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AAMAS-22 Tutorial on Recent Advances in Multi-Agent Path Finding

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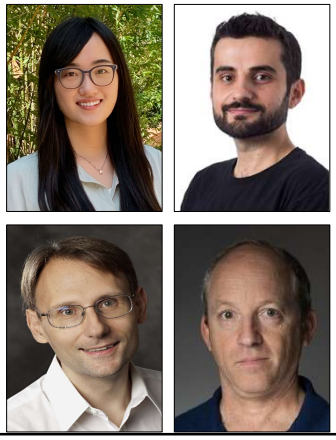

We will often say MAPF instead of multi-agent path finding.

1

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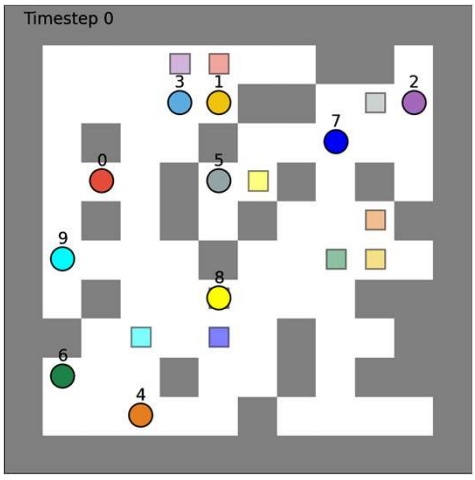
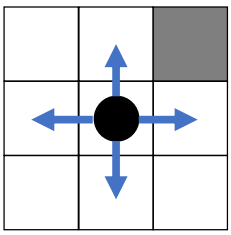
Multi-Agent Path Finding (MAPF)

- Optimization problem with the objective to minimize task-completion time (called makespan) or the sum of travel times (called flowtime)



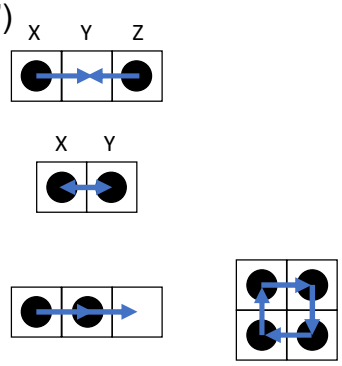
Simplifying assumptions



4

Multi-Agent Path Finding (MAPF)

- Assumptions
  - Each agent moves N, E, S or W to an adjacent unblocked cell or waits, in unit time
  - Not allowed ("vertex collision")
    - Agent 1 moves from X to Y
    - Agent 2 moves from Z to Y
  - Not allowed ("edge collision")
    - Agent 1 moves from X to Y
    - Agent 2 moves from Y to X
  - Allowed



[1] R. Stern et al., "Multi-Agent Pathfinding: Definitions, Variants, and Benchmarks", SoCS, 2019.

5

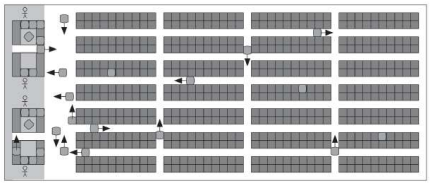
Automated Warehousing

not our work

- Amazon fulfillment centers – warehousing part

https://www.machinedesign.com/mechanical-motion-systems/article/21835788/changing-the-future-of-warehouses-with-amazon-robots

https://www.youtube.com/watch?v=8gy5tYVR-28



[1] P. Wurman et al., "Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses", AI Magazine 29(1), 9-20, 2008

7

Automated Warehousing

not our work

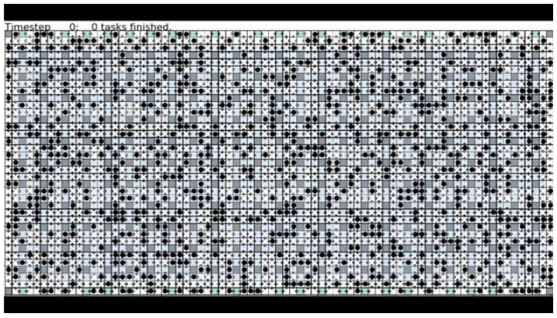
- Amazon fulfillment centers – sorting part

https://www.wired.com/story/amazon-warehouse-robots/

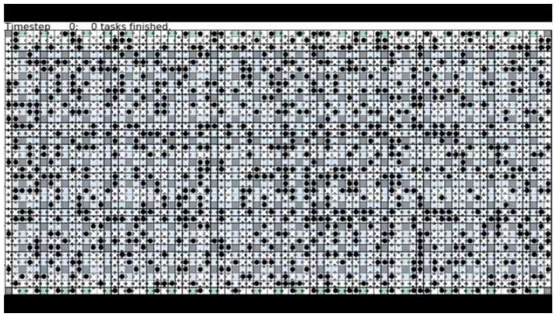
8

Multi-Agent Path Finding (MAPF)

- 800 robots (= 32% empty cells) on a 37x77 sorting-center map with 50 workstations and 275 chutes (joint project with Amazon Robotics)



Single-Agent Planner
= Traffic System



Our MAPF Planner

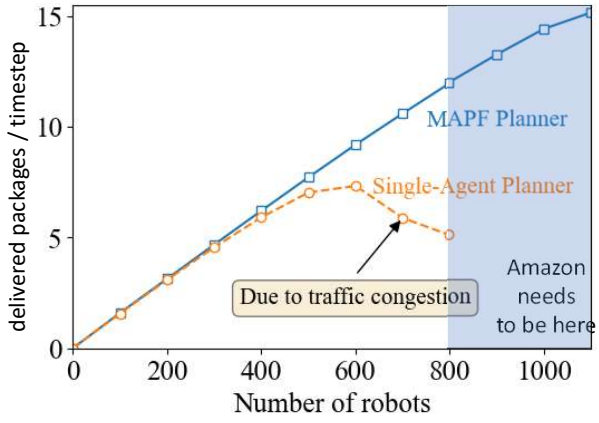
https://www.wired.com/story/amazon-warehouse-robots/

[1] J. Li et al., "Lifelong Multi-Agent Path Finding in Large-Scale Warehouses", AAAI, 2021.

9

Multi-Agent Path Finding (MAPF)

- 800 robots (= 32% empty cells) on a 37x77 sorting-center map with 50 workstations and 275 chutes (joint project with Amazon Robotics)



The Machine
Making sense of AI

Amazon's AI tool can plan collision-free paths for 1,000 warehouse robots

In a recent technical paper, researchers affiliated with the University of Southern California and Amazon Robotics explored a solution to the problem of lifelong multi-agent path finding (MAPF), where a team of agents must be moved

https://venturebeat.com/2020/05/18/amazons-ai-tool-can-plan-collision-free-paths-for-1000-warehouse-r

[1] J. Li et al., "Lifelong Multi-Agent Path Finding in Large-Scale Warehouses", AAAI, 2021.

10

Loading Docks

www.easternlifttruck.com

courtesy of Marcello Cirillo

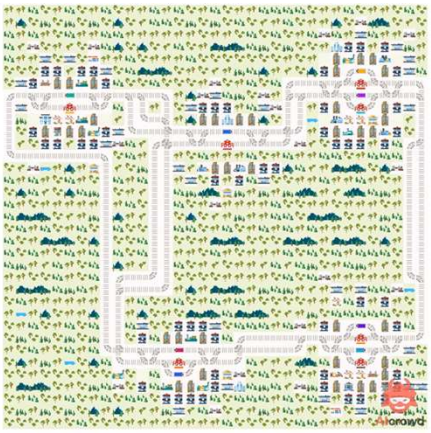
Linde CiTi Truck at Örebro University

[1] M. Cirillo et al., "Integrated Motion Planning and Coordination for Industrial Vehicles", ICAPS 2014.

12

Rail Scheduling

- NeurIPS 2020 Flatland Competition: 700 participants from 51 countries

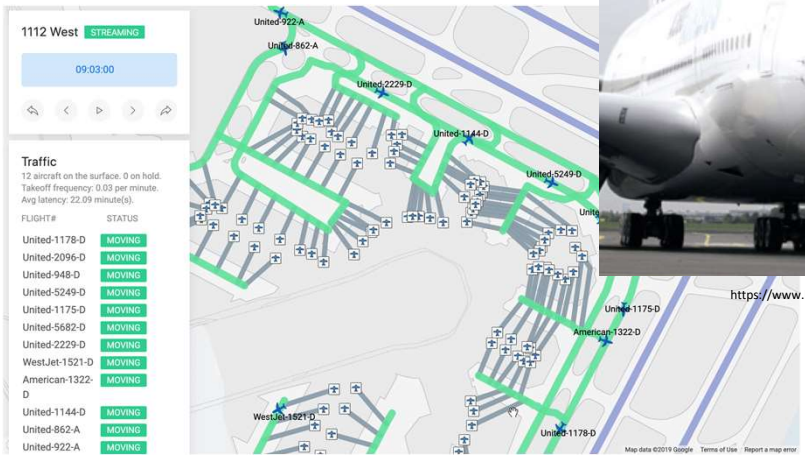


MAPF planner

[1] J. Li et al., "Scalable Rail Planning and Replanning: Winning the 2020 Flatland Challenge," ICAPS, 2021.

13

Airport Surface Operation



https://www.kessler-axles.de/en/markets/aircraft-ground-support/aircraft-towing-tractors/

[1] J. Li et al., "Scheduling and Airport Taxiway Path Planning under Uncertainty", AIAA, 2019.
[2] R. Morris et al., "Planning, Scheduling and Monitoring for Airport Surface Operations", AAAI-16 Workshop, 2016.

14

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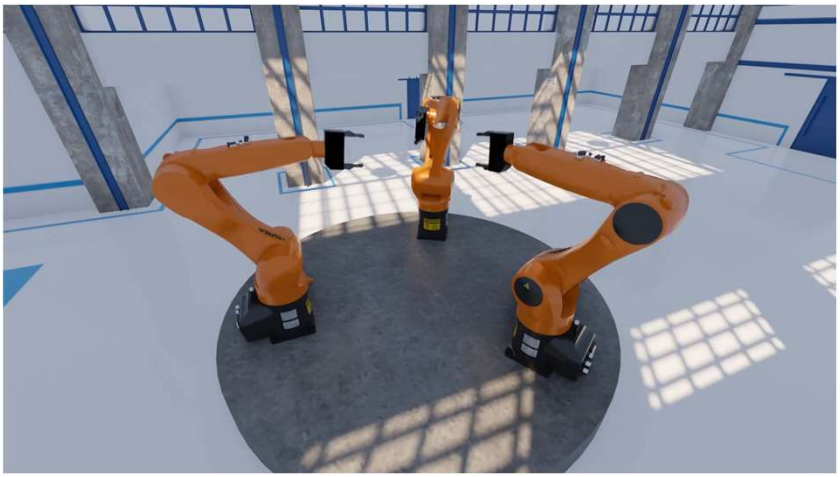
Multi-Arm Assembly



[1] J. Chen et al., "Cooperative Task and Motion Planning for Multi-Arm Assembly Systems", under review for IEEE Robotics a

15

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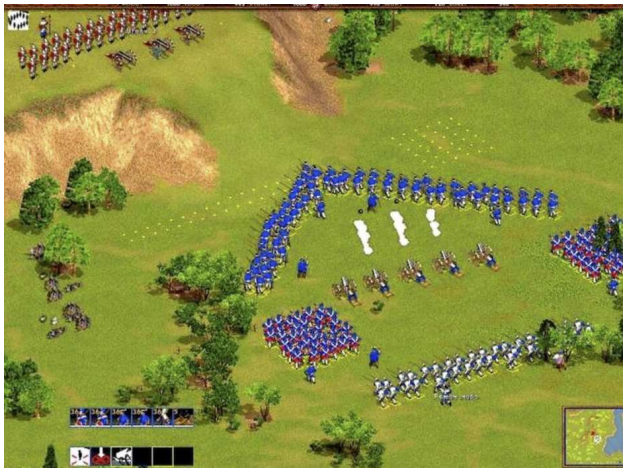
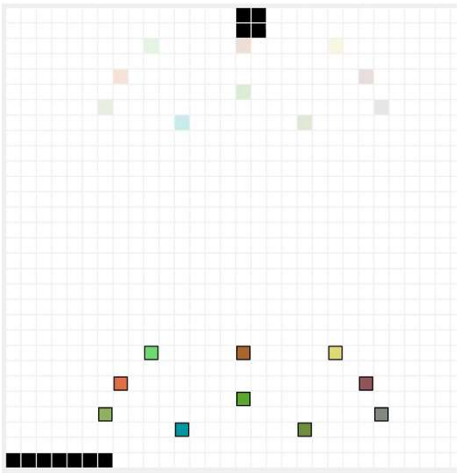
Moving in Formation for Video Games



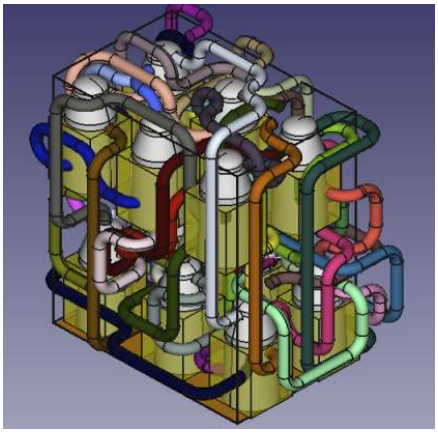
https://www.gamestar.de/galerien/cossacks_european_wars,51483.html

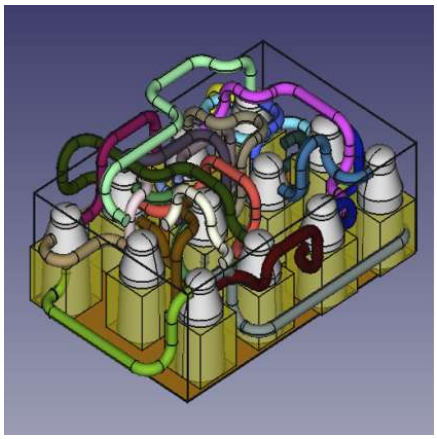


[1] J. Li, et al., Moving Agents in Formation in Congested Environments, AAMAS, 2020.

17

Pipe Routing





x-y-t

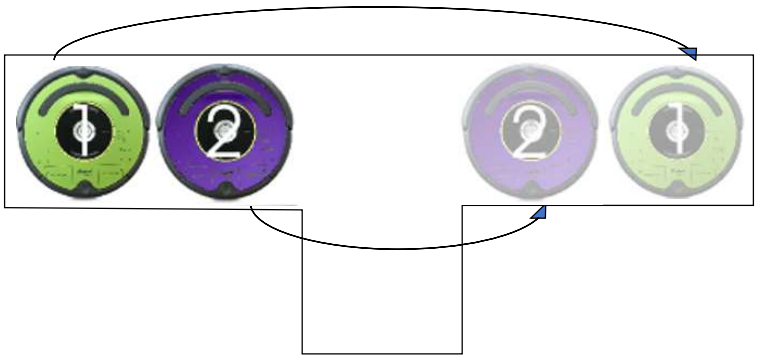
↓

x-y-z

[1] G. Belov et al., "From Multi-Agent Pathfinding to 3D Pipe Routing", SoCS, 2020.

18

Multi-Agent Path Finding (MAPF)

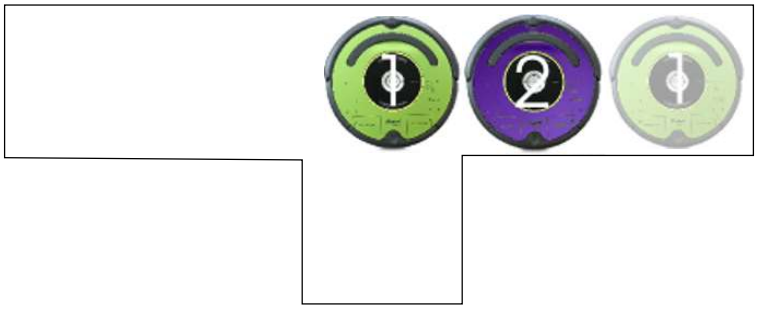


19

Multi-Agent Path Finding (MAPF)

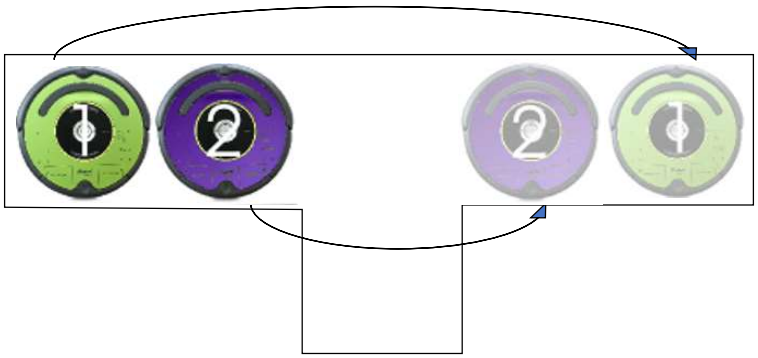
20

Multi-Agent Path Finding (MAPF)



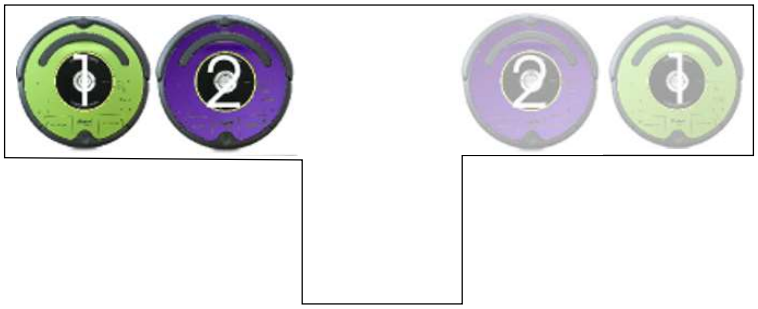
21

Multi-Agent Path Finding (MAPF)



22

Multi-Agent Path Finding (MAPF)



23

Multi-Agent Path Finding (MAPF)

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Multi-Agent Path Finding (MAPF)

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Multi-Agent Path Finding (MAPF)

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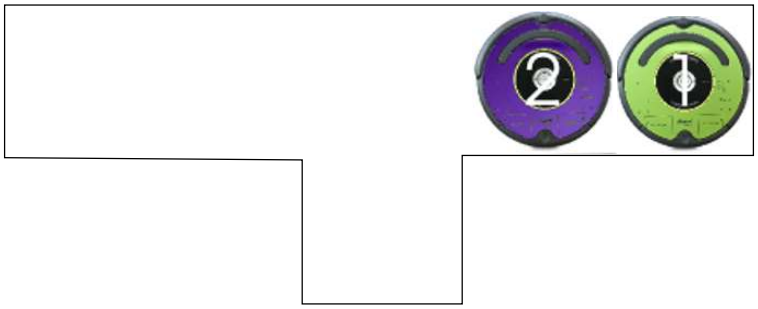
Multi-Agent Path Finding (MAPF)

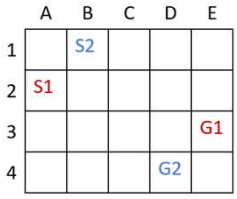


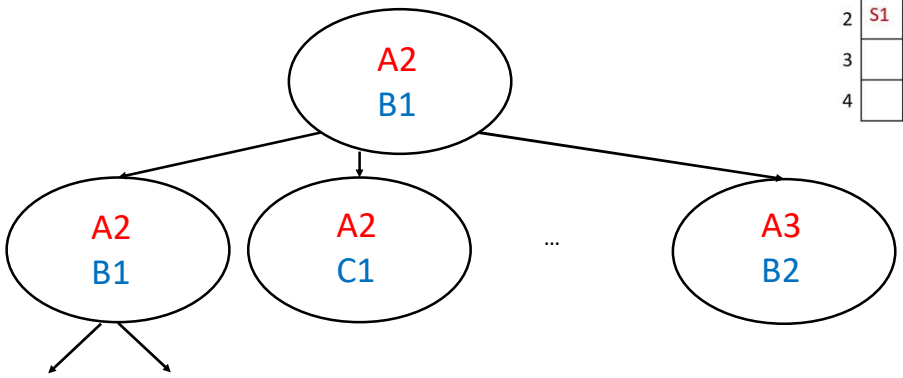
27

Multi-Agent Path Finding (MAPF)

not our work

- A*-based search in the joint state space



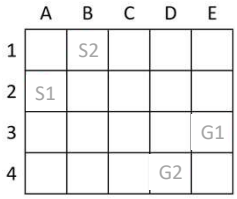


[1] T. Standley, "Finding Optimal Solutions to Cooperative Pathfinding Problems", AAAI, 2010.

28

Complexity of MAPF

- Optimal MAPF planning
  - Polynomal time to find a makespan-optimal MAPF plan with anonymous agents (= assignable goal locations) [1]



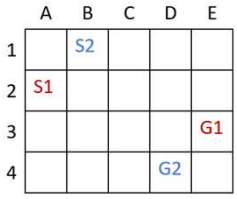
[1] J. Yu and S. LaValle, "Multi-Agent Path Planning and Network Flow", WAFR, 2012.

29

Complexity of MAPF

- Optimal MAPF planning
  - NP hard to find a makespan- or flow-time optimal MAPF plan [1], even on planar [2] or grid-like graphs [3]

https://www.pngegg.com/en/png-horua

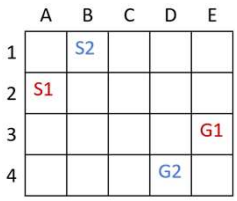


[1] J. Yu and S. LaValle, "Structure and Intractability of Optimal Multi-Robot Path Planning on Graphs", AAAI, 2013.
[2] J. Yu, "Intractability of Optimal Multi-Robot Path Planning on Planar Graphs", IEEE Robotics and Automation Letters, 2016.
[3] J. Banfi et al., "Intractability of Time-Optimal Multi-Robot Path Planning on 2D Grid Graphs with Holes", IEEE Robotics and Auto

30

Complexity of MAPF

- Bounded-suboptimal MAPF planning
  - NP-hard to find a makespan-bounded-suboptimal MAPF plan with suboptimality factors of less than 4/3 [1]



[1] H. Ma et al., "Multi-Agent Path Finding with Payload Transfers and the Package-Exchange Robot-Routing Problem", AAAI, 2016.

31

Complexity of MAPF

not our work

- Suboptimal MAPF planning (= finding any collision-free MAPF plan)
  - Undirected graphs
    - Polynomial time to find a suboptimal MAPF plan [1]
  - Directed graphs
    - Polynomal time to find a suboptimal MAPF plan on directed graphs that are strongly biconnected and have at least two unoccupied vertices [3]
    - NP-hard to find a suboptimal MAPF plan on directed graphs [2]

[1] J. Yu and D. Rus, "Pebble Motion on Graphs with Rotations: Efficient Feasibility Tests and Planning Algorithms", WAFR, 2014.
[2] B. Nebel, "On the Computational Complexity of Multi-Agent Pathfinding on Directed Graphs", ICAPS, 2020.
[3] A. Botea et al., "Solving Multi-agent Path Finding on Strongly Biconnected Digraphs", Journal of Artificial Intelligence Research,