

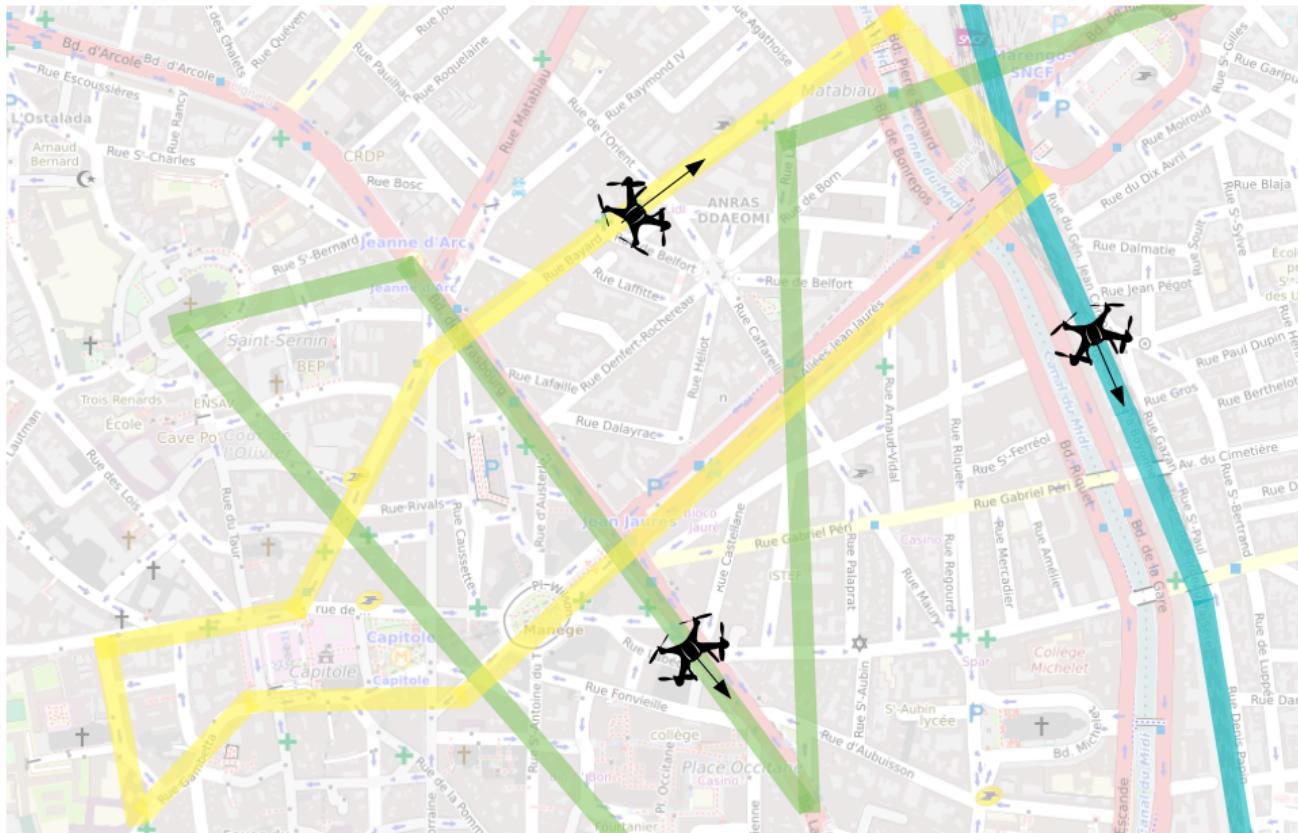
Résolution multicritère socialement acceptable du problème de réparation des contrats 4D dans le cadre de la gestion du trafic aérien sans pilote

Youssef Hamadi¹ Gauthier Picard²

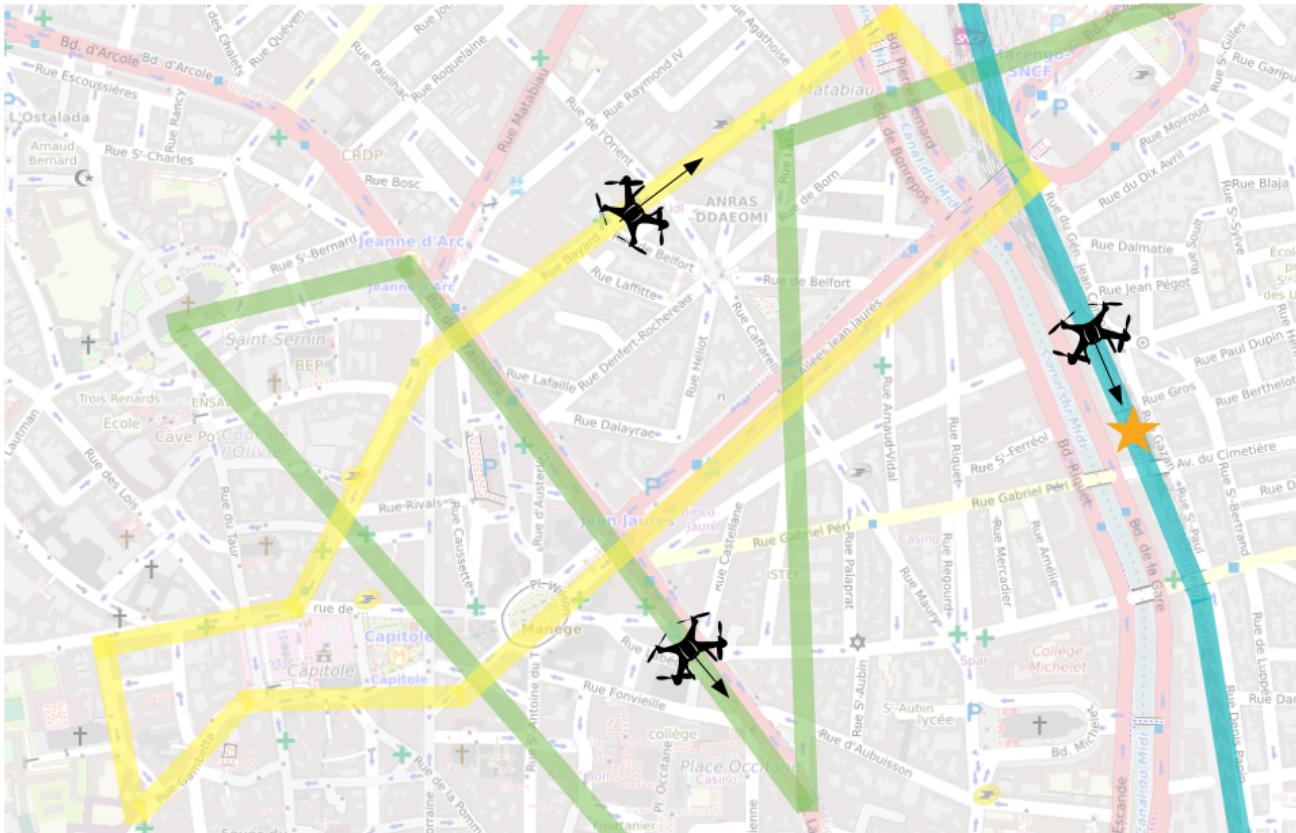
Journée Agents et IA à PFIA'24

¹Tempero, France ²DTIS, ONERA, Université de Toulouse, France

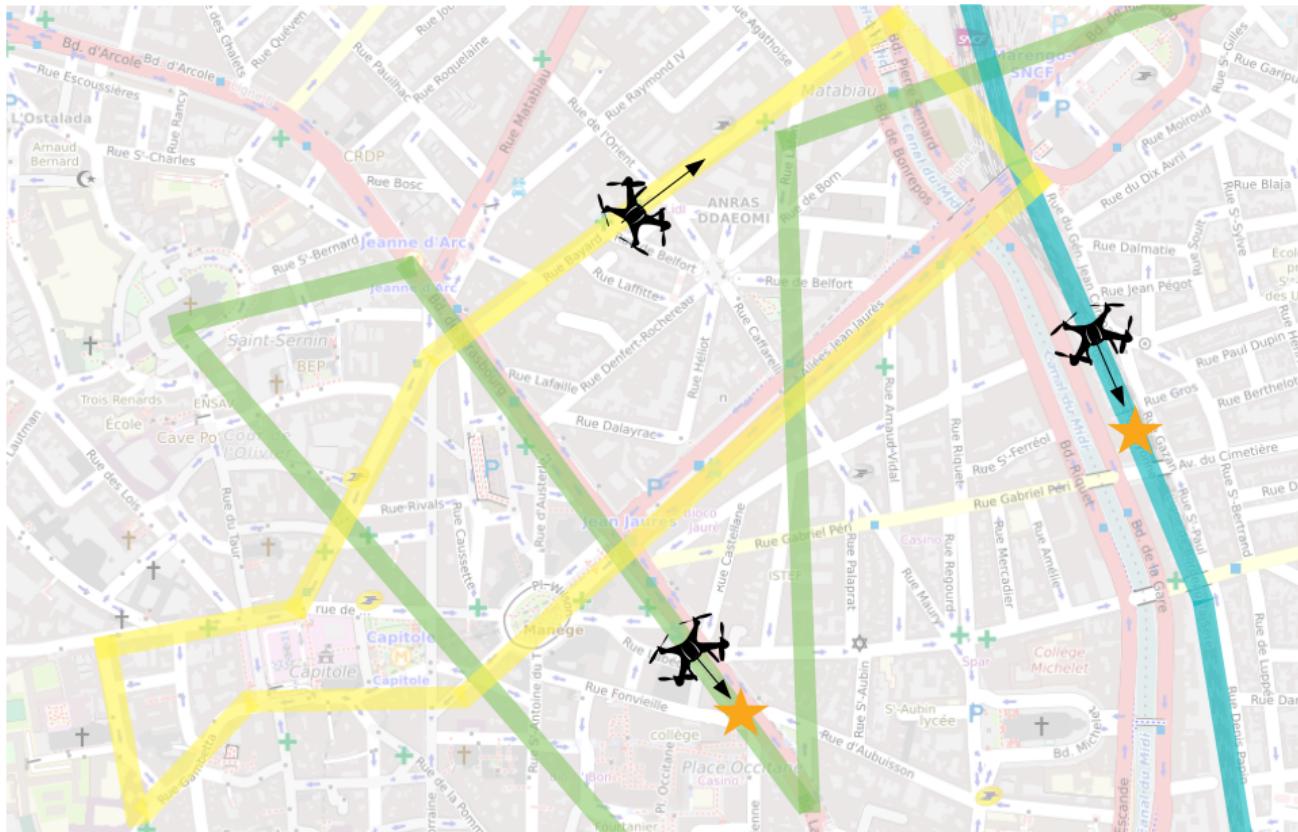
Illustrative Scenario: Urban UTM



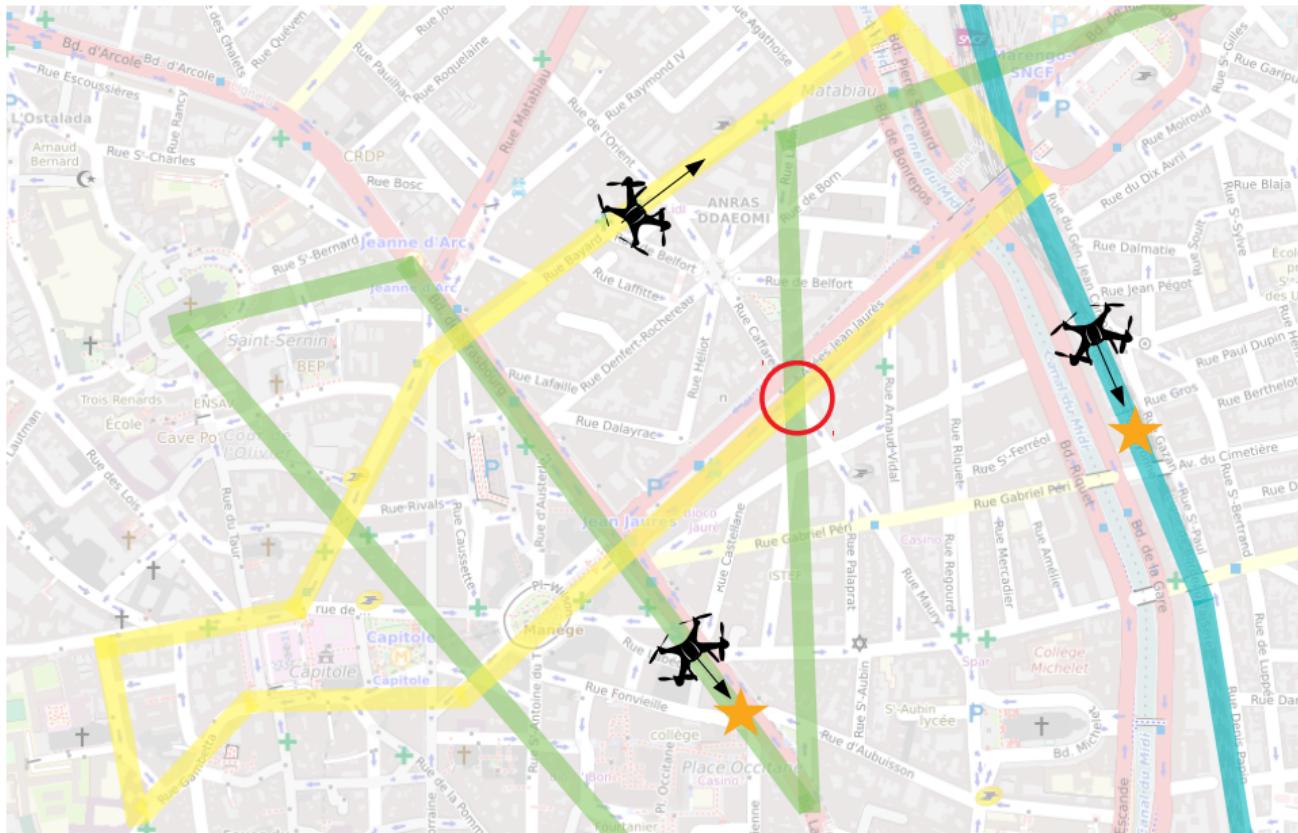
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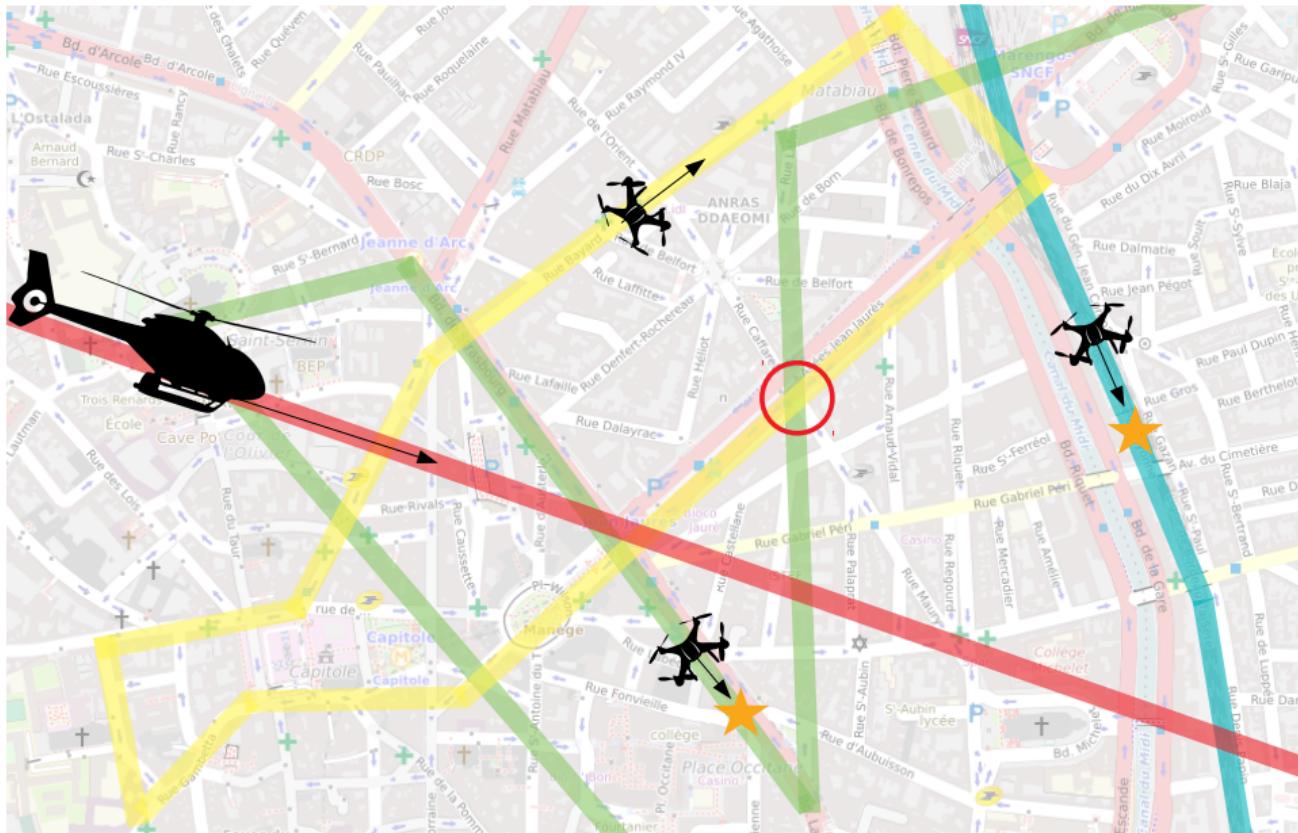
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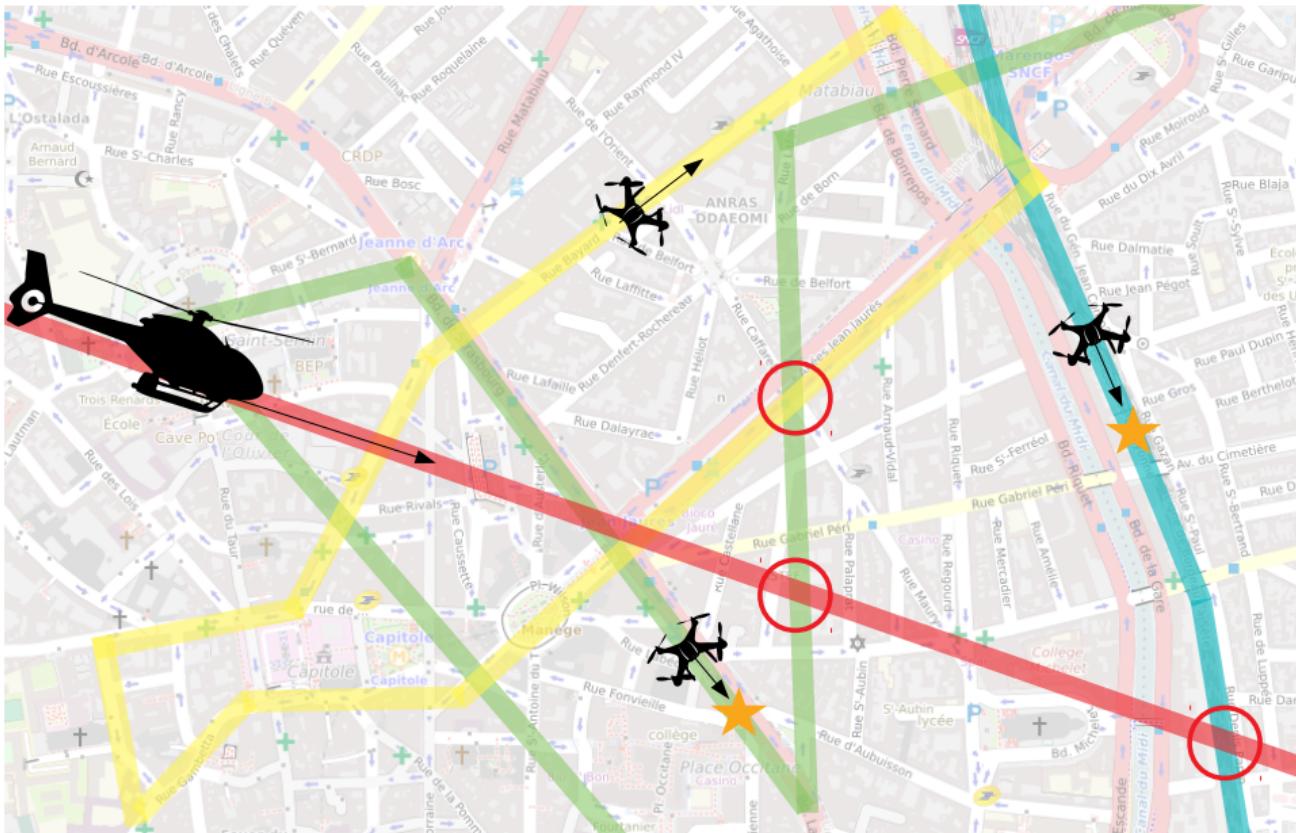
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1 Illustrative Scenario: Urban UTM

2 4D Contract Repair (4D-CRP)

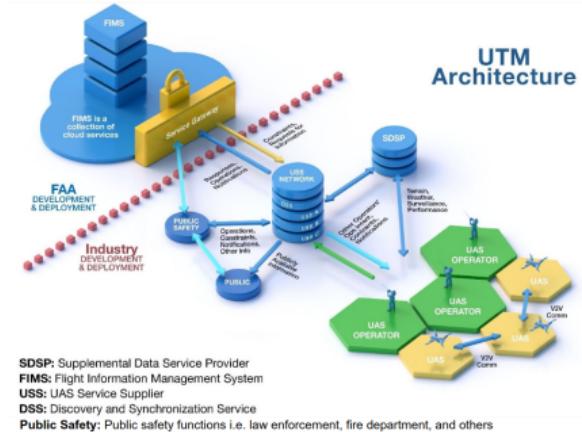
3 Solving the 4D-CRP

4 Experimental Evaluation

5 Conclusions

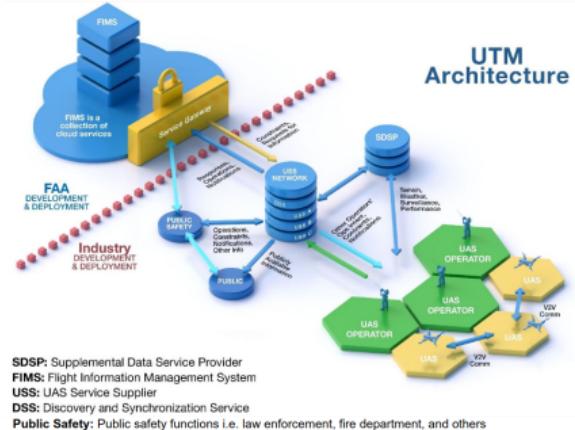
Unmanned Traffic Management

- **Concepts of operations** are still work in progress [FEDERAL AVIATION AGENCY, 2023]
- Numerous **challenging optimization problems** [HAMADI, 2020]
- **Centralized** [BENNACEUR et al., 2022; PELEGRÍN et al., 2023; VERMA et al., 2022] and **decentralized** approaches [Ho et al., 2019; PICARD, 2022; POLISHCHUK, 2018] to UTM



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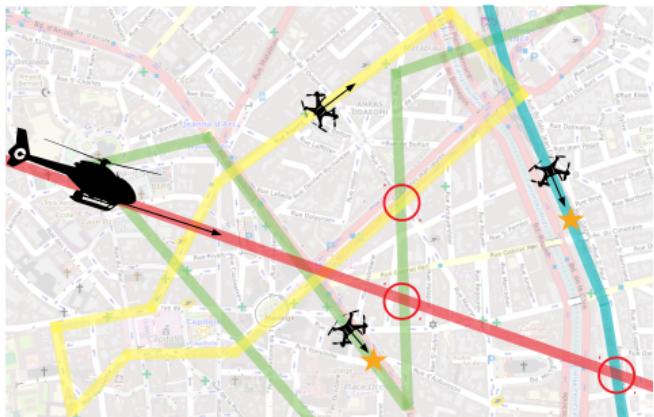


Our focus: 4D trajectory repair

- Free Route Airspace
- Multi-criteria 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

Core Concepts

- UAV: $u = (p, s, d, c, \omega)$
 - $p = (x, y, z, t) \in \mathbb{R}^4$
 - $s = (h, v, a) \leq (h_{max}, v_{max}, a_{max}) \in \mathbb{R}^3$
 - $d \in [0, 2\pi]$
 - c is its current state of charge
 - ω is its 4D trajectory/contract
- 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 trajectories expended by their safety tubes intersect spatially and timely



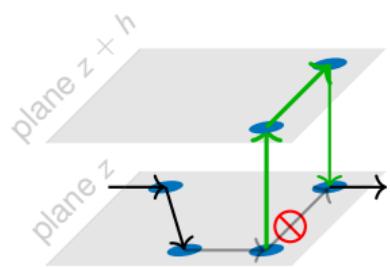
- Classical **operational optimization problem**
- Very well studied in the context of aircraft traffic management [DELAHAYE et al., 2014; DELAHAYE and PUECHMOREL, 2013]
- Building conflict-free trajectories is a **hard optimization problem**
 - e.g. simulated annealing ISLAMI et al., 2017 or evolutionary 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

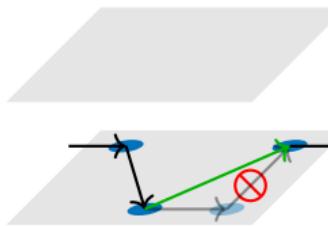
We focus on the **repair procedure**; not the generation of the initial set of trajectories

4D-Contract Repair Problem

Given a set of UAVs U , the *4D-Contract Repair Problem* (or 4D-CRP) amounts to find a set of **corrective actions** to solve all the conflicts between the trajectories of the UAVs from U , whilst minimizing the overall cost of the corrective actions



(a) $\text{elevate}(c, h)$



(b) $\text{skip}(c)$

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
⇒ 3 main options are opened for updating the contracts

Atomic Corrective 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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⇒ We need to install some coordination (and optimization)!

Cost of Corrective Actions

We consider the following functions to assess the cost of action a regardless of which UAV is performing it.

- $\kappa_c(a)$: difference between the initial number of conflicts before and after performing a
- $\kappa_b(a)$: energy consumption resulting from performing action a
- $\kappa_d(a)$: delay resulting from performing the action a
- $\kappa_w(a)$: number of missed waypoints

As to implement a multi-objective evaluation, we consider the criteria in a lexicographic manner, e.g. the $\kappa_c \succ \kappa_w$

We also propose to use criteria related to past concessions:

- $\overline{\kappa_b}(u)$: total energy conceded during past corrective actions performed by u
- $\overline{\kappa_d}(u)$: total delay conceded during corrective actions performed by u
- $\overline{\kappa_w}(u)$: total number of waypoints withdrawn during past corrective actions performed by u

As to ensure safety, we will consider in our experiments lexicographic criteria with κ_c as top-priority ($\kappa_c \succ \kappa$ for any $\kappa \neq \kappa_c$)

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Solving the 4D-CRP

We introduce three algorithms we have implemented to **solve 4D-CRP**

- **Graph Search** (centralized)
 - Explore the space of possible conflicts
 - Find the best sequence of corrective actions
- **Auctions** (semi-centralized)
 - Each UAV bids to solve each conflict sequentially
 - For each conflict, the UAV with the best cost will perform the corrective action
- **DCOPs** (decentralized)
 - For each conflict, the set of impacted UAVs solve a distributed constraint optimization problem
 - No need for a central authority

We propose **sequential action-selection algorithms**, as to select corrective actions, in a reactive manner

We consider **conflicts in a chronological order**, which aligns with the necessity for corrective actions to be comprehensible to human monitoring operators

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Experimental Evaluation



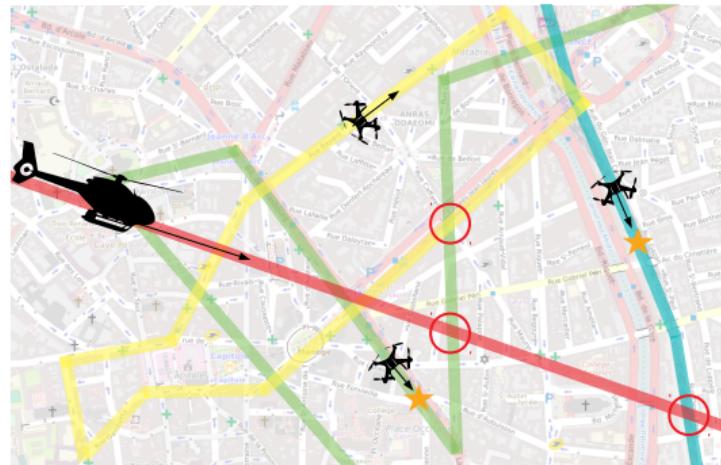
Environment

- 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 30 way-points
- Safety tubes are defined by $(h, v, t) = (30, 15, 1)$
- Number of UAVs in $\{5, 10, 15, 20, 25\}$
- 30000mAh batteries

Experimental Evaluation (cont.)

Unpredictable events

- 10 emergency trajectories
- each simulated second there is also a 5% chance an incident occurs close to a randomly chosen UAV



Experimental Evaluation (cont.)

Algorithms

- ucs, which solves conflicts with the centralized solver based on graph search
- ssi, which solves conflicts with the sequential single item auctions
- scdcop, which solves conflicts (one by one) with AFB

Actions

- $\text{postpone}(c, d)$ with $d \in \{20, 40, 60\}$
- $\text{elevate}(c, \pm 20)$
- $\text{skip}(c)$

Criteria

Actions are evaluated using some lexicographic criteria, which all have κ_c first (to ensure safety), and always use random as a final tie-breaker

- $b \equiv \kappa_c \succ \kappa_b$
- $d \equiv \kappa_c \succ \kappa_d$
- $w \equiv \kappa_c \succ \kappa_w$
- $wd \equiv \kappa_c \succ \kappa_w \succ \kappa_d$
- $bwd \equiv \kappa_c \succ \kappa_b \succ \kappa_w \succ \kappa_d$
- b concession $\equiv \kappa_c \succ \overline{\kappa_b} \succ \kappa_b$
- d concession $\equiv \kappa_c \succ \overline{\kappa_d} \succ \kappa_d$
- w concession $\equiv \kappa_c \succ \overline{\kappa_w} \succ \kappa_w$.

Result Analysis

Effects of criteria on action choices

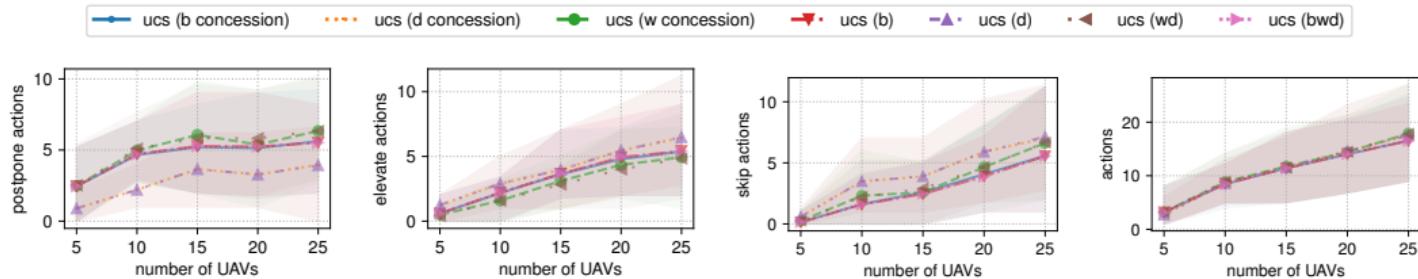


Figure: Decisions made by the different evaluation cost criteria when used with ucs solver.

- d and d concession criteria prefer using *postpone* actions and promote *skip* and then *elevate* actions as to reduce delay
- w, wd and w concession favor *elevate* to keep as many waypoints as possible
- b, bwd and b concession tend to achieve compromises between the two aforementioned families

Result Analysis (cont.)

Comparison of 4D-CRP solvers

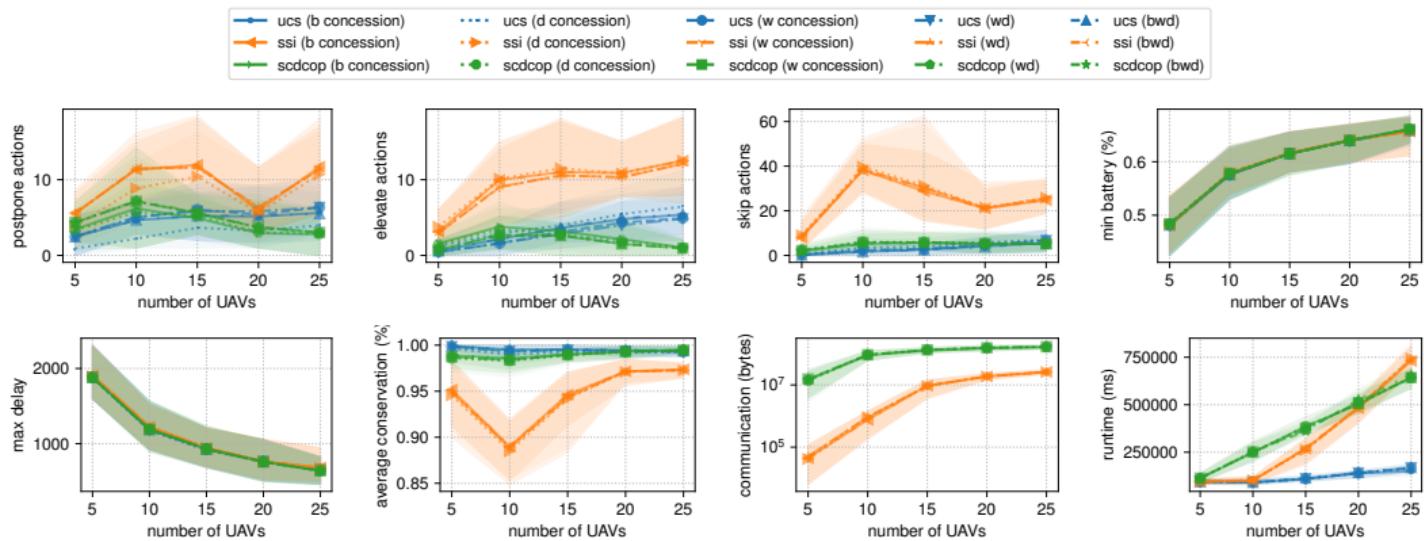


Figure: Average values over 20 instances for several performance metrics with increasing number of UAVs.

- ssi triggers far more corrective actions of any type
- ssi requires almost 8 times less information sharing than scdcop
- ssi struggles on some settings (size 10)
- scdcop tends to trigger more actions than ucs
- scdcop saves as many waypoints as ucs on larger settings sequences.

Result Analysis (cont.)

Comparison of 4D-CRP solvers

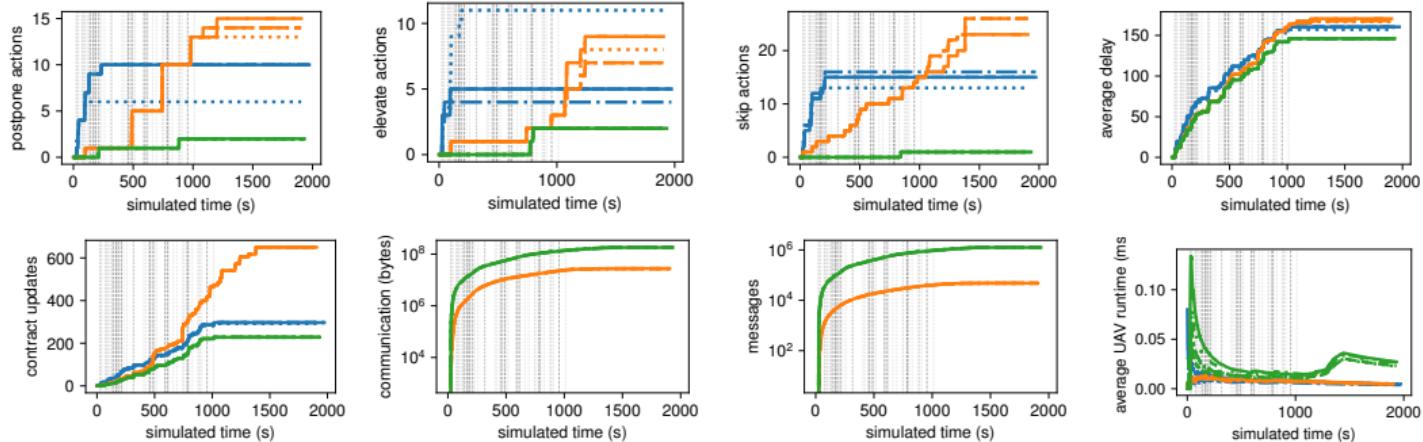


Figure: Results for one simulation with 25 UAVs and 10 emergency procedures (gray dashed) and 46 incidents (gray dotted).

- ucs mostly repair conflicts at the beginning of the scenario
- sdcop triggers few actions all along the time line
- ssi's sequences are often revised until the end of the scenario

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Conclusions

Our Approach

This paper investigates solutions for the **4D-Contract Repair Problem** (4D-CRP) in UAV traffic management

- We evaluated different **solvers**: ucs, ssi, and scdcop
- We defined **action cost functions** considering immediate consequences and past concessions
- We integrated **energy consumption** to promote battery-saving actions (adheres to regulations like [EUROPEAN UNION AVIATION SAFETY AGENCY (EASA), 2022])
- We evaluated various solver-criteria combinations in a **conflicting airspace scenario**

This approach offers UTM stakeholders **flexibility** and **understanding** for choosing coordination mechanisms

Conclusions (cont.)

Benefits and Future Work

- **Flexible and understandable** mechanisms (centralized/decentralized) for trajectory correction
- Diverse criteria for **improved acceptability and explainable decisions**
- Advantages of considering **concessions**, especially with heterogeneous fleets
- Need for evaluation in larger, **multi-hour scenarios** with numerous UAV iterations
- Investigation of **market-based (non-cooperative) approaches**
- **Human-in-the-loop** experiments for adapting explanations and user understanding

Conclusion

UTM deconfliction algorithms need to evolve with:

- **Social acceptability**
- **Algorithmic advancements** (future urban airspace information)
- Fleet deconfliction **preferences**

This work paves the way for a new class of adaptable UTM deconfliction algorithms



Merci pour votre attention !
Des questions ?

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