Collaborative Multi-Robot Systems with Provable Availability, Safety, and Optimality Guarantees

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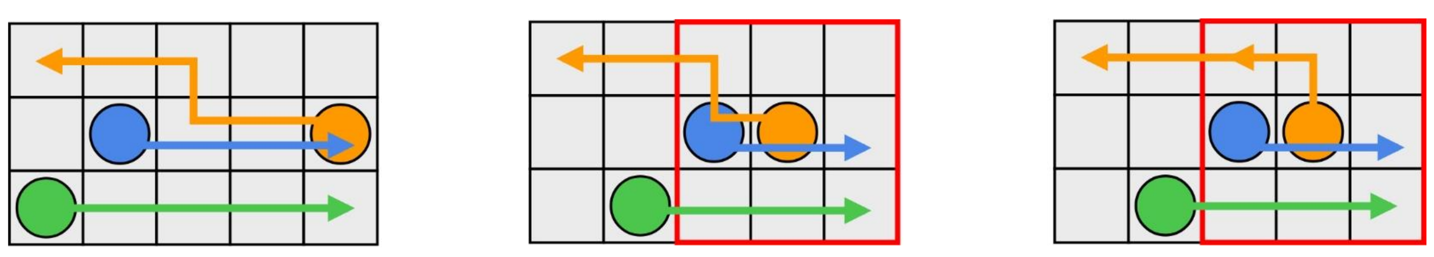
DDM: Fast, Near Optimal, Dynamic Multi-Robot Path & Motion Planning

Problems Studied: Multi-Robot Path and Motion Planning
- *Traditional one-shot formulation*: route multiple robots from a start configuration to a goal configuration near-optimally without collisions.
- *Dynamic formulation*: the robots constantly update their desired goals as old tasks are completed. Fast re-planning is essential.

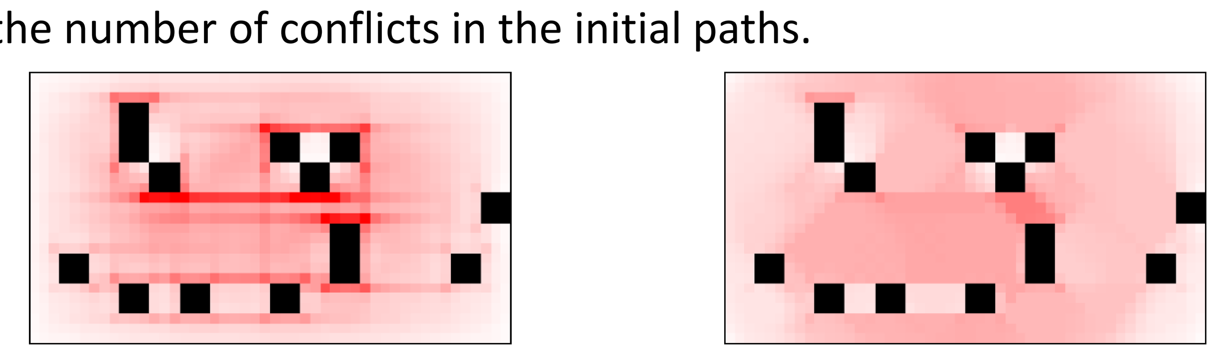
Contribution A two-phase algorithm with computation time that is **one to two magnitudes faster** than the state-of-the-art and produces high quality solutions.

Solution Framework
- Find a path for each robot, ignoring collisions.
- Resolve conflicts in 2×3 or 3×3 local areas.



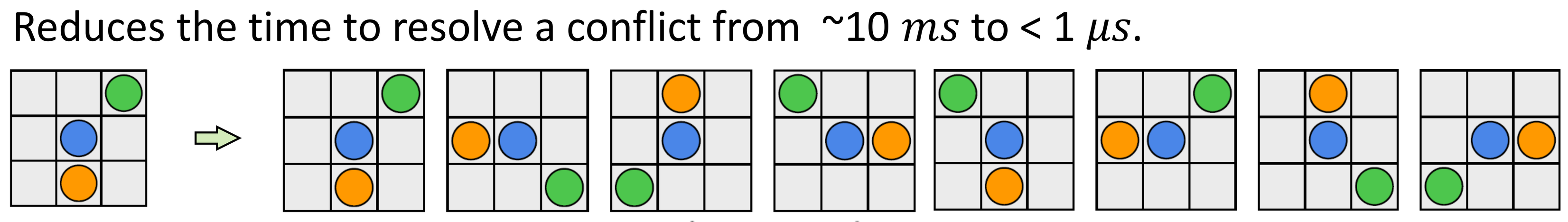
Initial paths *Conflict detected* *Conflict resolved*

Optimization Technique: the Path Diversification Heuristic
- Combines Manhattan distance heuristic with vertex occupancy information.
- Reduces the number of conflicts in the initial paths.



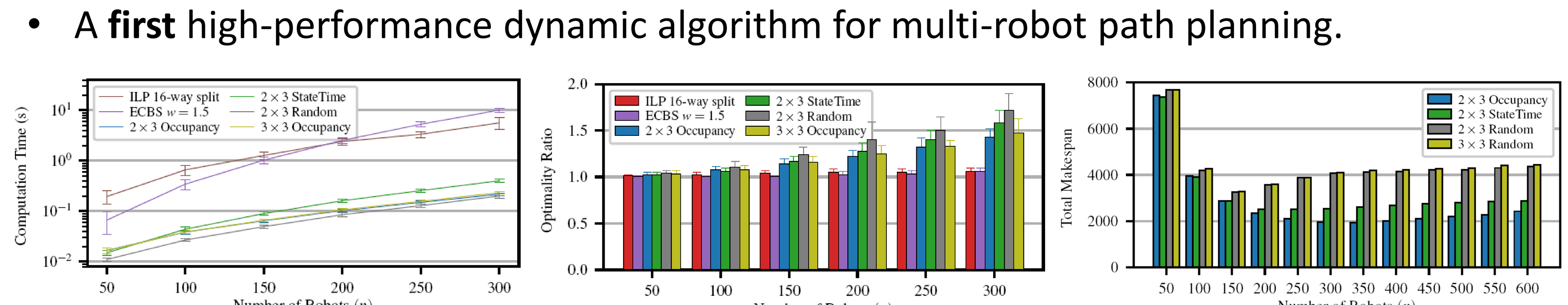
Without path diversification *With path diversification*

Optimization Technique: the Optimal Solution Database
- Contains the time-optimal solutions of all 3×3 and 2×3 problem instances.
- We explore permutation and geometric symmetries to make the database compact.
- Reduces the time to resolve a conflict from ~10 ms to < 1 μs.



Geometric symmetries speed up the database generation process

Evaluation Results.
- The proposed method produces near-optimal solutions.
- About two magnitudes faster than compared algorithms.
- A **first** high-performance dynamic algorithm for multi-robot path planning.

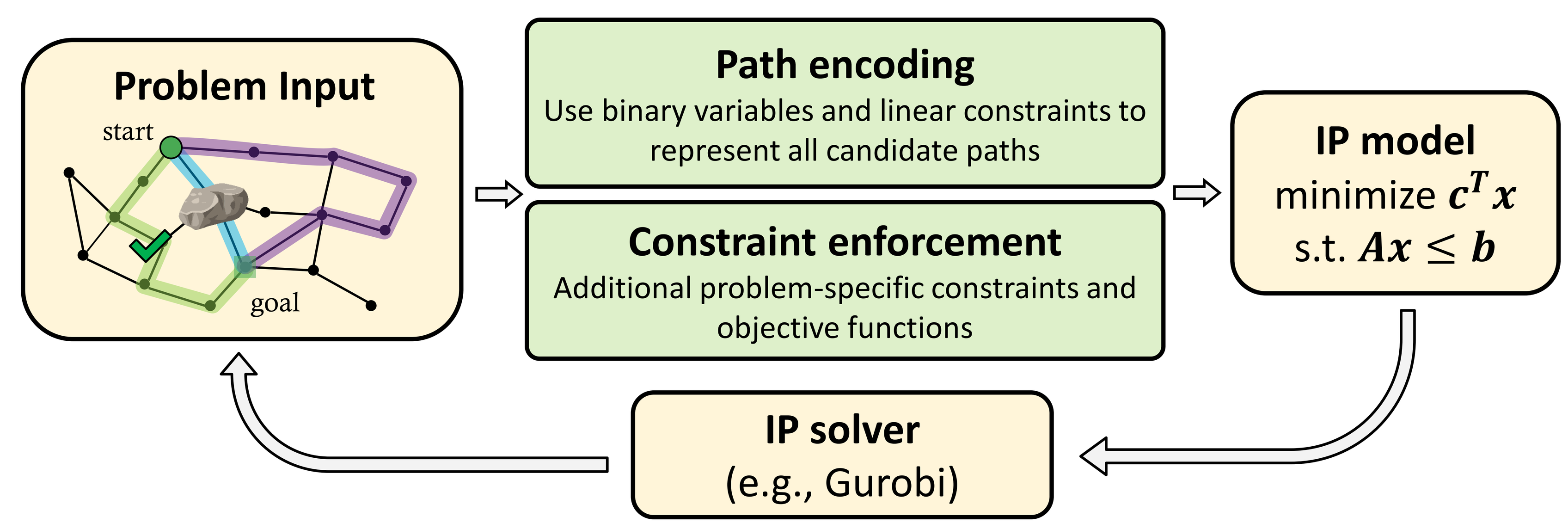


One-shot computation time *One-shot optimality ratio* *Dynamic setting total makespan*

Integer Linear Programming Framework for Path-Based Optimization

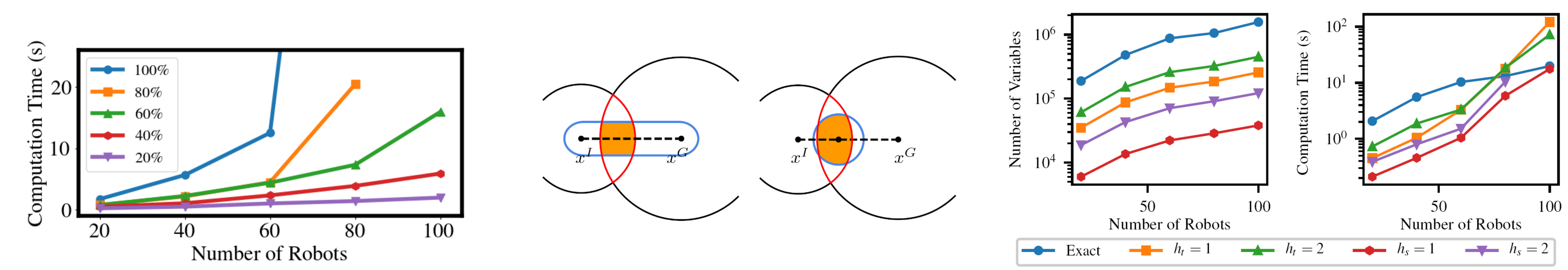
Problem Studied Path-based optimization problems: a general class of combinatorial problems that targets at finding some paths from a very large collection of possible paths to optimize some target objective function. The problems are often NP-hard.

Main Contribution An integer programming framework for path-based optimization problems: **simple to apply, flexible and frequently produces highly optimal solutions.**



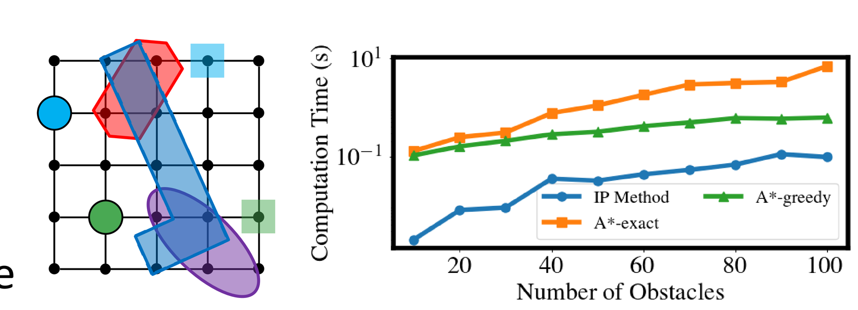
We use three applications to show the performance and flexibility of our framework.

Application Example: Optimal Multi-robot Path and Motion Planning
- Route multiple robots from a starts to a goals efficiently without collisions.
- We study a generalized setting which only requires a subset of robots to reach goals.
- With our framework, solving a partial problem results in significant savings in computation time.
- We also provide new effective heuristics to improve ILP solver's scalability.



Reduced computation time by finding partial solutions *New heuristics are effective in reducing the number of IP variables and improve scalability*

Application Example: Multi-Robot Minimum Constraint Removal
- Plan a path that collides with the minimum number of obstacles.
- We extend both the single-robot version and a multi-robot extension.
- Our IP-based solver outperforms the baseline A* solver on the multi-robot problem.



Application Example: Reward Collection Problems
- One or multiple robots need to collect a maximum reward in an environment given limited resources.
- Our framework readily applies and produces high quality solutions quickly with good scalability.

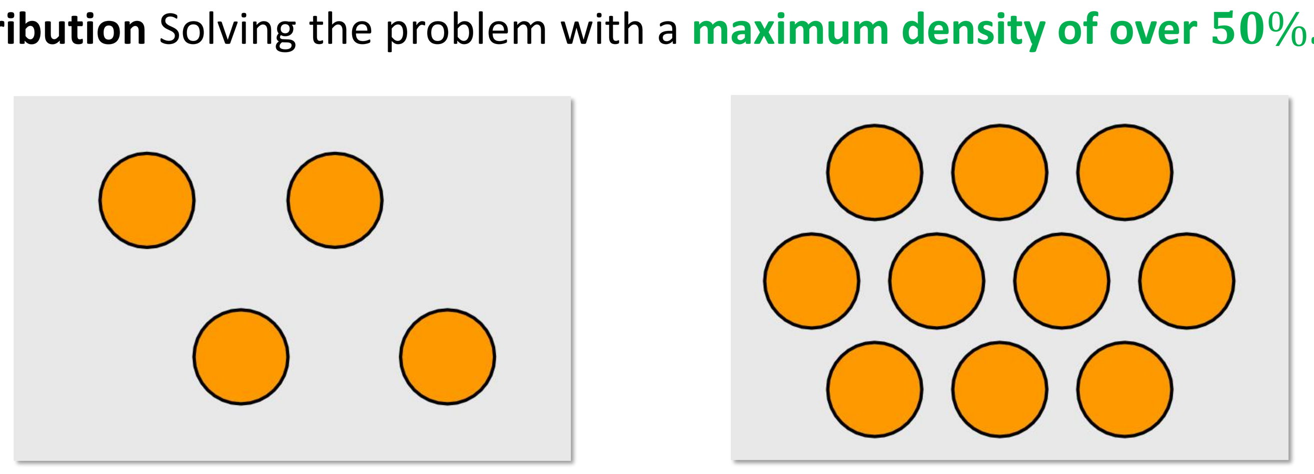
Optimal Tourist Problem

Finalists for **IROS 2019 Best Application Paper** and **Best Student Paper**

Coordinating the Motion of Labeled Disks under Extreme Density

Problem Studied Plan collision-free paths for multiple robots from starts to goals in a compact rectangular space $\subset \mathbb{R}^2$.

Main Contribution Solving the problem with a **maximum density of over 50%.**

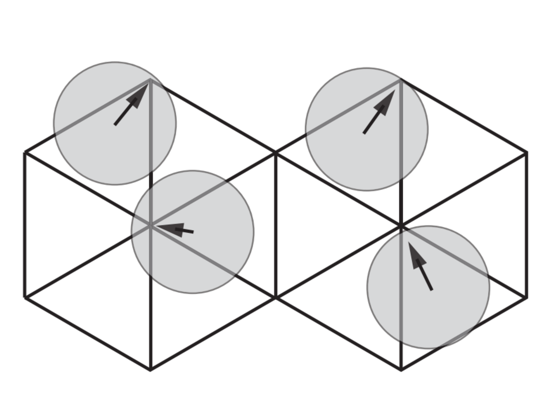


Previous work: ~23% density *This work: > 50% density*

Algorithm Outline
Discretization over a triangular grid.

Theorem. DiscretizeOLDR guarantees collision-free motion of the discs.

Two complete methods:
- a polynomial time, $O(1)$-approximation algorithm,
- a fast, near-optimal ILP algorithm.



Discretization

Project Progress and Products

During the past year, contributions have been made on **algorithm development for dynamic multi-robot path planning** and **general computational method development**.

Products during the past performance year:

❑ S. D. Han and J. Yu. DDM: Fast Near-Optimal Multi-Robot Path Planning using Diversified-Path and Optimal Sub-Problem Solution Database Heuristics. IEEE Robotics and Automation Letters, 2020.

❑ S. D. Han and J. Yu. Integer Programming as a General Solution Methodology for Path-Based Optimization in Robotics: Principles, Best Practices, and Applications. IROS 2019. **Best Student Paper Finalist** and **Best Application Paper Finalist**.

❑ S. W. Feng and J. Yu. Optimal Perimeter Guarding with Heterogeneous Robot Teams: Complexity Analysis and Effective Algorithms. IEEE Robotics and Automation Letters, 5(2), page(s): 430-437, 2020.

❑ Toward Fast and Optimal Robotic Pick-and-Place on a Moving Conveyor. S. D. Han, S. W. Feng, and J. Yu. IEEE Robotics and Automation Letters, 5(2), page(s): 446-453, 2020.

❑ Taming Combinatorial Challenges in Clutter Removal. W. N. Tang and J. Yu. 2019 International Symposium on Robotics Research (ISRR 2019)

❑ Average Case Constant Factor Time and Distance Optimal Multi-Robot Path Planning in Well-Connected Environments. J. Yu. Autonomous Robots, 2019.

❑ Efficient Algorithms for Optimal Perimeter Guarding. S. W. Feng, S. D. Han, K. Gao, and J. Yu. 2019 Robotics: Science and Systems (RSS 2019).

IIS-1734419 NRI: FND: Collaborative Multi-Robot Systems with Provable Availability, Safety, and Optimality Guarantees. PM: Ralph Wachter