Anytime Planning for End-Effector Trajectory Tracking

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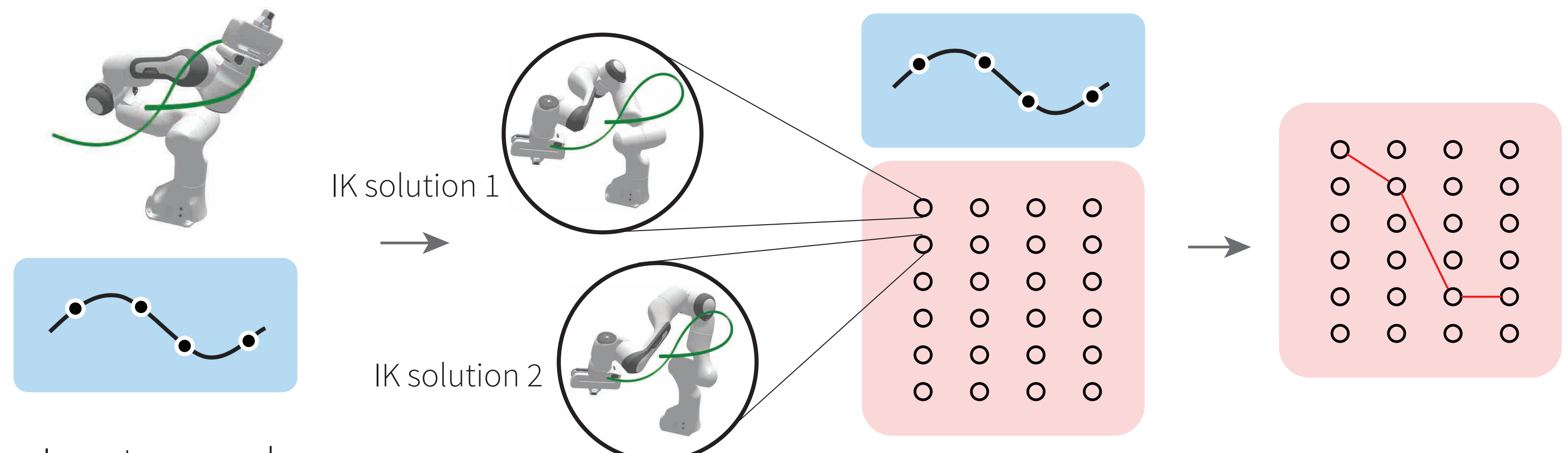
Synopsis: we present an anytime algorithmic framework that efficiently and effectively generate robot motions to track reference end-effector trajectories

Motivation

Both industrial tasks (welding, sanding, painting, visual tracking) and everyday manipulation (opening a door, sliding a drawer) require the robot to follow a desired end-effector trajectory precisely.

Problem Formulation



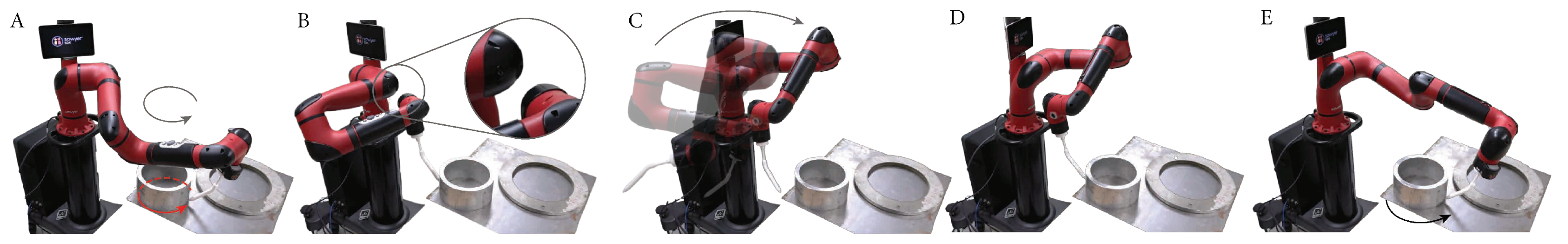
Input: an end-effector trajectory

Scenarios: the robot has redundancy

Output: a joint motion

Criteria: Minimze joint movement, joint velocity, reconfigurations

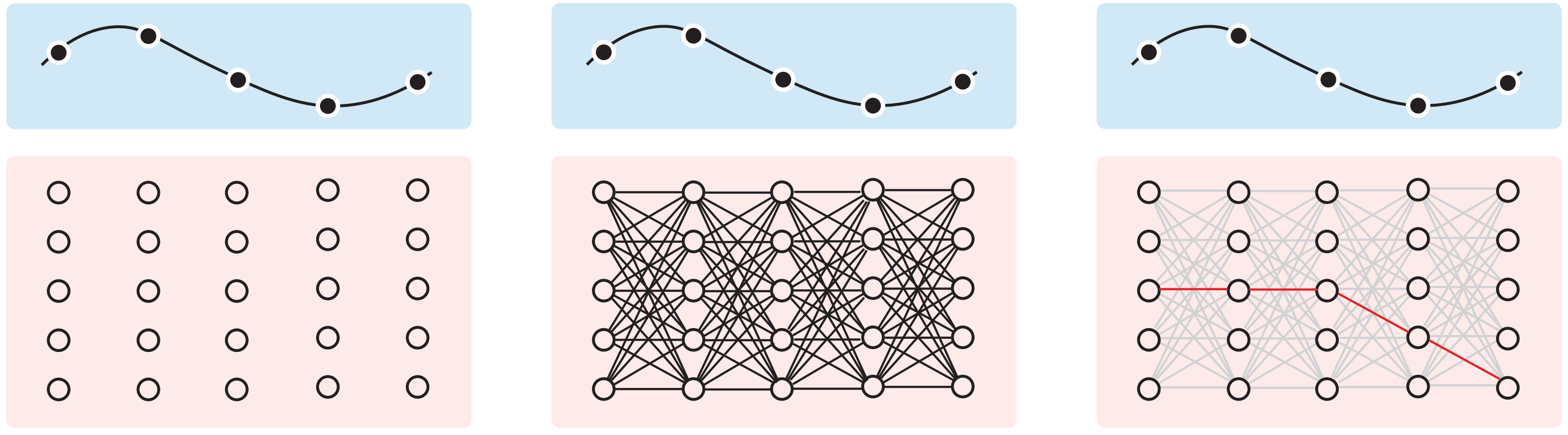
Reconfigurations: for a complex trajectory, it becomes necessary to divide it into shorter segments. Each division introduces a reconfiguration, in which the robot deviates from the reference trajectory, repositions itself in configuration space, and then resumes task execution.



Tracking a welding trajectory — Pause to avoid self-collision — Perform a *reconfiguration* — Resume task execution — Finish the welding task

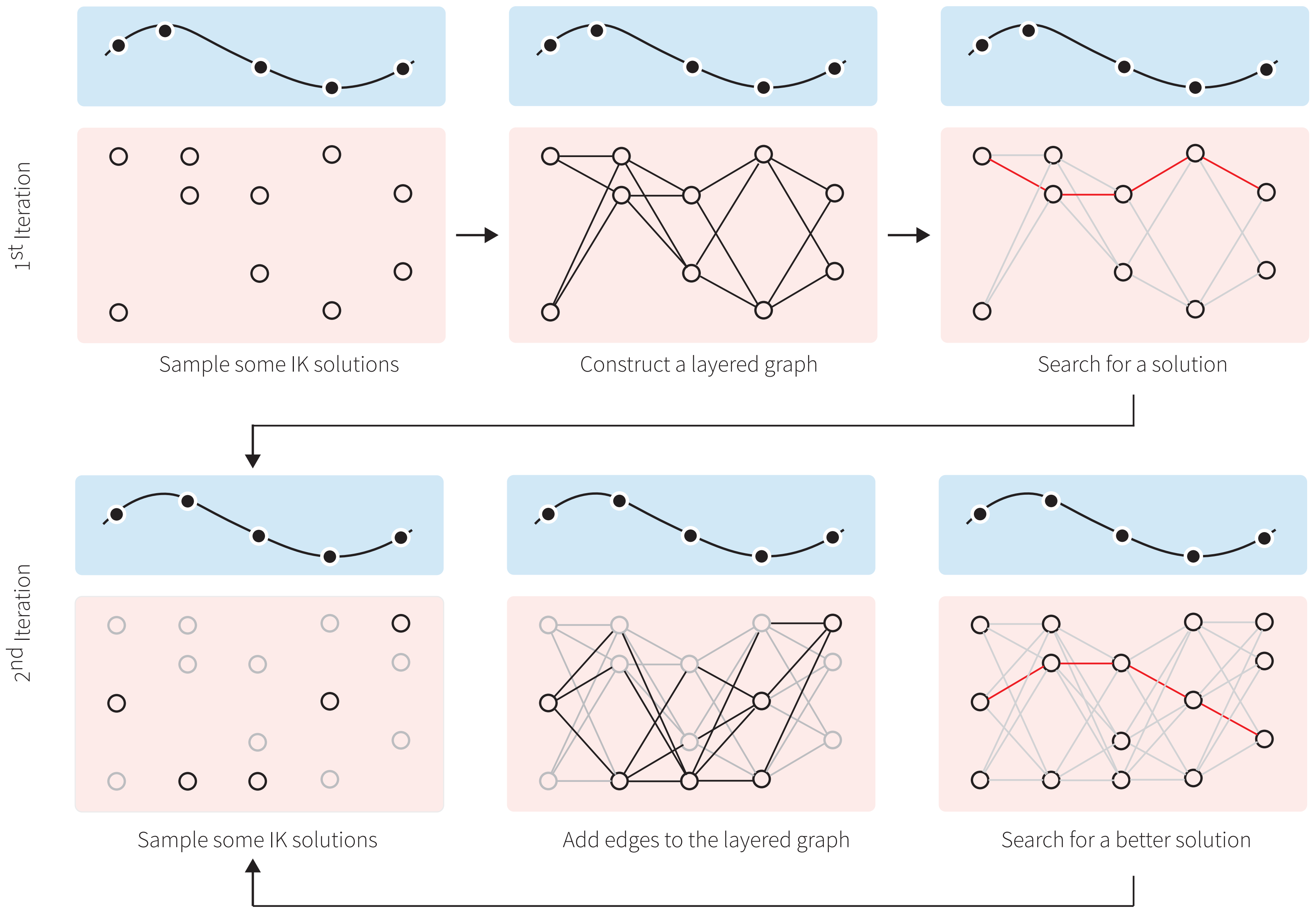
Background

Baseline 1: Existing graph-based algorithms (sequential framework) [1,2]



Sample all IK solutions — Construct a layered graph — Search for a solution

Baseline 2: Existing graph-based algorithms + naive anytime framework



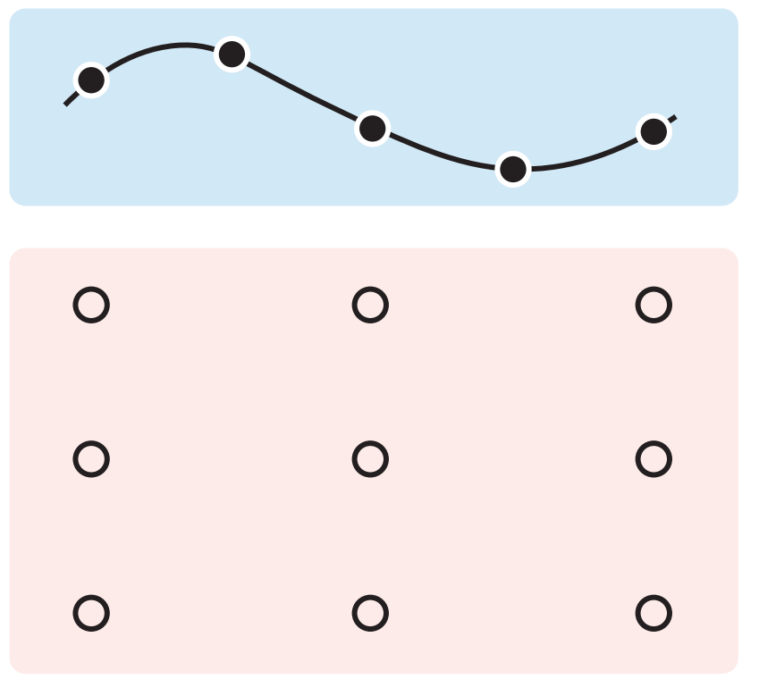
1st iteration: Sample some IK solutions — Construct a layered graph — Search for a solution

2nd iteration: Sample some IK solutions — Add edges to the layered graph — Search for a better solution

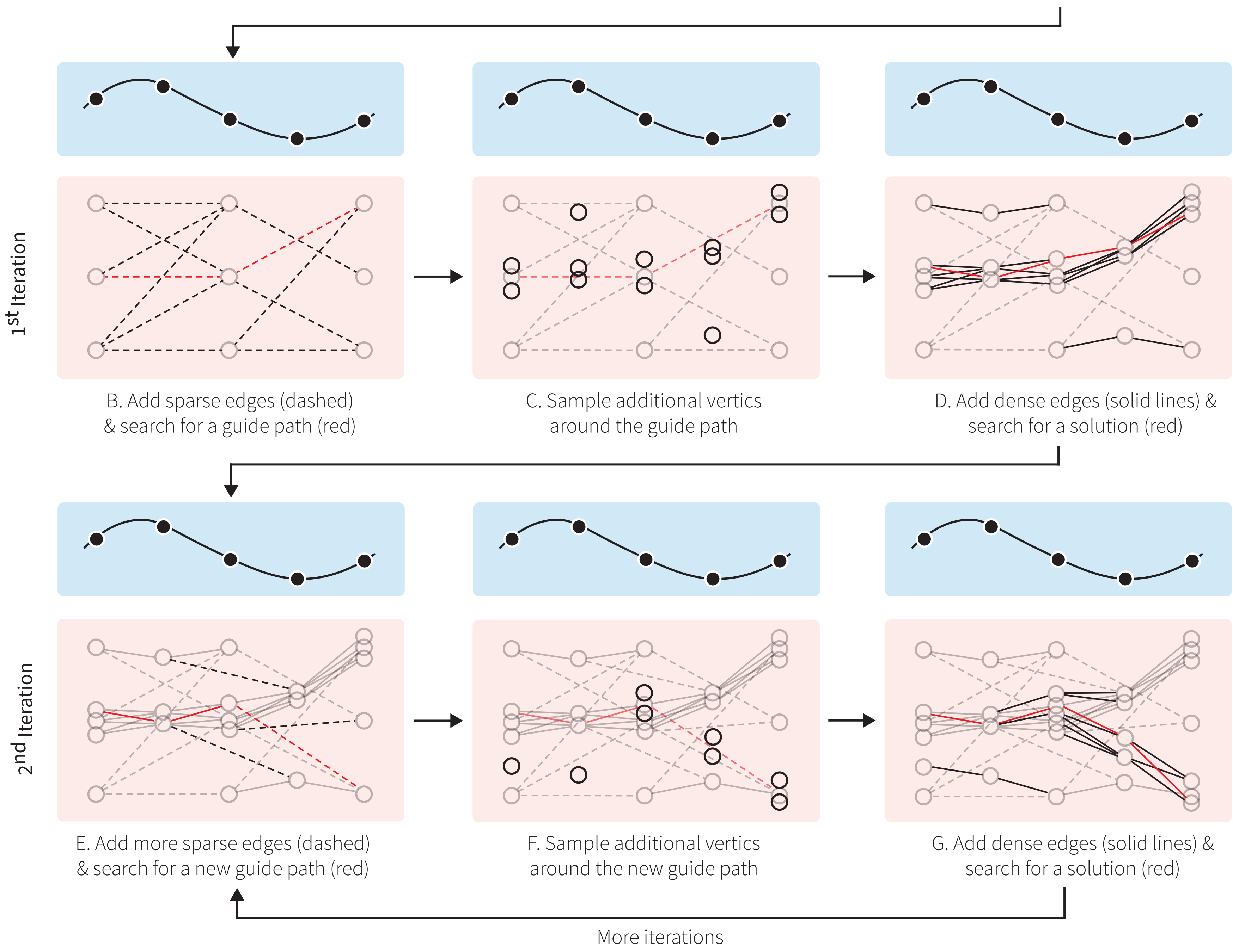
More iterations

Proposed Method

- Incorporate a heuristic to prioritize samples that are likely to lead to good solutions.
- Key insight: identify ***guide paths*** that approximately track the reference trajectory and strategically bias sampling toward the guide paths.



A. Sample sparse vertics



B. Add sparse edges (dashed) & search for a guide path (red)

C. Sample additional vertics around the guide path

D. Add dense edges (solid lines) & search for a solution (red)

E. Add more sparse edges (dashed) & search for a new guide path (red)

F. Sample additional vertics around the new guide path

G. Add dense edges (solid lines) & search for a solution (red)

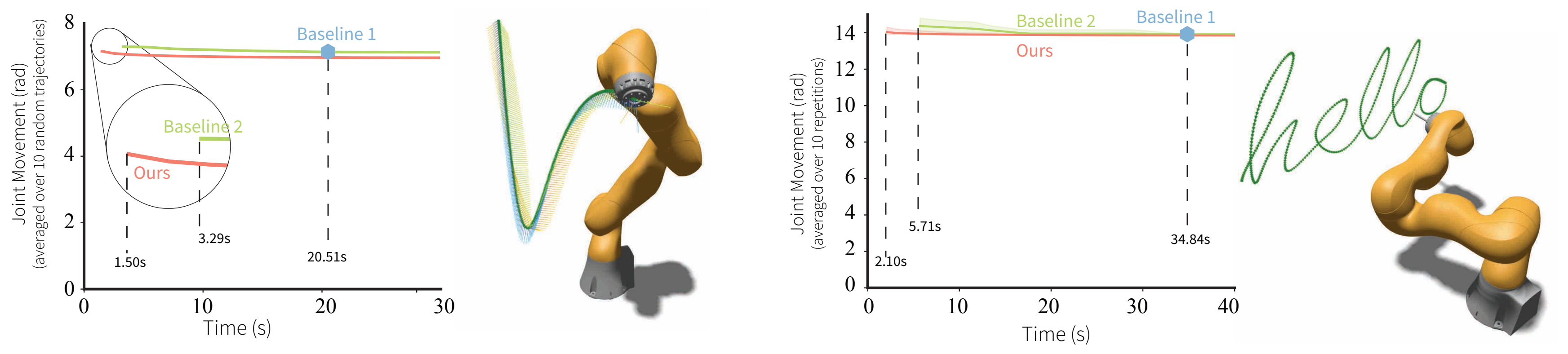
More iterations

Evaluation

We compare our approach with the two baseline approaches in three independent experiments

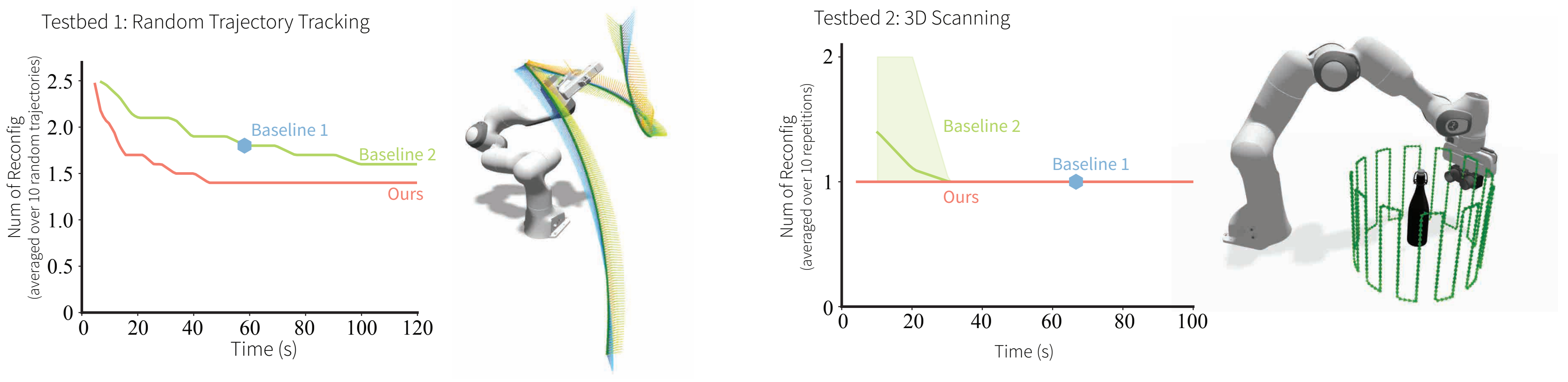
Experiment A: Minimal Joint Movements

Testbed 1: Random Trajectory Tracking — Testbed 2: Writing



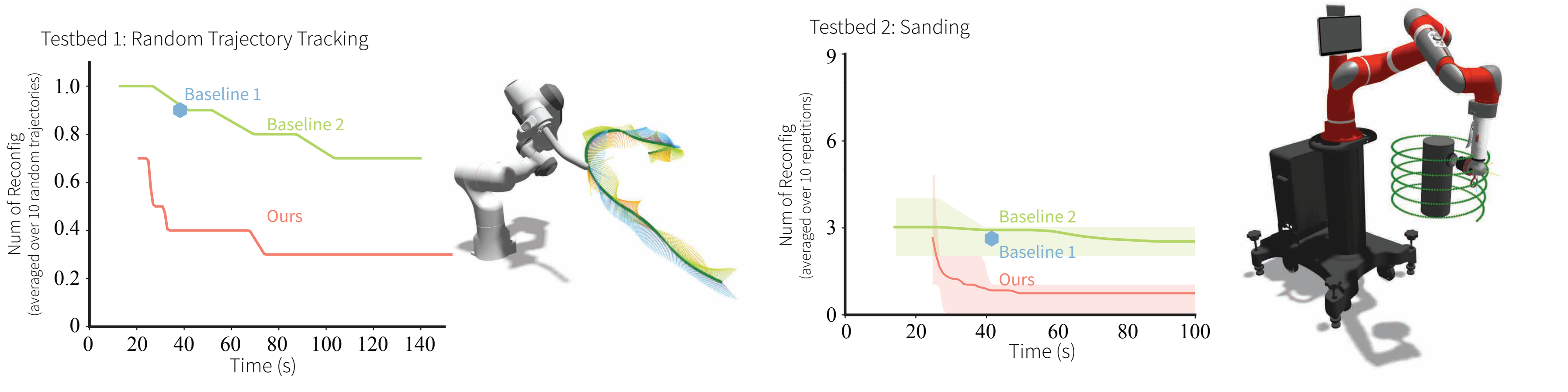
Experiment B: Minimal Reconfigurations

Testbed 1: Random Trajectory Tracking — Testbed 2: 3D Scanning



Experiment C: Trajectory with Tolerances

Testbed 1: Random Trajectory Tracking — Testbed 2: Sanding



Our framework accelerates both algorithms, finding solutions with less computation time than both baselines, while matching or exceeding their solution quality.

Method	Exp A				Exp B				Exp C			
	Testbed 1		Testbed 2		Testbed 1		Testbed 2		Testbed 1		Testbed 2	
	Time†	JM‡	Time†	JM‡	Time†	# RC‡	Time†	# RC‡	Time†	# RC‡‡	Time†	# RC‡
Baseline 1	20.5	7.14	34.8	13.92	58.2	1.8	66.7	**1.0**	38.3	0.9	41.6	2.6
Baseline 2	7.1	7.14	34.4	13.92	58.9	1.8	31.2	**1.0**	41.9	0.9	74.1	2.9
Ours (s=5)	**1.8**	**6.97**	**8.1**	**13.85**	**13.6**	**1.3**	**4.4**	**1.0**	20.9	**0.4**	**24.6**	**0.8**
Ours (s=3)	2.5	6.99	/	/	20.6	1.5	/	/	28.7	0.6	/	/
Ours (s=10)	3.5	7.01	/	/	22.2	1.6	/	/	**14.6**	0.7	/	/

†: Average computation time to achieve the same performance of Baseline 1 (the conventional framework)
‡: Average performance achieved within Baseline 1's computation time (JM=Joint Movement, # RC=Number of Reconfigurations)

Our code is open-sourced!

[1] Daniel Rakita, Bilge Mutlu, and Michael Gleicher, "Stampede: A discrete-optimization method for solving pathwise-inverse kinematics," ICRA'19

[2] Yeping Wang, Carter Sifferman and Michael Gleicher, "IKLink: End-Effector Trajectory Tracking with Minimal Reconfigurations," ICRA'24

[3] Yeping Wang, Pragathi Praveena, and Michael Gleicher, "RangedIK: An Optimization-Based Robot Motion Generation Method for Ranged-Goal Tasks", ICRA'23

This work was supported by Los Alamos National Laboratory,
the Department of Energy, and National Science Foundation award 2007436.