Adaptive structuring of unmanned traffic: A UTM concept -Complexity-optimal traffic assignment for future urban airspace

Zhengyi Wang, Daniel Delahaye, Jean-Loup Farges, Sameer Alam

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— Complexity-optimal traffic assignment for future urban airspace

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Context

The growing demand for unmanned and manned air vehicles brings new challenges to urban airspace in the near future. Most existing air transportation networks are not capable to handle this demand, which is likely to cause congestion, high traffic complexity, and safety issues.

To adapt the demand to the current airspace capacity, this poster presents some preliminary results of unmanned traffic structurization. The contribution of this work is three-fold:

- A flow dependent air traffic complexity criterion is developed from the air traffic complexity indicator based on trajectory measurement and Linear Dynamical System (LDS).
- A novel complexity-optimal air traffic assignment model is developed from the macroscopic point of view.
- The problem is efficiently solved using a two-step resolution algorithm based on Dafermos' algorithm.

Mathematical model

Air transportation network representation:

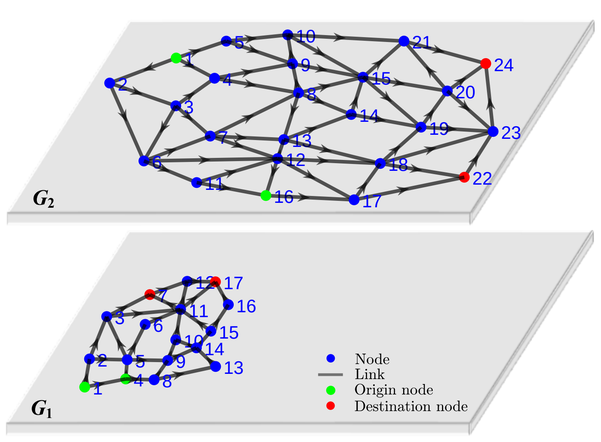


Figure 1: Example of a two-layer network

Density points, flow sharing and complexity area:

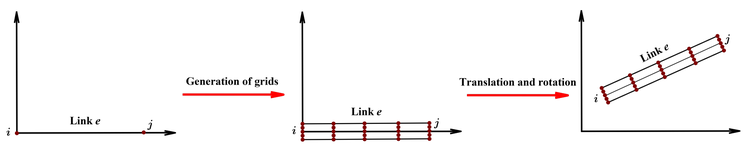


Figure 2: Grid partition on link e

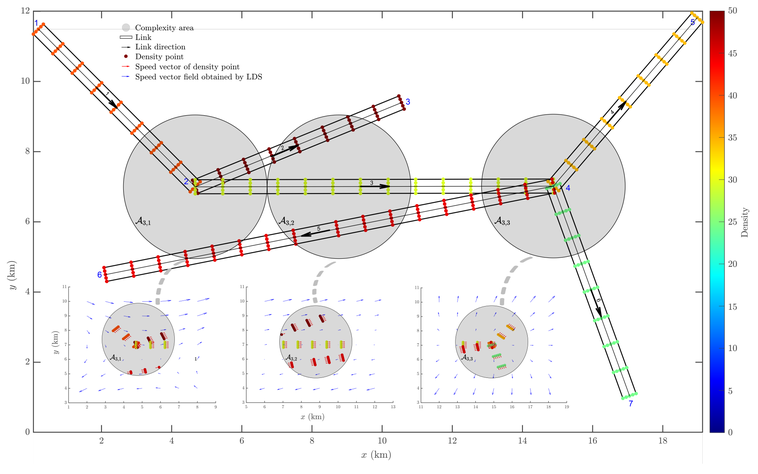


Figure 3: Illustration of density points on grids, discal complexity evaluation areas, and vector field of LDS

Linear dynamical system: In a two dimensional space, a LDS can be expressed as the following form of a differential equation of motion:

$$\mathbf{v} = \mathbf{A}\mathbf{x} + \mathbf{b} \tag{1}$$

where $\mathbf{x}$ denotes the state vector of the system, $\mathbf{v}$ represents the speed vector, $\mathbf{A}$ and $\mathbf{b}$ are coefficient matrix and vector.

The weighted Minimum Mean Square Error (MMSE) estimator is employed to adjust the parameters of LDS:

$$E_{e,i} = \sum_{g \in \mathcal{A}_{e,i}} \omega_g \|\mathbf{v}_g - (\mathbf{A}_{e,i}\mathbf{x}_g + \mathbf{b}_{e,i})\|^2 \tag{2}$$

The matrix $\hat{\mathbf{A}}_{e,i}$ that minimizes the MMSE can be derived by using Singular Value Decomposition (SVD) [1]. Let $\lambda^1_{e,i}$ and $\lambda^2_{e,i}$ be it's two eigenvalues. The dominant eigenvalue $\hat{\lambda}_{e,i}$ is defined as:

$$\hat{\lambda}_{e,i} = \max(|\mathrm{Re}(\lambda^1_{e,i})|, |\mathrm{Re}(\lambda^2_{e,i})|) \tag{3}$$

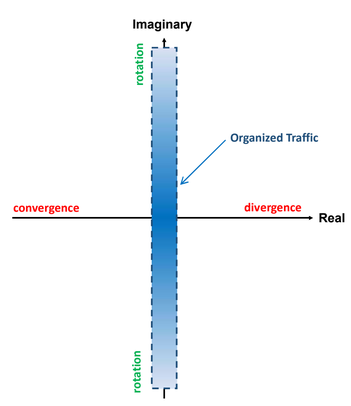


Figure 4: Evolution in terms of eigenvalues

Optimization problem formulation:

$$\begin{aligned}
\min_{\{f_e | e \in \mathcal{E}\}} \quad & \sum_{e \in \mathcal{E}} \frac{1}{N^e_{\text{eval}}} \sum_{i=1}^{N^e_{\text{eval}}} \hat{\lambda}_{e,i} \sum_{e' \in \mathcal{E}_{q_{e,i}}} f_{e'} \\
\text{s.t.} \quad & f_e - \sum_{w \in \mathcal{W}} \sum_{i=1}^{R_w} \delta_{e,w,i} F^i_w = 0, \quad e \in \mathcal{E} \\
& F^i_w \geq 0, \quad w \in \mathcal{W}, i \in \{1, ..., R_w\} \\
& \sum_{i=1}^{R_w} F^i_w = d_w, \quad w \in \mathcal{W}
\end{aligned} \tag{4}$$

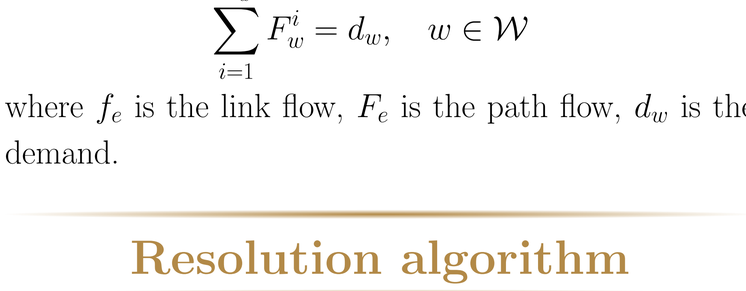
where f_e is the link flow, F_e is the path flow, d_w is the demand.

Resolution algorithm

Dafermos' algorithm is designed to determine the flow patterns under System Equilibrium (SE) in a transportation network [2]. Given the initial traffic distribution, this algorithm searches the most expensive route and the least expensive route in terms of marginal cost for each Origin-Destination (OD) pair.

We propose a two-step strategy to improve the Dafermos' algorithm:

1. Brute force, exact determination of path with the max and min marginal cost.
2. Random optimization strategy, forced flow transfer.



(a) Dafermos' algo (b) Mod Dafermos' algo

Figure 5: An iteration of original and modified algorithm

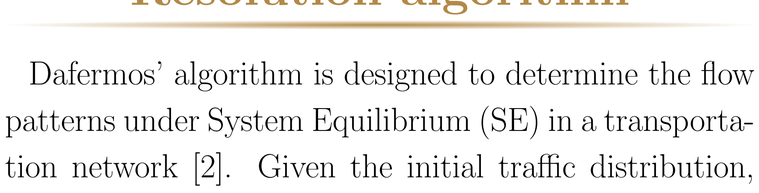
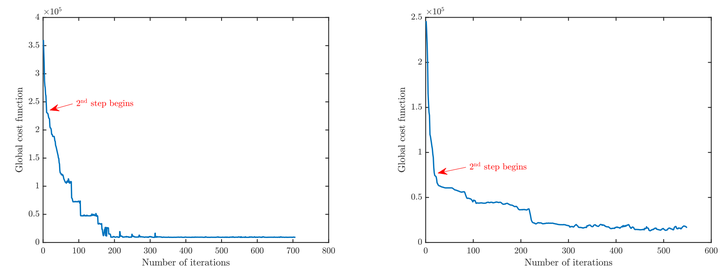


Figure 6: Random optimization strategy

Preliminary results

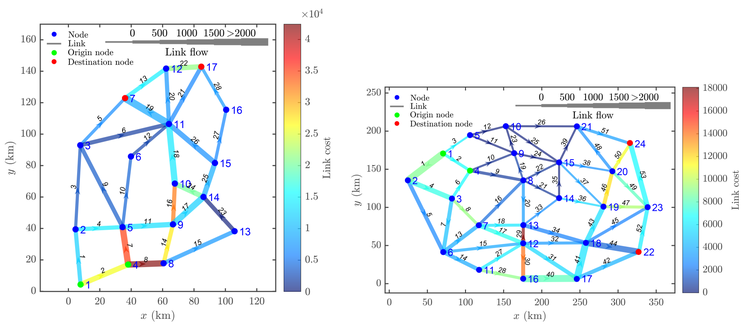
The initial global cost function value of these two networks are 367,225 and 245,940. These values goes down to 9,068.5 and 12,963 with application of the resolution algorithm.



(a) Network G_1 (b) Network G_2

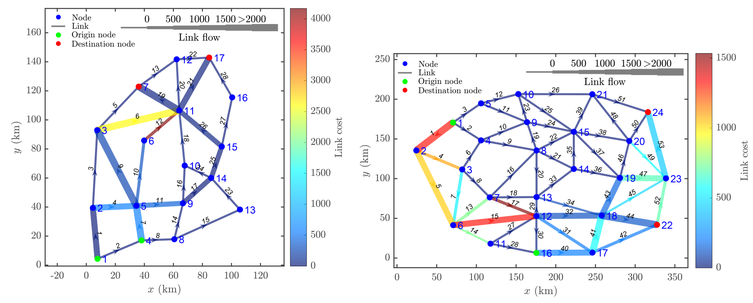
Figure 7: Evolution of global cost function

The resolution algorithm diverts the path from complex areas. Some unnecessary or long-distance paths may also be avoided. On the basis of the design of the link cost function, the link flow associated with the same node is balanced and optimally distributed to mitigate the congestion and traffic complexity. Even if some links are allocated with massive flows, their costs can be quite low.



(a) Network G_1 (b) Network G_2

Figure 8: Link costs under initial flow allocation



(a) Network G_1 (b) Network G_2

Figure 9: Link cost and flow after assignment

Conclusion

This poster presents a preliminary research that shed light on mitigating the traffic complexity and congestion of urban airspace based on the transportation network representation from a macroscopic perspective. With such traffic assignment strategy, aircraft will make effective use of networks in urban airspace. Congestion and traffic complexity are satisfying. Besides, the number and the difficulty of potential conflicts will also be strongly mitigated.

References

[1] D. Delahaye and S. Puechmorel, "Air traffic complexity: towards intrinsic metrics," in *Proceedings of the third USA/Europe Air Traffic Management R & D Seminar*, 2000.

[2] S. C. Dafermos, "The traffic assignment problem for multiclass-user transportation networks," *Transportation science*, vol. 6, no. 1, pp. 73–87, 1972.

Related links

Zhengyi Wang's website

Poster