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

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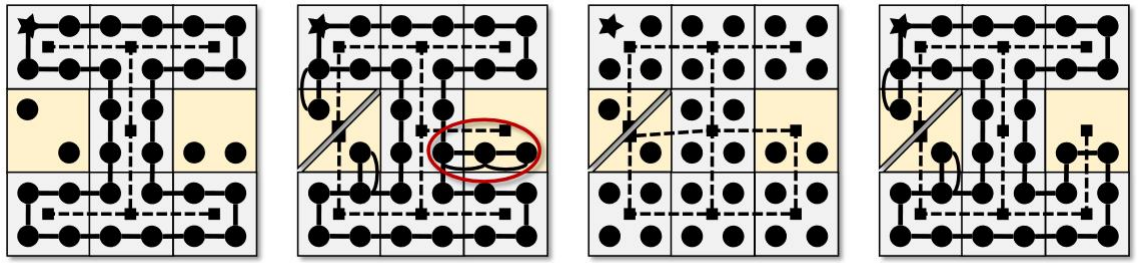
Motivation-1

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

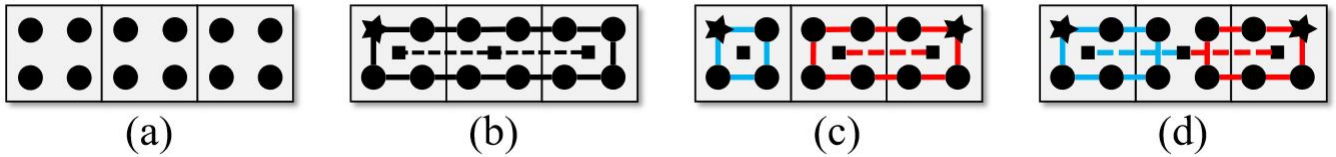
- Graph-based 方法只处理地图上能够完整划分成2 × 2的部分
- Full-STC 存在次优（suboptimal）的情况 → 提出 **Extended-STC**



Motivation-2

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

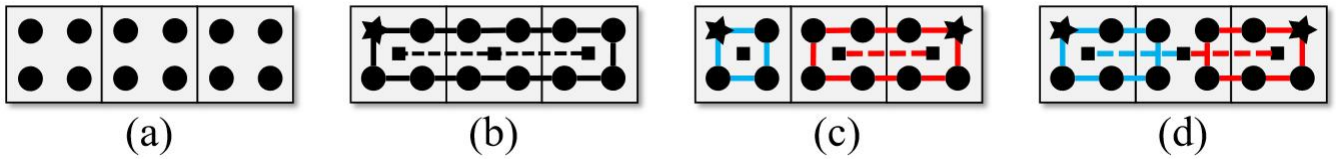
- Graph-based 方法存在suboptimal情况 → 提出 **LS-MCPP**



Problem Formulation

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

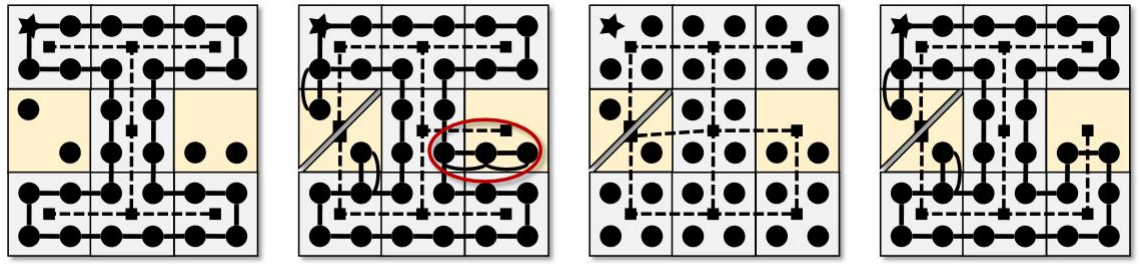
- 2D grid terrian graph $G = (V_g, E_g)$
- decomposed graph $D = (V_d, E_d)$
- $\delta_v \in V_g, v \in V_d$
- $\varepsilon = (\delta_u, \delta_v) \in E_g$



Full-STC v.s. Extended-STC

“Large-Scale Multi-Robot Coverage Path Planning via Local Search”. AAAI, 2024.

- G'：去掉G的一些边
- 斜对角的情况，拆分成两个点



- 赋予边$\varepsilon = (\delta_u, \delta_v)$权重

$$w_{\max} \cdot \frac{1}{2} \cdot \left(\sum_{\varepsilon \sim \delta_u} w_\varepsilon + \sum_{\varepsilon \sim \delta_v} w_\varepsilon\right) \quad (1)$$

where $w_{\max}$ is the maximal edge weights of E_g to prioritize using edges connecting complete terrain vertices. Fig. 2

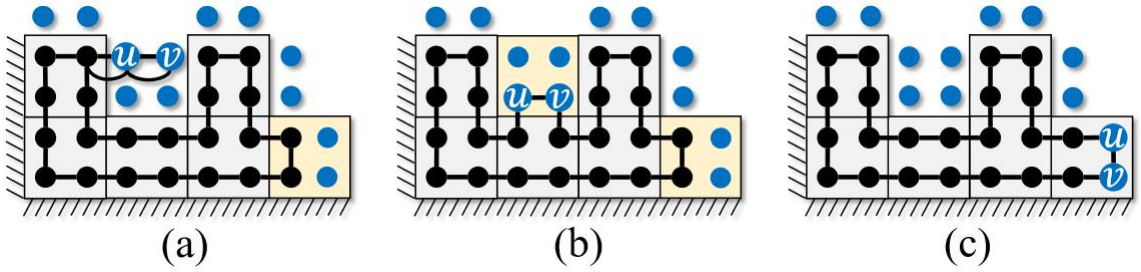
Boundary Editing Operators

Grow Operators

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

- $V^+ = \{v \in V_d | n_v > 1\}$表示被多次覆盖的点集合，$n_v$记录$v$在subgraph中被覆盖的次数

- $o_g(i, e)$
- $e = (u, v)$是有效的 当且仅当 D_i存在与之平行的边 (p, q)
- 执行完$o_g(i, e)$，如果$e = (u, v)$被其他subgraph覆盖，则将u, v加入V^+



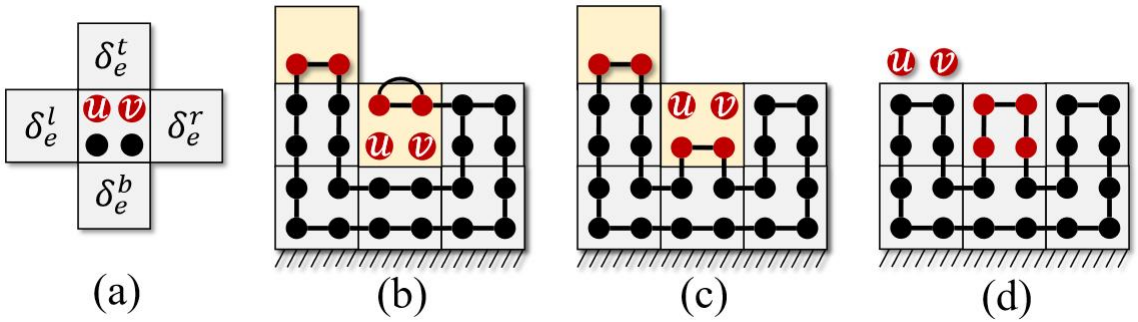
Boundary Editing Operators

Deduplicate Operators

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

- $o_d(i, e)$
- 判定$e = (u, v)$是有效的（可以被移除的）$\rightarrow u, v \in V^+ \cap V_{d,i}$

  且移除e之后 D_i 仍然是连通的
- δ_u 是 complete 的
  - δ_e^t 不在 $V_{g,i}$ 中
  - δ_e^b 中所有的点都在 $V_{g,i}$ 中
  - 如果$\delta = \delta_e^l, \delta_e^r$ 在 $V_{g,i}$ 中，那么δ中所有的点、δ与δ_e^b相邻的点都要在 $V_{g,i}$ 中



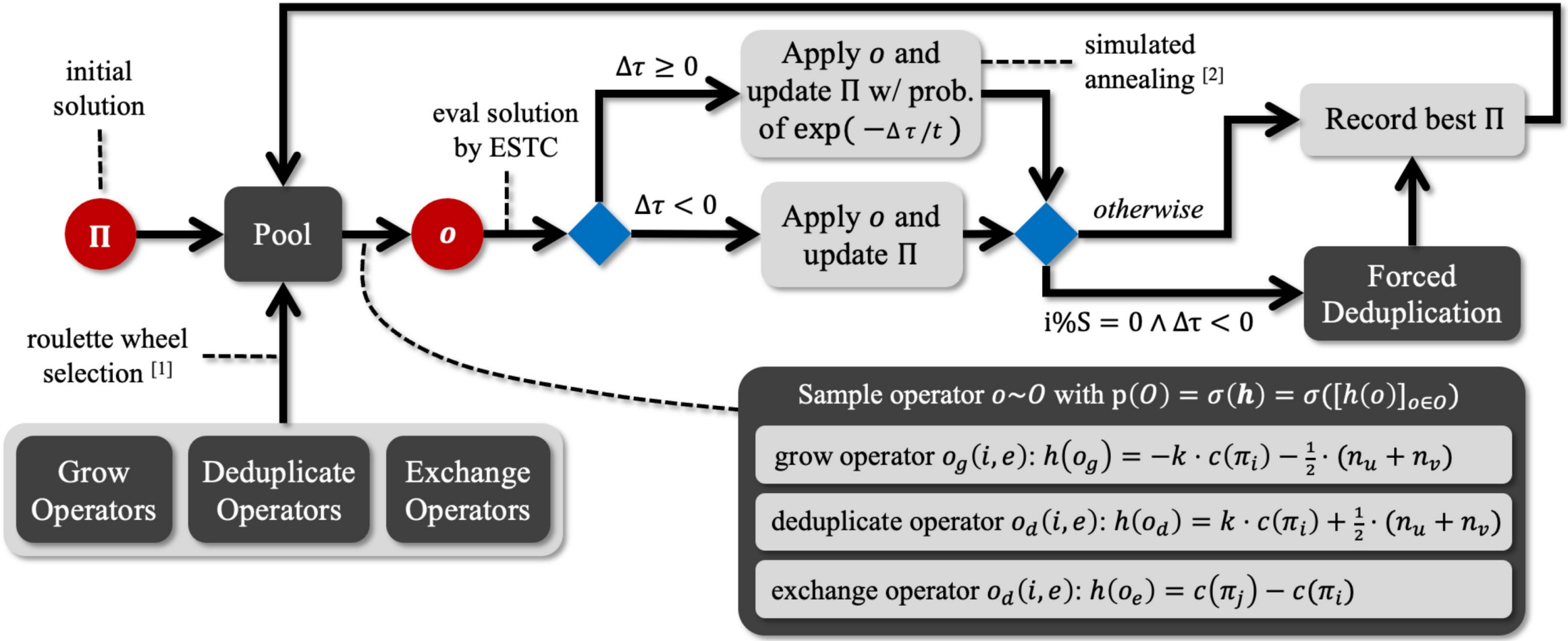
Exchange Operators

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

- $o_e(i,j,e)$ 表示$o_g(i,e)$ 和 $o_d(j,e)$，D_i增加边$e=(u,v)$，D_i删除边$e=(u,v)$

Framework

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.



Forced Deduplication

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

- 消除U-turn

Function FORCEDDEDUPLICATION(Π, O_d):
  for $i \in \arg\text{sort}\left(\{c(\pi_i)\}_{i \in I}\right)$ **do**
    while $(u, v) \leftarrow$ any U-turn in π_i **do**
      Remove u, v from D_i and update π_i
  for $i \in \arg\text{sort}\left(\{c(\pi_i)\}_{i \in I}\right)$ **do**
    while $\{o_d(j, e) \in O_d \mid i = j\} \neq \emptyset$ **do**
      $o \leftarrow \arg\min\left([h(o)]^T_{o \in \{o_d(j,e) \in O_d \mid i=j\}}\right)$
      Apply operator o, update Π and O_d

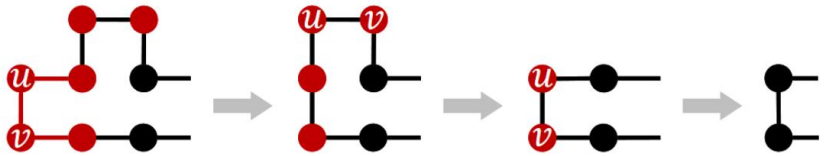


Figure 5: FORCEDDEDUPLICATION() executed on a coverage path π_i. Each red circle represents a duplication of $V_{d,i}$. In each frame, a U-turn $(u, v) \in \pi_i$ is found and u, v are removed from π_i until no U-turn exists.

Instances

"Mixed Integer Programming for Time-Optimal Multi-Robot Coverage Path Planning with Efficient Heuristics". RA-L, 2023.

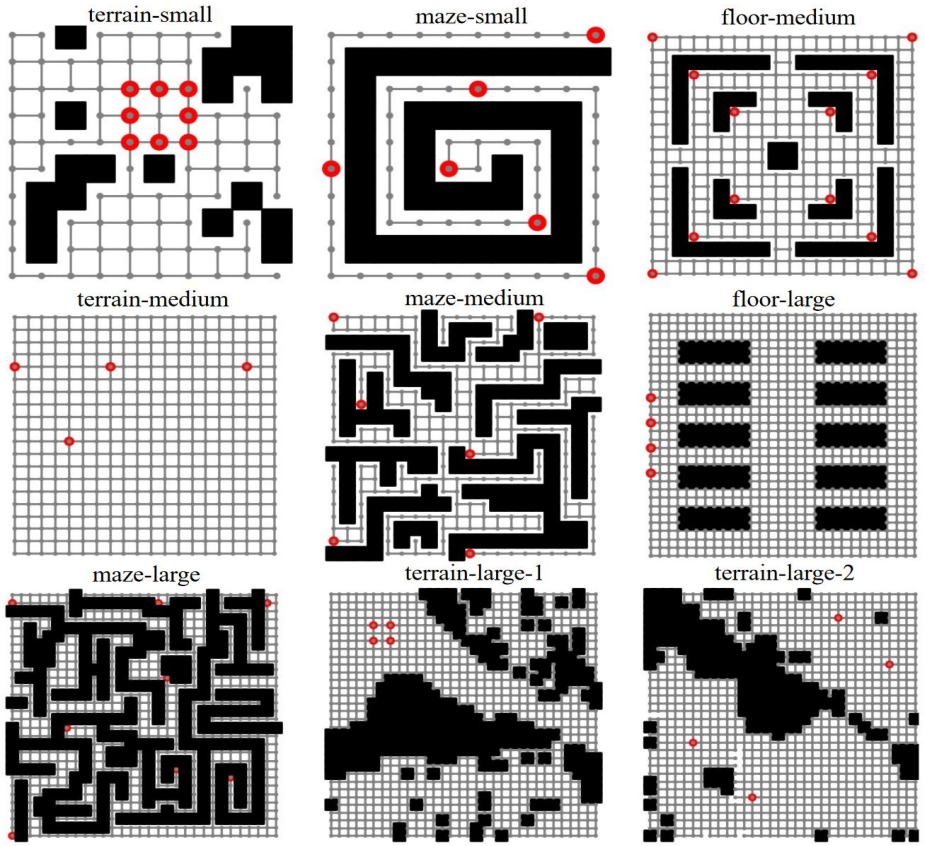


Fig. 5: MMRTC instances for MCPP performance evaluation.

Instance	Grid spec.	% of obs.	|V|	|E|	k	# of vars.	weighted
floor-small	5 × 10	8.0%	46	73	4	1061	×
terrain-small	10 × 10	20.0%	80	121	8	3545	✓
maze-small	10 × 10	40.0%	60	60	6	1441	×
floor-medium	20 × 20	19.0%	324	524	12	22753	×
terrain-medium	20 × 20	0.0%	400	760	4	10721	✓
maze-medium	20 × 20	39.0%	244	303	6	6919	×
floor-large	30 × 30	15.56%	760	1370	4	19481	×
maze-large	30 × 30	38.56%	553	717	8	21633	×
terrain-large-1	32 × 32	27.83%	739	1275	4	18257	✓
terrain-large-2	32 × 32	19.53%	824	1495	4	21237	✓

Instances

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

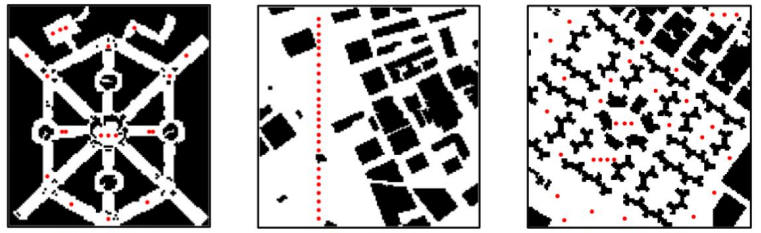


Figure 6: Three very large-scale MCPP instances adopted from 2D pathfinding benmarks (Sturtevant 2012). Red circles represent the initial vertices of robots.

Instance	Grid spec.	$\|V_g\|$	$\|E_g\|$	k	weighted
AR0701SR	107×117	4,860	8,581	20	✓
Shanghai2	128×128	11,793	22,311	25	×
NewYork1	128×128	11,892	21,954	32	✓

Ablation Study

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

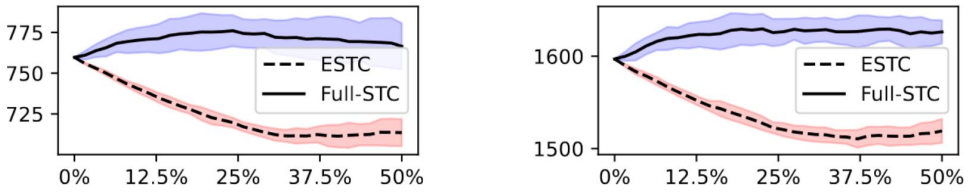


Figure 7: Single-robot coverage path costs (y-axis) with the percentages of incomplete terrain vertices (x-axis). Left and right sub-figures correspond to *flr-l* and *trn1-l*, respectively.

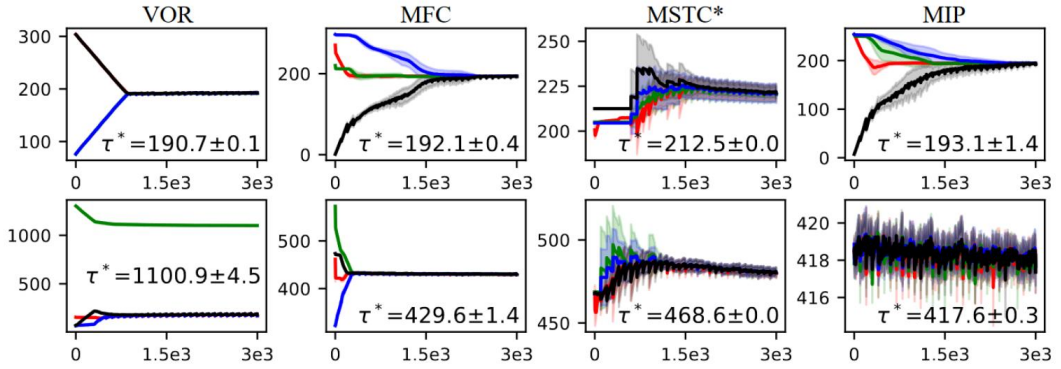


Figure 8: Path costs (y-axis) of 4 robots for LS-MCPP over iterations (x-axis) with different initial solutions. The upper and lower rows correspond to *flr-l* and *trn1-l*, respectively.

Ablation Study

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

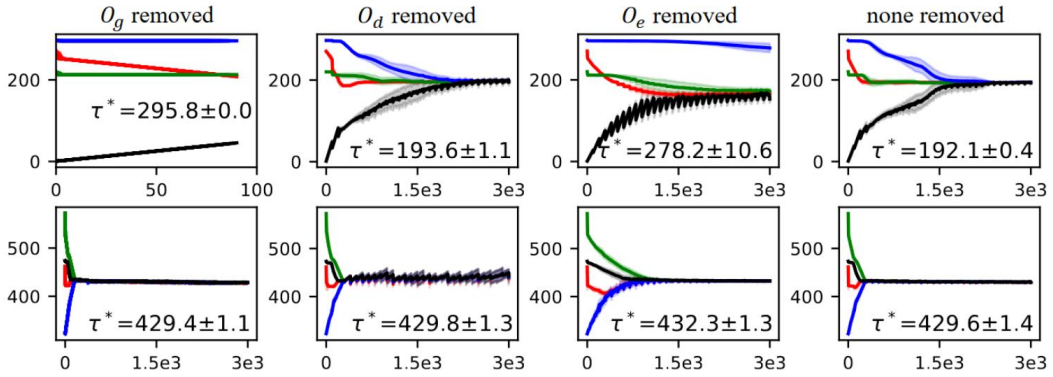


Figure 9: Path costs (y-axis) of 4 robots for LS-MCPP over iterations (x-axis) with different operators removed. The upper and lower row correspond to *flr-l* and *trn1-l*, respectively.

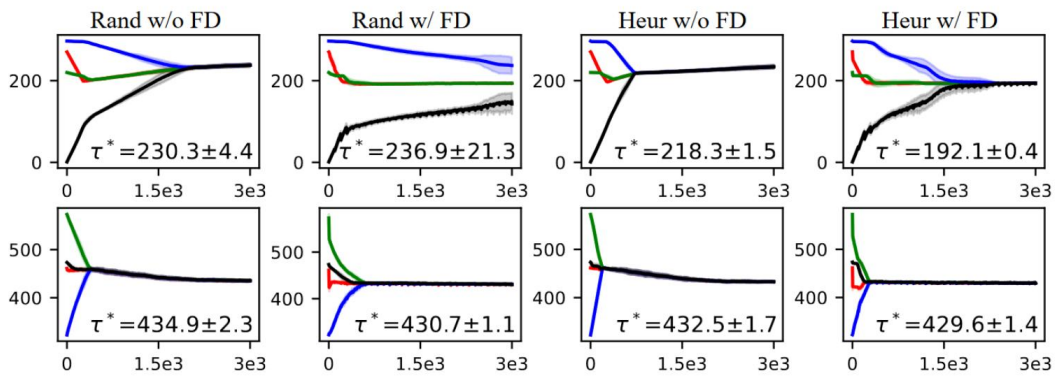


Figure 10: Path costs (y-axis) of 4 robots for LS-MCPP over iterations (x-axis) with different operator sampling and whether FORCEDDEDUPLICATION (FD) is used. The upper and lower row correspond to *flr-l* and *trn1-l*, respectively.

Comparative Study

"Large-Scale Multi-Robot Coverage Path Planning via Local Search". AAAI, 2024.

	VOR	MFC	MSTC*	MIP(H)		MIP		LS-MCPP (Ours)	
flr-s	42.75	23	21	**16**	0.0%	**16**	0.0%	16.75±0.3	21.5±2.1
	0.01s	0.03s	0.02s	13s		20s		5.3±0.13s	3.6±2.9s
trn-m	420.2	368.2	269.5	246.7	0.6%	246.7	1.6%	**244.5±0.8**	245±12.2
	0.04s	0.58s	0.32s	24h		24h		17.8±0.1s	19.6±1.3s
mze-m	134.8	67	69	52	0.0%	**51**	20%	54.3±2.9	65.0±4.2
	0.02s	0.35s	0.34s	4.9s		24h		10.7±0.1s	9.0±2.9s
flr-l	303.8	294	212.5	207	8.3%	254	25%	**192.1±0.4**	207±20.2
	0.07s	2.37s	0.09s	24h		24h		30.5±1.3s	35.2±1.6s
mze-l	193.8	105	139.5	**91.5**	0.0%	93	25%	97.3±0.5	104.8±7.6
	0.04s	0.10s	0.58s	54s		24h		15.4±0.2s	12.9±5.8s
trn1-l	1,303	597.4	468.6	435.1	9.7%	**419.1**	6.1%	429.6±1.4	444±11.2
	0.07s	1.67s	1.93s	24h		24h		34.3±0.4s	37.3±1.6s
AR07 01SR	1,301	1,254	878.7	1,351	42%	1,333	55%	**805.9±7.9**	1,024±74
	0.47s	36.9s	9.91s	24h		24h		6.3±0.1m	6.2±0.3m
Shanghai2	1,451	754	576.5	1,509	59%	/	/	**570.9±2.1**	719±73.0
	1.21s	7.2m	2.21s	24h		/		17.6±2.1m	12.5±0.8m
New York1	1,735	1,530	1,208	4,736	80%	/	/	**1,062±14**	1,563±110
	1.13s	2.4m	20.2s	24h		/		15.0±4.1m	12.6±0.5m