Multi-Modal Air Trajectory Traffic Management

Thomas C. Henderson[1], Vista Marston[1], and David Sacharny[2]

[1] University of Utah, Salt Lake City UT 84112, USA,
tch@cs.utah.edu,
WWW home page: www.cs.utah.edu/~tch
[2] Blyncsy Inc.
Salt Lake City UT 84102

Abstract. Although well-established air traffic control methods exist for manned aircraft systems (MAS) and frameworks are being created for Unmanned Aircraft Systems (UAS), the issue of combined MAS-UAS coordination has not been adequately addressed. We propose a lane-based multi-modal traffic management system, called Multi-Modal Air (*MM-AIR*), which provides efficient and effective strategic deconfliction for MAS and UAS flying in the same airspace, as well as the capability to schedule safe trajectories for other airborne objects (e.g., artillery rounds). The major contributions are:

1. The efficient scheduling of strategically deconflicted flights of platforms with different speeds and air space requirements, and
2. The capability to schedule the safe passage of other trajectories through the lane-based flights.

1 Introduction

Unmanned Aircraft Systems (UAS) are being developed with the goal of allowing potentially thousands of flights per day in most metropolitan areas. This includes delivery of goods as well as UAS taxi services. Given that manned aircraft may traverse regions where UAS platforms are flying, it is essential to provide a coordination method to keep such flights separated by an adequate distance. Air traffic controllers provide conflict resolution in congested areas of operation [1], e.g., airports, while pilot protocols [6, 11–13, 35] give a framework for pilots to safely avoid one another.

UAS traffic management is an active field of research, and many solutions are being studied [2–5, 7–9, 14, 16–20, 29–34].In our own work, we have proposed a lane-based approach to UAS traffic management (UTM) [23, 22, 10, 15, 24, 26–28, 21]. In this approach, a set of lanes in the air are defined and every flight must schedule a sequence of lanes from take-off to landing. A reservation is made if the flight path never allows two aircraft to be closer than the specified safe separation distance (called headway). The Lane-Based Strategic Deconfliction (LBSD) algorithm was developed to ensure this constraint, and due to the structure of the lanes, allows a low complexity algorithm. With this approach it is possible to schedule thousands of flights in dense operation over a restricted airspace.

However, our previous work considered the case where all UAS were flying at the same speed.

Here we propose to incorporate manned flights into the same traffic management system as the UAS to perform strategic deconfliction (no flight can be scheduled unless it is known to have no conflicts with any other aircraft during any portion of its flight). The above references also provide algorithms to handle contingencies that arise when flights cannot follow their assigned flight parameters. These are generally handled with the Closest Point of Approach Deconfliction (CPAD) algorithm which also takes advantage of the lane structure to guarantee efficiency. It turns out that trajectory information can also be used to determine safe trajectories for flying objects crossing the lane structure.

The contributions here include:

1. The efficient scheduling of strategically deconflicted flights of platforms with different speeds and air space requirements, and
2. The capability to schedule the safe passage of other trajectories through the lane-based flights.

2 Multi-Modal Strategic Deconfliction

2.1 Problem Statement

A UAS Traffic Management (UTM) system is defined as:

- a set of one-way lanes connected as a directed 3D graph,
- a set of launch nodes in the graph where aircraft can initiate their flights,
- a set of land nodes in the graph where aircraft can terminate their flights,
- a fully connected graph; i.e., there is a directed path from every node to every other node, and
- an imposed minimum safety separation distance.

Moreover, a *job set* is defined as a set of aircraft where each has:

- a desired directed path through the UTM graph,
- a desired speed along the path, and
- a proposed interval of allowable launch times.

Given these definitions, the *UTM Scheduling Problem* is defined as:

> For every aircraft in the job set, find a launch time in the proposed launch time interval so that in following its path at its selected speed, it never gets closer than the minimum safety distance to any other aircraft.

2.2 Multi-Speed LBSD

The integration of MAS and UAS flights into a common framework can be easily achieved by treating MAS flights just like UAS flights. That is, every flight follows the same procedure with respect to a lane-based system:

- Select a launch site from pre-defined sites.
- Select a land site from pre-defined sites.
- Select a lane sequence from launch site to land site.
- Select a speed for each lane in the lane sequence.
- Select a launch time interval (i.e., request to launch some time during this interval).
- Obtain from the UTM a designated launch time and reservations in the lane sequence for the corresponding times of passage through the lanes.

The major requirement for a multi-modal traffic management system is to allow for a variety of speeds for the aircraft; i.e., the aircraft will fly at a fixed speed in a given lane, but the assigned speed may be different in different lanes. To address this issue the original LBSD algorithm has been extended to a multi-speed LBSD (M-LBSD) algorithm.

The original LBSD algorithm was designed to handle UAS all traveling at the same speed. This is more efficient because it allows deconfliction to be achieved using only information concerning each lane independently. When a UAS can have different speeds in different lanes in its path sequence, this imposes new considerations concerning the incoming and outgoing lanes for each lane. Consider a flight, f, trying to schedule its traversal times through lane l_i (see Figure 1). Let lanes $l_{i,1}$ and $l_{i,2}$ be two incoming lanes to lane l_i, and let h_d be the minimal

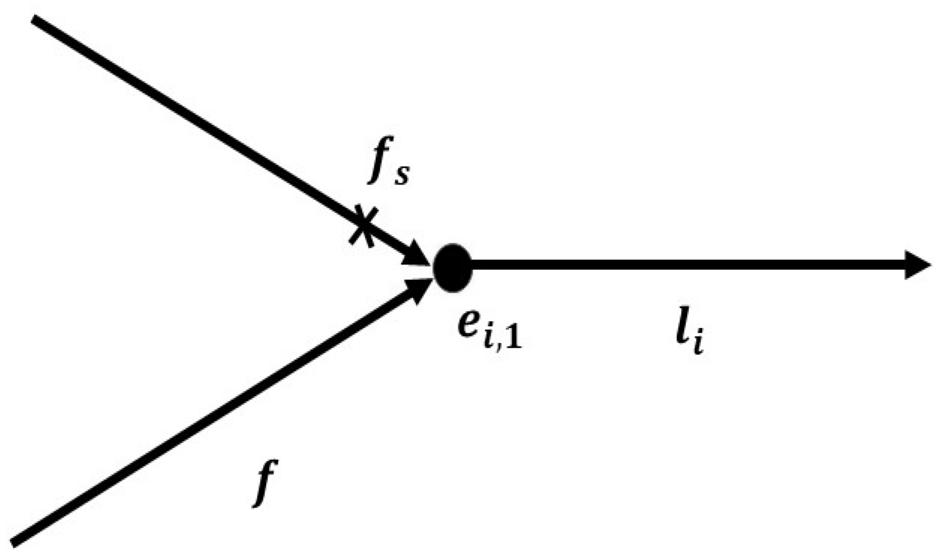

Fig. 1. Problem of Slow Flight Blocking Entry to Lane.

safe headway distance between two aircraft. Suppose that flight f_s is in lane $l_{i,1}$

and that f_s has a very low speed, s_{f_s}, so that it is near $e_{i,1}$, the entry point to lane l_i, for a long time. If flight f is moving much faster than f_s, then it should not pass through $e_{i,1}$ while f_s is closer than h_d to $e_{i,1}$. Since $d = rt$, the safe headway time, h_t, is given by:

$$h_t = \frac{h_d}{s_{f_s}}$$

Thus, to determine a safe time of arrival for flight f at lane l_i, the minimum speed of any flight coming into lane l_i must be used to exclude times of conflict. A similar discussion holds for all outgoing lanes from l_i as well; when scheduling a new flight f through l_i and comparing it to an already scheduled flight f_s in l_i, the headway time (i.e., the buffer between flights) must be based on the minimum of the speeds of f_s in l_i and its incoming and outgoing lanes. This analysis results in a new strategic deconfliction algorithm called *M-LBSD* based on these observations.

Algorithm M-LBSD (Multi-Lane-Based Strategic Deconfliction)

On input:
  lanes: lane sequence for requested flight
  speeds: requested flight's speeds in lanes
  $[q_1, q_2]$: requested launch interval
  n_c: number of lanes
  flights: flights per lane
  h_d: maximum required headway distance
On output:
  Safe time intervals to launch
begin
possible_intervals ← $[q_1, q_2]$
for each lane $c \in$ lanes
  possible_intervals ← possible_intervals + time_to_lane
  for each flight, f, in lane c
    new_intervals ← $\emptyset$
    $s_{min} \leftarrow min(s_f^{c-1}, s_f^c, s_f^{c+1})$
    $h_t = length(lane)/s_{min}$
    for each interval in possible_intervals
      $[t_1, t_2]$ ← interval i
      label ← get_label($p^c_{f,1}, p^c_{f,2}, s_{min}, t_1, t_2, s^r, h_t$)
      f_interval ← get_interval(label,$p^c_{f,1}, p^c_{f,2}, s_{min}, t_1, t_2, s^r, h_t$)
      new_intervals ← merge(new_intervals,f_intervals)
    end
  end
  possible_intervals ← new_intervals
end
possible_intervals ← possible_intervals - time to last lane

In this algorithm, s^c_f is the speed of flight f in lane c; $p^c_{f,1}$ and $p^c_{f,2}$ are the entry and exit times of flight f through lane c, and s^r is the requesting flight's speed through lane c. The algorithm ensures for each scheduled flight there is no conflict with the requested flight; this is done using the labels proposed in [28].

Proof of M-LBSD Correctness

Suppose that a flight has been assigned a flight plan; then the algorithm guarantees that for every lane the new flight passes through, no remaining allowable time interval has any point closer than h_t to any flight's time in the lane (note this is temporal separation). Now assume that at some point in some lane, the new flight is distance d from some flight in the lane, and $d < h_d$. Then:

$$
\begin{aligned}
& d < h_d \\
\rightarrow\ & \frac{d}{s_{min}} < \frac{h_d}{s_{min}} \\
\rightarrow\ & t < h_t
\end{aligned}
$$

but this violates the condition guaranteed in the interval selection.

2.3 Experimental Results

Figure 2 shows an example of s job set of 75 flights through a small UTM. This is a grid network, and the red objects represent the aircraft moving along the lanes in the airway. Of course, the airway lanes are virtual and only shown here for better understanding. These flights all have a random speed between 10 to 15 units per second. The performance was measured in terms of mean flight delay (e.g., actual launch time to requested) which in this case was 1.3 seconds; note that the mean flight duration is 14.69 seconds.

3 Scheduling Other Airborne Objects through the Lane-Based System

Consider the case of a scenario in which a set of UAS, flying at different speeds, are traveling through a UTM airway as in the previous section, and at the same time a set of projectiles are launched through the same airspace. An initial description of a similar setup for a warfare example is given in [21].

In this case, strategic deconfliction is achieved as follows:

- UAS and other flights are deconflicted using the M-LBSD algorithm.
- Deconfliction of lane-based scheduled flights and projectile trajectories not following lanes is achieved by:
  - sample the projectile's trajectory,
  - for each sample point, find the nearest point in the lane structure,
  - determine if any flight has a conflict at that point and time,
  - delay projectile if conflict exists and reschedule.

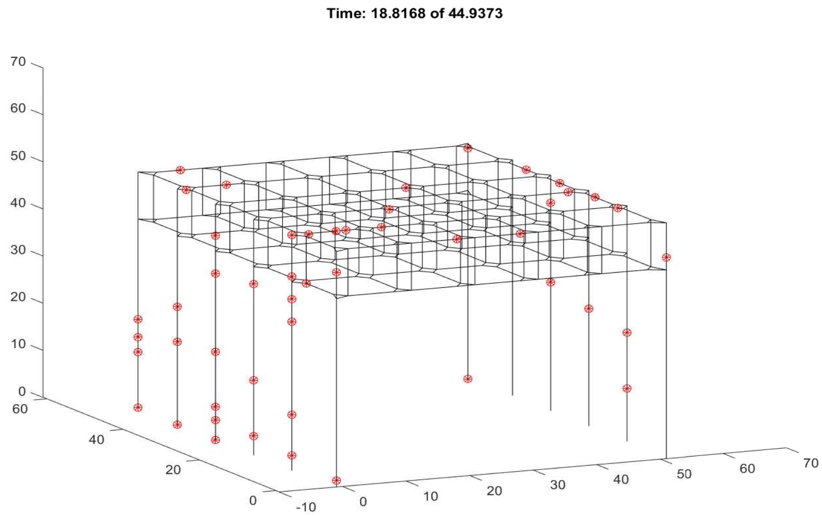

Fig. 2. An example state of the UTM (time step 18.8168) of 75 aircraft with a variety of speeds in the range [10,15].

3.1 Projectile Experiments

In the experimental setup we consider the trajectories of projectiles with the following characteristics: 500 unit effective range, 250 units/sec launch velocity, and 71.7° maximum angle of launch. Air resistance is not considered.

Figure 3 shows the simulation paths for all UAS flights (blue) and projectiles (red) traversing the region. The projectile tracks have all been deconflicted, and their paths through the lane systems pose no safety threats for the UAS flights operating there.

4 Conclusions and Future Work

The Lane-Based Strategic Deconfliction algorithm has been extended to handle aircraft flying at a variety of speeds, and the correctness of the algorithm shown. The fact that a simple solution has been found affords this approach a tremendous advantage over the PSPACE hard complexity of other approaches (e.g., NASA/FAA who schedule arbitrary aircraft trajectories). In addition, we demonstrated here the use of trajectory information to allow strategic deconfliction of non-lane trajectories that traverse the UTM airway.

In the future, the integration of MAS and UAS will require not just the development of theoretical frameworks which work well in simulation, but a detailed examination of the platform requirements for UAS to be able to follow the assigned flight plan in terms of speed maintenance, turning radius, altitude

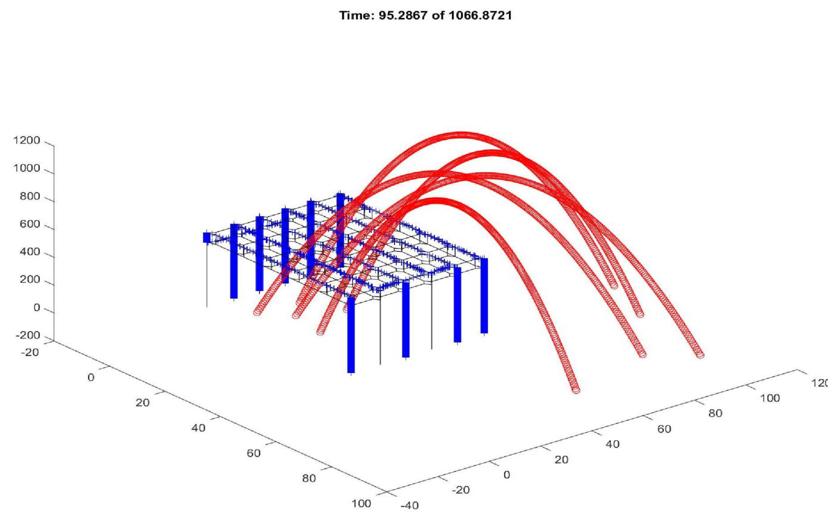

Fig. 3. The trajectories of all UAS (blue) flying through the airspace as well as the trajectories of the projectiles (red). All trajectories are strategically deconflicted.

maintenance, etc. In addition, safe contingency handling measures must be developed for MAS-UAS integrated systems. Finally, robust adaptive measures like that in [25] need to be studied which allow the entire lane structure system to dynamically respond to external interference.

References

1. Federal Aviation Administration. Order JO 7110.65Z, Air Traffic Organization Policy, 2021.
2. AirMap. Five Critical Enablers or Safe, Efficient, and Viable UAS Traffic Management (UTM). Technical report, AirMap, Santa Monica, CA, January 2018.
3. D. Alejo, J. M. Díaz-Báñez, J. A. Cobano, P. Pérez-Lantero, and A. Ollero. The Velocity Assignment Problem for Conflict Resolution with Multiple Aerial Vehicles Sharing Airspace. *Journal of Intelligent and Robotic Systems: Theory and Applications*, 69(1-4):331–346, 1 2013.
4. A. Alharbi, A. Poujade, K. Malandrakis, I. Petrunin, D. Panagiotakopoulos, and A. Tsourdos. Rule-Based Conflict Management for Unmanned Traffic Management Scenarios. In *AIAA/IEEE 39th Digital Avionics Systems Conference (DASC)*, San Antonio, TX USA, October 2020.
5. Swee Balachandran, Cesar Munoz, and Maria C. Consiglio. Implicitly Coordinated Detect and Avoid Capability for Safe Autonomous Operation of Small UAS. In *17th AIAA Aviation Technology, Integration, and Operations Conference*, Reston, Virginia, 6 2017. American Institute of Aeronautics and Astronautics.

6. J. Barbagello. Instrument Procedures Handbook. Technical Report FAA-H-8083-16B, Federal Aviation Administration, Washington, DC, August 2017.
7. H.A.P. Blom and G.J. Bakker. Conflict Probability and Incrossing Probability in Air Traffic Management. In *Proceedings of the 41st IEEE Conference on Decision and Control, 2002*, pages 2421–2426, Las Vegas, NV, USA, 2002.
8. Vishwanath Bulusu, Raja Sengupta, Valentin Polishchuk, and Leonid Sedov. Cooperative and Non-Cooperative UAS Traffic Volumes. In *2017 International Conference on Unmanned Aircraft Systems, ICUAS 2017*, Miami, FL, USA, 2017.
9. W.P. Coutinho, M. Battara, and J. Fliege. The Unmanned Aerial Vehicle Routing and Trajectory Optimisation Problem, A Taxonomic Review. *Computers and Industrial Engineering*, 120:116–128, 2018.
10. Thomas C. Henderson David Sacharny and Michael Cline. An Efficient Strategic Deconfliction Algorithm for Large-Scale UAS Traffic Management. Technical Report UUCS-20-010, University of Utah, Salt Lake City, UT, June 2020.
11. S. Devasia, M. Heymann, and G. Meyer. Automation Procedures for Air Traffic Management: A Token-based Approach. In *Proceedings of the American Control Conference*, Anchorage, AK, May 2002.
12. S. Devasia, D. Iamratanakul, G. Chatterji, and G. Meyer. Decoupled Conflict-Resolution Procedures for Decentralized Air Traffic Control. *IEEE-T on Intelligent Transportation Systems*, 12(2), June 2011.
13. Federal Aviation Administration. Unmanned Aircraft Systems (UAS) Traffic Management (UTM) Concept of Operations, V2.0. Technical report, Federal Aviation Administration, 2020.
14. A. Fluegenschuh and D. Muellenstedt. Flight Planning for Unmanned Aerial Vehicles. In *4th IMA Conference on Mathematics in Defence*, Harwell Oxford, UK, November 2015.
15. T C Henderson, D Sacharny, and M Cline. An Efficient Strategic Deconfliction Algorithm for Lane-Based Large-Scale UAV Flight Planning. Technical Report UUCS-19-005, University of Utah, September 2019.
16. Dae-Sung Jang, Corey A. Ippolito, Shankar Sankararaman, and Vahram Stepanyan. Concepts of Airspace Structures and System Analysis for UAS Traffic flows for Urban Areas. In *AIAA Information Systems-AIAA Infotech @ Aerospace*, Grapevine, Texas, 1 2017. American Institute of Aeronautics and Astronautics.
17. V. Lappas, G. Zoumponos, V. Kostopoulos, H.Y. Shin, A. Tsourdos, M. Tantarini, D. Shmoko, J. Munoz, N. Amoratis, A. Maragkakis, T. Machairas, and A. Trifas. EuroDRONE, A European Unmanned Traffic Management Testbed for U-Space. *Drones*, 6(53), 2022.
18. C.C. Murray and R. Raj. The Multiple Flying Sidekicks Traveling Salesman Problem: Parcel Delivery with Multiple Drones. *Trnsportation Research Part C Emerging Technologies*, January 2020.
19. J.L. Rios. UAS Traffic Management (UTM) Project Strategic Deconfliction: System Requirements Final Report. Technical Report NASA Report, NASA, Moffet Field, CA, July 2018.
20. J.L. Rios, I.S. Smith, P. Venkatesan, D.R. Smith, V. Baskaran, S. Jurack, S. Iyer, and P. Verma. UTM UAS Service Supplier Development, Sprint 2 Toward Technical Capability Level 4. Technical Report NASA/TM-2018-220050, NASA, Moffet Field, CA, December 2018.
21. D. Sacharny and T. Henderson. *Lane-Based UAS Traffic Management*. Springer Verlag, Berlin, Germany, 2022.

22. D. Sacharny, T. Henderson, and M. Cline. Large-Scale UAS Traffic Management (UTM) Structure. In *IEEE Multisensor Fusion and Integration Conference*, Karlsruhe, Germany, September 2020.
23. D. Sacharny, T. Henderson, and E. Guo. A DDDAS Protocol for Real-Time UAS Flight Coordination. In *InfoSymbiotics/Dynamic Data Driven Applications Systems Conference*, Boston, MA, October 2020.
24. D. Sacharny, T. Henderson, and V. Marsten. Lane-Based Large-Scale UAS Traffic Management. *IEEE-T Intelligent Transportation Systems*, 23(10):18835–18844, October 2022.
25. D. Sacharny, T. Henderson, and N. Wernecke. Dynamic Airspace Contol via Spatial Network Morphing. In *Dynamic Data Driven Applications Systems Conference*, Boston, MA, October 2022.
26. D. Sacharny and T.C. Henderson. A Lane-based Approach for Large-scale Strategic Conflict Management for UAS Service Suppliers. In *IEEE International Conference on Unmanned Aerial Systems*, Atlanta, GA, June 2019.
27. D. Sacharny, T.C. Henderson, and E. Guo. A DDDAS Protocol for Real-Time UAS Flight Coordination. In *InfoSymbiotics/Dynamic Data Driven Applications Systems Conference*, Boston, MA, October 2020.
28. David Sacharny and Thomas C. Henderson. A Lane-Based Approach for Large-Scale Strategic Conflict Management for UAS Service Suppliers. In *2019 International Conference on Unmanned Aircraft Systems (ICUAS)*, pages 937–945, Atlanta, GA, June 2019. Institute of Electrical and Electronics Engineers (IEEE).
29. Leonid Sedov and Valentin Polishchuk. Centralized and Distributed UTM in Layered Airspace. In *8th International Conference on Research in Air Transportation*, pages 1–8, 2018.
30. Manuel Soler, Maryam Kamgarpour, Javier Lloret, and John Lygeros. A Hybrid Optimal Control Approach to Fuel-Efficient Aircraft Conflict Avoidance. *IEEE Transactions on Intelligent Transportation Systems*, 17(7):1826–1838, 2016.
31. Emmanuel Sunil, Jacco Hoekstra, Joost Ellerbroek, Frank Bussink, Dennis Nieuwenhuisen, Andrija Vidosavljevic, and Stefan Kern. Metropolis : Relating Airspace Structure and Capacity for Extreme Traffic Densities. In *11th USA/Europe Air Traffic Management Research and Development Seminar*, Lisbon, Portugal, 2015.
32. M. Torabbeigi, G.J. Lim, and S.J. Kim. Drone Delivery Scheduling Optimization Considering Payload-Induced Battery Consumption Rates. *Jnl of Intelligent Robotics and Systems*, 97:471–487, 2020.
33. M. Tra, E. Sunil, J. Ellerbroek, and J. Hoekstra. Modeling the Intrinsic Safety of Unstructured and Layered Airspace Designs. In *12th USA/Europe Air Traffic Management Research and Development Seminar*, Seattle, Washington, USA, 2017.
34. A.L. Weinstein and C. Schumacher. UAV Scheduling via the Vehicle Routing Problem with Time Windows. Technical Report AFRL-VA-WP-TP-2007-306, Air Force Research Lab, Wright-Patterson AFB, OH, January 2007.
35. J. Yoo and S. Devasia. Provably Safe Conflict Resolution with Bounded Turn Rate for Air Traffic Control. *IEEE-T on Control Systems Technology*, 21(6), November 2013.