Hierarchically Accelerated Coverage Path Planning for Redundant Manipulators

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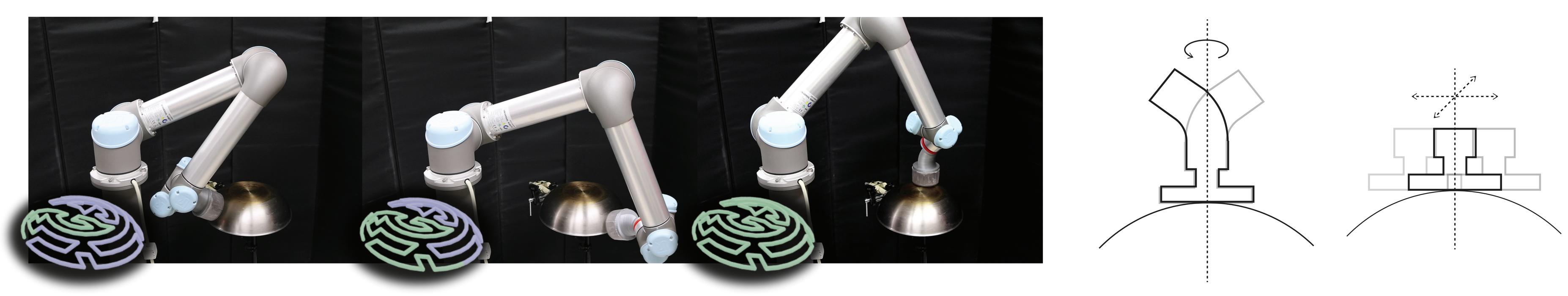
Synopsis: we present a motion planner that enables a robotic arm to cover a surface with its end-effector, while exploiting the manipulator's redundancy and task tolerances to minimize joint space costs.

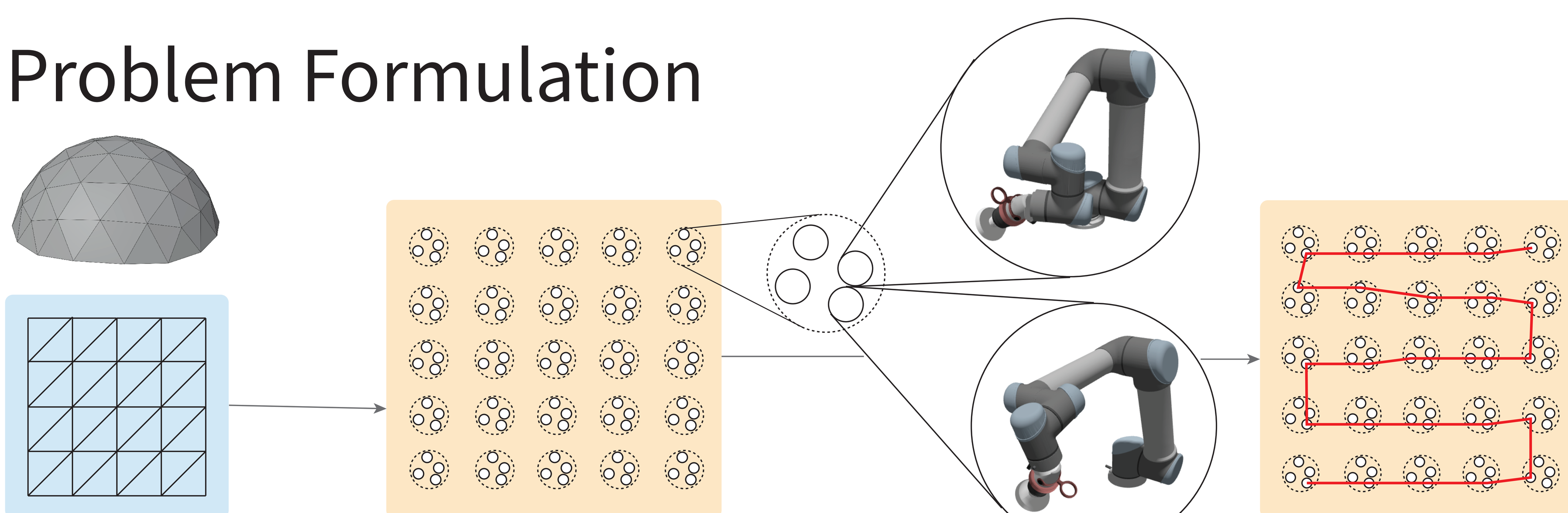
Motivation

In tasks like sanding, polishing, wiping, or scanning, a robot must move its end-effector to cover a surface. With redundancy or task tolerances, multiple inverse kinematics (IK) solutions exist. A coverage path planner should exploit this flexibility to generate joint motions that achieve full surface coverage while minimizing joint movement.



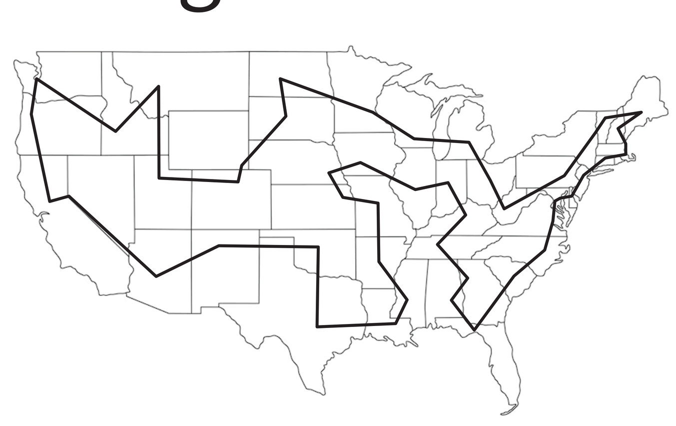
In this mock wok polishing example, the task has rotational redundancy around the tool's principal axis and translational tolerance tangential to the wok surface, as the finishing disk can have multiple contact points with the wok.

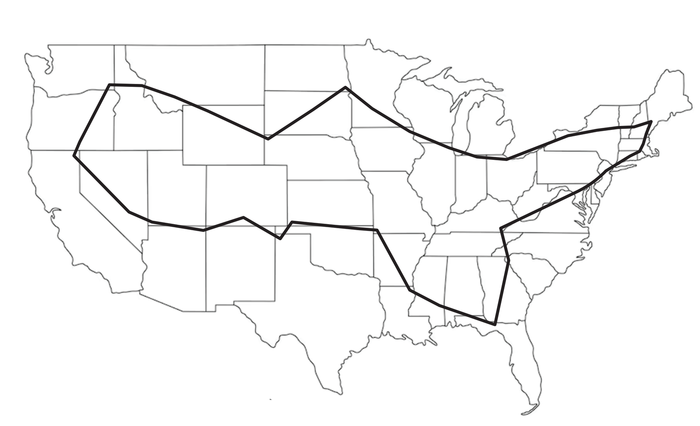
Problem Formulation



Input: surface mesh | Scenarios: the robot has redundancy | Output: a joint motion

Background



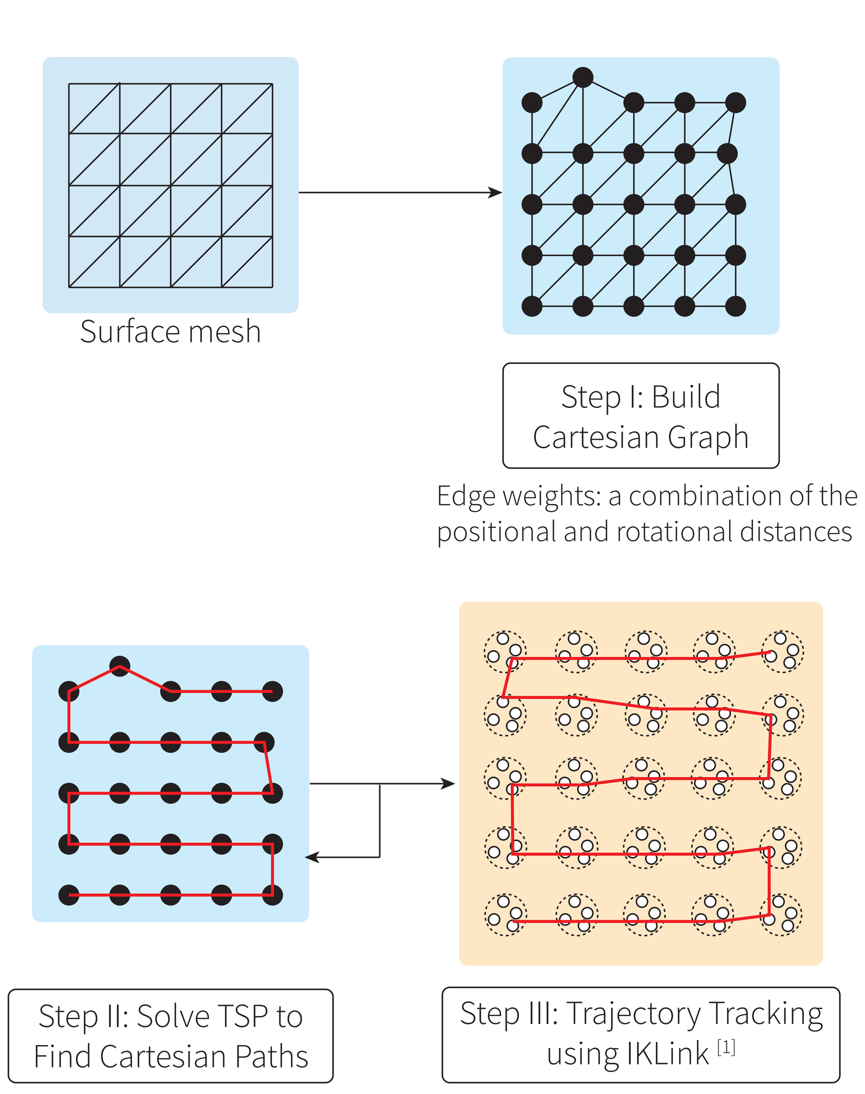


Traveling Salesman Problem (TSP) seeks the shortest route visiting each city once and returning to the start. This example shows the shortest route that visits the capital of the 48 contiguous US States.

Generalized Traveling Salesman Problem (GTSP) seeks the shortest route that visits exactly one city from each predefined *group* and returns to the starting point. This example shows the shortest route that visits one city from each of the 48 contiguous U.S. states.

Baseline 1: Cart-TSP-IKLink

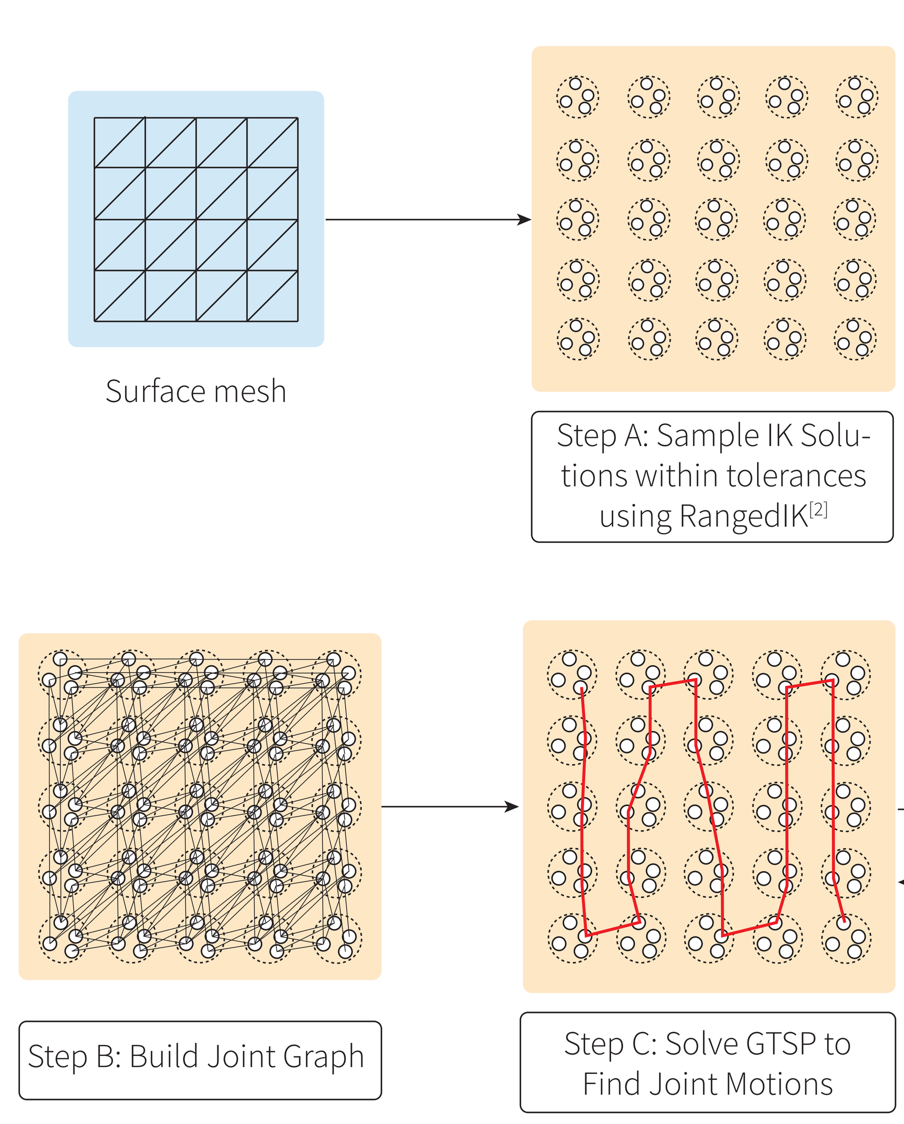
This approach constructs a graph in Cartesian space, uses a Traveling Salesman Problem (TSP) solver to find paths that visit each node exactly once, and generates joint motions to track the paths using IKLink.



This method is efficient but plans in Cartesian space and can not achieve joint space objectives such as minimizing joint movements

Baseline 2: Joint-GTSP

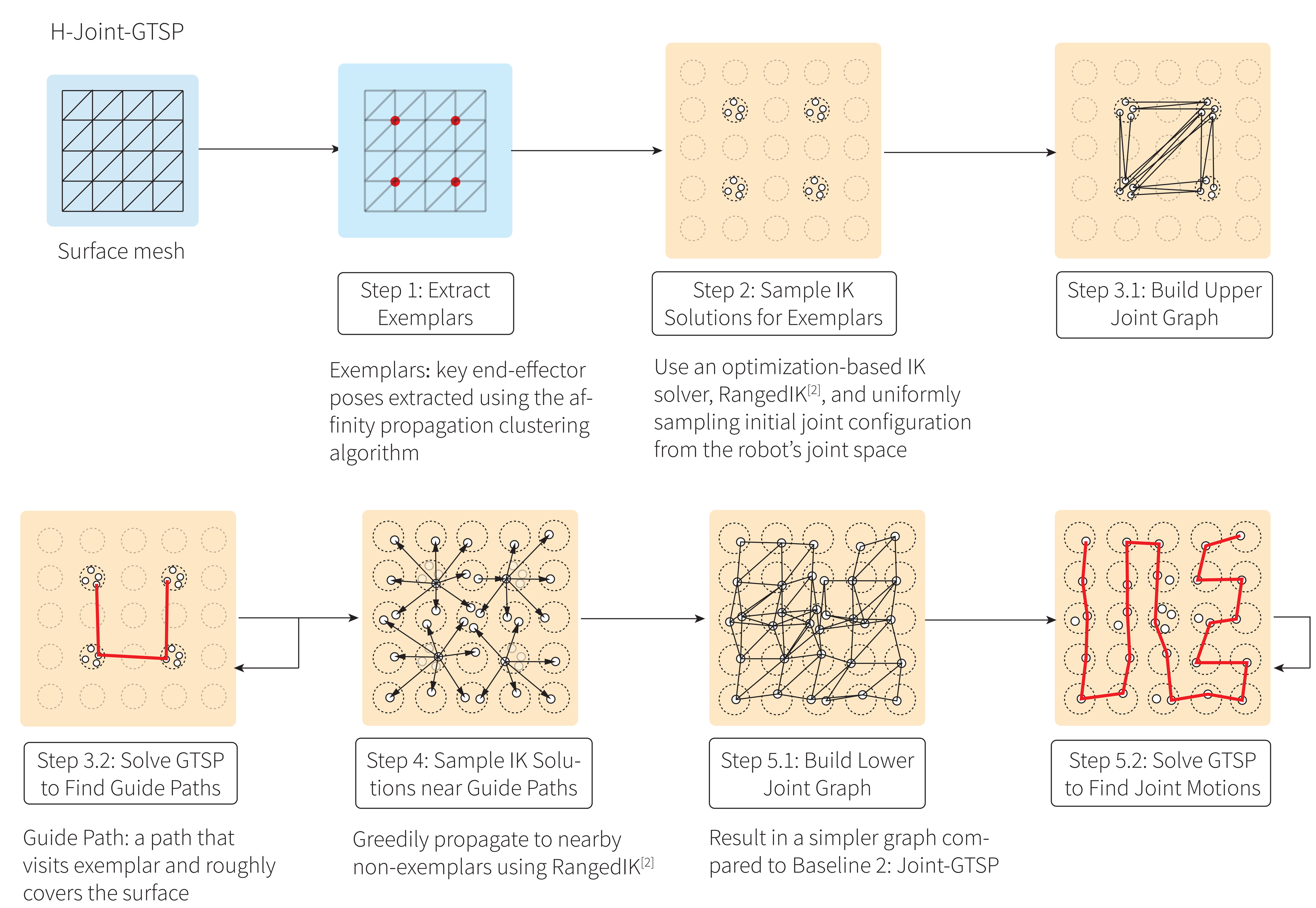
This approach samples multiple inverse kinematics (IK) solutions for each end-effector target, builds a graph in joint space, and finds paths using a Generalized Traveling Salesman Problem (GTSP) solver.



This approach solves an NP-hard problem on a large graph, so it is slow and does not scale well

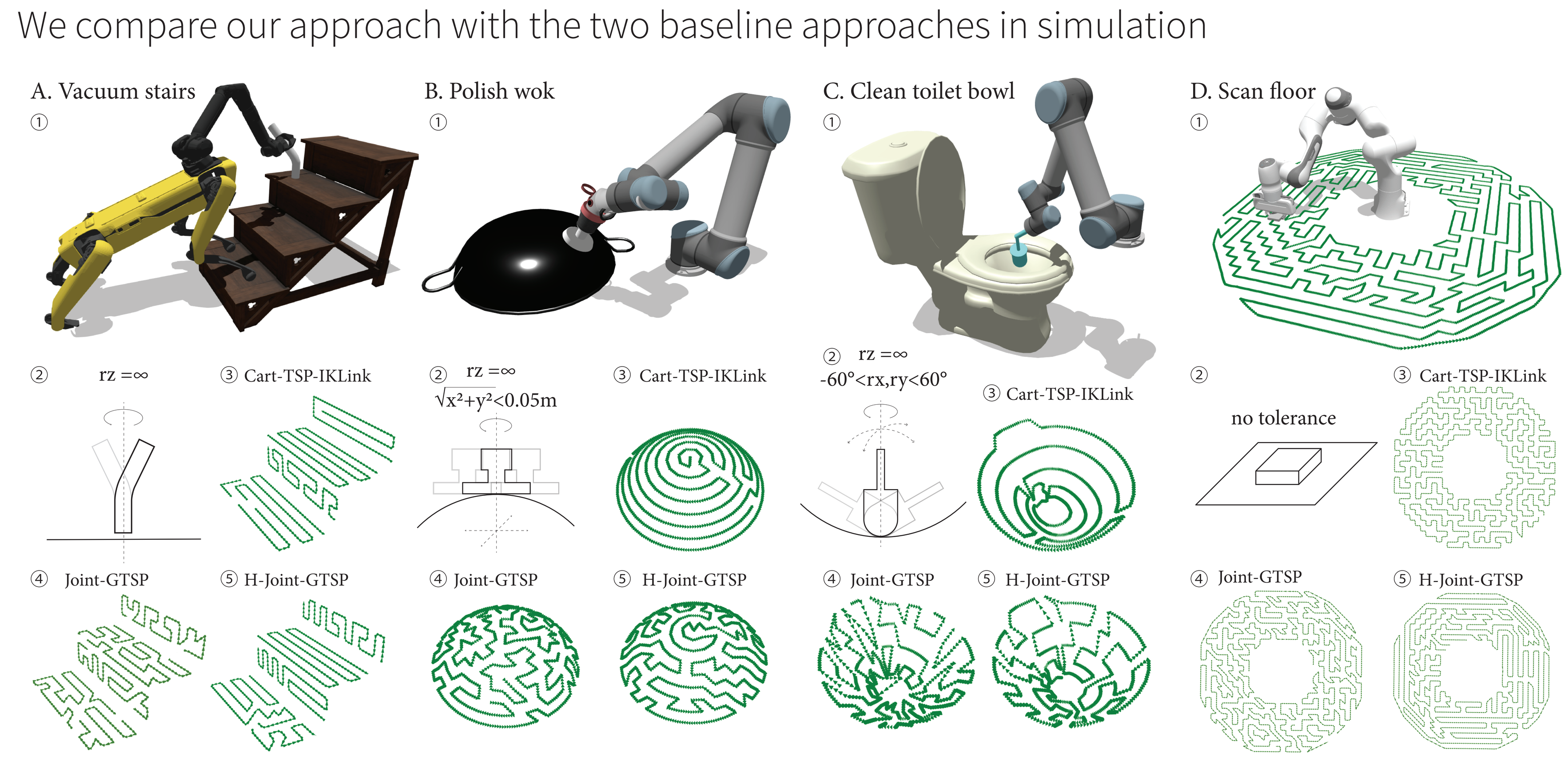
Proposed Method

1. Formulate as Generalized Traveling Salesman Problems (GTSP)
2. Use a strategy to accelerate the computation by solving a sequence of smaller GTSP. It identifies guide paths that roughly cover the surface and samples IK solutions near them.



Evaluation

We compare our approach with the two baseline approaches in simulation



The proposed approach consistently outperformed the baseline approaches across all four benchmark applications, generating higher-quality motions with shorter computation time.

TABLE I
EXPERIMENT RESULTS AND METRICS OF THE TARGET SURFACE

Benchmark	Method	Mean Num of Reconfig	Mean Joint Movements (rad)†	Mean Computation Time (s)	Max Position Error (m)‡	Max Rotation Error (rad)‡	Number of End-Effector Targets n
Vacuum Stairs	Cart-TSP-IKLink	5.00±0.00	32.20±0.41	47.40± 0.35	7.7e-4	9.5e-3	208
	Joint-GTSP	5.10±0.94	33.00±1.11	146.22±35.27	7.9e-4	10.0e-3	
	H-Joint-GTSP	**4.30**±0.46	**26.66**±0.51	**43.59**±14.07	9.8e-4	9.9e-3	
Polish Wok	Cart-TSP-IKLink	**0.00**±0.00	57.78±0.33	99.82± 1.00	8.3e-4	9.2e-3	209
	Joint-GTSP	14.70±3.41	58.27±4.93	566.26±95.83	7.6e-4	9.7e-3	
	H-Joint-GTSP	**0.00**±0.00	**41.71**±0.83	**74.56**±19.71	9.6e-4	10.0e-3	
Clean Toilet Bowl	Cart-TSP-IKLink	**0.00**±0.00	80.78±1.63	89.62± 0.37	9.0e-4	n/a	157
	Joint-GTSP	17.29±6.09	61.58±3.93	624.35±211.82	9.5e-4	n/a	
	H-Joint-GTSP	**0.00**±0.00	**17.91**±1.66	**61.35**± 9.13	9.8e-4	n/a	
Scan Floor	Cart-TSP-IKLink	2.00± 0.00	166.23±0.52	262.18± 5.12	9.9e-4	9.7e-3	674
	Joint-GTSP	21.60±13.71	161.29±9.88	1106.65±198.65	9.9e-4	7.9e-3	
	H-Joint-GTSP	**1.30**± 0.46	**123.37**±1.29	**207.84**± 69.13	10.0e-4	10.0e-3	

Our code is open-sourced!

[1] Yeping Wang, Carter Sifferman and Michael Gleicher, "IKLink: End-Effector Trajectory Tracking with Minimal Reconfigurations," ICRA'24
[2] Yeping Wang, Pragathi Praveena, and Michael Gleicher, "RangedIK: An Optimization-Based Robot Motion Generation Method for Ranged-Goal Tasks", ICRA'23

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