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Research status of operational environment partitioning and path planning for multi - robot systems

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Abstract. There is a lot of applications for multi-robot systems instead of single robot systems. Therefore, coordination algorithms have become popular in the field of robotics for two decades. This paper analyzes and summarizes the current research status of coordinated algorithms for multi-robot systems, from perspectives of partitioning the environment, and path planning.

1. Introduction

Multi-robot systems have become popular in the field of robotics. However, the systems still face problems such as task allocations, cooperation, and resource competition. They are referred to as coordination of teammate robots. Therefore, this paper reviews the state of the art of coordinated algorithms for multi-robot systems from aspects of operational environment partitioning and path planning for robots.

2. Partitioning the Environment

Partitioned the environment can reduce the time consumed by the multi-robot system to search the task and avoid the repetitive search of the same regions by different robots. Factors that affect the partitioning are environment structure, target uncertainty, communication uncertainty, and mission urgency.

2.1. According to Target Moving Mode

In case of a static target search, the search map model can be cooperatively searched on the basis of the priori information of the environment and prediction of the target distribution, when the environmental is known in advance. Hu, Xie, Lum and Xu [1] studied the problem of multiple unmanned aerial vehicle (UAV) cooperative searches for multiple static targets on the ground using a search map. In the case of detection and communication constraints, the entire monitoring area is divided into units, each of which is associated with a probability of an individual target, which constitutes the probability map of the entire region. Each UAV preserves a single probability model for the existence of objects within each cell, and updates the probability model based on the distributed iteration Bayesian method. Non-linear transformation is used to linearism Bayesian analysis. A multi-protocol graph fusion scheme was proposed there and proved that all the individual probability maps converge to a same probability map, which reflects the real existence or non-existence of static objects in each unit. Peng, Shen and Zhu [2] proposed a distributed model predictive control for the multi-UAV cooperative search decision. The result is based on a Nash (optimality) and particle swarm optimization (PSO), and is used to solve the problem of small-scale distributed optimization of UAVs. Zigzag and the internal spiral patterns were used for unknown environment. Since the UAVs have minimal turning radius, they flew outside the area in order to ensure full coverage. This leads to a longer search path, resulting in a waste of search resources and reduced fleet search efficiency. The internal spiral patterns [3] require more turns near the center of the area. In side by side formation searching, because flight path length difference, a wide difference in the UAV speed is required. Therefore, the internal spiral patterns are not conducive to the



project. Therefore, Wu, Zhou, Yin and Liu [4] adjusted the turning time and turning position of each UAV in the formation, and successfully completed the area coverage search task.

If the targets are dynamic, then the above methods are not applicable. For example, the targets are randomly distributed evenly and dynamically in time. The moving target search algorithm employing a vertical line search pattern, with a slanted line search pattern or with Voronoi partitions and bionic algorithms, can be used. For the targets in a dynamic random environment with obstacles distributed uniformly, Xuan et al. [5] used a method based on Centroidal Voronoi Partitions (CVPs) for a cooperative distributed search decision. This research yielded the target assignment algorithm and proved the convergence of the algorithm. The proposed CVP strategy can be used to search the random target effectively and realize shorter target waiting times. The search space can be re-partitioned by remained UAVs when a UAV is out of order. Compared with the standard coverage search strategy, the proposed system has obvious advantages in case of the increasing number of multi-UAV, and the average waiting time of the target decreases as the number of multi-UAV increases and as the turning radius of the UAV decreases. At the same time, Wu, Zhou, Liu, and Yin [6] established improved centrally distributed multi-UAV cooperative search architecture. In this strategy, clustering analysis and Voronoi partitioning was employed. The collaborative search decision by controlling the improved model can effectively increase the UAV prediction range. Multi-UAV searches can be more effectively completed in the target area. Coordinated searching to solve the uneven distribution of resources at the same time. Based on the bionics algorithm, the problem of multi-UAV cooperatively track ground moving target is studied. Wang, Peng, Zhu and Shen [7] proposed a cooperative target tracking method for a multi-UAV system employing active perception. The distributed unscented information filter is used to estimate the state of the target, and the method of the combination of the receding horizon control and the genetic algorithm are used to realize the online cooperative trajectory planning of the UAV.

2.2. According to Specific Regions

To solve the multi-UAV target searching problem in an uncertain environment, priori information is employed to explore the environment division. Uncertain environment can be divided into unknown, known, and prohibited regions. Each of them will be processed individually. When making target searches, the search path should cover as many unknown areas as possible in areas of unknown attention and in areas of high attention with higher frequency of search; as far as possible, it should avoid known areas and completely avoid prohibited areas [8]. To guarantee complete avoidance of the prohibited areas, Wu, Huang, Song, Tang and Bai [9], in considering environmental information and data communication delay, introduced the search returns function, which generates prohibited areas to avoid decisions, identifies the unknown environment to search, and circumvents the known environment of a prohibited area completely avoid. This achieves better search results, but it is not the optimization on the spatial distribution of the UAV. In the approach proposed by Qiao and Wang [10] an unmanned combat air vehicle (UCAV) in collaborative route principle, will take both search efficiency and combat efficiency into account. They used search function returns and weighted average distance to guide of UCAV, strengthen patrols of the high attention areas, and improved the spatial distribution for UCAVs. On this basis, Li and Qiao [8] proposed the route planning model for the simulation of PSO. The results show that the proposed collaborative patrol route planning algorithm has better search efficiency than the results of document [10]. The particle swarm algorithm makes the UCAV completely avoid prohibited areas and reduces the search of the known area.

In searching for an uncertain environment, Fu, Wei and Gao [11] took multi-UAV kinematics and prohibited areas into account together when realizing cooperative searching. A search algorithm based on predictive control was proposed to consider current and future searching costs. It also analyzes the communication constraints for collaborative area searches and tests this with the Monte Carlo method.

2.3. According to Information Integrity

Communications among robots are suffered from limited distance, message delay, limited bandwidth, and so on. Communication among robots can be divided into three kinds: global communication, local communication and no communication. The factors that influence the inconsistency of environmental information are the initial prior information, the detection information, and the communication

information. For the message delay problem, the Kalman filtering method can effectively estimate the communication delay state. The information inconsistency compensation method, based on state estimation, can eliminate the environment information deviation caused by the global communication delay. Consequently, the auction algorithm and the consistency information filtering algorithm are proposed in local communications. Among them, Capitan, Spaan, Merino and Ollero [12] reduced the communication load through decentralized data fusion. Sun, Zhou, Zou and Ding [13] has improved the information consistency filtering (ICF) algorithm in order to realize the distributed information fusion of each UAV node in the communication and measurement range. In addition, the problem of UAV distributed filtering and control under conditions of limited communication and measurement is solved by using the communication connection robustness function. In no communication case, an extreme case in which each UAV cannot share information with other UAVs, leading to the environmental information of each UAV being completely inconsistent [14]. In addition, when the remote UAV is carrying out the continuous target tracking, Zhu and Zhou [15] used a nonlinear model predictive control (NMPC) to realize the UAV cooperative distributed online optimization to ensure the dynamic maintenance of the whole communication network. A variety of computational methods are inspired by biology. In addition to the aforementioned calculation method's usefulness in achieving a multi-robot system coordination strategy [16-17], it can also be used to solve the inherent problems of multi-robot system communication [18]. Feng and Swindlehurst [19] considered a collection of single-antenna ground nodes communicating with a multi-antenna UAV over a multiple- access ground-to-air communications link. They designed a device with multiple mobile ground-based terminals and developed an algorithm for dynamically adjusting the UAV heading.

In addition, Puig, Garcia and Wu [20] proposed a three-layer optimization coordination algorithm, which can reduce the waiting time of each robot in the local area. Lazarus, Tsourdos, White, Silson and Zbikowski [21] proposed a method of cooperative guidance and estimation. The computational efficient data information algorithm can lead to build and update the map which is based on geometrical tool known as two-dimensional splinegon. It also enables multi-UAV to efficiently search and explore unknown environments. Janchiv, Batsaikhan, Kim, Lee and Lee [22] proposed a region partitioning algorithm that combines exact cell decomposition and templates matching. But the algorithm only applies to cases where the coverage area and the barrier boundary are parallel to the rectangular edge.

3. Path Planning

The evaluation criteria of multi-robot path planning are real-time, reach ability, robustness, and optimization.

The ways to achieve path planning can be divided into traditional methods and intelligent optimization methods. The traditional methods of path planning include the visual graphical method, free space method, grid method, Voronoi diagram method, and artificial potential field method. The genetic algorithm, ant colony algorithm, immune algorithm, neural network, reinforcement learning, etc., are the main methods of using intelligent optimization for path planning [23]. Ma [24] used the method of constructing a Voronoi polygon graph to model. Dijkstra algorithm is introduced into the graph of the environment. The Voronoi diagram is searched, and the initial route is obtained. The algorithm improves real-time planning and can satisfy various constraints and obtain reasonable planning results. Based on a simultaneous consideration of the team cost and computation time, Savas and Ahmet [25] put forward a new method that combined with the Travelling Salesman Problem solution and Dijkstra shortest path solution for calculating bids. The approach has great advantages, including less computation, better real-time performance, a stronger ability to find the optimal result, etc. Compared with other algorithms, the genetic algorithm has strong universality and robustness. It is particularly suitable for solving complex problems that other methods cannot solve. The genetic algorithm is used to path planing of the multi-UAV.

Combining the traditional path planning method with the intelligent optimization path planning method can improve the robustness of multi-robot system path planning and improve the efficiency of motion planning.

Multi-robot path planning methods can be categorized also as centralized architecture, and distributed architecture, or hybrid architecture. Centralized architecture can make decisions on global information, with a high degree of coordination. But the real-time and dynamic of the centralized

architecture is weak. Commonly used methods are ant colony algorithm, hybrid genetic algorithm and so on. Ebtehal and Hisham [26] researched the methods used to solve multi-autonomous vehicle path-planning for an application of heavy traffic control in cities. Considering the obstacles and other robots' paths, each robot has to reach its destination in the minimum time and number of movements. They used decoupled centralized approaches to solve the problem.

Distributed architecture make decisions on local information, and has better real-time performance and stronger fault-tolerant ability. But the global ability of the distributed architecture is poor. Commonly used methods are traffic rules, mutual exclusion method, the priority method [27], distributed colorless information filtering [7] and so on. Wang, Peng, Zhu and Shen [7] proposed a kind of multi-UAV cooperative target tracking method based on active perception. A distributed multi-UAV online coordinated flight path optimization algorithm is designed, based on distributed colorless information filtering, to achieve fusion target state estimation, a stochastic search, and rolling time domain control. It can get better tracking performance by optimizing the UAV track online with the predicted target states. Cichella [28] et al. introduced a time-coordination problem for multi-robots cooperating based on distributed control rules. It supports time-varying network to exchange information. Even if there are faulty in communication networks, temporary link losses, and switching topologies, it would ensure that UAVs meet the desired temporal assignments of the mission.

The hybrid architecture makes up for the poor global performance and poor real-time performance in a distributed environment. The hybrid architecture has better overall situation and real-time performance. Xiao and Yan [29] proposed an ICCEAA algorithm to improve the global coordination ability and the adaptive level of the robot effectively under the architecture of the fusion immune co-evolutionary algorithm and APF algorithm. The algorithm has better superiority in path planning in a dynamic environment. It can distribute tasks reasonably and accomplish tasks in a short time.

The path planning process requires a large amount of calculation. When the environment is complicated, the environment of the robot is too tight, especially when the number of robots is large; the time/space complexity of the algorithm is bound to be the key of the algorithm. In order to improve the efficiency of the path planning algorithm, the parallelism of path planning should be considered. Therefore, the parallelism of the method should be considered in the design and operation of the algorithm. As for the path planning of multiple robots, the distributed multi process and mixed multi process planning mechanism should be adopted as much as possible to realize the parallelism of each robot's path planning.

4. Conclusions

The multi-robot system has a good development prospect and is extremely challenging. In this paper, the environment partitioning and path planning of multi-robot system is reviewed and the corresponding solutions are proposed.

The research of path planning technology for multi robot systems has achieved fruitful results, but each method has its own advantages and disadvantages, and no one method can be applied to any occasion. Therefore, it is an open question to combine some methods and combine the advantages of various methods to achieve better results. In addition, in order to solve the uncertainty of environment partitioning and path planning for multi-robot systems, and improve the robustness of multi-robot system, this research is also the focus of future development. The commonly used methods to solve the problem of uncertainty are Markov Decision Process (MDP), fuzzy control method and rough set theory. Among them, the most classical method is based on the Markov decision process model in decision theory to study the coordination of multi-robot system, it is an effective tool to deal with the uncertainty of the robot system. In the future multi-robot system path planning, the behavior of each robot is modeled by Partially Observable MDP (POMDP), and then apply these models to the case of multi-robot system in environmental monitoring and target instances. The mobile robot's exploration process belongs to the continuous state of POMDP, and a large number of approximation methods have been given for the solution of POMDP. Besides the foregoing, the methods related to robot applications include the task shortening method, the evolutionary strategy method, etc.

With the development of science and technology, the multi-robot application area will continue to expand, and the area of multi-robot spatial environment division and path planning will also be further. With the practicality as the ultimate goal, constantly promote its development forward.

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