Analysis of Energy-Aware Coverage Path Planning in a Large-Scale Multi-Robot System

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대규모 다중 로봇 시스템에서의 에너지 인지 커버리지 경로 계획 분석

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Abstract

Energy constraints impose a fundamental limitation on large-scale multi-robot coverage missions, where inefficient path planning and reactive charging strategies often lead to excessive detours and increased total travel distance. This paper analyzes an energy-aware coverage path planning framework for heterogeneous multi-robot systems, with emphasis on reducing travel distance under strict energy constraints. The framework combines a global coverage visiting order with proactive recharge-aware planning, enabling charging visits to be scheduled before critical depletion. Simulations with 21 heterogeneous robots show that the proactive strategy reduces total travel distance compared to conventional reactive charging, while producing smoother trajectories. These results indicate that explicitly integrating energy awareness into coverage planning improves scalability and operational efficiency in large-scale multi-robot missions.

Ⅰ. Introduction

Coverage path planning (CPP) is a fundamental problem in robotics, essential for applications such as environmental monitoring, inspection, surveillance, and agricultural exploration. In large-scale missions, multi-robot systems are deployed to achieve complete area coverage cooperatively. However, these systems operate under finite energy constraints, which significantly impact mission efficiency.

Classical CPP methods primarily focus on geometric completeness and overlap reduction, often optimizing path length while treating energy as a secondary constraint or ignoring it entirely [1]. In real-world scenarios, neglecting energy constraints during the planning phase can lead to mission failure or severe inefficiency due to premature battery depletion. While energy-aware CPP has been explored in single-robot settings [2], these approaches do not adequately address the coordination challenges inherent in large-scale multi-robot systems. Many existing multi-robot path planning approaches rely on reactive charging strategies. In a reactive framework, a robot only detours to a charging station when its battery level drops below a critical threshold. As the distance to charging stations varies, this often results in late detours, significant backtracking, and redundant travel, particularly in large environments with sparse charging infrastructure [3].

To address this, recent studies suggest proactive energy-aware planning, where charging decisions are integrated into the path generation phase rather than deferred to emergency situations [4,5]. This paper analyzes the impact of such a proactive framework on a large-scale heterogeneous multi-robot system.

Ⅱ. Method

We formulate a multi-robot coverage mission on a binary occupancy grid representing large-scale terrains with static obstacles. The system comprises N heterogeneous robots, each with a specific battery capacity E_{max} and distance-dependent energy

Table 1. Comparison of distance traveled (distance units) for heterogeneous robots (R1- R21).

Robot	R1	R2	R3	R4	R5	R6	R7	R8	R9	R10	R11	R12	R13	R14	R15	R16	R17	R18	R19	R20	R21
Conv.	323	441	336	298	315	315	294	211	211	233	266	265	338	280	259	271	280	218	290	312	286
Prop.	**273**	**375**	**275**	**297**	**223**	**240**	**219**	**211**	**194**	**175**	**255**	**254**	**304**	**236**	**251**	**251**	**232**	**190**	**288**	**267**	**245**

consumption. The objective is to minimize total travel distance D_{total} while guaranteeing complete coverage without energy depletion. Finally, we implement a proposed local optimization strategy, where the planner inserts charging visits into the trajectory before critical energy levels are reached. This is compared against a conventional reactive strategy, where robots detour to the nearest station only when battery levels fall below a dynamic safety threshold, often causing substantial backtracking.

Ⅲ. Simulation

Simulations were conducted using a map derived from Antarctic satellite imagery with a team of 21 heterogeneous robots (R1- R21). Qualitative analysis (Fig. 1) reveals that the conventional method results in sharp, erratic deviations due to emergency backtracking, whereas the proposed proactive method yields smoother, consistent trajectories by synchronizing charging stops with the coverage path. Quantitative results (Table 1) demonstrate a significant efficiency gain, with the proposed strategy reducing total travel distance by up to 13% compared to the reactive approach (e.g., R1 distance reduced from 323 to 273 units).

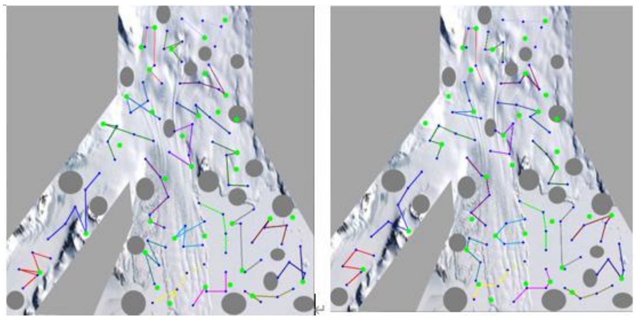

Fig. 1. Comparison of multi-robot trajectories: (left) conventional reactive strategy; (right) proposed proactive strategy.

Ⅳ. Conclusion

This paper presented an analysis of an energy-aware multi-robot coverage path planning approach, specifically examining the impact of proactive planning on travel distance. Simulations with 21 robots confirm that incorporating charging decisions during route planning outperforms traditional reactive strategies, producing smoother trajectories and reducing total travel distance.

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REFERENCES

[1] E. Galceran and M. Carreras, “A survey on coverage path planning for robotics,” Robotics and Autonomous Systems, vol. 61, no. 12, pp. 1258- 1276, 2013.

[2] M. Wei and V. Isler, “Coverage path planning under the energy constraint,” in Proc. IEEE Int. Conf. Robotics and Automation (ICRA), 2018, pp. 368- 373.

[3] N. Kumar, J. J. Lee, S. Rathinam, S. Darbha, P. Sujit, and R. Raman, “The persistent robot charging problem for long-duration autonomy,” IEEE Robotics and Automation Letters, 2025.

[4] J. Gong, M. O. Oluma, and S. Lee, “Proactive mission-time-efficient coverage path planning using hierarchical heuristics,” Information Sciences, 2025.

[5] M. O. Oluma and S. Lee, “Mission-Efficient Energy-Aware Multi-Robot Coverage Path Planning,” submitted to Proc. IEEE Int. Conf. on Robotics and Automation (ICRA), 2026.(submitted)