RÉPUBLIQUE
FRANÇAISE
Liberté
Égalité
Fraternité

ONERA
THE FRENCH AEROSPACE LAB

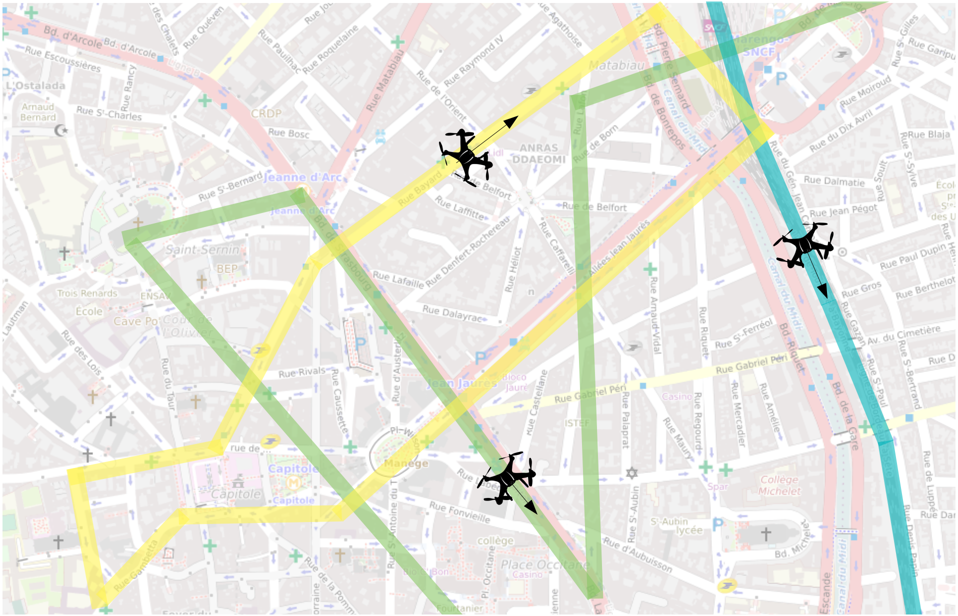
Coordination de trajectoires 4D par optimisation distribuée dans la gestion du trafic aérien sans pilote

Gauthier Picard
`gauthier.picard@onera.fr`

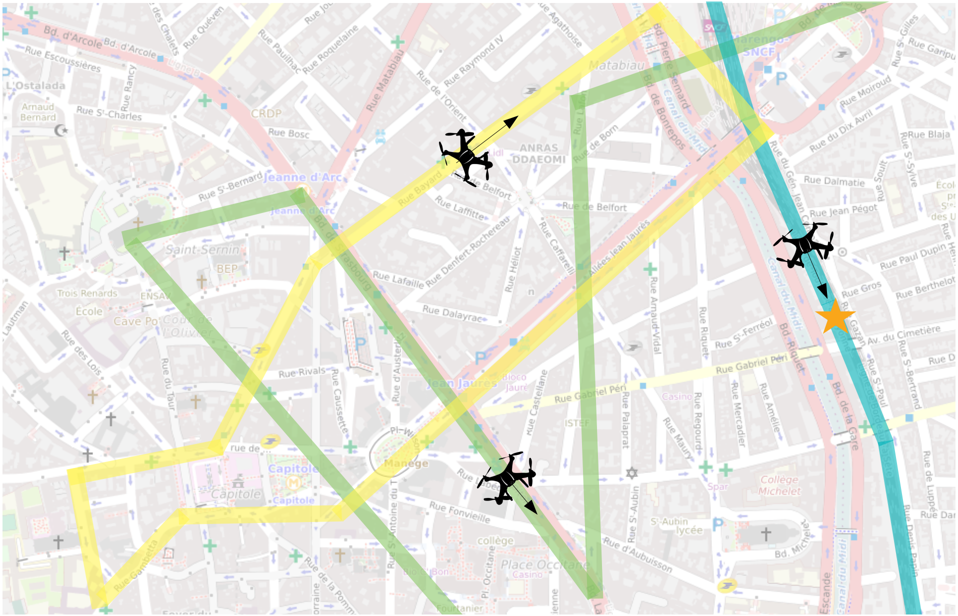
JFSMA'22 — 27 juin 2022

ONERA, DTIS-SYD, Université de Toulouse

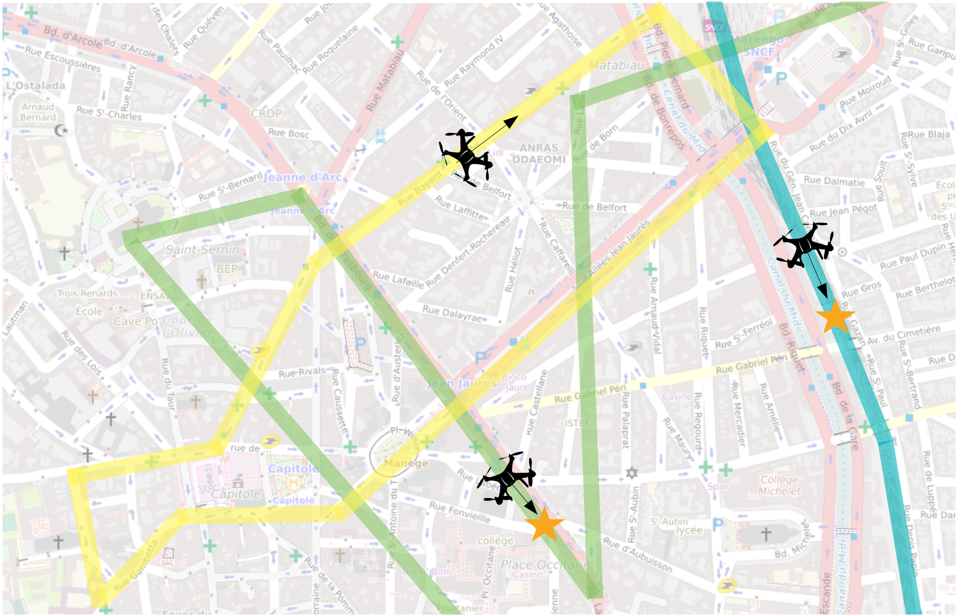
Illustrative Scenario: Urban UTM



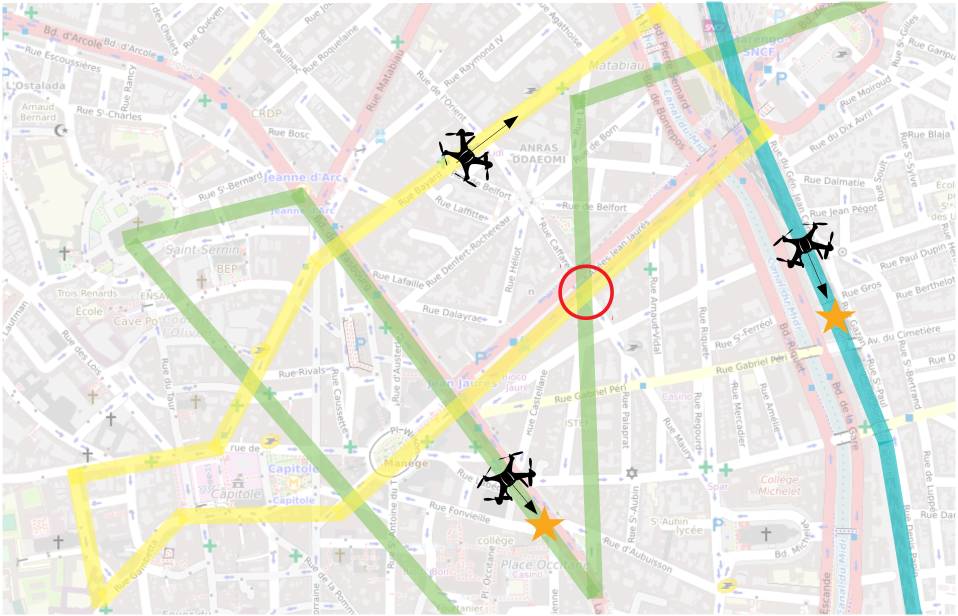
Illustrative Scenario: Urban UTM



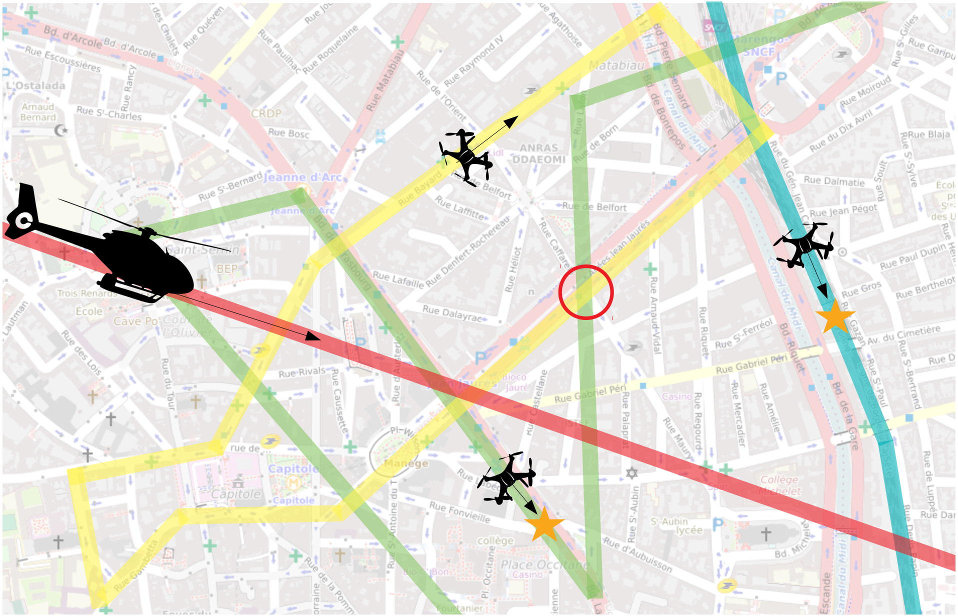
Illustrative Scenario: Urban UTM



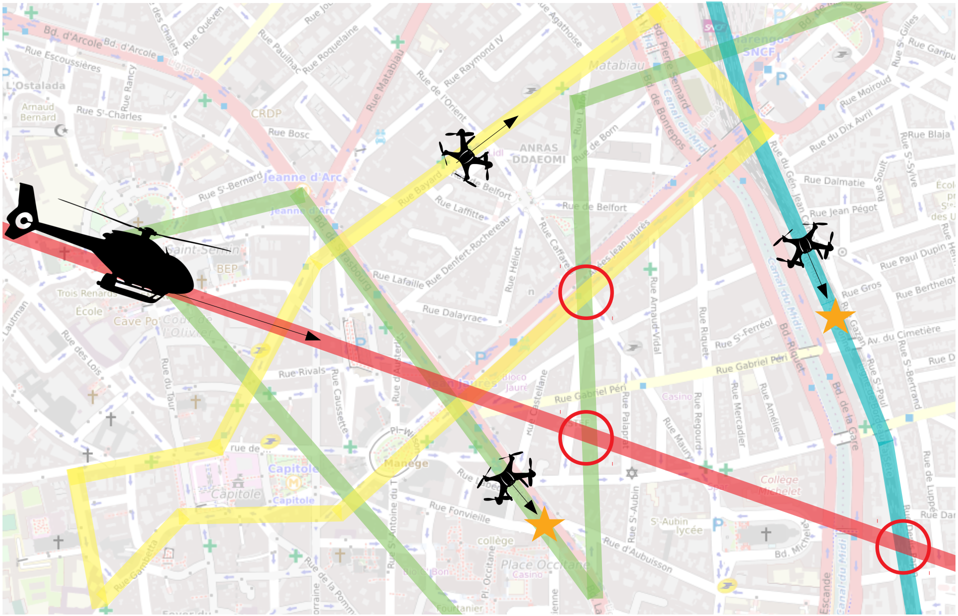
Illustrative Scenario: Urban UTM



Illustrative Scenario: Urban UTM

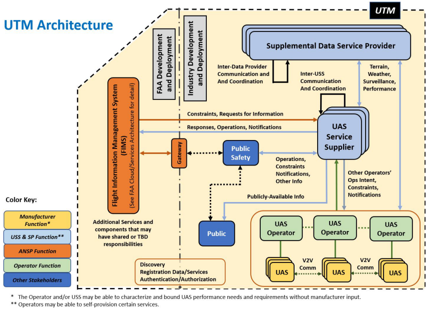


Illustrative Scenario: Urban UTM



Unmanned Traffic Management

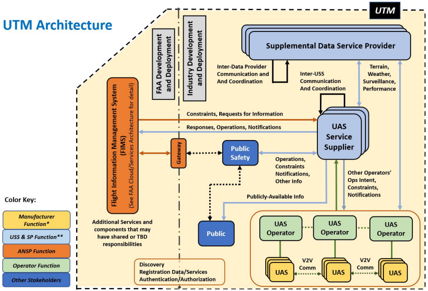
- **Concepts of operations** are still work in progress [Federal Aviation Agency, 2020; SESAR, 2019]
- Youssef Hamadi identified several **challenging optimization problems** [Hamadi, 2020]



Unmanned Traffic Management

- **Concepts of operations** are still work in progress [Federal Aviation Agency, 2020; SESAR, 2019]
- Youssef Hamadi identified several **challenging optimization problems** [Hamadi, 2020]

UTM Architecture



* The Operator and/or USS may be able to characterize and bound UAS performance needs and requirements without manufacturer input.
** Operators may be able to self-provision certain services.

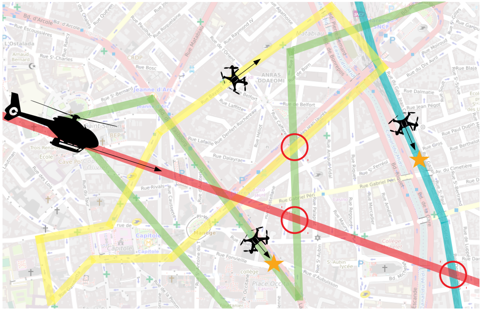
Our focus: 4D trajectory repair

- **Free Route** Airspace
- Decisions at the **UAS level**
- UAVs can directly exchange information via **V2V communication**
- Tactical and reactive **coordination mechanisms** between several (semi-)autonomous UAS
- Focus on small UAVs able to perform **stationary flight** and operating at low altitude (between 0m and 300m)

Core Concepts

- UAV: $u = (p, s, d, W)$
  - $p = (x, y, z, t) \in \mathbb{R}^4$
  - $s = (h, v, a) \leq (h_{max}, v_{max}, a_{max}) \in \mathbb{R}^3$
  - $d \in [0, 2\Pi]$
- Trajectory/4D Contract: a set $W \subset \mathbb{R}^4$ of *4D points* $w = (x, y, z, t)$

  (We will only consider several planes separated by a constant height)
- Safety tube: $\tau = (h, v, t)$ is defined horizontally, vertically and timely
- Conflict: when two trajectores expended by their safety tubes intersect spacially and timely



Building 4D Trajectories

- Classical **operational optimization problem**
- Very well studied in the context of aircraft traffic management [DELAHAYE et al., 2014; DELAHAYE and PUECHMOREL, 2013]
- Building conflict-free trajectories is a **hard optimization problem**
  - e.g. simulated annealing ISLAMI et al., 2017 or evolutionary algorithms [YAN and CAI, 2017]
- Small UAVs able to change direction and speed in a more flexible way than classical aircrafts, it's still hard
  - e.g. PSO [ALEJO et al., 2013] or multi-agent systems [ZHAO et al., 2020]
- Here, *unstructured*, **free route airspace**, contrary to usual ATM operational concepts [NAVA–GAXIOLA et al., 2018]

Repairing 4D Trajectories

We focus on the **repair procedure**; not the generation of the initial set of trajectories

Optimization criteria

1. *minimizing the number of conflicts* generated by the trajectory adaptation, as to ensure flight safety
2. *minimizing the number of missed way-points*, as to ensure the quality of the trajectories, especially in urban context, where trajectories are defined to fulfill some missions between and at these way-points
3. *minimizing the overall delay* induced by the adaptation

Such a problem is non-trivial and may require some **trade-off**; e.g. skipping conflicting segments improves safety but reduces quality of service

Deconfliction Actions and Behaviors

Conflicts consist in intersections on the same plane + UAVs can perform stationary flight
$\Rightarrow$ 3 main options are opened for updating the contracts

Atomic Repair Actions

- *postpone* : delay the next waypoints by a given duration
- *elevate* : create a bridge to avoid the conflict
- *skip* : bypass the waypoint just after the conflict

Deconfliction Actions and Behaviors

Conflicts consist in intersections on the same plane + UAVs can perform stationary flight
$\Rightarrow$ 3 main options are opened for updating the contracts

Atomic Repair Actions

- *postpone* : delay the next waypoints by a given duration
- *elevate* : create a bridge to avoid the conflict
- *skip* : bypass the waypoint just after the conflict

If a UAV decides alone of such action, it may generate not repair the trajectory properly wrt. our optimization criteria

Deconfliction Actions and Behaviors

Conflicts consist in intersections on the same plane + UAVs can perform stationary flight
$\Rightarrow$ 3 main options are opened for updating the contracts

Atomic Repair Actions

- *postpone* : delay the next waypoints by a given duration
- *elevate* : create a bridge to avoid the conflict
- *skip* : bypass the waypoint just after the conflict

If a UAV decides alone of such action, it may generate not repair the trajectory properly wrt. our optimization criteria

$\Rightarrow$ We need to install some coordination (and optimization)!

DCOP-based Coordination

- UAVs choose between several deconfliction actions when a conflict is detected
- UAVs involved in the same conflict coordinate to choose the best action using a DCOP

Definition

A DCOP is a tuple $\langle \mathcal{A}, \mathcal{X}, \mathcal{D}, \mathcal{C}, \mu \rangle$, where

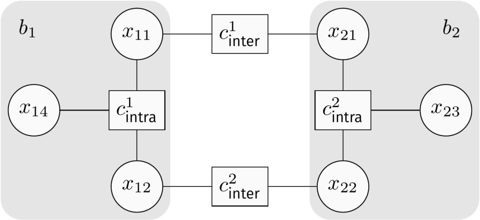
- $\mathcal{A} = \{a_1, \dots, a_{|A|}\}$ is a set of agents
- $\mathcal{X} = \{x_1, \dots, x_n\}$ are variables owned by the agents
- $\mathcal{D} = \{\mathcal{D}_{x_1}, \dots, \mathcal{D}_{x_n}\}$ is a set of finite domains
- $\mathcal{C} = \{f_1, \dots, f_m\}$ is a set of soft constraints, where each f_i defines a cost $\in \mathbb{R}^+ \cup \{+\infty\}$ for each combination of assignments to a subset of variables
- $\mu : \mathcal{X} \rightarrow \mathcal{A}$ maps variables to their associated agent function, representing the global cost of a complete variable assignment

DCOP-based Coordination (cont.)

- The optimization objective is represented by a function f, which, in general, is considered as the sum of costs: $f = \sum_i f_i$
- A *solution* to a DCOP P is a complete assignment to all variables
- A solution is *optimal* if it minimizes f

DCOP have been widely studied and applied to many areas [FIORETTO et al., 2018]

DCOP solution methods implement direct message passing



Solving Conflicts with DCOP

- $\mathcal{A} \subseteq U$ is the set of UAVs that have been alerted by a *conflict detection service*
- Each u is aware of its conflicts $C(u)$ and the other UAVs it is in conflict with, $U(C(u)) = \{v \in U \mid v \neq u, C(u) \cap C(v) \neq \emptyset\}$
- For a given conflict c, u is able to perform some deconfliction actions; e.g. $\mathsf{postpone}(c, 20)$, $\mathsf{elevate}(c, -15)$, $\mathsf{elevate}(c, +15)$ and $\mathsf{skip}(c)$
(we note $\mathcal{I}$ this set of actions)
- The decisions consist in choosing the deconfliction action to trigger for each known conflict
- $x_{u,c,i} \in \{0, 1\}$ states whether UAV u decides to solve conflict c using action i

Thus,

- $\mathcal{X} = \{x_{u,c,i} \mid u \in \mathcal{A}, c \in C(u), i \in \mathcal{I}\}$
- $\mathcal{D} = \{d_{x_{u,c,i}} = \{0, 1\} \mid u \in \mathcal{A}, c \in C(u), i \in \mathcal{I}\}$
- $\mu : x_{u,c,i} \mapsto u$

Solving Conflicts with DCOP (cont.)

Constraints fall into two categories: unary costs (preferences for actions), and coordination constraints

- Preferences for actions generating less conflicts without decreasing the quality of service (i.e. increasing the number of missed way-points), and delaying the mission

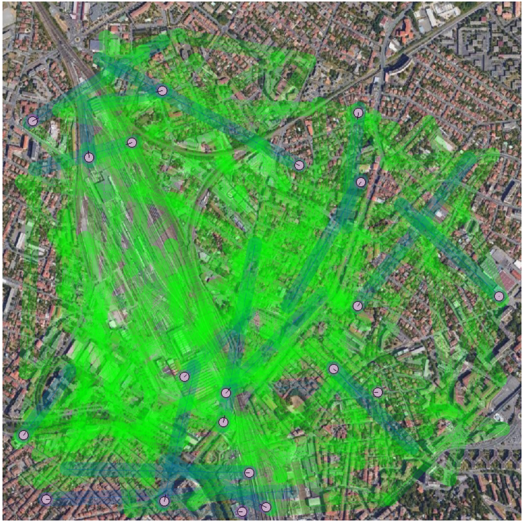
$$f_{\text{pref}}(x_{u,c,i}) = \omega^2 \cdot v_{\text{conflict}}(i, c) + \omega \cdot v_{\text{missed}}(i, c) + v_{\text{delay}}(i, c) \qquad (1)$$

- We must ensure exactly one $x_{i,c,u}$ variable is set to 1 for the same conflict:

$$\sum_{u \in U} \sum_{i \in \mathcal{I}} x_{i,c,u} = 1 \qquad (2)$$

The objective is the sum of all these constraints, i.e. optimization criteria + coordination

Experimental Evaluation



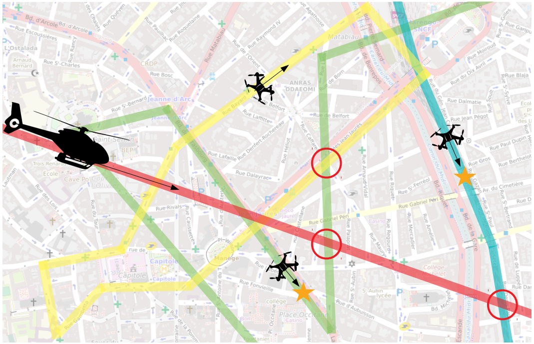
Environment

- We consider an area of 2km by 2km, with vertical airspace planes at 20m, 40m and 60m
- We consider $h_{max} = 18m.s^{-1}$, $v_{max} = 6m.s^{-1}$, $a_{max} = \Pi/2rad.s^{-1}$, $\Delta h_{\max} = \Delta v_{\max} = 6m.s^{-2}$, $\Delta a_{\max} = \Pi/2rad.s^{-2}$
- Initial speed is set to $(0, 0, 0)$
- Initial UAV trajectories are randomly generated with 60 way-points
- Safety tubes are defined by $(h, v, t) = (30, 15, 1)$
- Number of UAVs in $\{5, 10, 15, 20, 25\}$

Experimental Evaluation (cont.)

Unpredictable events

- 3 emergency trajectories
- each simulated second there is also a 1% chance an incident occurs close to a randomly chosen UAV



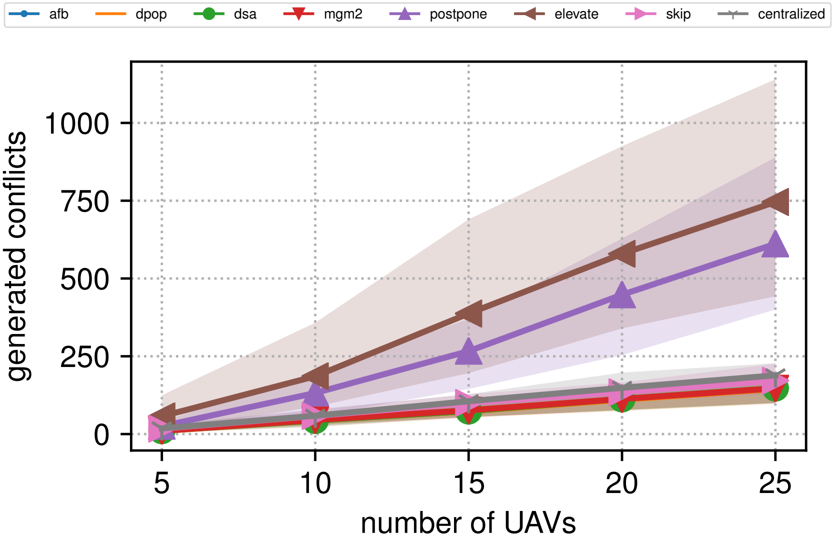
Experimental Evaluation (cont.)

Behaviors

- postpone: UAVs only perform a $\mathsf{postpone}(c, 20)$ action when a conflict is identified
- elevate: UAVs only perform $\mathsf{elevate}(c, \pm 15)$ actions, depending on their current plane, when a conflict is identified
- skip: UAVs only perform $\mathsf{skip}(c)$ action when a conflict is detected
- afb [Gershman et al., 2006], dpop [Petcu and Faltings, 2005], maxsum (perturbed) [Farinelli et al., 2008], dsa (variant C) [Zhang et al., 2005], mgm2 [Maheswaran et al., 2004]: UAVs perform a coordinated and adaptive decision using a DCOP algorithm to deconflict, that opt between $\mathsf{postpone}(c, d)$ with $d \in \{20, 40, 60\}$, $\mathsf{elevate}(c, \pm 15)$ and $\mathsf{skip}(c)$
- centralized: tree-search based algorithm computing the optimal sequence of repair actions

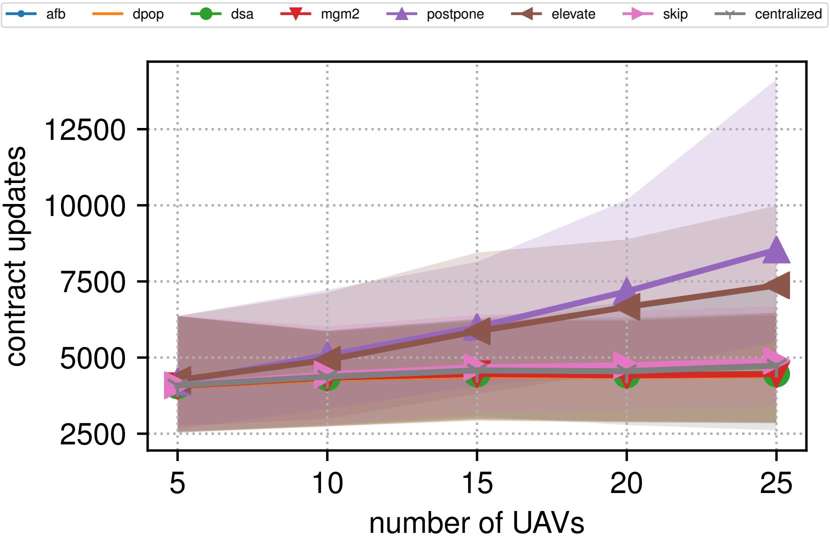
Result Analysis

Without coordination, numerous conflicts and/or some violations



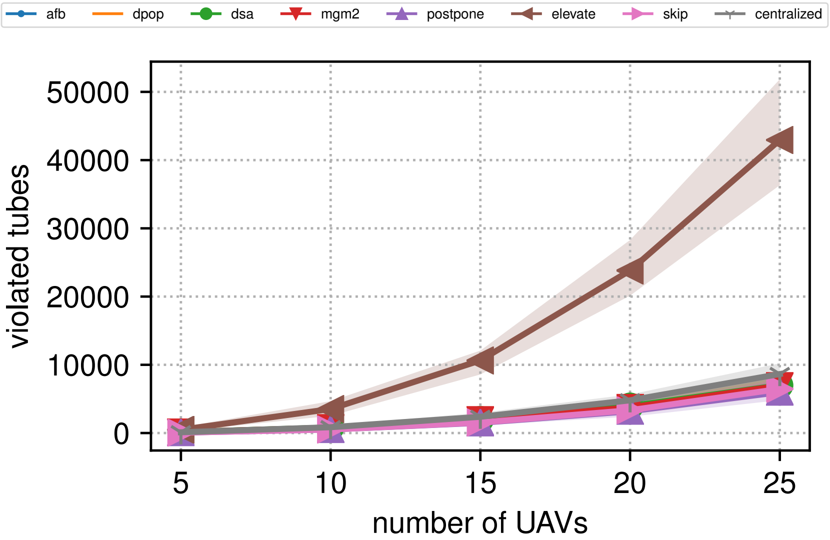
Result Analysis

Without coordination, numerous conflicts and/or some violations



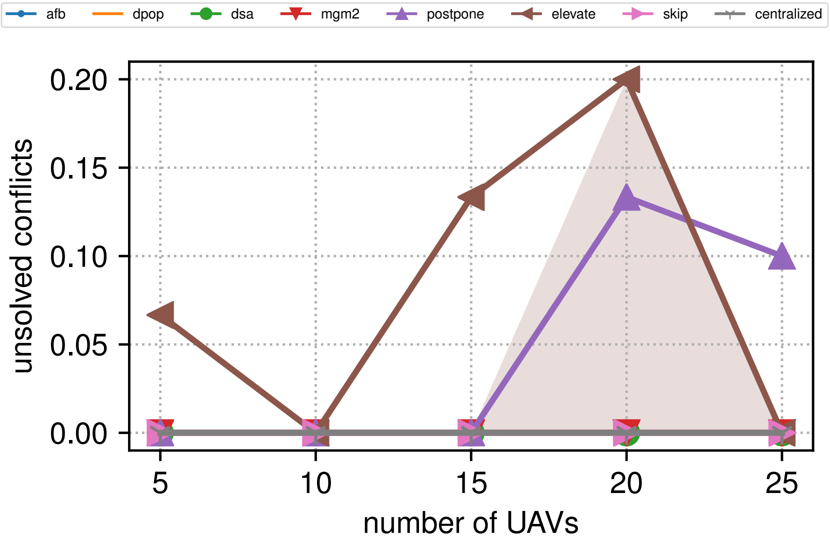
Result Analysis

Without coordination, numerous conflicts and/or some violations



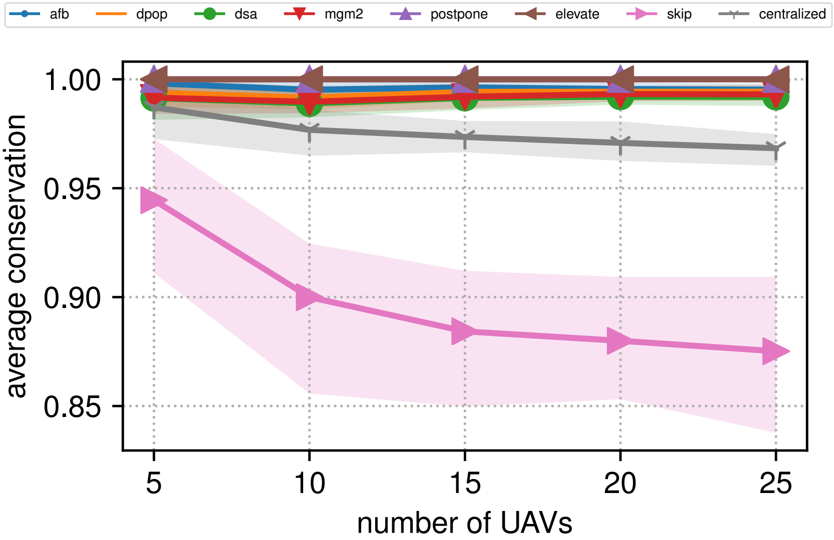
Result Analysis

Without coordination, numerous conflicts and/or some violations



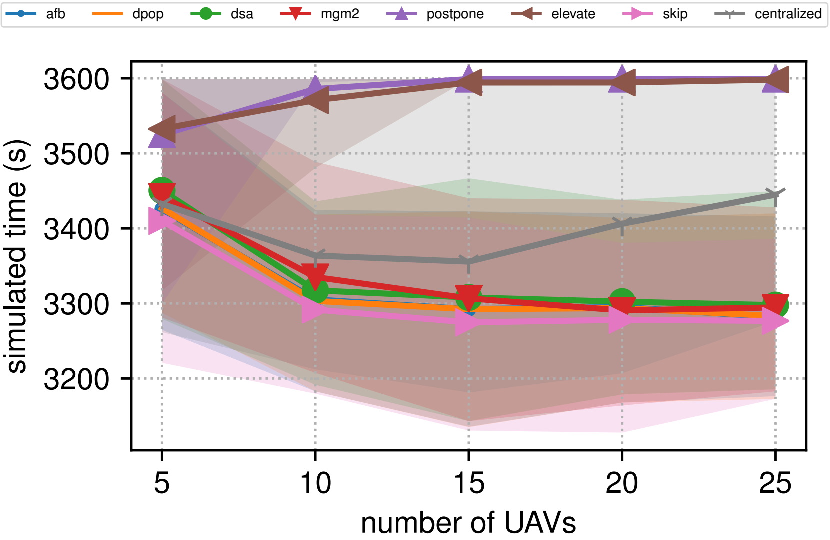
Result Analysis (cont.)

Without coordination, increased delays or reduced QoS



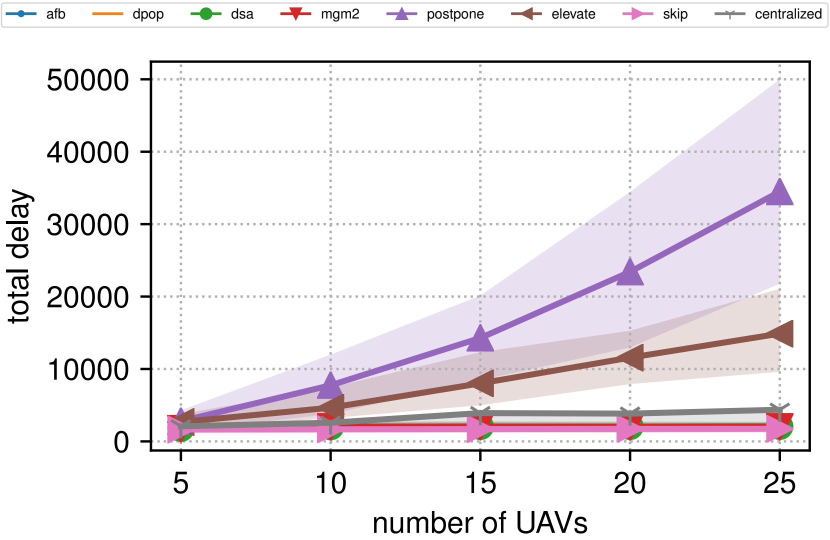
Result Analysis (cont.)

Without coordination, increased delays or reduced QoS



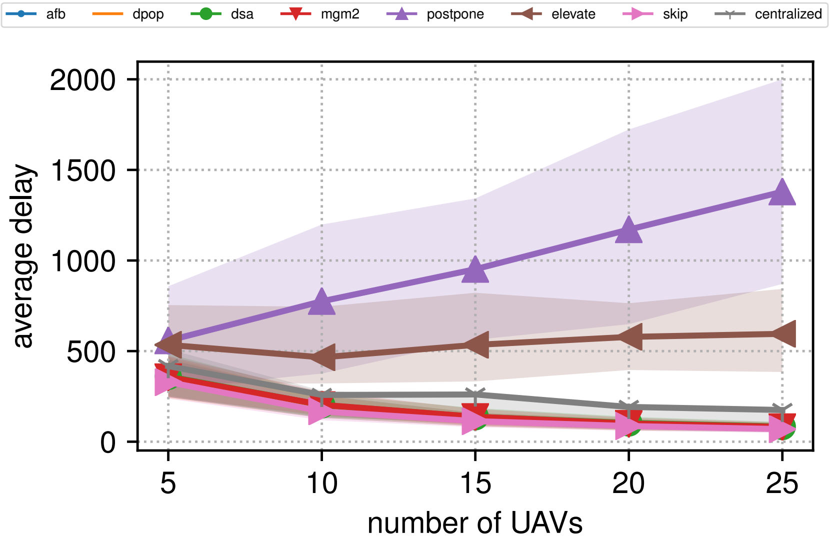
Result Analysis (cont.)

Without coordination, increased delays or reduced QoS



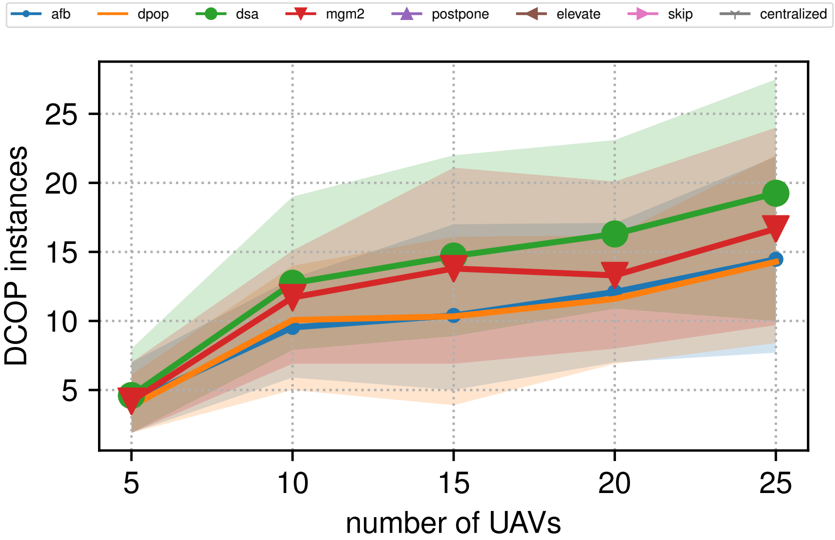
Result Analysis (cont.)

Without coordination, increased delays or reduced QoS



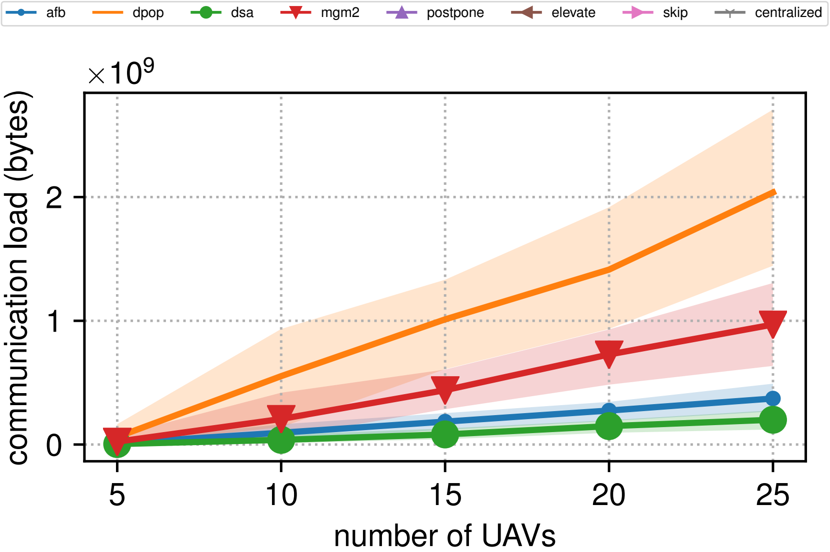
Result Analysis (cont.)

Coordination group size are small ⇒ communication/computation overload are limited



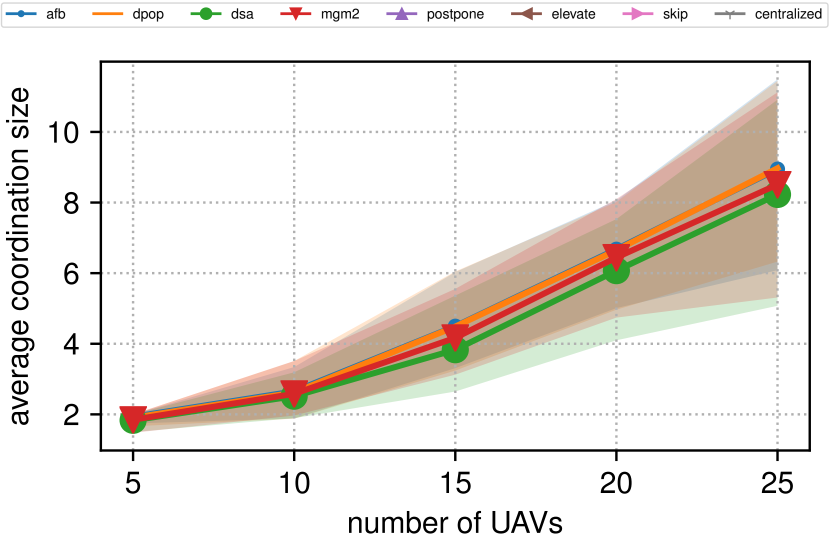
Result Analysis (cont.)

Coordination group size are small $\Rightarrow$ communication/computation overload are limited



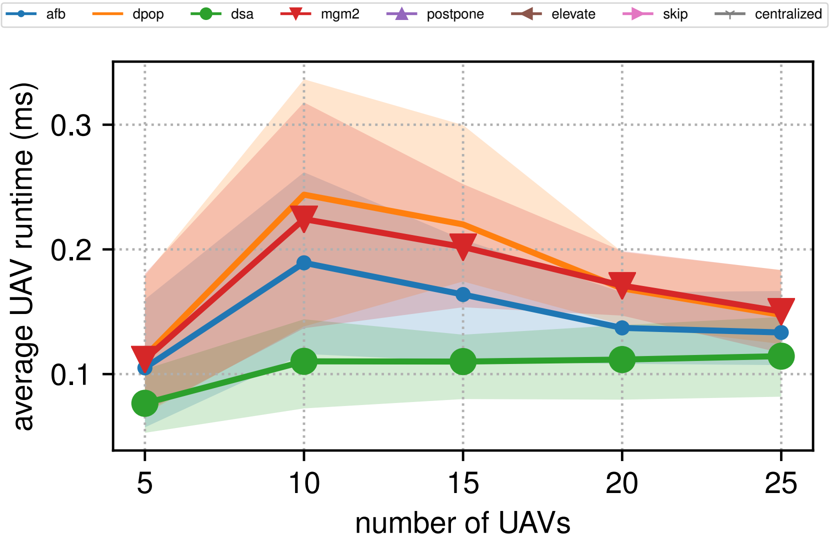
Result Analysis (cont.)

Coordination group size are small ⇒ communication/computation overload are limited

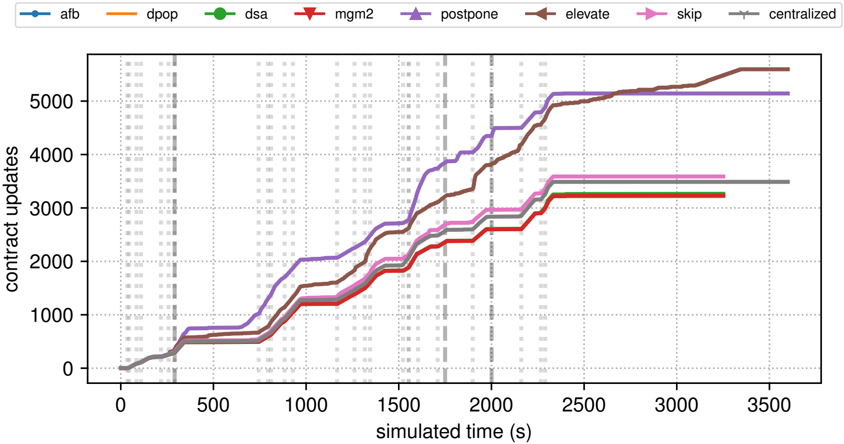


Result Analysis (cont.)

Coordination group size are small ⇒ communication/computation overload are limited

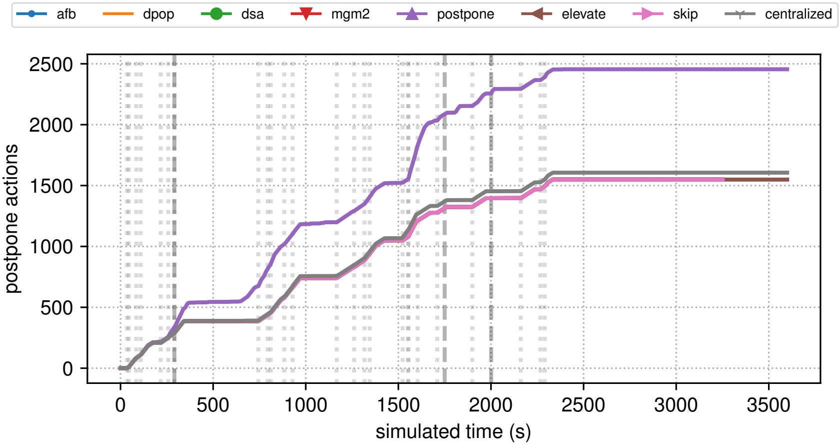


Result Analysis (cont.)
Focus on a specific instance

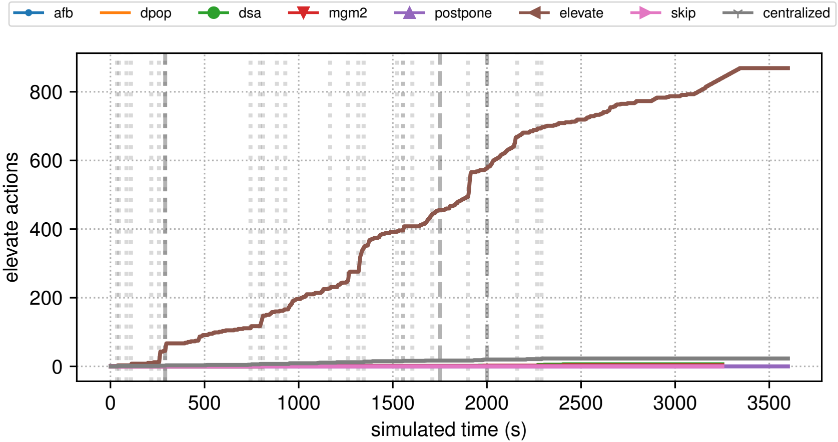


Result Analysis (cont.)

Focus on a specific instance

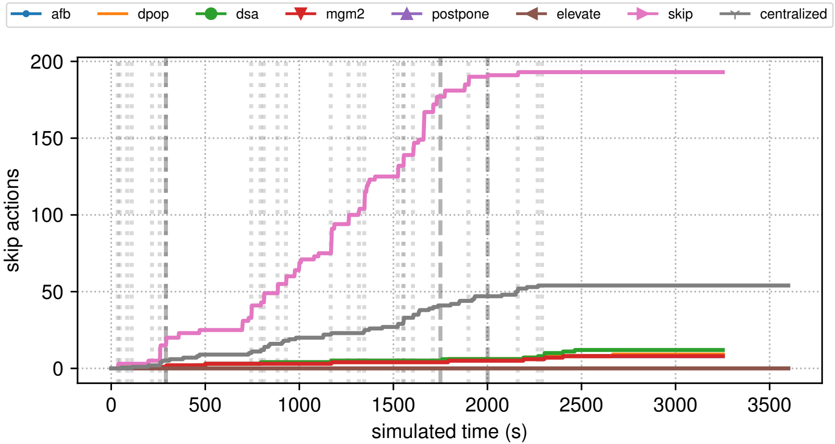


Result Analysis (cont.)
Focus on a specific instance



Result Analysis (cont.)

Focus on a specific instance



Summary

⚠ Very **stressing configuration**: UAVs have to constantly update their trajectories

Summary

- ⚠ Very **stressing configuration**: UAVs have to constantly update their trajectories
- ✗ postpone behavior is bad on two dimensions: **delays and conflicts**
- ✗ elevate behavior is a good candidate for trajectory conservation, but with **extra delays**
- ✗ skip generates few conflicts, at the expense of **missed way-points**

Summary

⚠ Very **stressing configuration**: UAVs have to constantly update their trajectories

✗ postpone behavior is bad on two dimensions: **delays and conflicts**

✗ elevate behavior is a good candidate for trajectory conservation, but with **extra delays**

✗ skip generates few conflicts, at the expense of **missed way-points**

✓ dcop is positioned as a **good compromise** between elevate and skip

- ✓ Almost equivalent to centralized solving quality
- ✓ Complete algorithm (e.g. abt) are better then incomplete ones
- ✗ but not robust to message loss...

Conclusion

Contributions

- We promoted and implemented a **multi-agent coordination** mechanism for UAVs
- Coordination is built upon a **DCOP protocol**, with several optimization criteria
- Using a coordinated and adaptive deconfliction, provides solutions with **reduced conflicts, missed way-points and accumulated delay**

⚠ Still, this coordination requires some **extra coordination communication messages** to be exchanged

Future Research

- Extension to more **structured airspaces** [BAURANOV and RAKAS, 2021; CAPITÁN et al., 2021]
- **Adapt DCOP solution methods** to our settings (e.g. MO-DCOPs)
- Devise **less communication intensive coordination** algorithms

RÉPUBLIQUE
FRANÇAISE
Liberté
Égalité
Fraternité

ONERA
THE FRENCH AEROSPACE LAB

Coordination de trajectoires 4D par optimisation distribuée dans la gestion du trafic aérien sans pilote

Gauthier Picard
gauthier.picard@onera.fr

JFSMA'22 — 27 juin 2022

ONERA, DTIS-SYD, Université de Toulouse

References

Alejo, D., J. A. Cobano, G. Heredia, and A. Ollero (2013). "Particle Swarm Optimization for collision-free 4D trajectory planning in Unmanned Aerial Vehicles". In: *2013 International Conference on Unmanned Aircraft Systems (ICUAS)*, pp. 298–307. DOI: 10.1109/ICUAS.2013.6564702.

Bauranov, Aleksandar and Jasenka Rakas (2021). "Designing airspace for urban air mobility: A review of concepts and approaches". In: *Progress in Aerospace Sciences* 125, p. 100726. ISSN: 0376-0421. DOI: https://doi.org/10.1016/j.paerosci.2021.100726. URL: https://www.sciencedirect.com/science/article/pii/S0376042121000312.

Capitán, Carlos, Héctor Pérez-León, Jesús Capitán, Ángel Castaño, and Aníbal Ollero (2021). "Unmanned Aerial Traffic Management System Architecture for U-Space In-Flight Services". In: *Applied Sciences* 11.9. ISSN: 2076-3417. DOI: 10.3390/app11093995. URL: https://www.mdpi.com/2076-3417/11/9/3995.

Delahaye, D., S. Puechmorel, P. Tsiotras, and E. Feron (2014). "Mathematical Models for Aircraft Trajectory Design: A Survey". In: *Air Traffic Management and Systems*. Tokyo: Springer Japan, pp. 205–247. ISBN: 978-4-431-54475-3.

Delahaye, Daniel and Stéphane Puechmorel (2013). *Front Matter*. John Wiley & Sons, Ltd. ISBN: 9781118743805. DOI: https://doi.org/10.1002/9781118743805.

Farinelli, A., A. Rogers, A. Petcu, and N. R. Jennings (2008). "Decentralised Coordination of Low-Power Embedded Devices Using the Max-Sum Algorithm". In: *Proceedings of the International Conference on Autonomous Agents and Multiagent Systems*. AAMAS 2008, pp. 639–646.

Federal Aviation Agency (2020). *UTM concept of operations version 2.0*. Technical Report. URL: https://www.faa.gov/uas/research_development/traffic_management/media/UTM_ConOps_v2.pdf.

Fioretto, F., E. Pontelli, and W. Yeoh (2018). "Distributed Constraint Optimization Problems and Applications: A Survey". In: *Journal of Artificial Intelligence Research* 61, pp. 623–698.

References (cont.)

GERSHMAN, Amir, Amnon MEISELS, and Roie ZIVAN (2006). "Asynchronous Forward-Bounding for Distributed Constraints Optimization". In: *ECAI 2006*. NLD: IOS, 103–107. ISBN: 1586036424.

HAMADI, Youssef (2020). "Optimization for Urban Air Mobility". In: *Learning and Intelligent Optimization*. Ed. by Ilias S. KOTSIREAS and Panos M. PARDALOS. Cham: Springer International Publishing, pp. 1–8. ISBN: 978-3-030-53552-0.

ISLAMI, Arianit, Supatcha CHAIMATANAN, and Daniel DELAHAYE (2017). "Large-Scale 4D Trajectory Planning". In: *Air Traffic Management and Systems II: Selected Papers of the 4th ENRI International Workshop, 2015*. Ed. by Electronic Navigation Research INSTITUTE. Tokyo: Springer Japan, pp. 27–47. ISBN: 978-4-431-56423-2. DOI: 10.1007/978-4-431-56423-2_2. URL: https://doi.org/10.1007/978-4-431-56423-2_2.

MAHESWARAN, R. T., J. P. PEARCE, and M. TAMBE (2004). "Distributed Algorithms for DCOP: A Graphical-Game-Based Approach.". In: *ISCA PDCS*, pp. 432–439.

NAVA–GAXIOLA, Cesar, Cristina BARRADO, and Pablo ROYO (2018). "Study of a Full Implementation of Free Route in the European Airspace*". In: *2018 IEEE/AIAA 37th Digital Avionics Systems Conference (DASC)*, pp. 1–6. DOI: 10.1109/DASC.2018.8569543.

PETCU, A. and B. FALTINGS (2005). "A scalable method for multiagent constraint optimization". In: *International Joint Conference on Artificial Intelligence (IJCAI'05)*, pp. 266–271.

SESAR (2019). *U-Space: Concept of Operations*. Tech. rep. SESAR Joint Undertaking.

YAN, SU and Kaiquan CAI (2017). "A multi-objective multi-memetic algorithm for network-wide conflict-free 4D flight trajectories planning". In: *Chinese Journal of Aeronautics* 30.3, pp. 1161–1173. ISSN: 1000-9361. DOI: https://doi.org/10.1016/j.cja.2017.03.008. URL: https://www.sciencedirect.com/science/article/pii/S1000936117300808.

ZHANG, W., G. WANG, Z. XING, and L. WITTENBURG (2005). "Distributed Stochastic Search and Distributed Breakout: Properties, Comparison and Applications to Constraint Optimization Problems in Sensor Networks". In: *Artificial Intelligence* 161.1–2, 55–87. ISSN: 0004-3702.

References (cont.)

Zhao, Wenjie, Zhou Fang, and Zuqiang Yang (2020). "Four-Dimensional Trajectory Generation for UAVs Based on Multi-Agent Q Learning". In: *Journal of Navigation* 73.4, 874–891. DOI: 10.1017/S0373463320000016.