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Conflict Detection and Resolution Considering Human–Machine and Air–Ground Interaction

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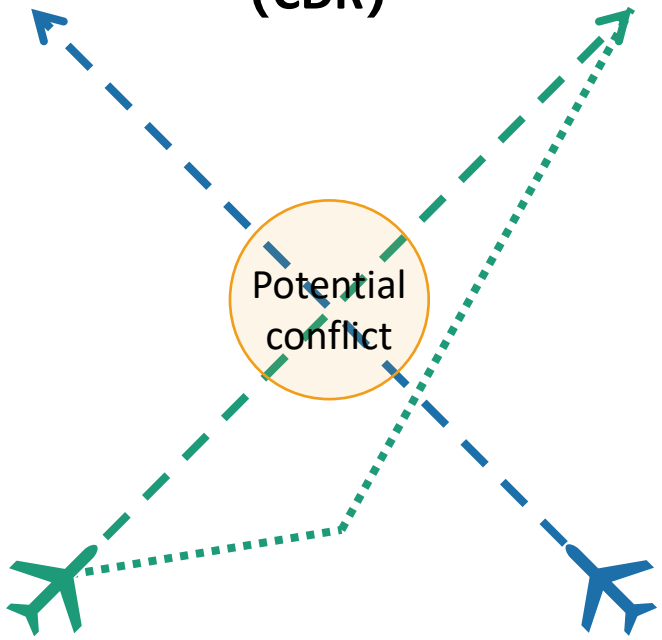
Nanyang Technological University (NTU), Singapore

2025 SESAR Innovation Days, Bled, Slovenia



Background

Conflict Detection and Resolution (CDR)



Theoretical Methods

- Geometric Methods
- Optimization-Based Methods
- Sampling / Search-Based Methods
- Game-Theoretic Methods
- AI / Learning-Based Methods
- …

Applied?

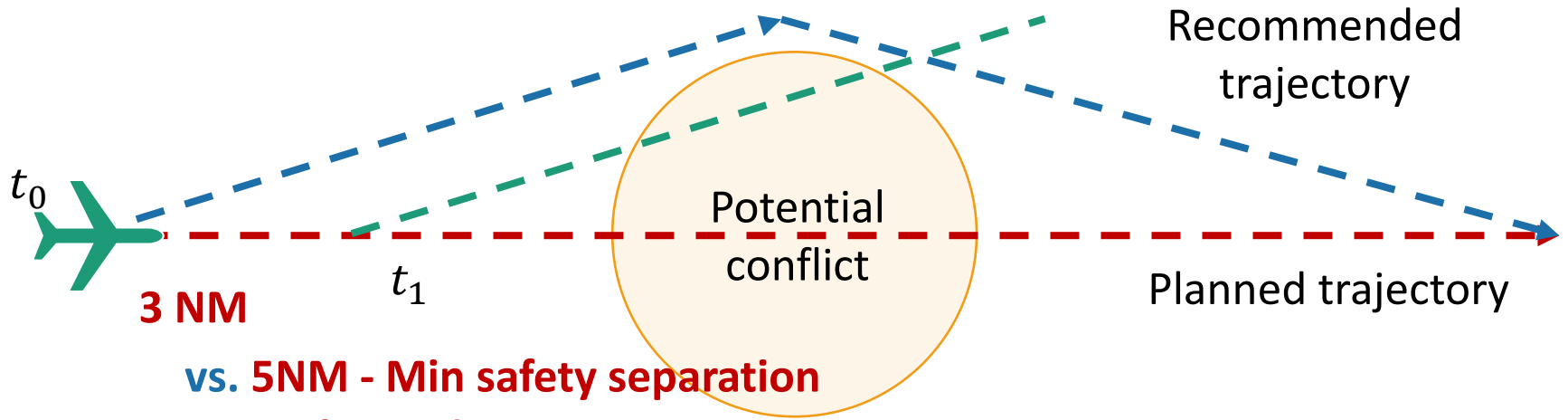
Human-centered

sesar JOINT UNDERTAKING HYPERSOLVER NeoMetSys EUROCONTROL LFV NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE ENAC WARWICK THE UNIVERSITY OF WARWICK

Grant agreement ID: 101114820

Human–AI teaming for solving ATM problems

Background



Timeline

20 s

t_0 Decision-support system generates a recommended solution

Human-machine interaction: Controller reviews the solution for the flight and decides

Air-ground interaction: Controller communicates with the flight's crew

t_1 The flight starts to perform the maneuver

Conflict Detection and Resolution Decision Support Considering Human–Machine and Air–Ground Interaction

I. Controller workload model considering human–machine and air–ground interaction

II. Trajectory prediction considering uncertainty in air–ground interaction response time

Constraints

Scenarios

III. Robustness-aware conflict-free trajectory planning optimization

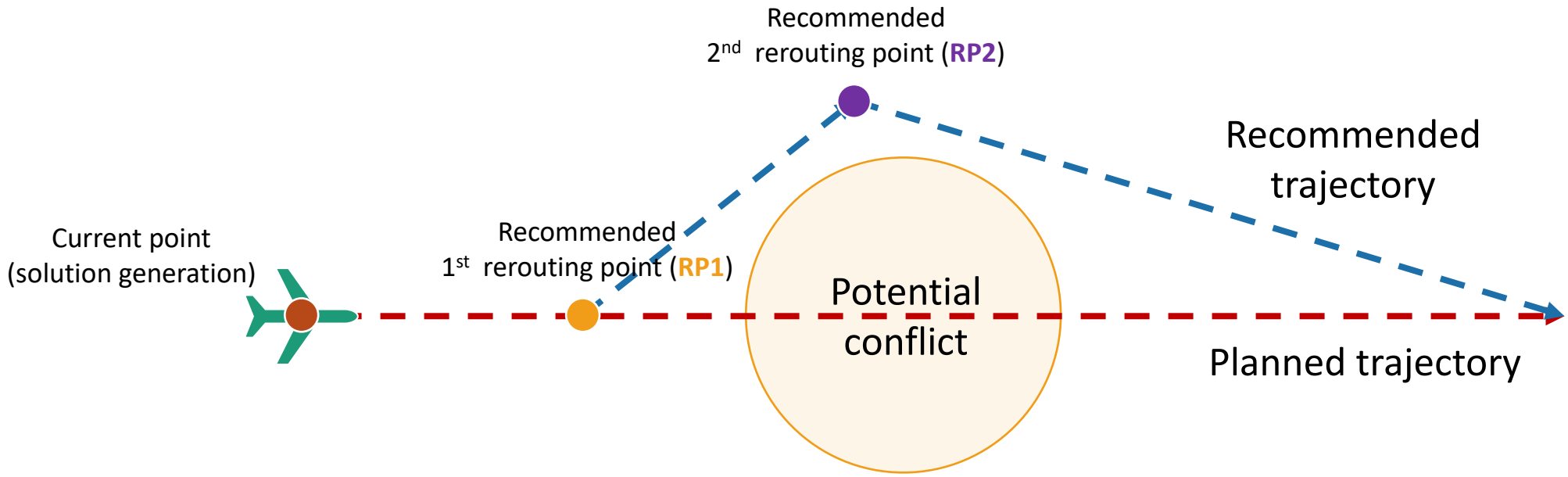
Solving

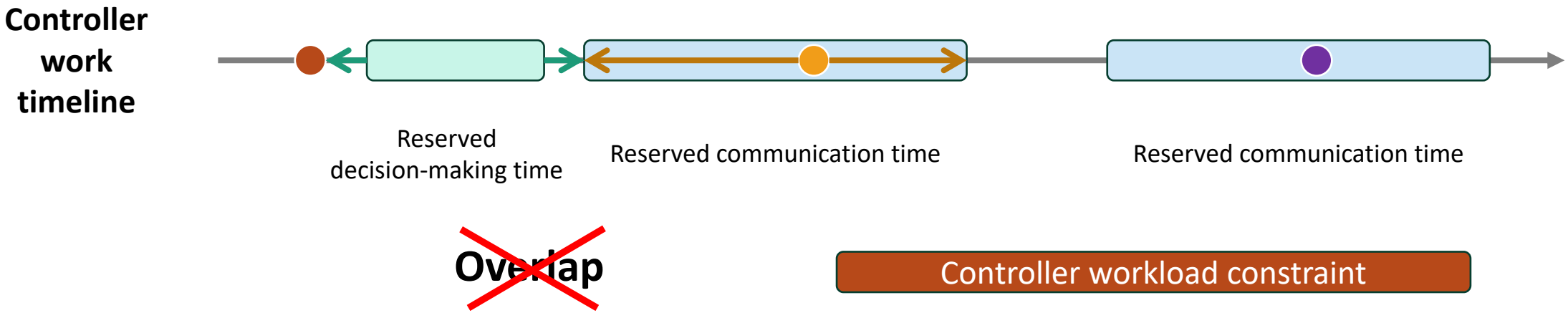
IV. Adaptive dynamic search for conflict-free trajectories

Validation

Fast-time simulation experiments incorporating interaction time uncertainty

Module I. Controller Workload Model





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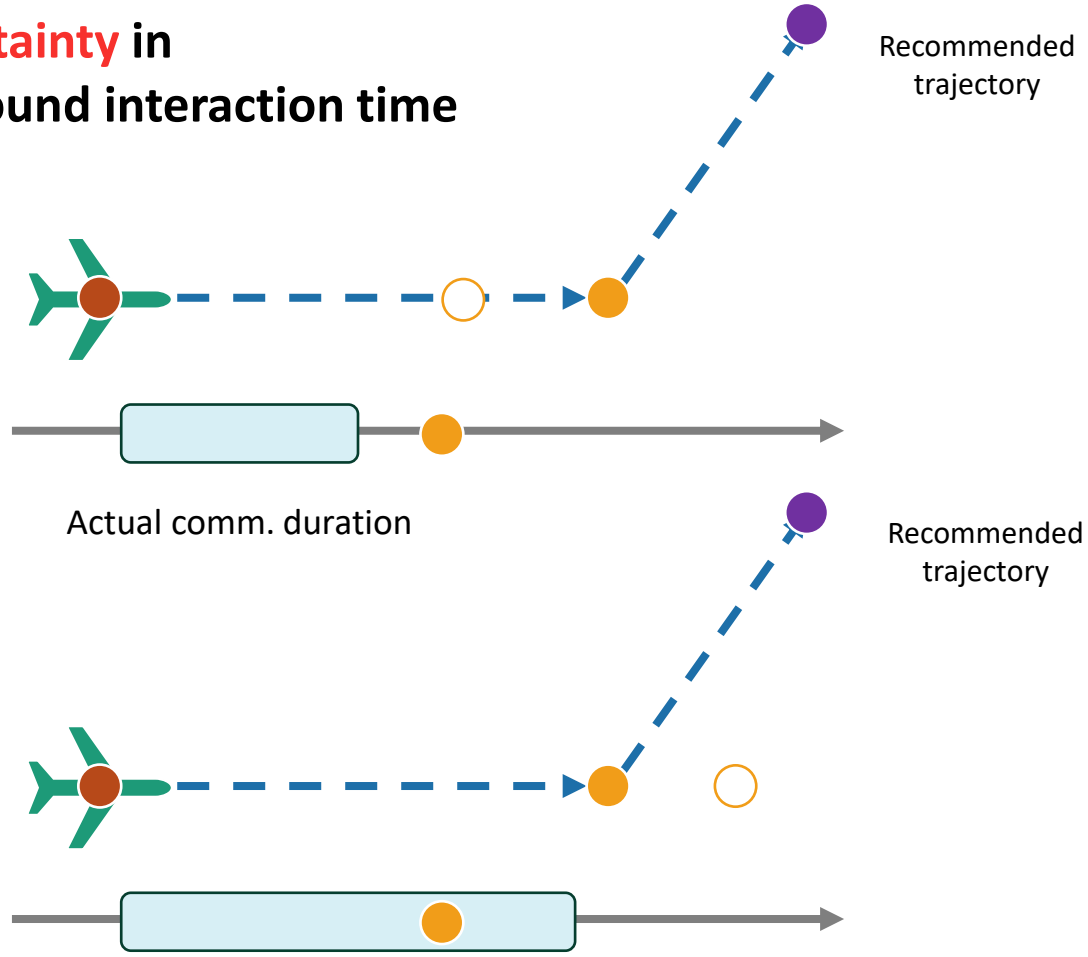
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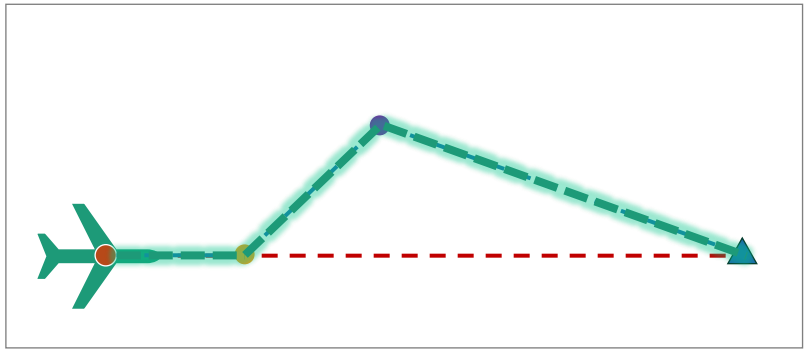
Module II. Trajectory Prediction

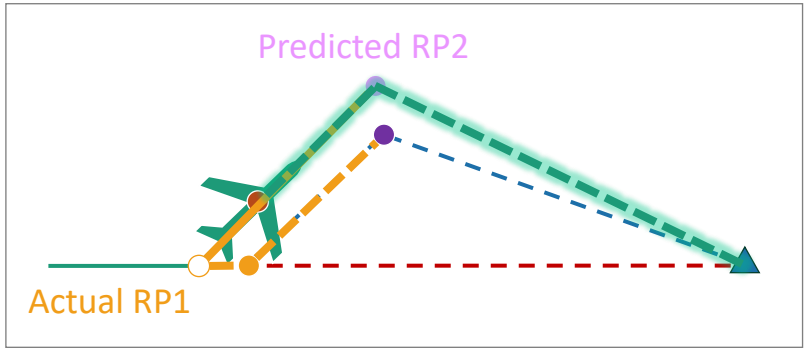
CDR decision-support system updates in real time
--> predict flight trajectories continuously

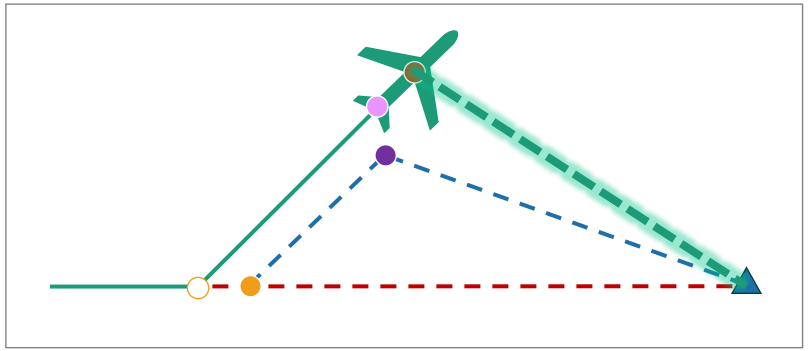
Uncertainty in
air-ground interaction time



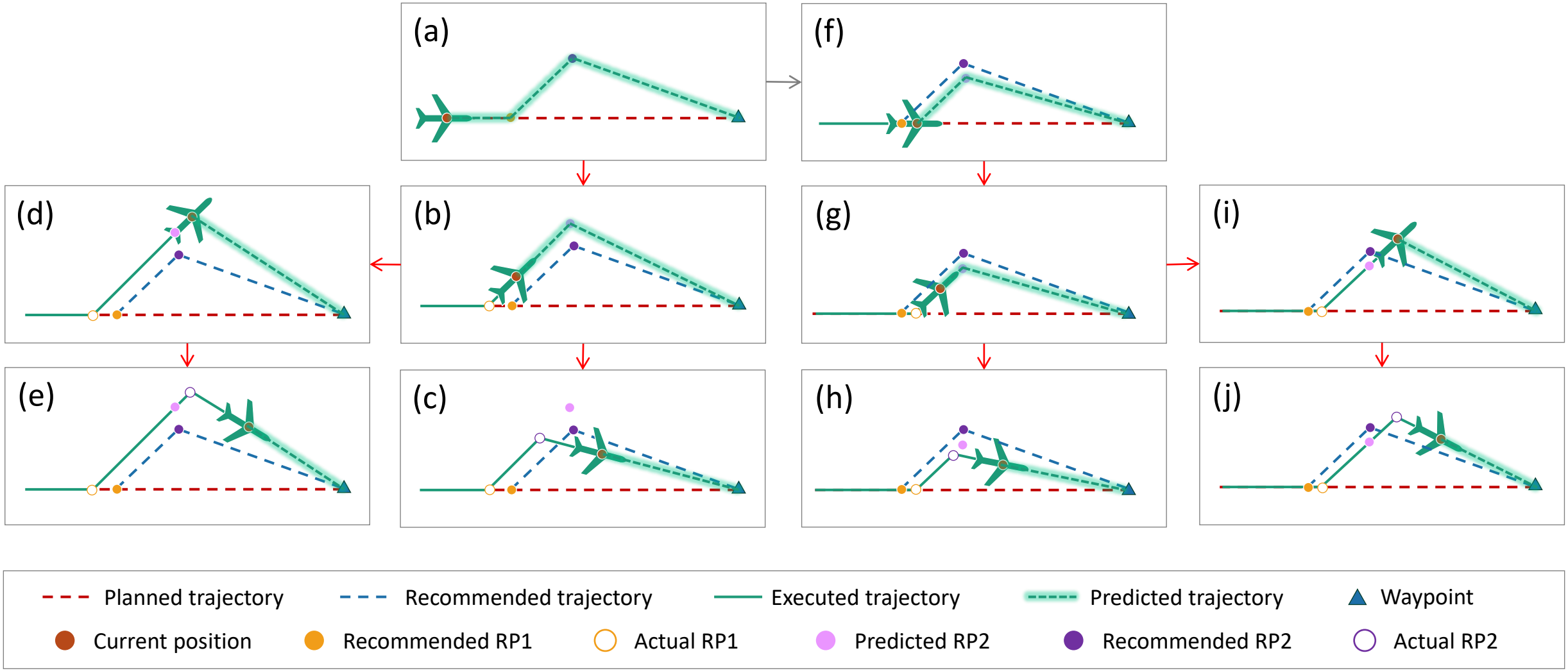
different models --> different situations







Module II. Trajectory Prediction



helps the conflict detection adapt better to the uncertainty in air–ground interaction time

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Module III. Trajectory Optimization Model

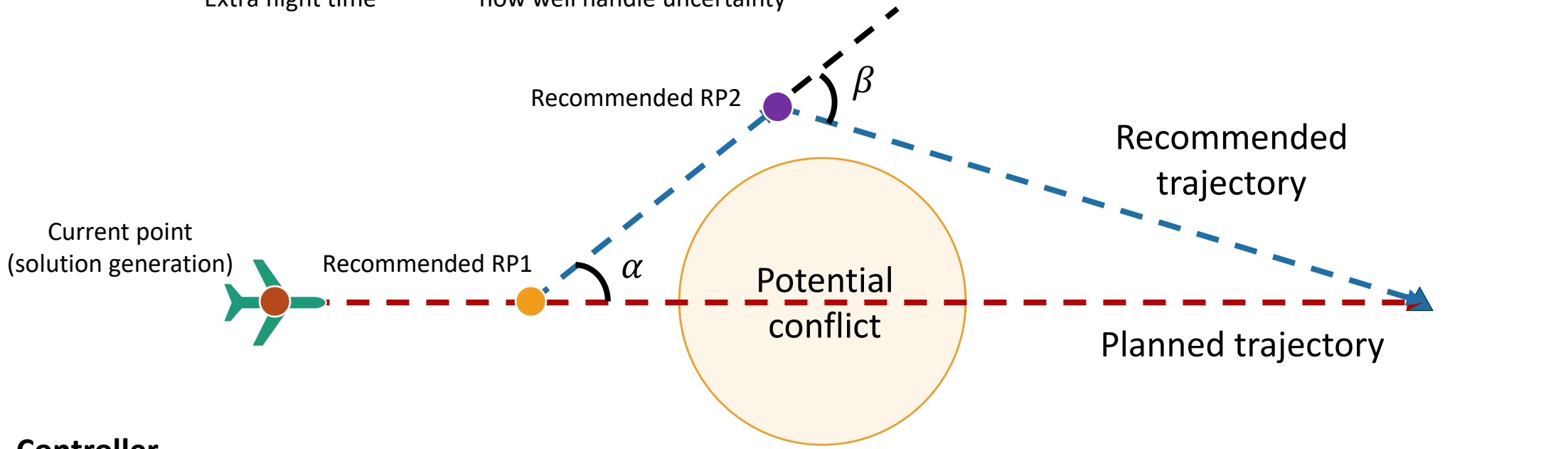
Decision variables: Positions of recommended RP1 and RP2

Constraints: Aircraft performance | Controller workload | Safety separation -- *First come first served*

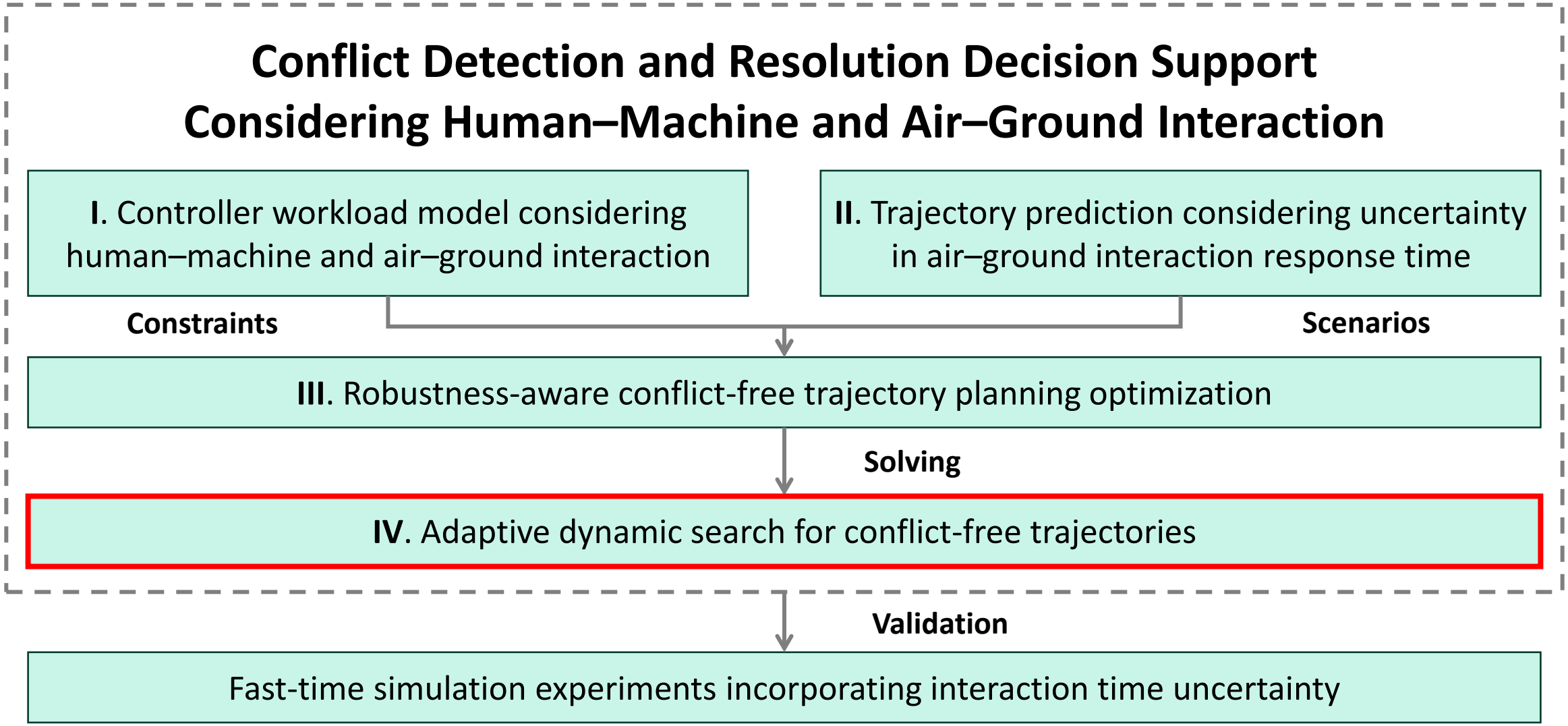
Objectives: Extra flight cost ↓ | Robustness index ↑ -- *Weighted sum*

Extra flight time

how well handle uncertainty



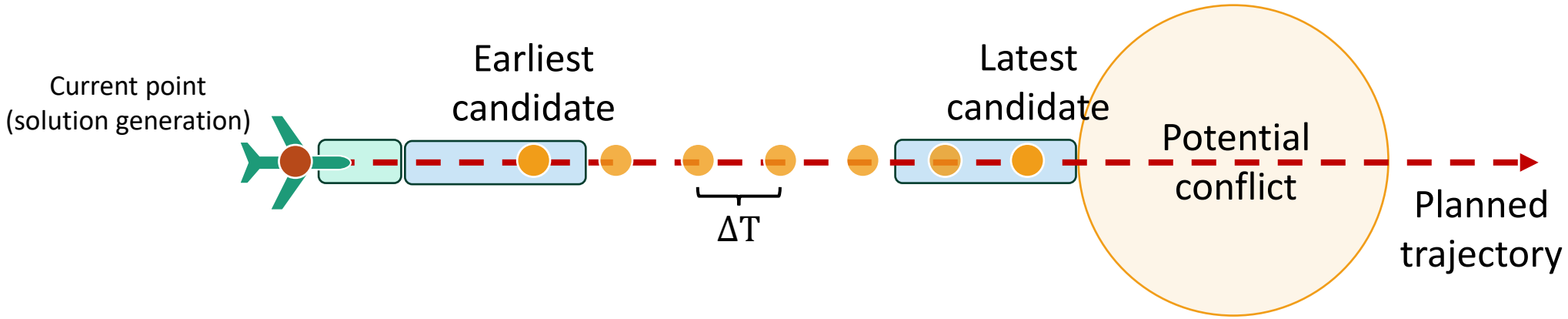


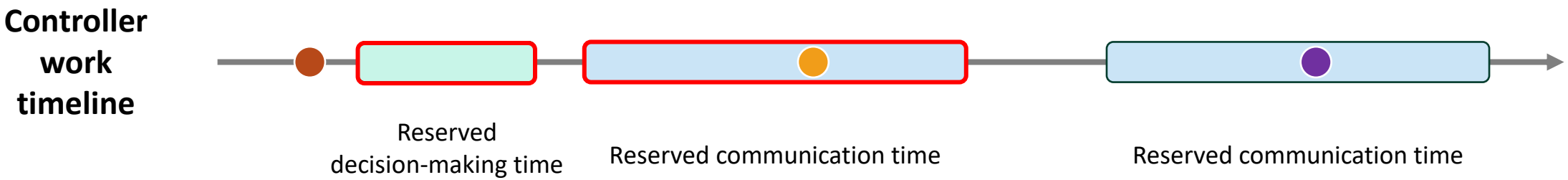

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Module IV. Adaptive Dynamic Search

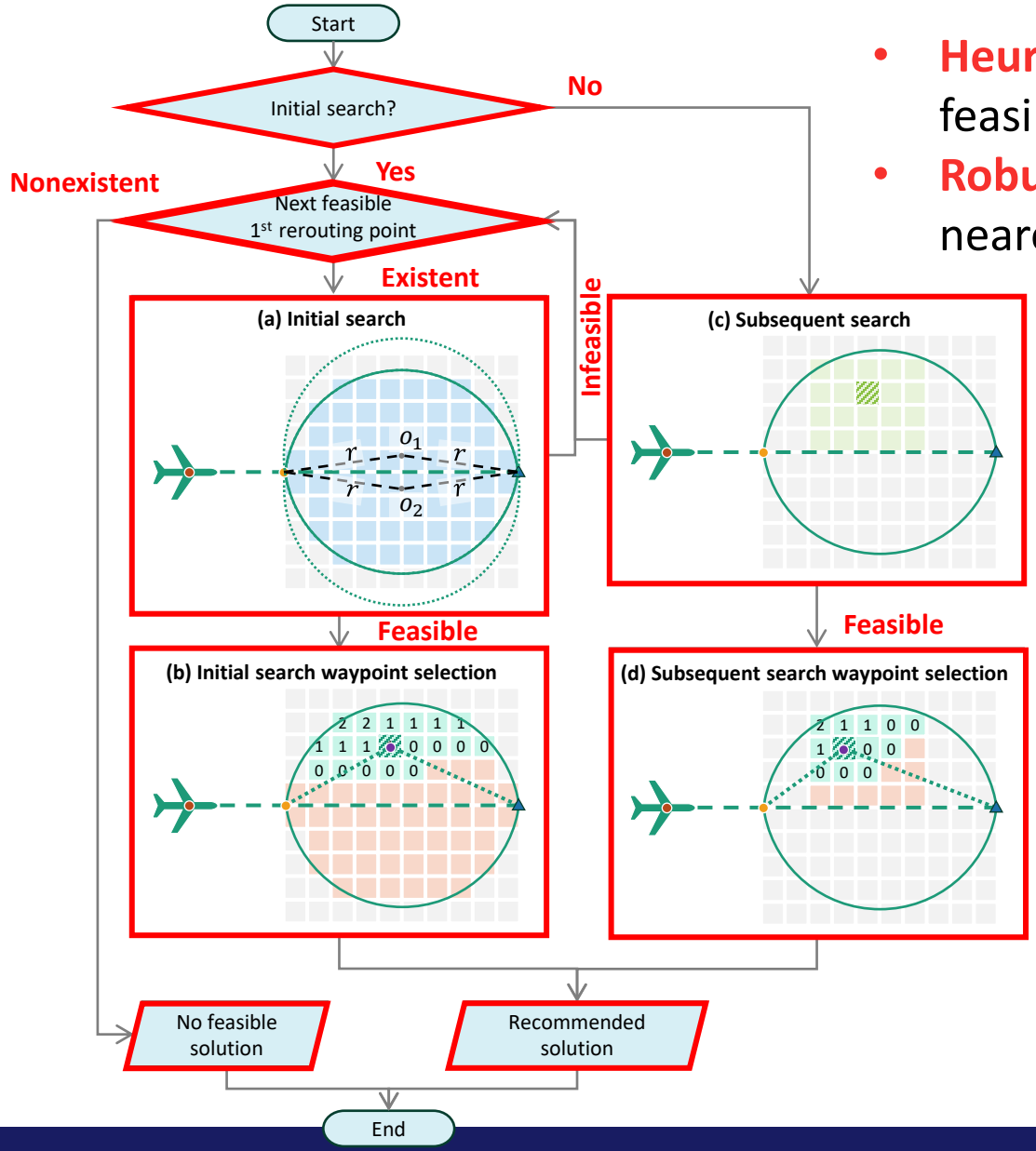
- **Heuristic idea 1**: earlier maneuvers usually give a larger solution space
- **Search strategy**: the earliest feasible RP1 with the best RP2

RP1 candidate set:



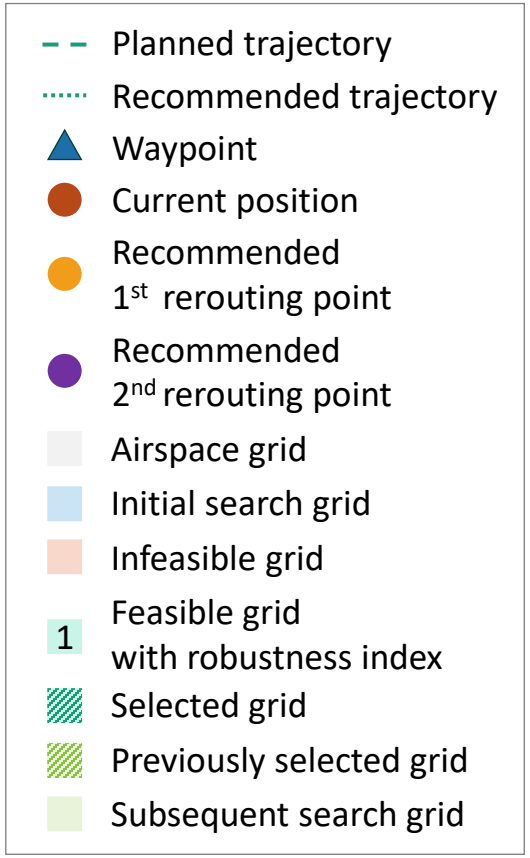


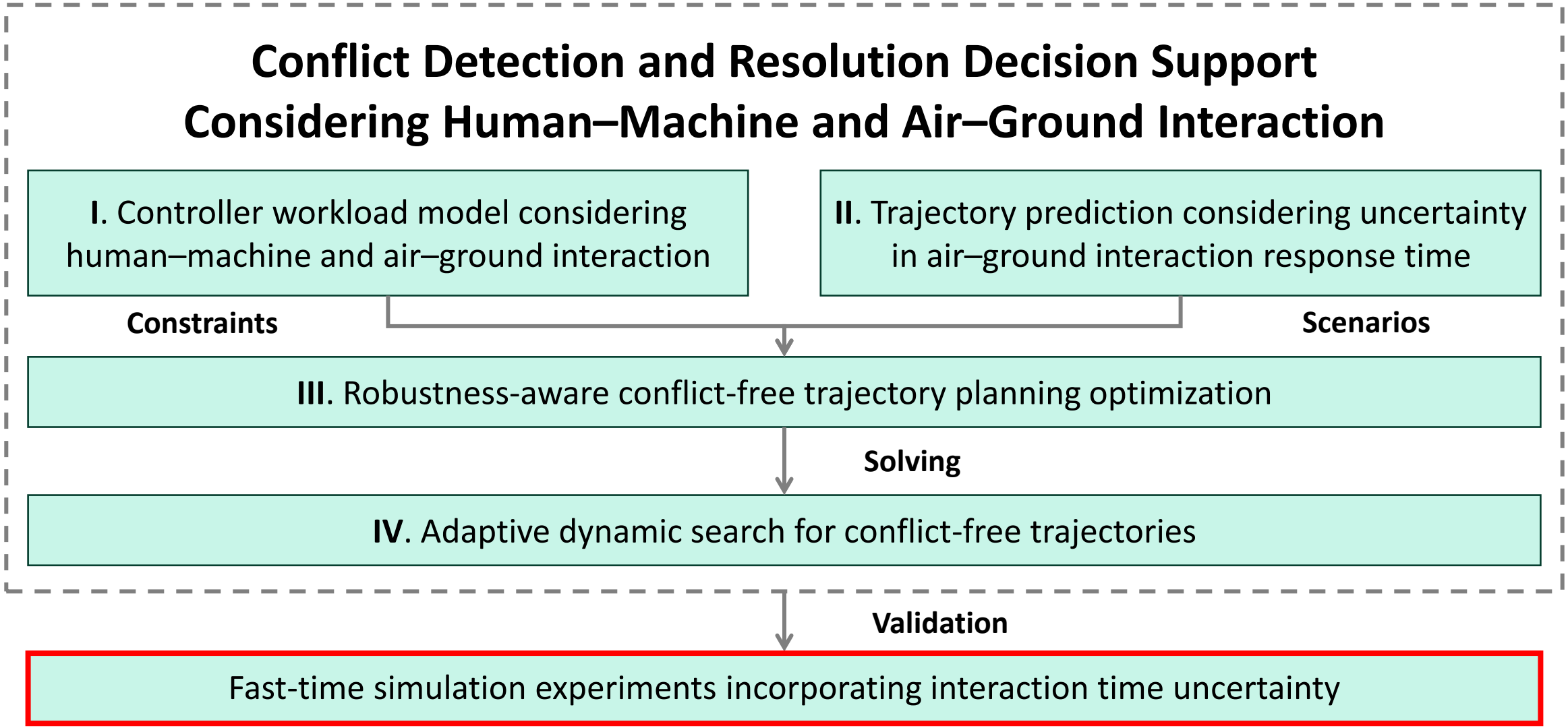
Module IV. Adaptive Dynamic Search



Optimal RP2:

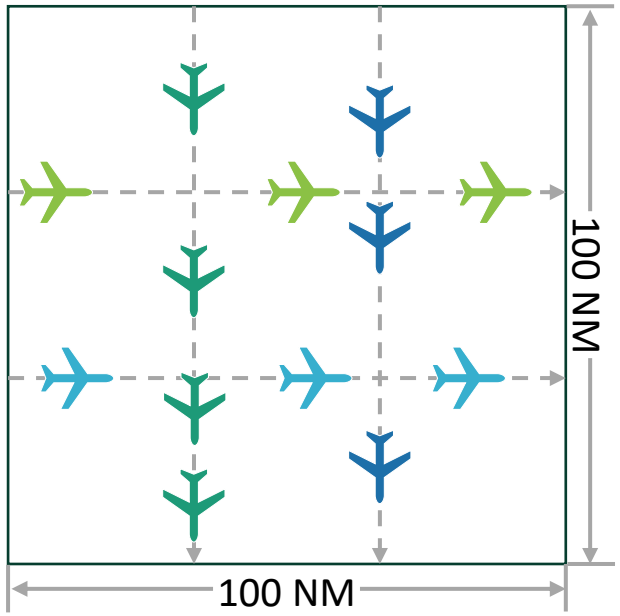
- **Heuristic idea 2**: After environment changes, feasible solutions stay close to the previous one
- **Robustness index**: the number of grid steps to the nearest infeasible point




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Experimental Setting

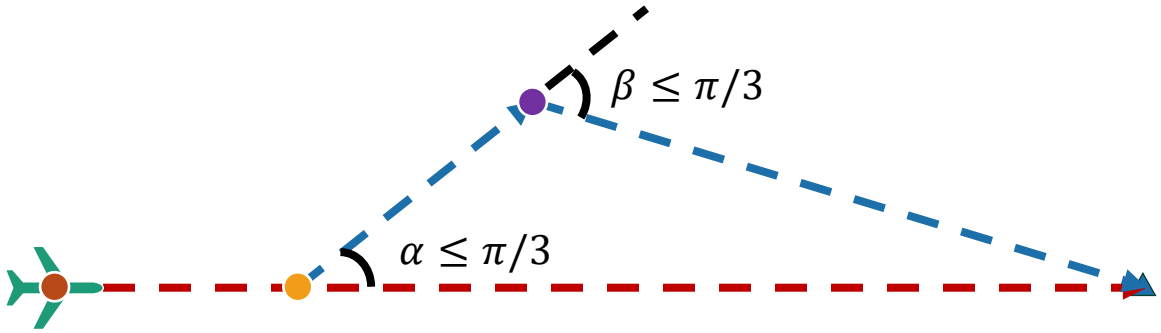
Single flight level



Minimum safe separation distance: 5 NM

Grid length: 5 NM

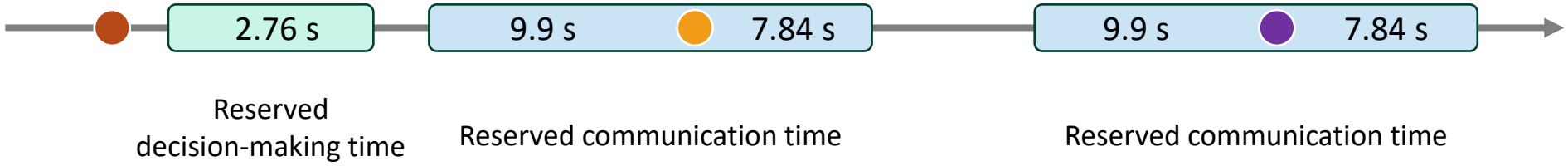
Advisory update interval: 5 s



Decision-making time: 1.91 ~ 2.76 s [1]

Communication time: 4 ~ 17.74 s [2]

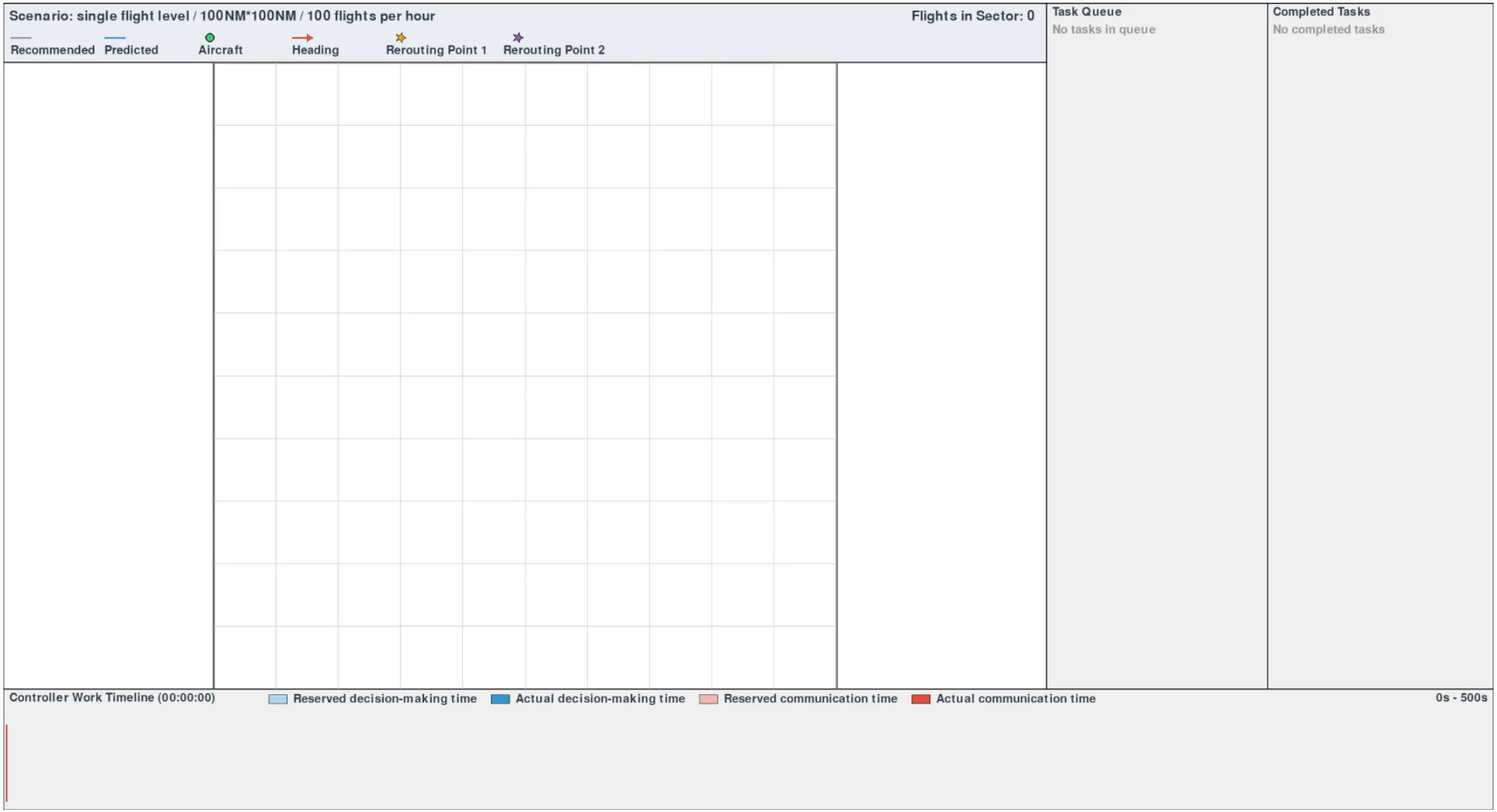
Controller work timeline



[1] Y. Shang-wen, H. Ming-hua, Estimation of air traffic longitudinal conflict probability based on the reaction time of controllers, Safety Science 48 (7) (2010) 926–930.
[2] K. M. Cardosi, Time required for transmission of time-critical air traffic control messages in an en route environment, The International Journal of Aviation Psychology 3 (4) (1993) 303–313.

Fast Simulation Demo

3× the maximum real-world traffic density



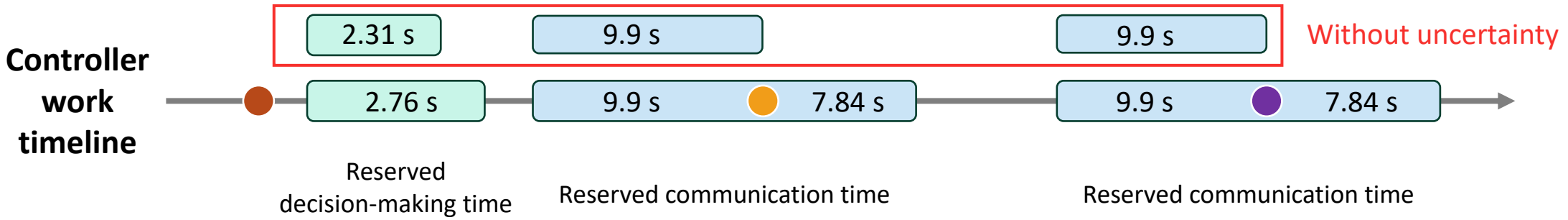
Comparison Models

Model	Workload constraint	Heuristic search	Uncertainty
W	✓	-	-
H	-	✓	-
WH	✓	✓	-
WHU	✓	✓	✓

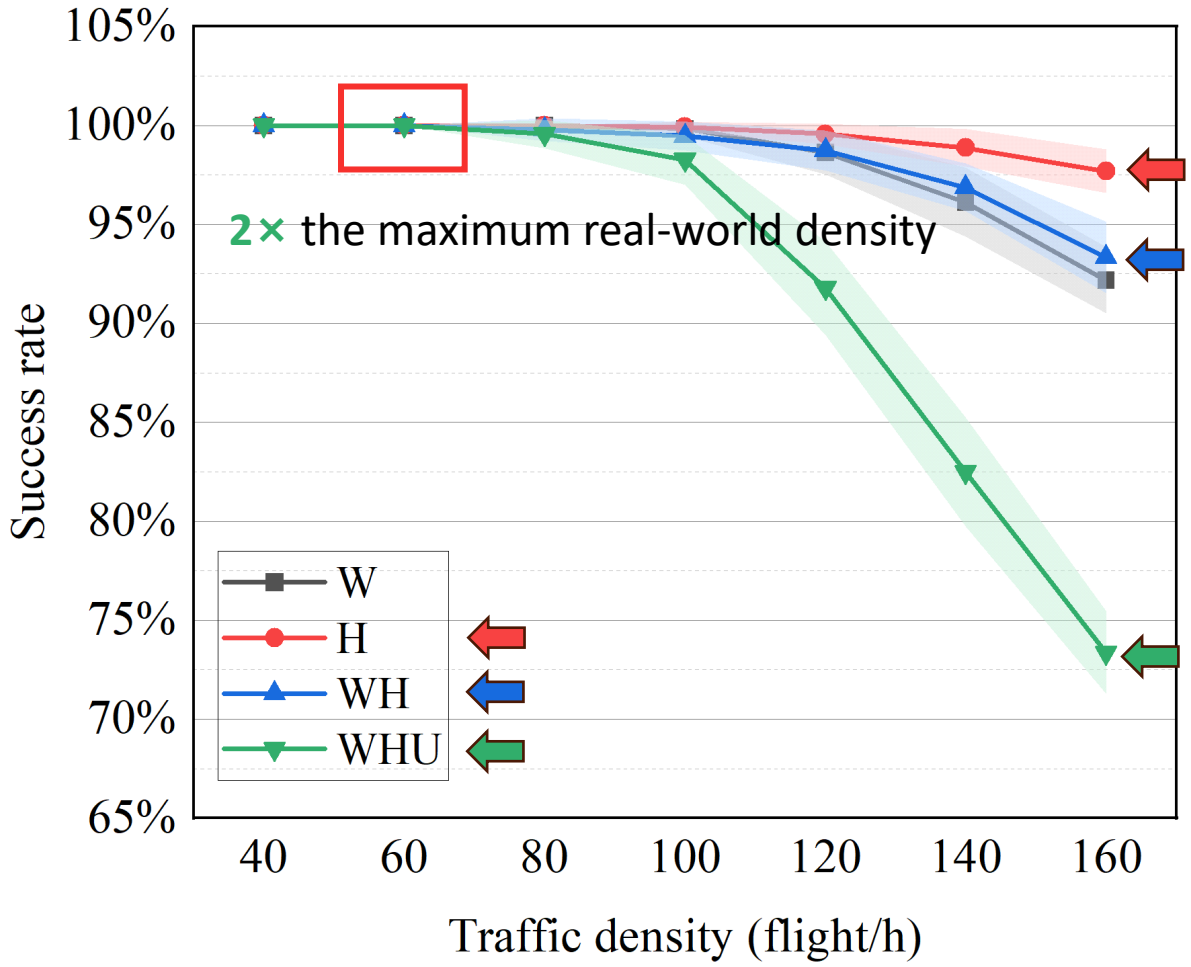
Workload constraint (W): Whether controller workload constraint is considered

Heuristic search (H): Whether heuristic search is adopted, otherwise global search is applied

Uncertainty (U): Whether the time uncertainty of human–machine and air–ground interactions is considered



Results: Success Rate



Larger solution space

Without controller workload constraint

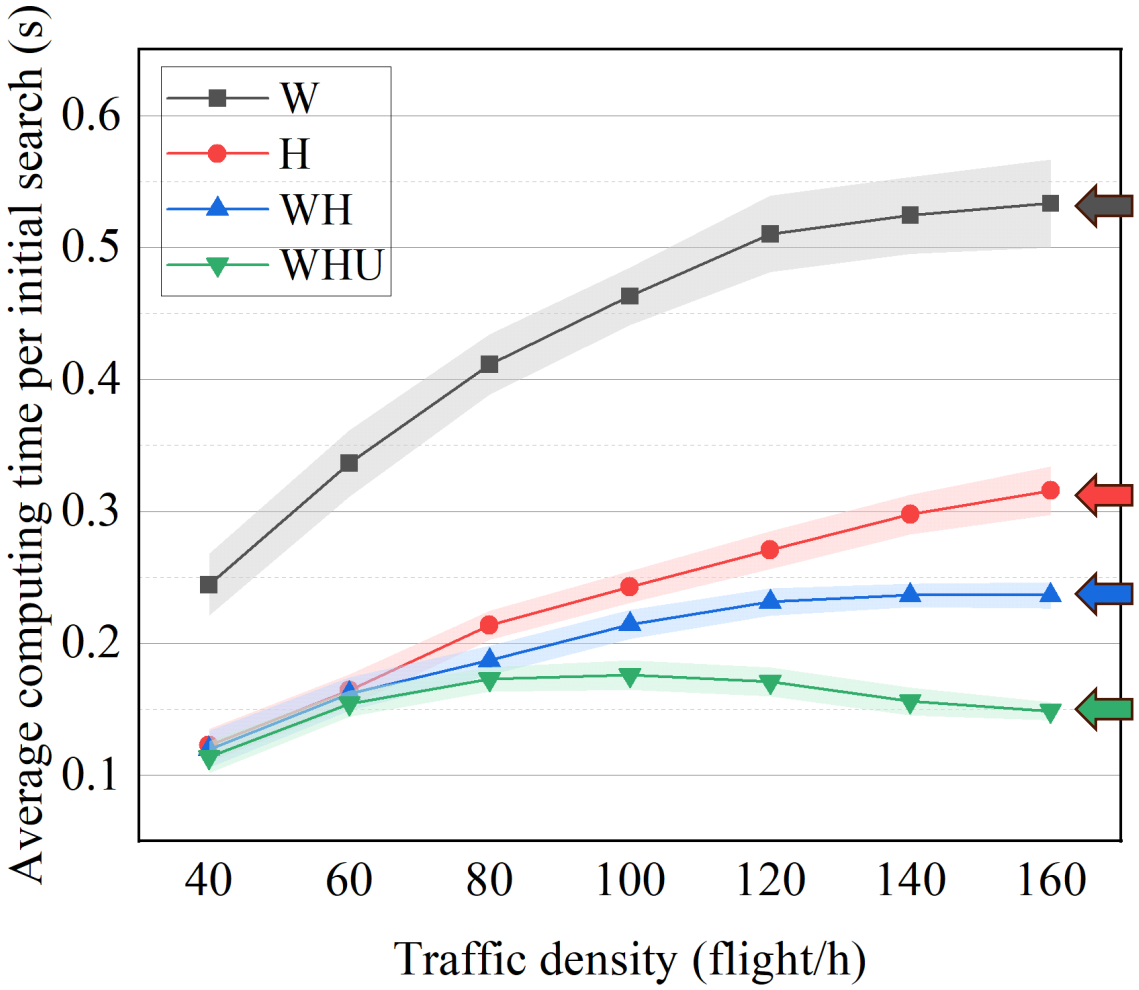
Without interaction time uncertainty

Longer reserved time windows, so smaller solution space

With interaction time uncertainty

- Without considering **workload constraint**, CDR methods can be overestimated
- Without considering **interaction time uncertainty**, CDR methods can be overestimated

Results: Computing Time



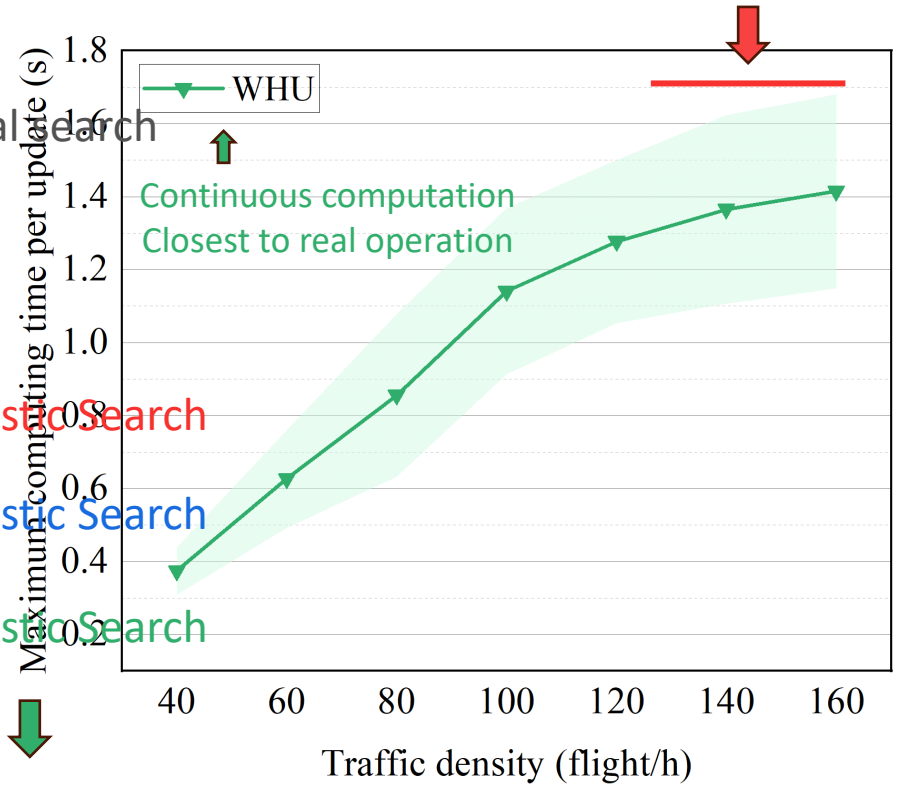
Global search

Heuristic Search

Heuristic Search

Heuristic Search

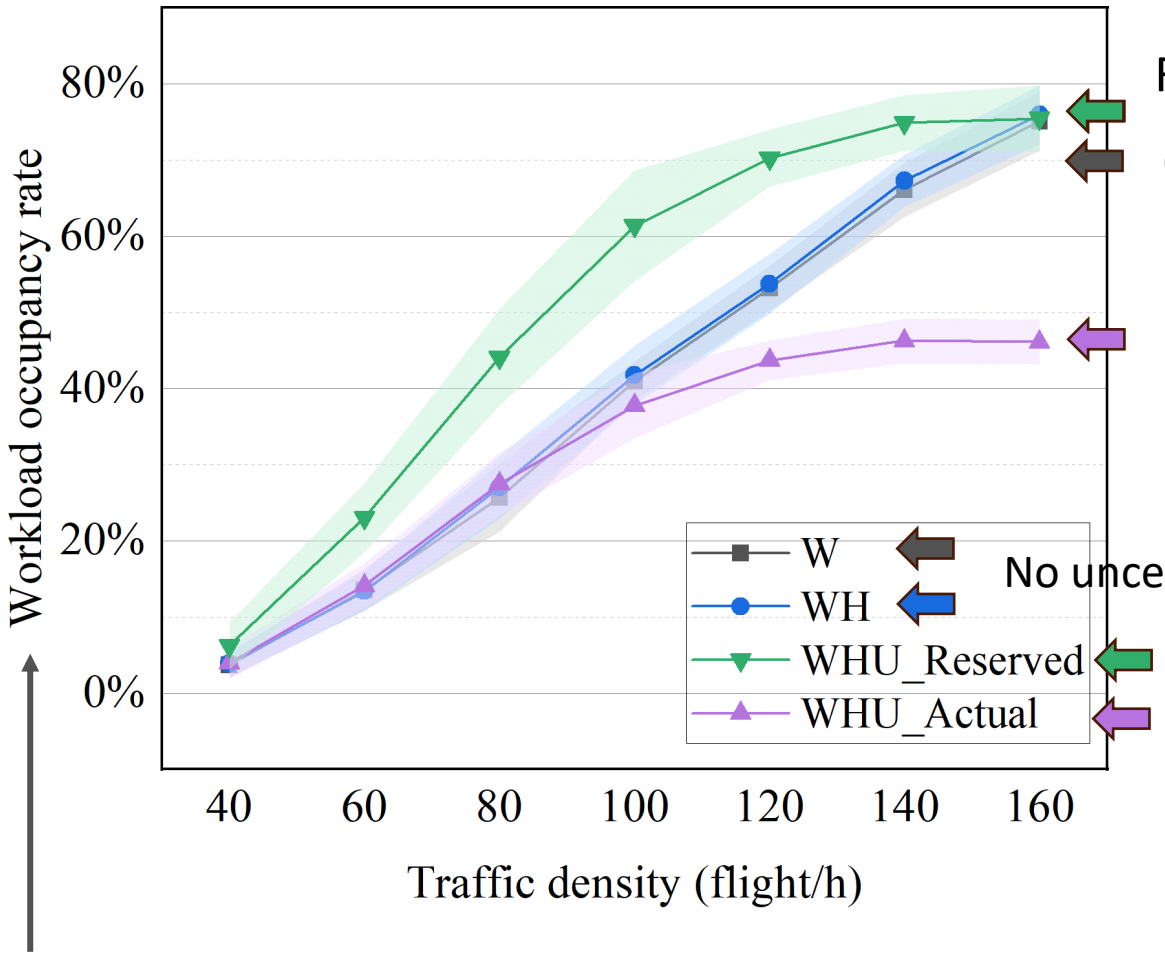
Advisory update interval: **5 s** vs. **1.7 s**



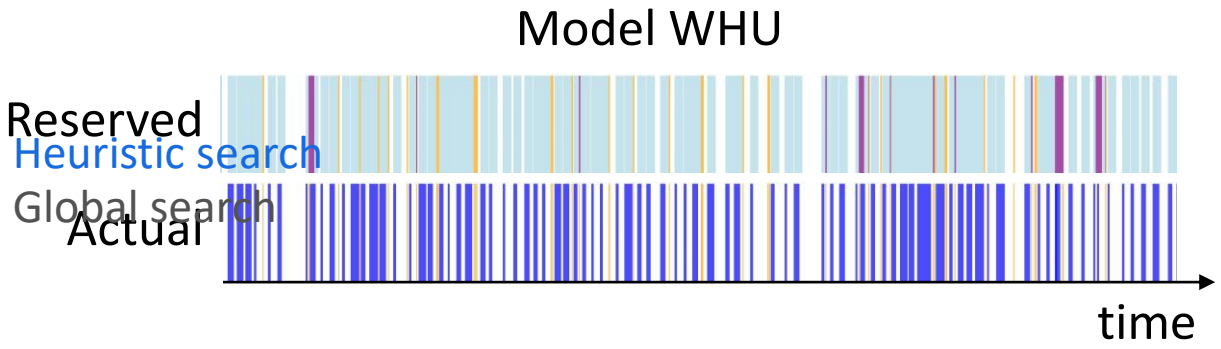
Uncertaitny -> longest reserved time windows -> fewest potential feasible solutions that need to be checked

- potential for **real-time operational** use

Results: Workload



proportion of the controller's timeline that is occupied by tasks



finishes a task earlier than expected ->
cannot dynamically shift the subsequent tasks forward

No uncertainty -> Reserved = Actual

Actual ≈ 2/3 Reserved

- Search method has **little impact** on workload
- Need to make the workflow framework more **flexible**

Summary

Conclusion

- Proposed a CDR framework considering human–machine and air–ground interaction.
- Developed multi-scenario trajectory prediction with response-time uncertainty.
- Designed a robustness-aware optimization and heuristic search.
- Demonstrated feasibility and high success rate in fast-time simulations.

Future Work

- Improve workflow flexibility to better utilize controller free time.
- Conduct full sensitivity analysis on objective-weight settings.
- Extend the simulator into an interactive HMI for human-in-the-loop experiments.
- Scale up experiments to more complex multi-flight-level and multi-sector scenarios.

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