An Evaluation of UTM ConOps for Drone Deliveries: 4D Trajectory Planning with or without Pre-Planned Routes

Xinyu He[a], Zewen Wang[c], Bangyan Zhang[c], Guoquan Huang[c], Yinian Mao[c], Lishuai Li[a,b,*]

[a] Hong Kong Institute for Data Science, City University of Hong Kong, Hong Kong SAR, China
[b] School of Data Science, City University of Hong Kong, Hong Kong SAR, China
[c] Meituan UAV, Beijing, China
[*] Corresponding author, lishuai.li@cityu.edu.hk

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1 Introduction

The Unmanned Aircraft System Traffic Management (UTM) Concept of Operations (ConOps) outlines the integration and management of UTM systems within airspace to ensure the safe and efficient operation of unmanned aircraft, or drones. This concept is crucial for developing guidelines, procedures, and technologies to support the increasing use of drones in sectors such as delivery services, surveillance, and recreational activities (EUROCONTROL, 2019, FAA, 2022, Sunil *et al.*, 2015, Vascik & Hansman, 2017, Vascik & Jung, 2016).

Urban drone deliveries pose unique challenges and opportunities, leading to specific considerations in the design of UTM Concepts of Operations. This study evaluates three distinct ConOps for urban drone deliveries, each differing in airspace structure and traffic management: Concept A uses spatially-separated, pre-planned routes; Concept B allows intersections between pre-planned routes; and Concept C supports real-time, dynamically planned 4D trajectories without pre-planned routes. Illustrated in Figure 1, these concepts vary in flexibility, infrastructure requirements, and management complexity. The objective is to assess their performance in various urban environments and order scenarios.

2 Methodology

We evaluate the performance of three UTM ConOps across typical built environments and order profiles via a simplified simulation set-up, as shown in Figure 2. It is a simplified Monte-Carlo simulation, in which Gaussian noises are added to each planned 4D trajectory to capture the uncertainties brought by communications, navigation, and surveillance as a lump-sum.

For each of the ConOps under evaluation, we develop a suite of algorithms tailored for graph construction, route design, and trajectory planning, as depicted in Figure 3. The algorithms and parameter settings selected for this study are not necessarily the most advanced or sophisticated available; instead, they are representative of the most commonly used methodologies in the field. This approach ensures that the algorithms are comparable across the three ConOps. Our comparison primarily emphasizes the impacts of differing airspace structures and traffic

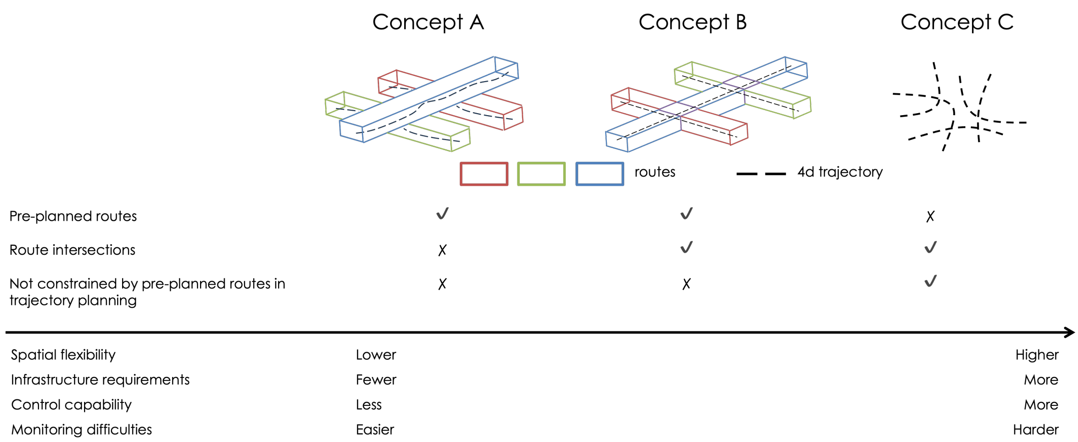


Figure 1 – *Three UTM ConOps under evaluation in this study*

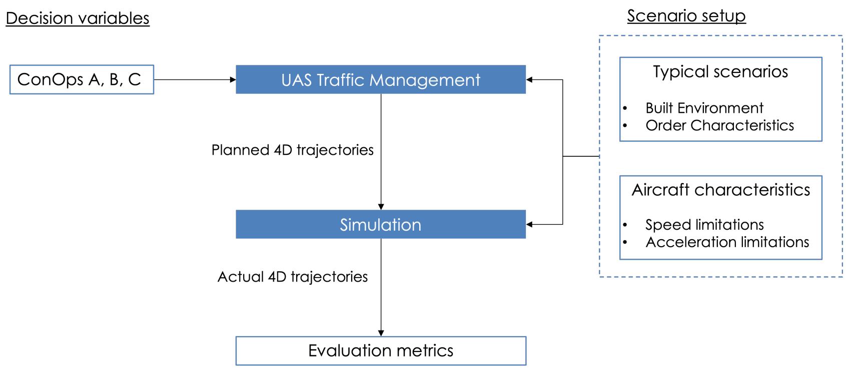


Figure 2 – *Simulation evaluation of UTM ConOps*

management strategies on system performance, rather than focusing on the nuances of specific algorithm implementations.

In Concept A, a spatially separated UAS route network is pre-planned based on aggregated historical order data (He *et al.*, 2024). For real-time orders, the trajectory planning module generates planned 4D trajectories that drones follow, utilizing these pre-planned airways whenever available. In Concept B, the route design module permits intersections among the routes. Upon receiving a real-time order, the planner checks for potential conflicts and employs temporal delays to mitigate them within the expected duration of the flight. This strategy helps manage the flow of traffic across intersecting routes effectively. Concept C adopts an approach akin to "free flight," allowing drones to navigate along preferred paths without reliance on pre-planned routes. The 4D route and trajectory planning module in Concept C dynamically plans 4D trajectories in real time, each triggered by a new order. It ensures the generation of conflict-free trajectories using a 4D grid graph, optimizing flight time and flight distance based on current traffic and airspace conditions.

Regarding performance evaluation, we employ six indicators to measure various aspects of a UTM system under different ConOps. Safety is assessed using the **loss of separation** metric, which tracks instances where drones violate minimum safe separation distances in their 4D trajectories. Delivery service business performance is evaluated by the **delivery failure rate**, reflecting the percentage of unfulfilled orders. The operational efficiency of drone flights is gauged through average flight time and distance, which assess cost and operational effectiveness. For UTM's perspective, airspace occupancy is determined by the **number of grid cells** have been occupied by drones, and the **total computational time** measures the computational resources required.

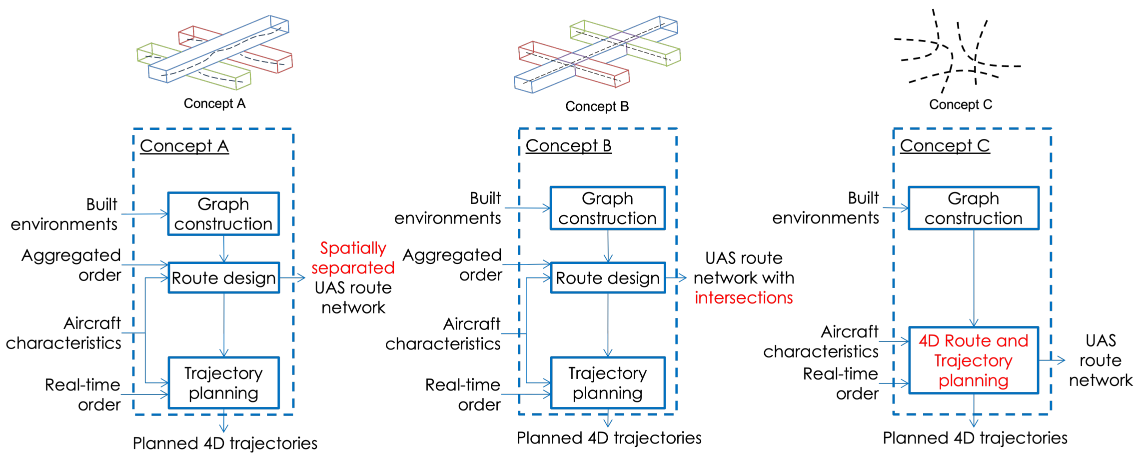


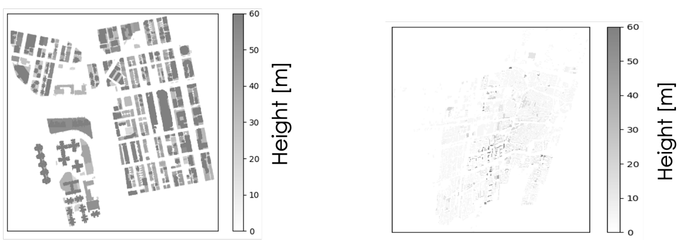
Figure 3 – *Method and Algorithms in each ConOps*

3 Scenarios Set-up

For the simulation evaluations, we have established typical delivery scenarios. Regarding built environments, Mong Kok in Hong Kong SAR is used to exemplify dense urban settings characterized by high-rise buildings, while Delft in the Netherlands serves as an example of an open and sparse urban landscape with low-rise structures, as depicted in Figure 4.

The order profiles considered include (as illustrated in Figure 5):

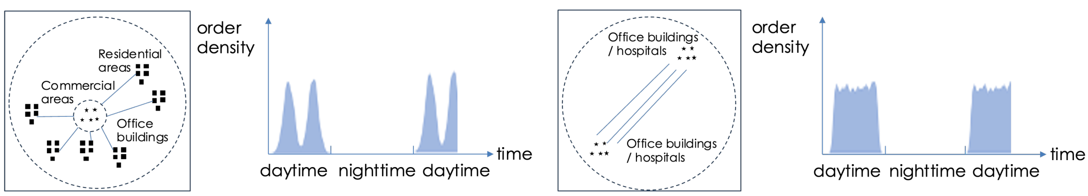
- Hub-to-destination deliveries, which represent deliveries from a commercial center to surrounding residential areas and office buildings, featuring two peak hours during the day;
- Hub-to-hub deliveries, which represent deliveries between two commercial districts or two hospitals, characterized by a uniform temporal distribution throughout the day.



(a) *Dense: Mong Kok, Hong Kong SAR*

(b) *Sparse: Delft, Netherlands*

Figure 4 – *Scenario set-up: built environment*



(a) *Hub-to-destination deliveries*

(b) *Hub-to-hub deliveries*

Figure 5 – *Scenario set-up: order profile*

4 Preliminary Results

The preliminary results of the simulation evaluations are presented from Figure 6 to Figure 9. It should be noted that Mong Kok is smaller than Delft, and hub-to-destination deliveries have shorter direct distances than hub-to-hub deliveries. It is important to note that the absolute values of these results should not be overly emphasized, as they are contingent upon the specific details of the algorithm implementation and the scenario and simulation setups. However, analyzing the relative differences between these values can provide valuable insights.

Concept A experiences fewer loss-of-separation events compared to Concepts B and C when using the same setup, definitions, and algorithm implementations. However, it lacks the flexibility to accommodate orders for locations outside the predefined route network. As a result, the average flight time and distance in Concept A are relatively higher than those in Concepts B and C, and Concept A also occupies more airspace. On the plus side, Concept A requires minimal computational resources for operation. In contrast, Concept C, while experiencing more loss-of-separation events, supports dynamic orders and reduces both the average flight time and distance. It also occupies less airspace, provided there is sufficient computational power available. Concept B exhibits median performance across most indicators.

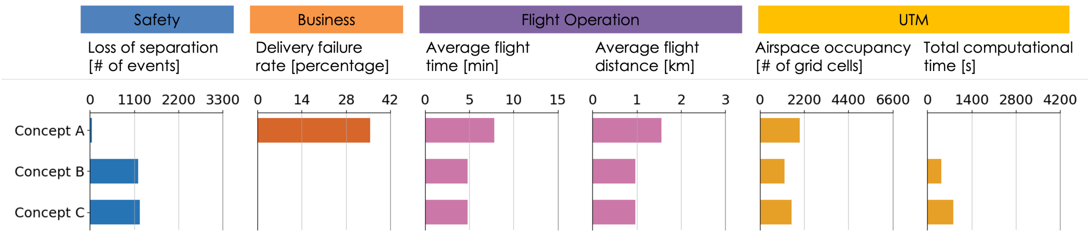


Figure 6 – *Results of Scenario 1: hub-to-destination deliveries in dense built environment*

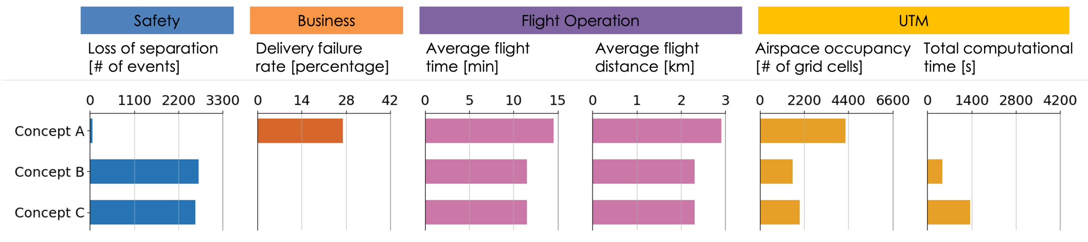


Figure 7 – *Results of Scenario 2: hub-to-hub deliveries in dense built environment*

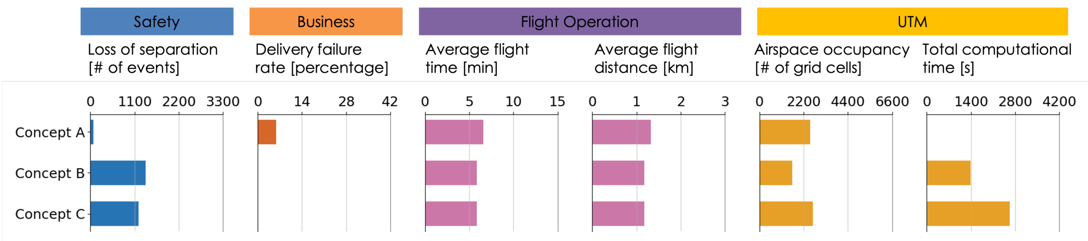


Figure 8 – *Results of Scenario 3: hub-to-destination deliveries in sparse built environment*

References

EUROCONTROL. 2019. *U-space Concept of Operations.*
FAA. 2022. *UTM ConOps v2.*

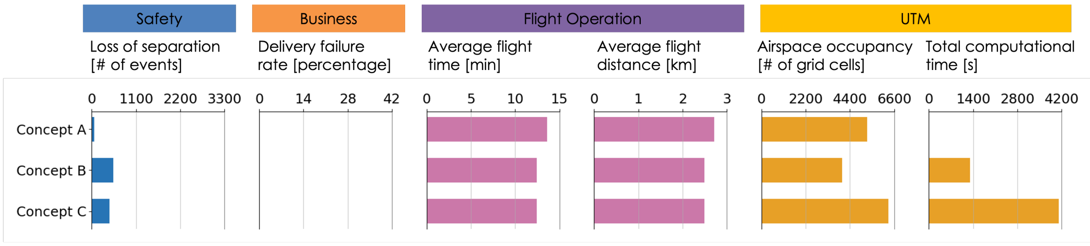


Figure 9 – *Results of Scenario 4: hub-to-hub deliveries in sparse built environment*

He, Xinyu, Li, Lishuai, Mo, Yanfang, Huang, Jianxiang, & Qin, S. Joe. 2024. A distributed route network planning method with congestion pricing for drone delivery services in cities. *Transportation Research Part C: Emerging Technologies*, **160**, 104536.

Sunil, Emmanuel, Hoekstra, Jacco, Ellerbroek, Joost, Bussink, Frank, Nieuwenhuisen, Dennis, Vidosavljevic, Andrija, & Kern, Stefan. 2015. Metropolis: Relating airspace structure and capacity for extreme traffic densities. *In: Proceedings of the 11th USA/Europe Air Traffic Management Research and Development Seminar, June 23-26, 2015.*

Vascik, Parker D, & Hansman, R John. 2017. Evaluation of key operational constraints affecting on-demand mobility for aviation in the Los Angeles basin: ground infrastructure, air traffic control and noise. *Page 3084 of: Proceedings of the 17th AIAA Aviation Technology, Integration, and Operations Conference.*

Vascik, Parker D, & Jung, Jaewoo. 2016. Assessing the impact of operational constraints on the near-term unmanned aircraft system traffic management supported market. *Page 4373 of: Proceedings of the 16th AIAA Aviation Technology, Integration, and Operations Conference.*