Efficient Airport Taxiing Operations: Conflict-Based Multi-Agent Path Finding with Speed Deviations

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Efficient Airport Taxi Operations

Efficient coordination of aircraft taxiing is crucial to *reducing congestion and emissions at airports*. With a growing airline industry, the need to address these issues is becoming increasingly urgent.

- 54% of landing/take-off cycle emissions stem from taxiing

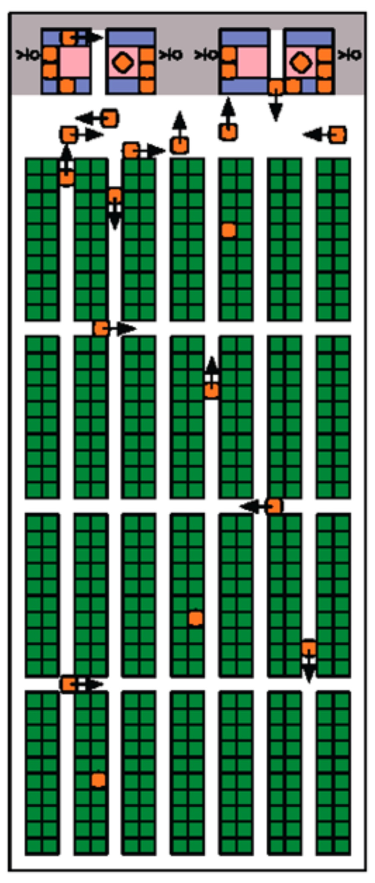
Aim: Optimise autonomous engine-off taxiing operations

Multi-Agent Path Finding (MAPF)

Multi-Agent Path Finding (MAPF) involves planning collision-free paths for multiple agents (such as aircraft) moving from their start locations to their destinations.

- Efficient *coordination* in complex environments
- Flexible, adaptable, fast, *optimal**
- Proven effective in real-world applications

[1]

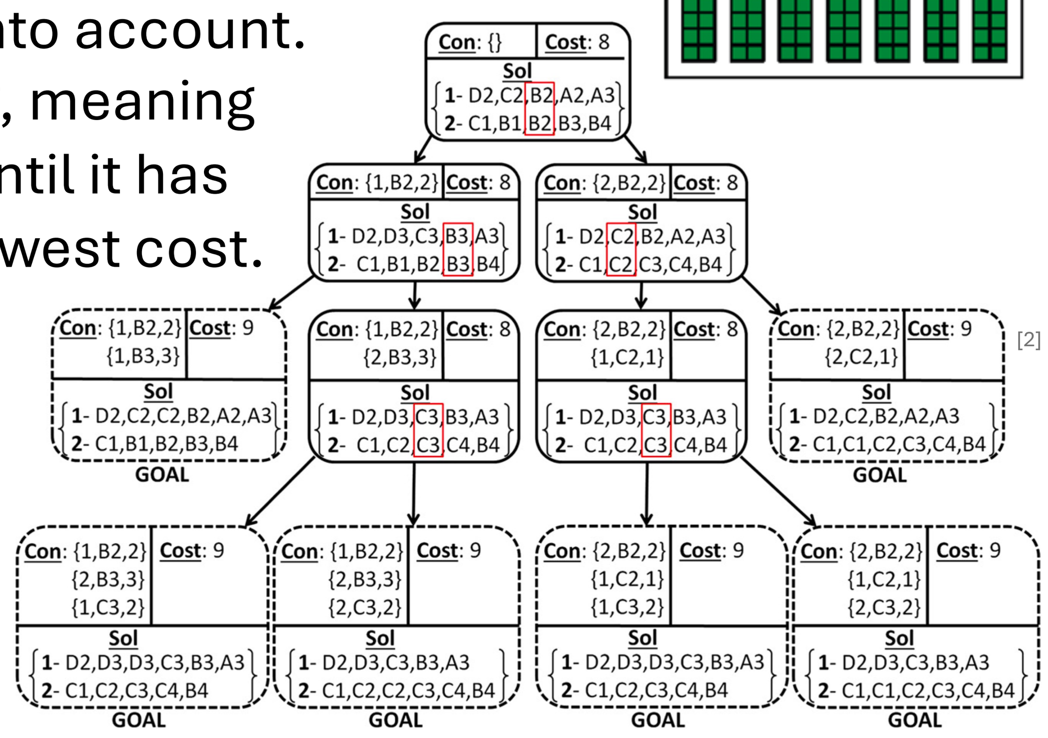


Conflict-Based Search (CBS)

CBS is an optimal and complete algorithm designed to solve MAPF problems by resolving conflicts through the imposition of constraints.

- **High-level search**: Explores the solution space also known as a *constraint tree*.
- **Low-level search:** Heuristic search (*A* search*) to find optimal paths for each agent, taking constraints into account.

CBS is *cost minimising*, meaning that it is not satisfied until it has the solution with the lowest cost.



[2]

[1] P. Wurman, R. D'Andrea, and N. Mountz, "Coordinating Hundreds of Cooperative, Autonomous Vehicles in Warehouses," AI Magazine, vol. 29, no. 1, pp. 9–19, Mar. 20, 2008.

[2] G. Sharon, R. Stern, A. Felner, and N. R. Sturtevant, "Conflict-based search for optimal multi-agent pathfinding," Artif. Intell., vol. 219, pp. 40–66, Feb. 2015, doi: 10.1016/j.artint.2014.11.006.

Deviations

A deviation refers to an *unplanned change in speed of an agent*. Aircraft taxi speed depends on the pilot; therefore, speed changes from prediction-based artificially generated paths are common.

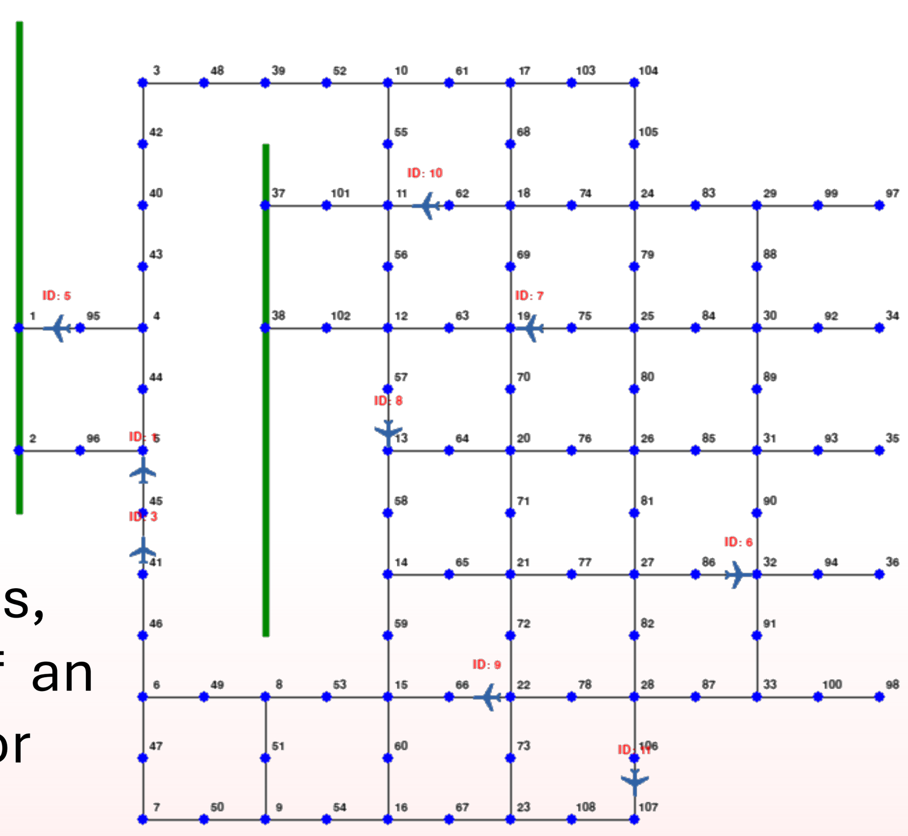
- Deviations lead to *discrepancies* between planned and actual positions.
- When deviations occur, the original conflict-free paths planned by CBS are *invalidated*, requiring the system to *re-plan*.

Research Question

How do speed deviations affect the overall performance of CBS for automated path planning in airport taxiing operations under various traffic density conditions?

Objective

Through *agent-based modelling* of an airport environment, this study aims to evaluate the impact of speed deviations on CBS under varying traffic densities. Thus, challenging the *resilience* of an otherwise optimal system for efficient planning.

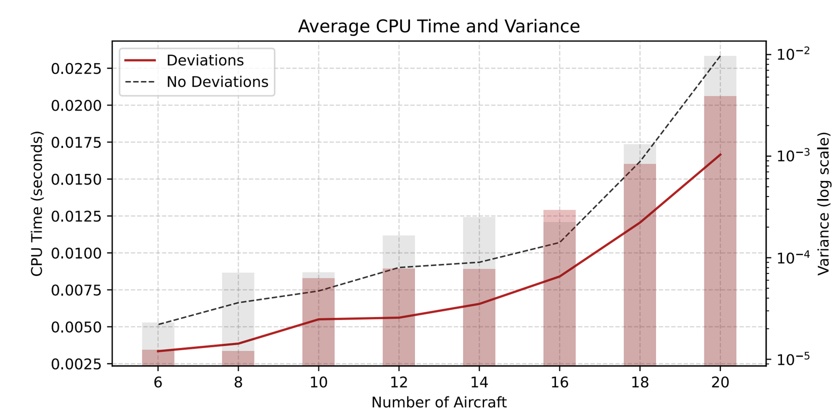


Experiments

Computational and operational performance is measured through the following performance metrics:

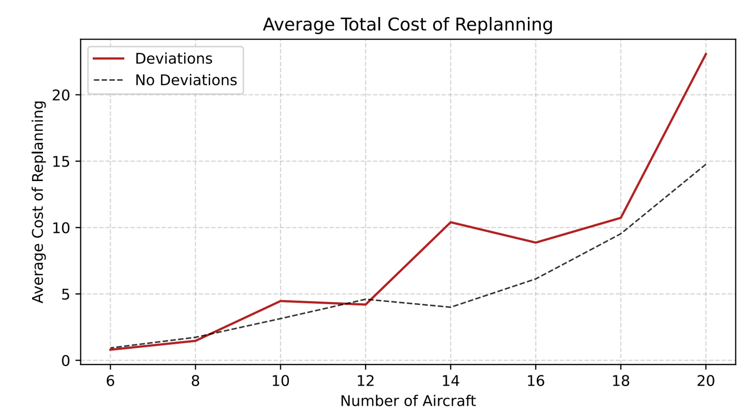
- **CPU Time:** Measures the computational resources required for planning, reflecting the efficiency of the algorithm.
- **Path Optimality:** Assesses the difference between an agent's actual path and its ideal path, indicating how well the system manages to retain optimal routes despite deviations.

CPU Time



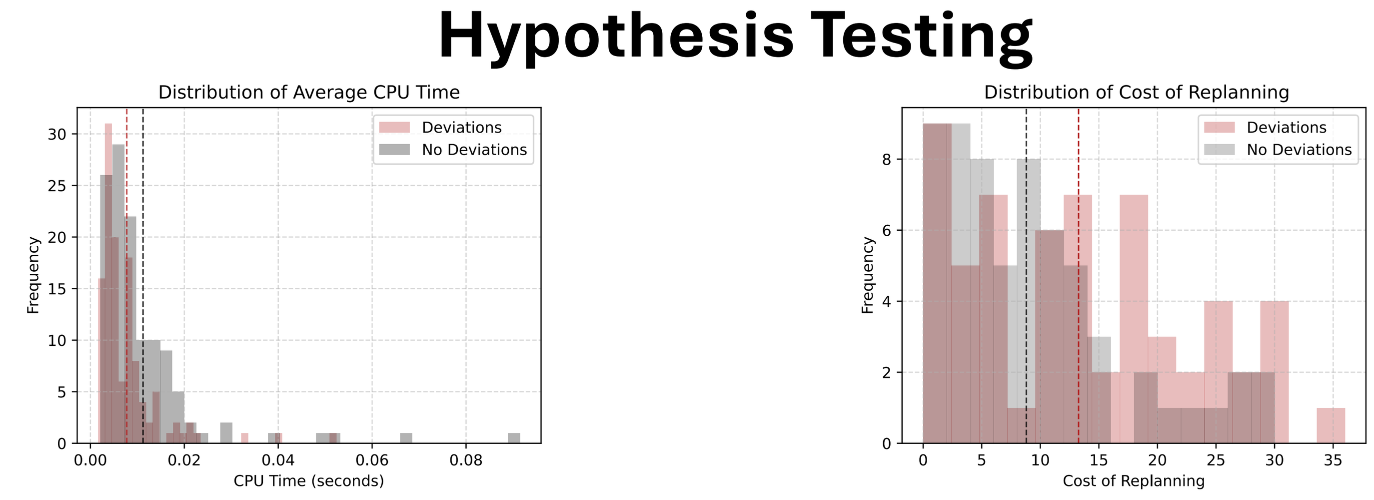
- Increases with the number of agents involved.
- Average CPU time is lower when agents deviate.
- Search times become increasingly unpredictable as the number of agents rises.

Path Optimality



- Increases with the number of agents involved.
- Impact of deviations is not clear in less dense traffic.
- However, the impact is *significant* in dense traffic.

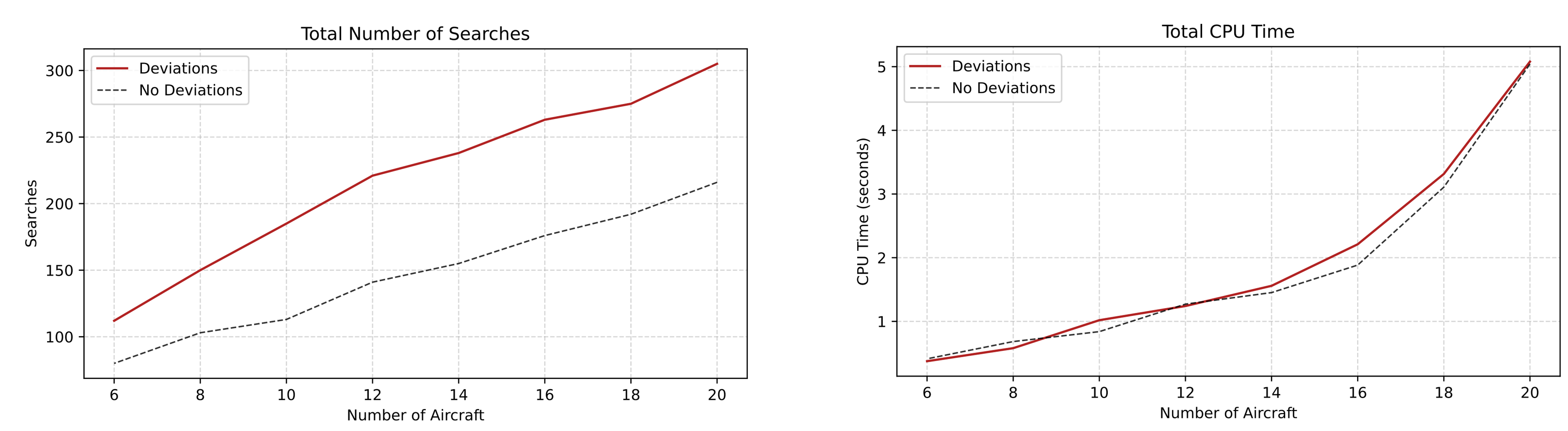
Hypothesis Testing



The distributions are left-skewed; therefore, to validate the results, a Mann-Whitney U-Test is conducted.

- Non-parametric test compares the rank-sum.
- Confirms that average CPU times are significantly *lower* when agents *deviate*.
- Path costs difference becomes significant only in *high-density traffic* scenarios.

Total CPU Time



The difference in **average** CPU time does not give a complete overview of the CBS algorithm's performance. Therefore, **total** CPU time is analysed:

- Sum of CPU times for all simulations.
- More frequent planning due to deviations compensates for lower average search time.
- CPU time is preserved regardless of deviations.

Conclusion

The study demonstrates that CBS is a robust and efficient method for managing airport taxiing operations even when the plans are not followed.

- Planning frequency increases but CBS maintains optimality.
- Feasibility for real-time path planning in dynamic environments is supported.
- Kinematics of aircraft still need to be considered for real-world applications.