A REVIEW OF COLLABORATIVE OPTIMIZATION OF TASK ALLOCATION AND PATH PLANNING IN MULTI-ROBOT SYSTEMS

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Abstract. Multi-robot systems are widely used in intelligent manufacturing, smart logistics and unmanned systems with high robustness and parallel operation capability. Task allocation and path planning are the core of collaborative decision-making, but their joint optimization is challenged by dynamic environments, communication constraints and heterogeneous conflicts. This paper defines the Co-MAPF problem, compares three system architectures, classifies mainstream algorithms, and summarizes the development trend of collaborative optimization for multi-robot systems.

Keywords. Multi-robot systems; Task allocation; Path planning; Collaborative optimization; Communication constraints; Deep reinforcement learning

Introduction

Multi-robot systems are key to meeting the requirements of large-scale, high-precision operations in aerospace, smart warehousing and urban inspection [1－3]. The core of collaboration lies in task allocation and path planning. Early sequential "allocate-then-plan" methods lead to suboptimal solutions and deadlock [4]. In recent years, joint optimization of task allocation and path planning has become a research hotspot. This paper systematically reviews collaborative optimization technologies, and clarifies the research status and development characteristics of this field.

Problem Definition

Collaborative Multi-Agent Path Finding (Co-MAPF) extends the classical MAPF by integrating task allocation. The workspace is represented as an undirected graph $G = (V, E)$, and the agent set $A = \{a_1, \dots, a_k\}$ corresponds to tasks τi with start si and goal gi. The optimization objectives include total makespan, energy consumption and number of completed tasks. Co-MAPF realizes active collaboration instead of passive collision avoidance, emphasizing real-time interaction and dynamic decision-making.

System Architectures

Multi-robot systems adopt centralized, distributed and hybrid architectures, as shown in Table 1.

Table 1 – Comparison of three system architectures

Architecture Type	Advantages	Disadvantages	Applicable Scenarios
Centralized	Global optimal, high path quality	High computation, single point failure	Small-scale static systems
Distributed	Strong robustness, good scalability	Local optima, complex protocols	Large-scale dynamic swarms
Hybrid	Balance optimality and flexibility	Complex interfaces, communication bottlenecks	Large-scale complex tasks

Search-Based Algorithms

Typical algorithms include HCA*, CO-WHCA* and CBS. CBS uses high-level conflict management and low-level path planning to ensure optimality, but computational complexity grows exponentially with the number of agents. TC-CBS enhances the coupling of task allocation and path planning.

Sampling-Based Algorithms

RRT, PRM and Multi-RRT* are suitable for high-dimensional spaces. They support distributed asynchronous planning and reduce centralized computation load, but path quality and convergence speed are uncertain.

Intelligent Optimization Algorithms

Genetic algorithm, PSO and ACO solve nonlinear multi-objective problems. DAC-GA and AFSA-PSO balance global convergence and local search, but require parameter tuning and have high computation costs.

Learning-Based Algorithms

Deep reinforcement learning (DRL) and graph neural networks (GNN) adapt to dynamic environments. The CTDE framework realizes centralized training and decentralized execution. GNN improves communication efficiency and handles dynamic topology.

Communication-Aware Joint Optimization

Communication constraints (bandwidth, delay, packet loss) are integrated into the planning model. “Task-Control-Communication” co-design couples trajectory planning and communication optimization, improving system robustness under limited bandwidth.

Conclusion

Task allocation and path planning are developing from separate design to deep joint optimization. The research field has formed a complete technical system including problem modeling, architecture design and algorithm implementation. Centralized, distributed and hybrid architectures adapt to different application scenarios, while search-based, sampling-based, intelligent optimization, learning-based and communication-aware algorithms provide effective solutions for collaborative optimization. The continuous integration of communication, control and artificial intelligence will further promote the practical application of multi-robot collaborative systems in complex real-world scenarios.

Core Challenges

1.Trade-off between real-time performance and algorithm scalability.
2. Adaptive capacity to dynamic environments and uncertainties.
3. Collaborative robustness under communication constraints.
4. Efficient deep coupling mechanism for task allocation and path planning.
5. Coordination of heterogeneous robots and large-scale swarms.

References:

1. Xiong J, Zhang W, Xiong Z, et al. Journal of System Simulation, 2025, 37(12): 3033 –3049.
2. Zhang Z, Mao J, Tan H. Acta Automatica Sinica, 2024, 50(1): 21 –41.
3. D’Andrea R. IEEE Transactions on Automation Science and Engineering, 2012, 9(4): 638 –639.
4. Greshler N, Gordon O, Salzman O. 2021 International Symposium on Multi-Robot and Multi-Agent Systems, IEEE, 2021: 20 –28.