial Vehicle), for example, are studies of systems with small heterogeneity. Moreover, the proposed approaches are typically ad-hoc to the specific system configuration and it is unclear whether such solutions will perform well for other system configurations. Therefore, the development of an automation framework able to comprehensively handle arbitrary configurations of heterogeneous MRS, comprised of teams of robots with high heterogeneity and overlapping capabilities is required. The purpose of this research is to seek a scheme of automation frameworks for the general configuration of a heterogeneous team of robots for exploration and mapping tasks.

In this study, a centralized planning approach is adopted for realizing the automation framework. First, a novel routing problem formulation for the general configuration of a heterogeneous team of robots, namely the Generalized Team Orienteering Problem(GTOP) is introduced. In GTOP, a team of robots with heterogeneous abilities have to visit a set of goals with different completion requirements corresponding to the various abilities of the robots. This enables to express the routing of a general configuration of heterogeneous systems mathematically. The advantage of using a centralized planning method is to guarantee a certain level of solution quality. However, the disadvantage of it is the computational complexity which exponentially scales with the size of the problem. To cope with this issue, a novel solving technique inspired by the adaptation principle of neural circuits, namely the adaptive routing technique, is proposed in this research. One noteworthy property of the proposed algorithm is the small computational complexity which mekes it possible to use such a centralized automation scheme for practical applications. The background of the research and existing researches regarding automation algorithms for MRS are introduced in chapter 1 and chapter 2.

The performance of the proposed adaptive routing technique is analyzed in chapter 3. Firstly, parameter sensitivity analysis is performed. The most important parameter in the proposed algorithm is the number of neurons used in the planning process, which determines the required computational complexity to solve a problem. From the result of this study, it has appeared that with a certain required threshold, a fixed number of neurons is sufficient to perform routing independently from the number of robots in the system. This property ensures the computational complexity does not scale to the size of the system. This property is distinctive compared to conventional metaheuristics.

Secondly, the comparative study of the performance of the adaptive routing is performed. Since the GTOP is a novel problem formulation, existing works that propose efficient metaheuristics cannot be found. Ant Colony Optimization(ACO) which has been proposed as a solution for the Team Orienteering Problem(TOP), the special case of GTOP, is expanded as a GTOP solver and compared to the proposed method. The results confirmed that as a TOP solver, the adaptive routing technique is not greatly inferior to the ACO approach in terms of performance, i.e. the quality of the solution. As a GTOP solver, the performance of the adaptive routing technique is greater than the ACO approach especially when the size of the problem is large. Moreover, the computational complexity of the algorithm is confirmed not to scale with the number of robots and the number of capabilities of the system.

The results show that the advantage of the proposed method is especially significant for solving large size of problems where the number of goals, the number of capabilities of the system and the number of robots in the system are large.

To confirm the effectiveness of the proposed automation framework in the context of a practical application, an exploration and mapping problem based on the lunar and planetary cave exploration scenario is defined in chapter 4. Caves which have been discovered on the surface of the moon and Mars are considered as the highly desirable exploration targets because of their expected scientific interest. Moreover, such caves are beneficial from an engineering perspective as well. Inside a cave, the radiation level is much lower and the temperature is much more stable than on the surface. Furthermore, the possibility of access to water resource increases its value as a construction site for a human base in the future. With such background, a robotic exploration mission to understand the environment inside caves is currently planned by the space agencies around the world.

In the simulation study, the heterogeneous team of robots, where different sensors are distributed between robots with different roles, are assumed to explore the bottom of the cave. The robots continue the exploration as long as their equipped battery capacity allows. The exploration aims to expand the known area as much as possible with limited energy resources, as well as to construct an environmental map in terms of radiation, mineral resources, and water resources. Such regions of interest are considered as goals and the proposed routing framework find out the route of each robot to efficiently accomplish the exploration and mapping. A team of robots with 4 types is assumed in the simulation. Abilities considered in this problem are geometric map construction by a camera, measurement of mineral resources by a spectrometer and measurement of water resources by a moisture sensor. Each type of robots possesses a different set of such abilities but they are not independent with each other. The exploration performance of the team of robots using the proposed framework is compared with the performance of a conventional greedy exploration scheme. It is observed that the team of robots with the proposed framework explore the unknown environment more efficiently than with the conventional method, and marked higher exploration score as a result. Such a tendency is more clearly observed when a system with a large number of robots is considered. A comparative study of the performance of a team of robots assuming heterogeneous abilities and a team of robots assuming homogeneous abilities is also performed. As a result, it is confirmed that the superiority of the heterogeneous system is greatly affected by the difference of the automation algorithm.

Chapter 5 concludes and discusses the prospects of this study. To realize an automation framework for the general configuration of a heterogeneous team of robots, a centralized routing framework is proposed in this study. The proposed framework consists of a novel mathematical formulation of a routing problem of a heterogeneous team of robots and a novel solving approach based on the adaptation principle of neural circuits. The notable property of the proposed framework is its small computational complexity that does not scale with the size of the system. This property makes it possible to automate a team of a large number of robots in a centralized manner. The effectiveness of the proposed framework in a practical scenario is evaluated under the case study of lunar and planetary caves exploration.

The proposed framework can be applied to not only planetary exploration but also a lot of MRS applications such as environment monitoring, mobility on demand, large warehouse management and so on. In order to the proposed framework to support such robotic technology sustaining the future society, the outcome of this study should be expanded in the following manner. Incorporating the proposed routing framework with the perception algorithms using the artificial intelligence which is notably developed in recent years should be investigated. It is also necessary to accumulate research effort for practical application through real-world experiments.