Large-Scale Multi-Robot Coverage Path Planning via Local Search*

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Introduction

We study the Multi-Robot Coverage Path Planning (MCPP), which aims to coordinate the paths of multiple robots to completely cover the given terrain. We follow existing graph-based MCPP algorithms (Zheng et al. 2010) that represent the terrain to be covered as a 4-connected 2D grid graph G and then leverage STC (Gabriely and Rimon 2001) to generate coverage path on a decomposed graph D of G for each robot by circumnavigating a subtree of G. Specifically, in an MCPP instance, we are given a terrain graph $G = (V_g, E_g)$ and its corresponding decomposed graph $D = (V_d, E_d)$, where each terrain vertex in V_g is decomposed into four small adjacent vertices in V_d (see Fig. 1-(a)). Given a set $I = \{1, 2, ..., k\}$ robots with a set $R = \{r_i\}_{i \in I} \subseteq V_d$ of initial root vertices, the graph-based MCPP problem is to find a set $\Pi = \{\pi_i\}_{i \in I}$ of k paths such that each $v \in V_d$ is visited by at least one path for complete coverage and each π_i starts and ends at r_i. The solution quality is measured by the makespan $\tau = \max\{c(\pi_1), c(\pi_2), ..., c(\pi_k)\}$, where the cost $c(\pi)$ of any path π is defined to be the sum of the weight w_e of every edge $e \in E_d$ in π. In essence, existing STC-based MCPP algorithms reduce MCPP to the NP-hard min-max rooted tree cover problem on G, which aims to optimize the weight of the largest-weighted tree in the tree cover since it determines the makespan of the resulting coverage paths on D. However, operating exclusively in G does not ensure complete coverage for an incomplete terrain graph G where some decomposed vertices are absent in D. As they explore only a portion of the solution space that encompasses all possible sets of coverage paths on D, the resulting MCPP solutions are often suboptimal even with an optimal tree cover on G (see Fig. 1-(c) and (d)). Therefore, we propose the LS-MCPP framework that takes a different route to explore how to systematically search for good coverage paths directly on the decomposed graph. Our extensive experiments demonstrate the effectiveness of LS-MCPP, consistently improving the initial solution returned by two state-of-the-art baseline algorithms that compute suboptimal tree covers on G. Moreover, LS-MCPP consistently matches or surpasses the results of optimal tree cover computation with orders of magnitude faster runtime.

*Code: https://github.com/reso1/LS-MCPP

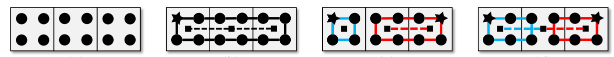

Figure 1: Graph-based CPP and MCPP: Gray squares, black circles, and black stars represent terrain graph vertices, decomposed graph vertices, and initial vertices of robots, respectively; Solid lines and dashed lines represent coverage paths and spanning edges, respectively. (a) Terrain graph with uniform edge weights. (b) Single-robot coverage path generated by STC. (c)(d) Suboptimal and optimal 2-robot MCPP solutions with makespans 2 and 1.5, respectively.

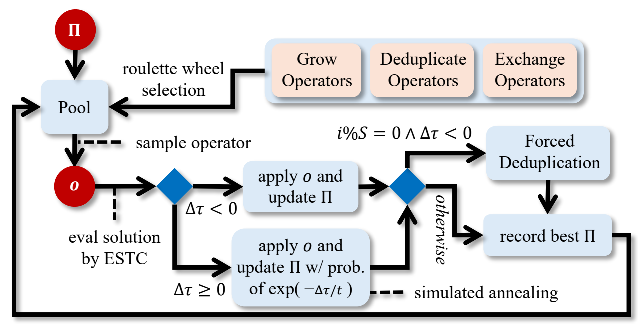

Figure 2: The proposed LS-MCPP algorithmic framework.

The LS-MCPP Framework

As demonstrated in Fig. 2, LS-MCPP employs a hierarchical sampling approach for efficient exploration of the constructed neighborhood and uses ESTC to evaluate a set $\{D_i = (V_{d,i}, E_{d,i})\}_{i \in I}$ of k connected subgraphs of D in each iteration of its local search. Given an initial solution Π, it first selects an operator pool using the *roulette wheel* selection from three pools, each containing operators of the same type. We define a *duplication* set $V^+ = \{v \in V_d \,|\, n_v > 1\}$, where $n_v = \sum_{i \in I} |\{x \in V_{d,i} | x = v\}|$ counts the occurrences of vertex $v \in V_d$ across all subgraphs. Then, three heuristics functions are tailored to evaluate their potential in guiding the neighborhood search and improving the solution. Considering an edge $e = (u, v)$, the heuristic for a grow operator $o_g(i, e)$ of D_i is defined as $-k \cdot c(\pi_i) - (n_u + n_v)/2$ with the considerations of (1) prioritizing growing light subgraphs with small coverage path costs and (2) prioritizing covering vertices with less duplication, the heuristic value for deduplicate operators $o_d(i,e)$ of D_i is defined as $k \cdot c(\pi_i) + (n_u + n_v)/2$ with the opposite consideration comparing to grow operator, and the heuristic value for exchange operators $o_e(i,j,e)$ of D_i and D_j is defined as $c(\pi_j) - c(\pi_i)$ to prioritize two subgraphs with a big difference in their coverage path costs. After sampling the operator, *simulated annealing* is adopted to determine whether to accept the current solution or not. LS-MCPP also calls the FORCEDDEDUPLICATION function periodically to exploit the current neighborhood and achieve a low-makespan solution in two folds. First, it iterates through each coverage path $\pi_i \in \Pi$ in a cost-decreasing order to remove any U-turn, defined as an edge $(u,v) \in \pi_i$ with $u,v \in V^+ \cap V_{d,i}$ satisfying $\exists\,(p,q) \in \pi_i$ such that $(u,p),(v,q) \in \pi_i$. Second, it recursively applies all deduplicate operators in D_i in descending order of the path costs and ascending order of the heuristic values.

Extended-STC (ESTC): To address CPP on incomplete terrain graphs, ESTC cleverly integrates a path-deformation procedure of Full-STC into the offline computation of STC. ESTC operates on the augmented terrain graph G' where some edges in G are removed in G' to reflect the connectivity between its terrain vertices. Specifically, edge $\varepsilon = (\delta_u, \delta_v) \in E_g$ is removed in G' if each decomposed vertex u of terrain vertex δ_u is nonadjacent to each v of δ_v. ESTC considers non-uniform edge weights. An edge $\varepsilon = (\delta_u, \delta_v)$ has the same weight as in G if both δ_u and δ_v are complete. Otherwise, ε has a manipulated edge weight of $w_{\max} \cdot \frac{1}{2} \cdot \left(\sum_{\varepsilon \sim \delta_u} w_\varepsilon + \sum_{\varepsilon \sim \delta_v} w_\varepsilon\right)$, where $w_{\max}$ is the maximal edge weights of E_g to prioritize using edges connecting complete terrain vertices. With the above modifications, ESTC produces the same circumnavigating coverage path on the minimum spanning tree of G'. By applying ESTC on each CPP instance relating to each D_i in the set of k subgraphs, LS-MCPP addresses the suboptimality problem in STC-based MCPP algorithms with a larger search space.

Boundary Editing Operators: We introduce three types of boundary editing operators designed to modify the boundaries of each subgraph D_i. Denoting set $F_i = \{(u,v) \in E_{d,i} \mid \delta_u = \delta_v\}$, a boundary editing operator alters the set $\{D_i\}_{i \in I}$ of subgraphs using an edge $e \in F_i$, but ensures that its property of complete coverage and subgraph connectivity remains invariant. Fig. 3-(a) shows a grow operator $o_g(i,e)$ adding edge $e \in F_i$ with $u,v \in B_i$ and all relevant edges into D_i, where $\exists\,(p,q) \in E_{d,i}$ such that $(u,p),(v,q) \in E_{d,i}$, and B_i is the set of vertices that are not part of D_i but adjacent to a vertex of D_i. In Fig. 3-(c), a deduplicate operator $o_d(i,e)$ removes edge $e \in F_i$ with $u,v \in V^+ \cap V_{d,i}$ and all relating edges from D_i if δ_u is incomplete, otherwise satisfying that: (1) δ_e^t is not in $V_{g,i}$; (2) all decomposed vertices of δ_e^b are in $V_{d,i}$; and (3) if $\delta = \delta_e^l, \delta_e^r$ is in $V_{g,i}$, then all decomposed vertices of both δ and its (only) common neighboring vertex with δ_e^b are in $V_{d,i}$. An exchange operator $o_e(i,j,e)$ is a combination of a grow operator $o_g(i,e)$ and a deduplicate operator $o_d(j,e)$ that adds $e \in F_i$ and all relevant edges into D_i and removes them from D_j.

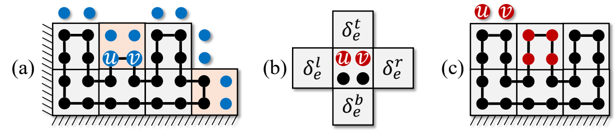

Figure 3: (a) Grow operator $o_g(i,e)$. (b) Four neighbors of terrain vertex δ_u. (c) Deduplicate operator $o_d(i,e)$.

Empirical Evaluation

We test LS-MCPP on nine MCPP instances, where their numbers of graph vertices, graph edges, and robots range from 46 to 11892, 60 to 22311, and 4 to 32, respectively. Through our extensive ablation study, we have several findings relating to the components of LS-MCPP: 1) ESTC consistently outperforms Full-STC on incomplete terrain graphs; 2) MFC (Zheng et al. 2010) strikes a balance between efficiency and solution quality as the initial solutions for LS-MCPP; 3) the three types of operators on LS-MCPP are necessary to guide an efficient neighborhood search; 4) the proposed heuristic sampling method and the FORCEDDEDUPLICATION function helps LS-MCPP a fast convergence. We compare LS-MCPP against VOR (based on Voronoi decomposition and ESTC), MFC (Zheng et al. 2010), MSTC* (Tang, Sun, and Zhang 2021), and MIP/MIP(H) (Tang and Ma 2023). In summary, LS-MCPP outperforms VOR, MFC, MSTC* for all instances within 20 minutes, demonstrating a makespan reduction of up to 67.0%, 35.7%, and 30.3%, and on average, 50.4%, 26.7%, and 13.4%, respectively. For the first six smaller instances where MIP(H) and MIP can almost compute the optimal tree cover, LS-MCPP achieves an average makepan reduction of -1.02% and 1.16% with orders of magnitude faster runtime.

Acknowledgements

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