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

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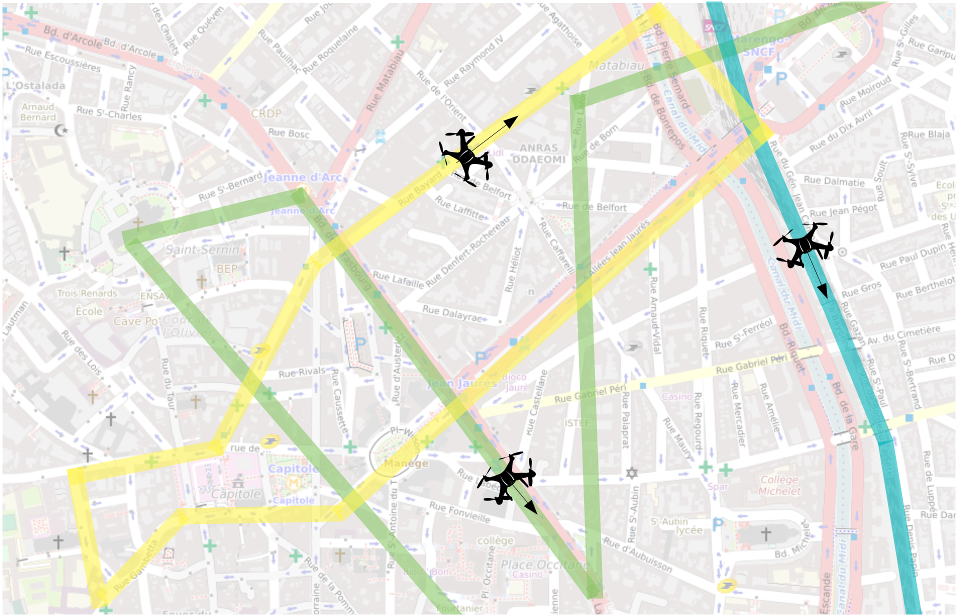
Illustrative Scenario: Urban UTM



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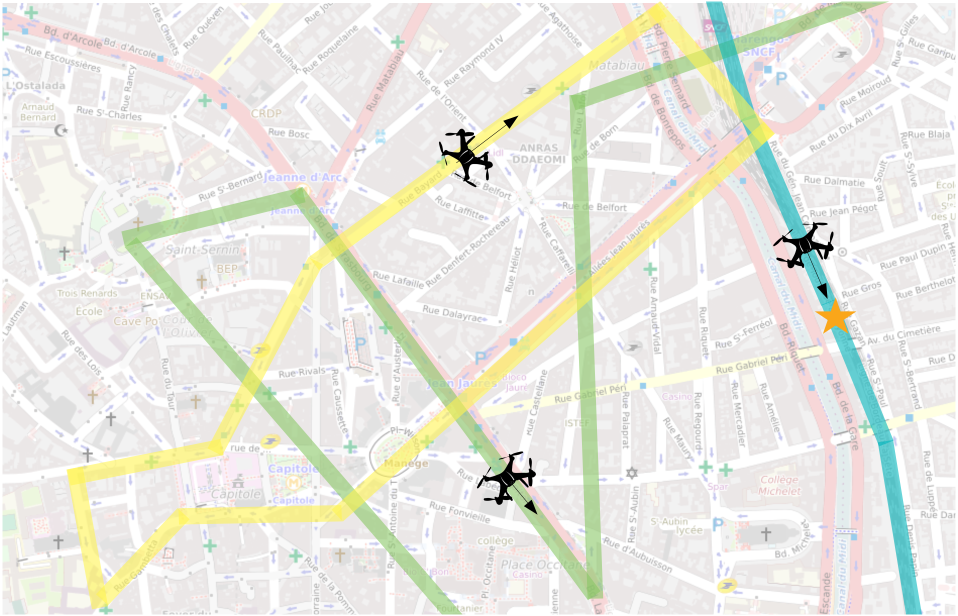

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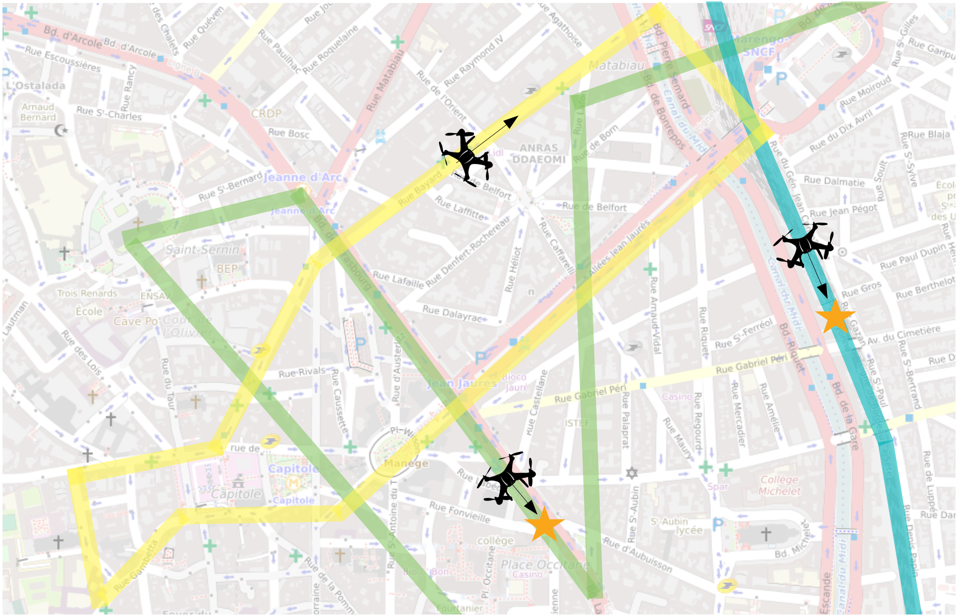

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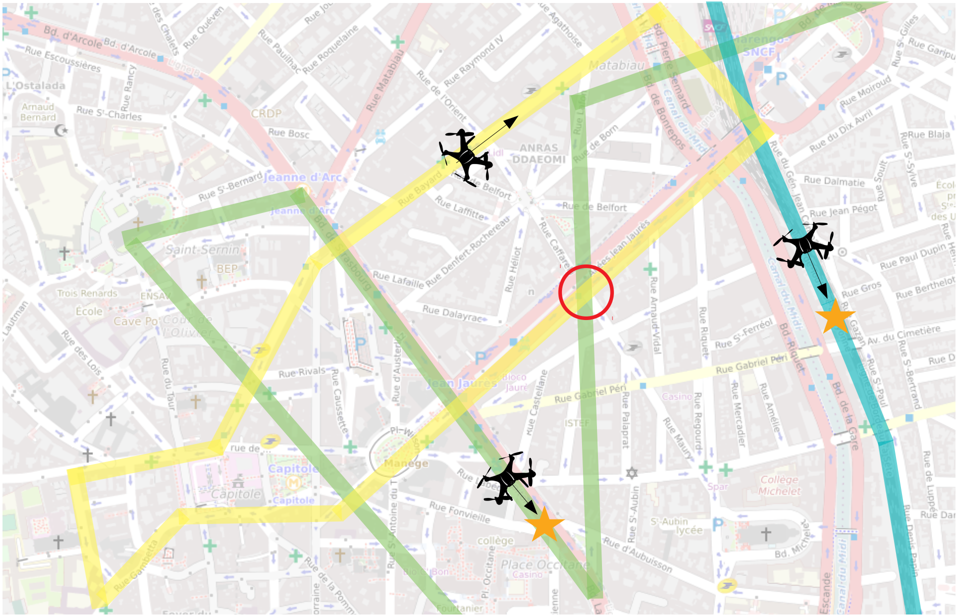

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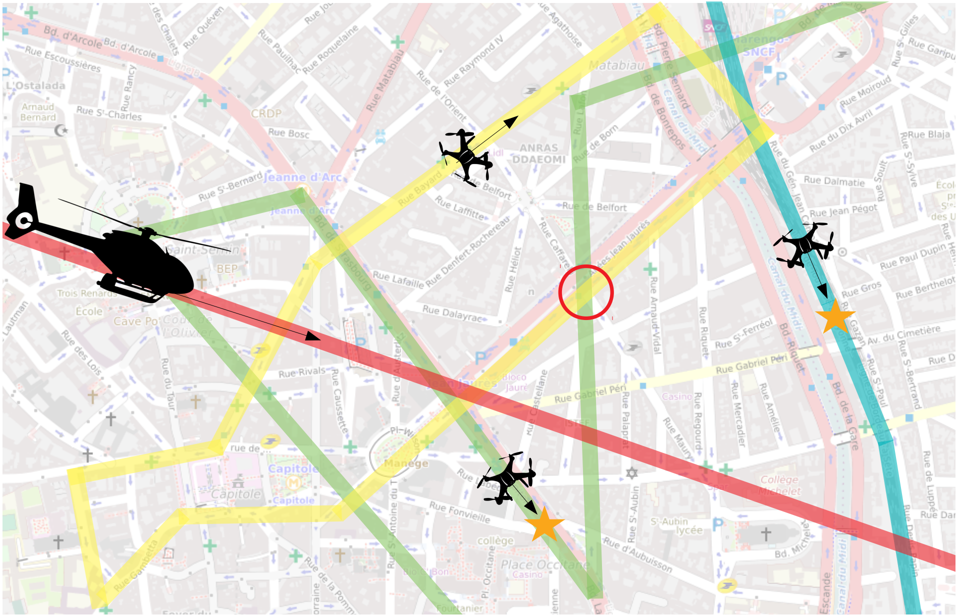

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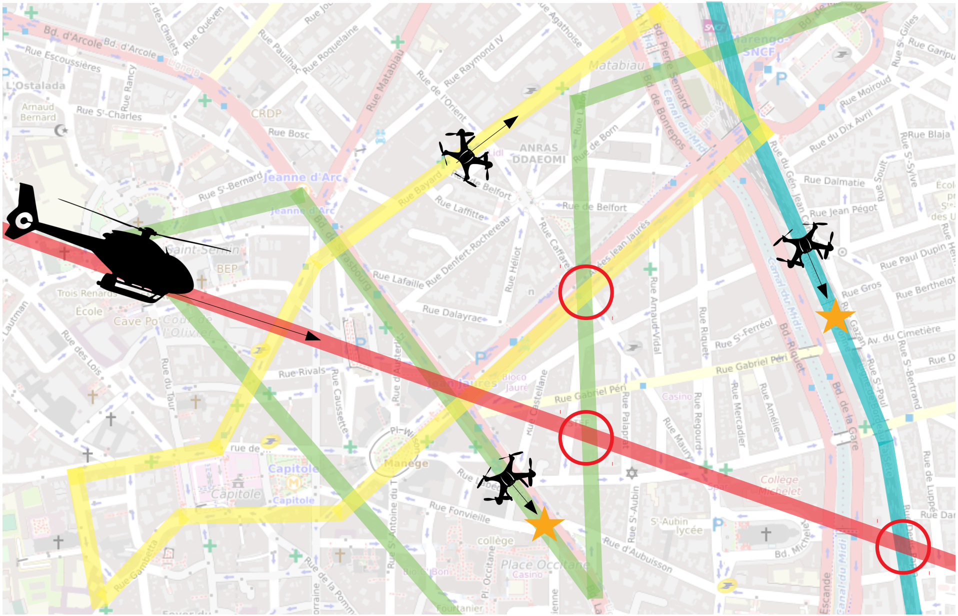
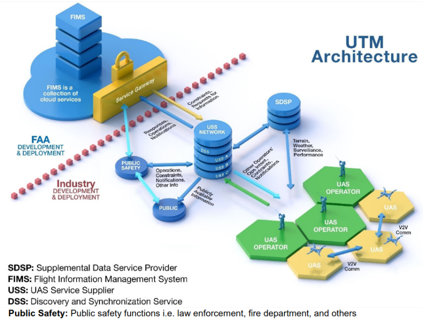


Menu

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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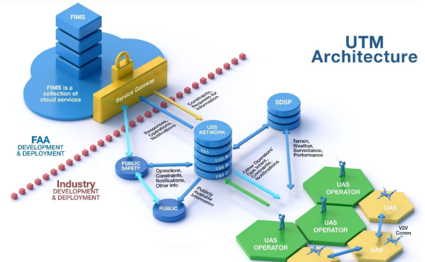


SDSP: Supplemental Data Service Provider
FIMS: Flight Information Management System
USS: UAS Service Supplier
DSS: Discovery and Synchronization Service
Public Safety: Public safety functions i.e. law enforcement, fire department, and others

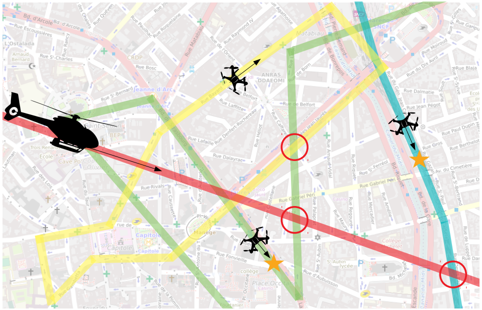
Our focus: 4D trajectory repair

- **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 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

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) *elevate*(c, h) (b) *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
$\Rightarrow$ 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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$\Rightarrow$ 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.

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

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:

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

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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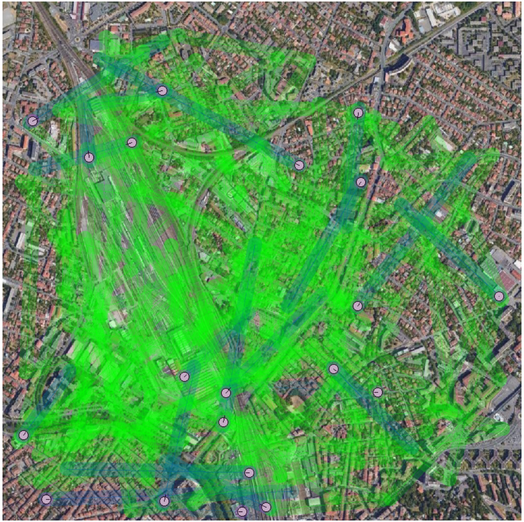
Experimental Evaluation



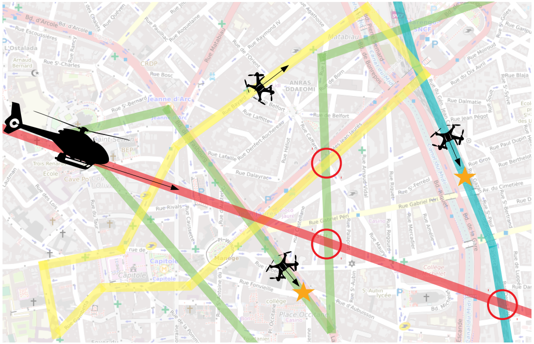
Environment

- 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

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

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

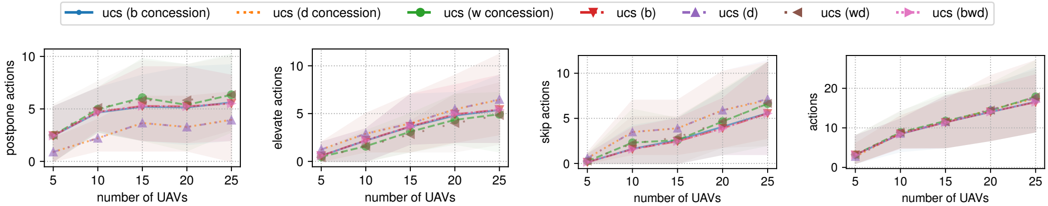


Figure: Decisions made by the different evaluation cost criteria when used with ucs solver.

- 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

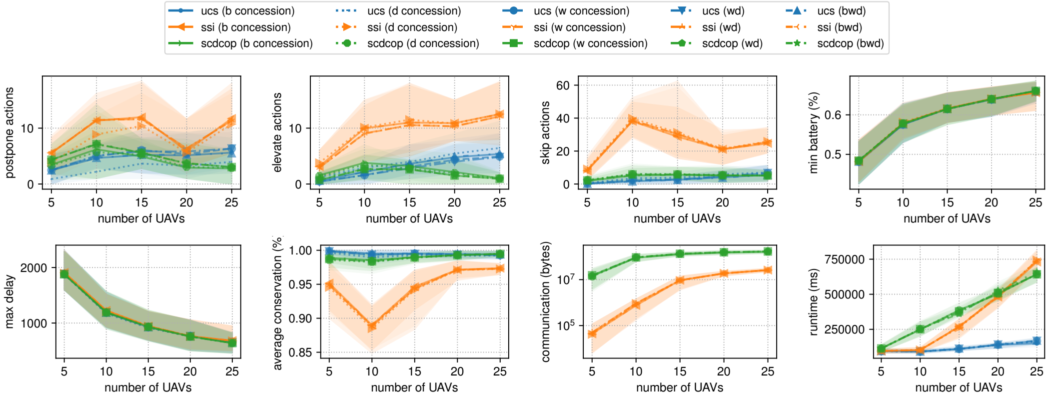


Figure: Average values over 20 instances for several performance metrics with increasing number of UAVs.

- 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

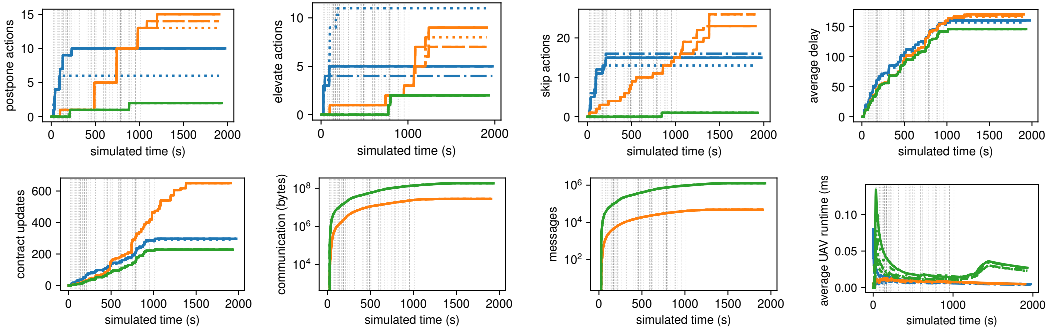


Figure: Results for one simulation with 25 UAVs and 10 emergency procedures (gray dashed) and 46 incidents (gray dotted).

- 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

Menu

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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