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Trajectory Coordination based on Distributed Constraint Optimization Techniques in Unmanned Air Traffic Management

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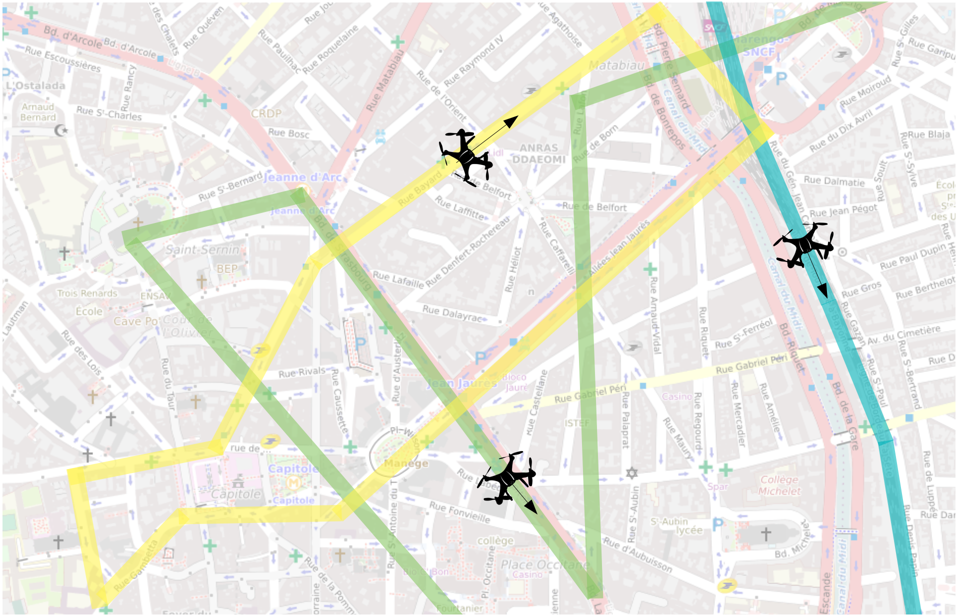
AAMAS'22 — May 11th, 2022

ONERA, DTIS-SYD, Université de Toulouse

Illustrative Scenario: Urban UTM



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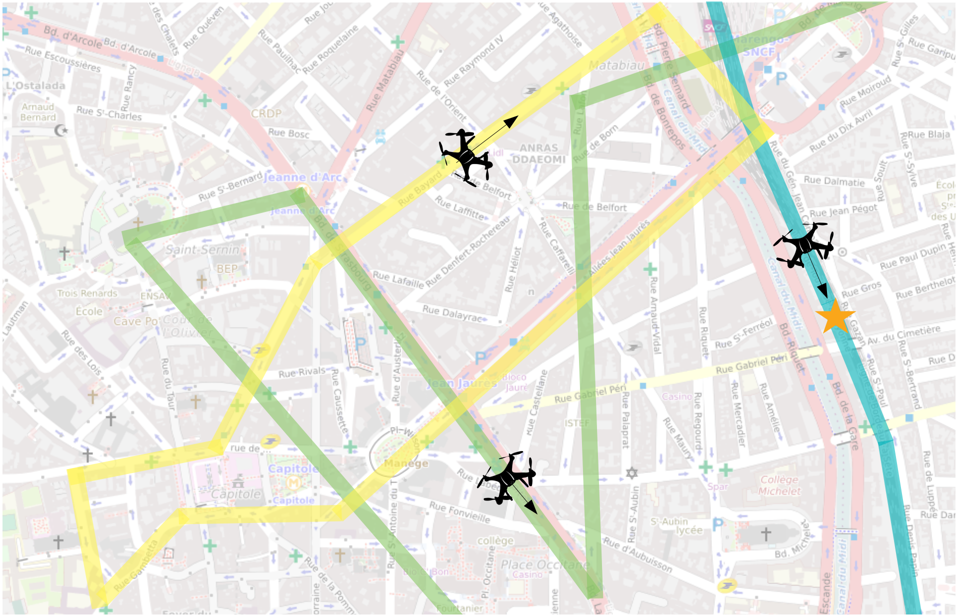

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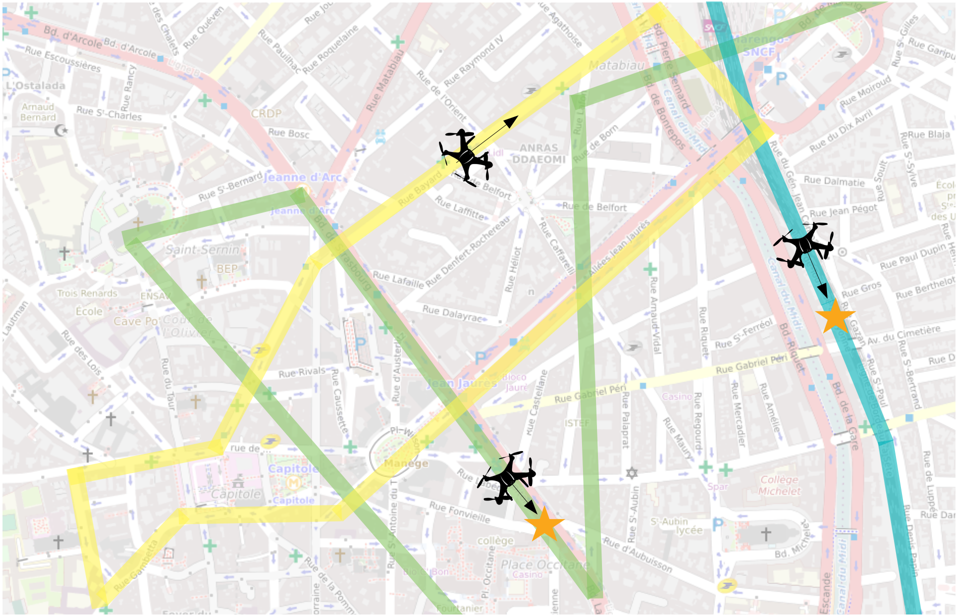

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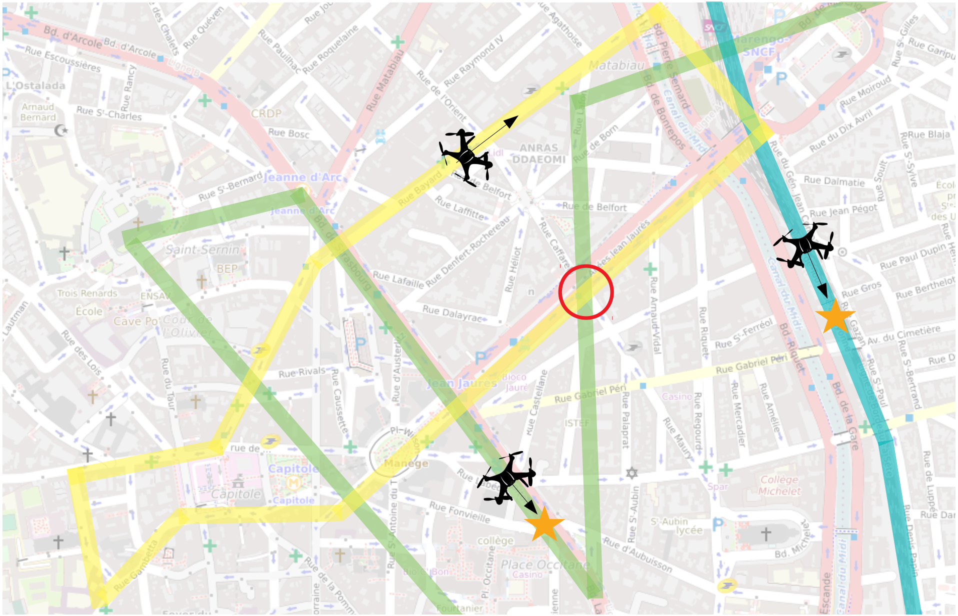

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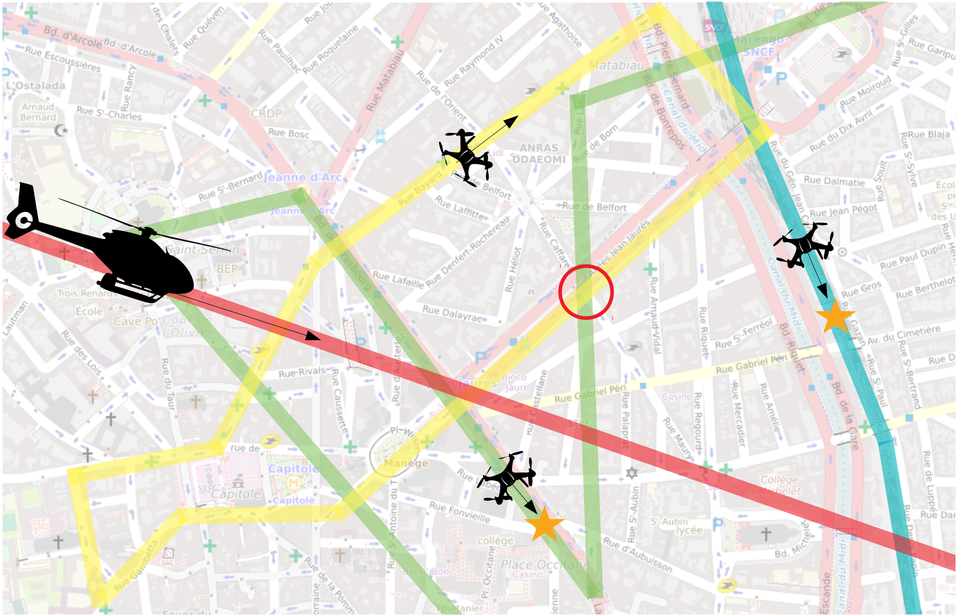

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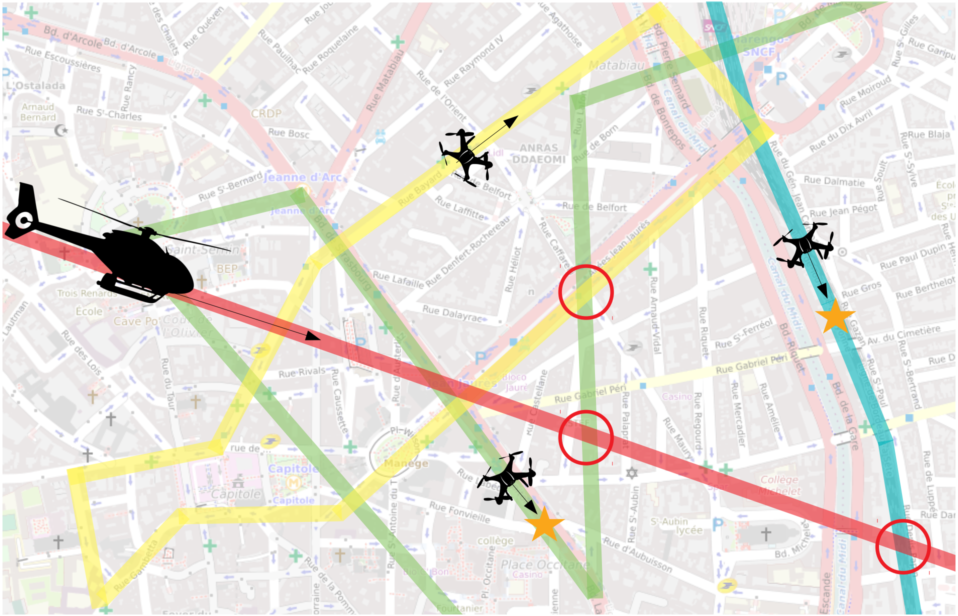
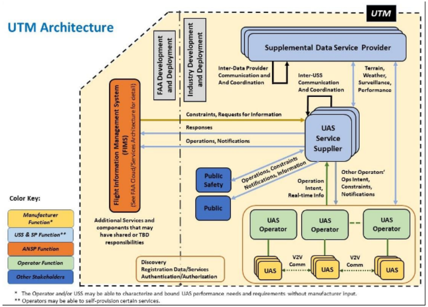


Unmanned Traffic Management

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



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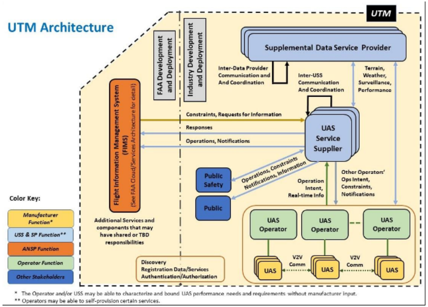


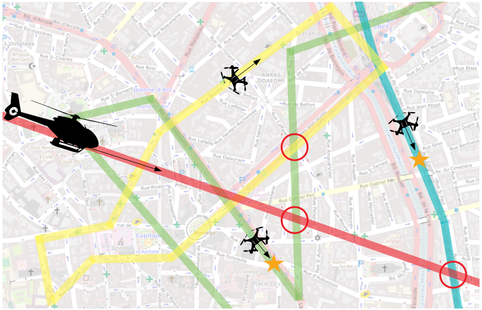
Our focus: 4D trajectory repair

- **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

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$\Rightarrow$ 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

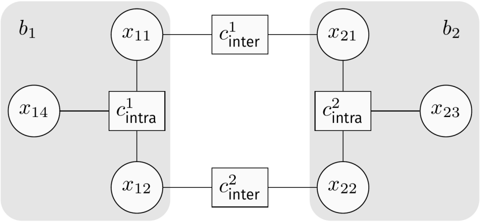
- $\mathcal{A} = \{a_1, \ldots, a_{|A|}\}$ is a set of agents
- $\mathcal{X} = \{x_1, \ldots, x_n\}$ are variables owned by the agents
- $\mathcal{D} = \{\mathcal{D}_{x_1}, \ldots, \mathcal{D}_{x_n}\}$ is a set of finite domains
- $\mathcal{C} = \{f_1, \ldots, f_m\}$ is a set of soft constraints, where each f_i defines a cost $\in \mathbb{R}^+ \cup \{+\infty\}$ for each combination of assignments to a subset of variables
- $\mu : \mathcal{X} \to \mathcal{A}$ 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 $\mathsf{skip}(\mathsf{c})$
  (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

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

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

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

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

Experimental Evaluation

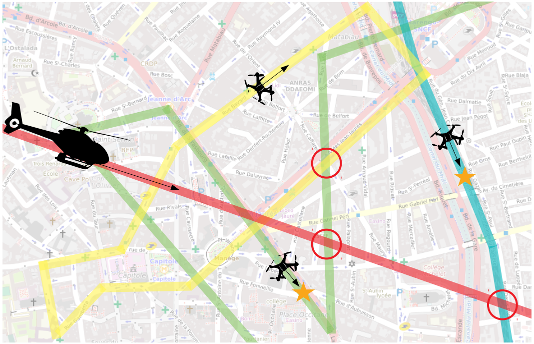
Environment

- 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



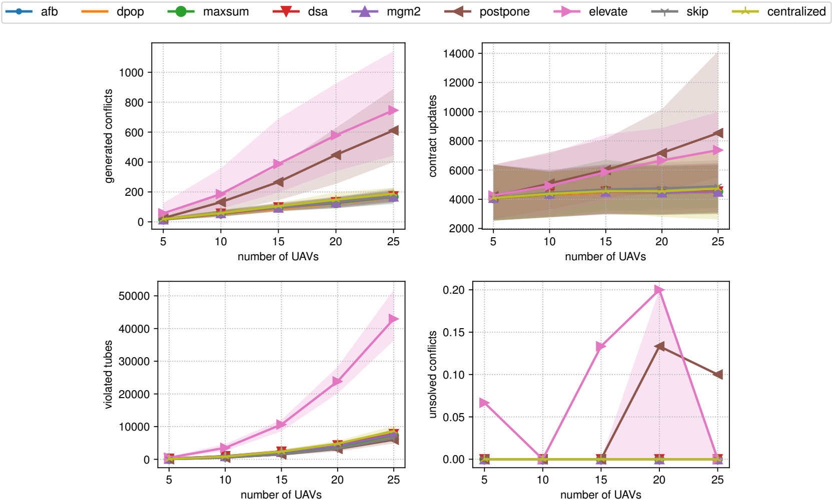
Experimental Evaluation (cont.)

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

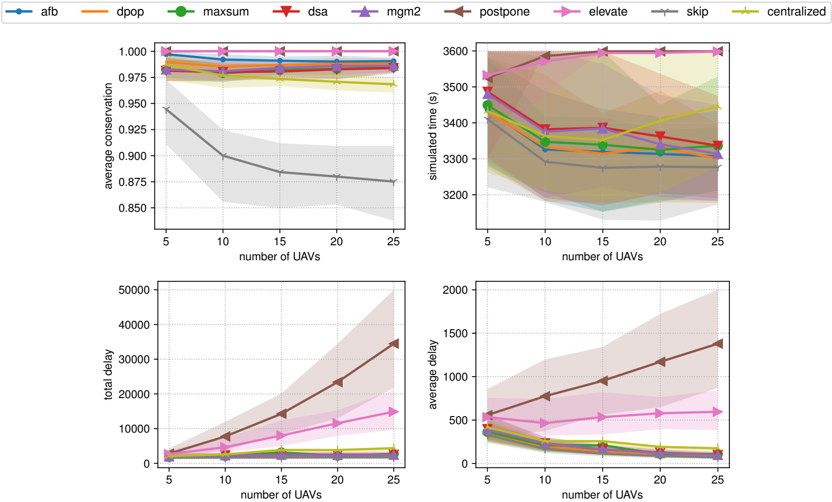
Result Analysis

Without coordination, numerous conflicts and/or some violations



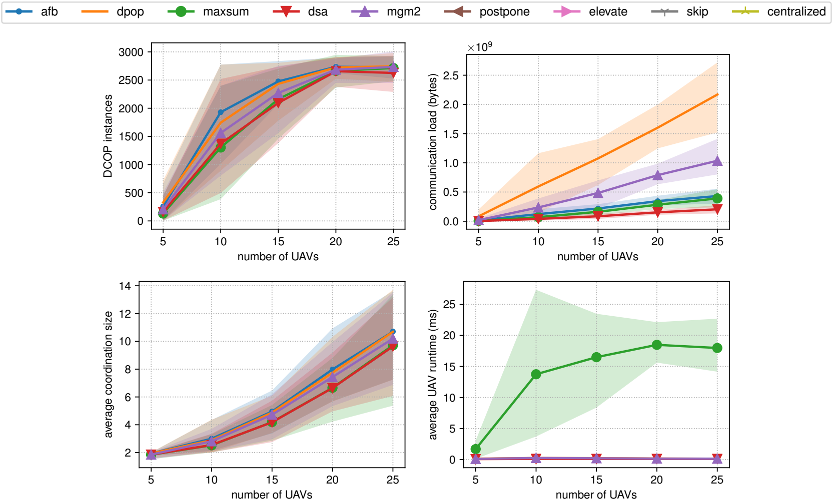
Result Analysis (cont.)

Without coordination, increased delays or reduced QoS



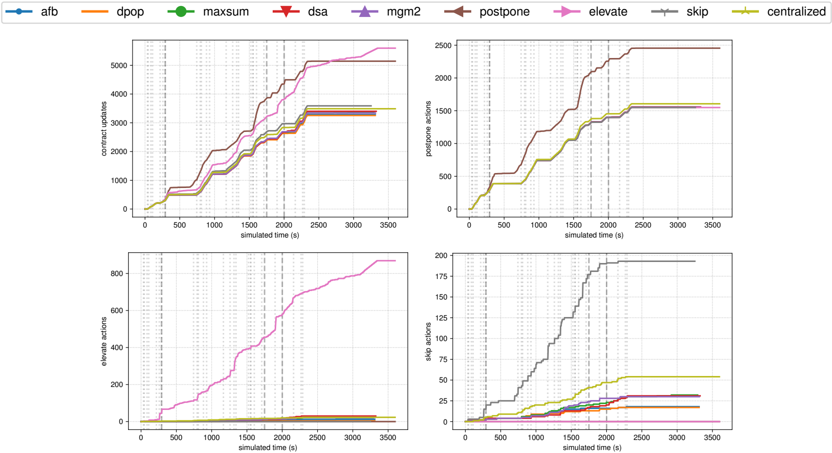
Result Analysis (cont.)

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



Result Analysis (cont.)

Focus on a specific instance



Summary

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- ✗ 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**

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✗ 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

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