A DDDAS Protocol for Real-Time Large-Scale UAS Flight Coordination

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Problem:

Coming soon everywhere!
1000’s of drones
How to Manage all these Flights?

FAA-NASA:

Pairwise deconfliction of all flights in common space-time

The UAS Traffic Management (UTM) Problem

Schedule Flights:
- USS 1: Green Lines
- USS 2: Blue Lines

Proposed Flight:
- USS 3: Red Dashed Line
How to Manage all these Flights?

Our Proposal:

Lane-based
Strategic Deconfliction
(lanes defined by Air Management Authorities)
UTM and the DDDAS Paradigm

Model:
- Lane-Based UTM (System Policies and Structure)
- UAS Behaviors (Onboard and Real-Time Algorithms)

Data:
- Schedules
- Contingencies

Metrics:
- Average Speed
- Average Delay
- Failed Schedules
UAS Traffic Management

UTM: structure and rules of airways

FAA-NASA Approach

USS-UAS
- Nominal behaviors
- Contingency behaviors

- Deconfliction rules
- Airway structure
- Contingency handling
UTM Structure & Policies

• Lanes
  • One-way
  • Linear (skeleton)
  • Virtual volume (e.g., circular tube along skeleton)
  • Speed constraints
  • Headway constraints

• Roundabouts
  • Defined at intersections
  • Basic units
    • 3-Merge
    • 3-Diverge
UTM Structure & Policies

• 3-Merge/Diverge v. Cross Conflict
  - SD Constraint: Trajectories must not violate headway (separation) distance

![Diagram]

Strategic bottleneck – can be designed to maintain correct separation

![Diagram]

Expanded Constraints

- Lane 3 is SD

![Diagram]

Expanded Constraints

- Lane 3 is SD
- Lane 4 is SD
- Intersection is SD

Requires zone constraints to ensure separation at intersection
UTM Structure & Policies

• Lanes versus Free-Flight

Free-Flight
Each Aircraft Must Perform a Search in 4D Space

Lanes
Reusable Paths – Each aircraft only searches in 1D time
UTM Structure & Policies

• Emergency Protocols
• Contingency Handling
• Lane Creation/Deletion/Modification
• Flight Authorization
• Aircraft Certification
• Strategic Deconfliction
Lane-Based UTM

Proposed Lane System

NASA-FAA Grid System
Lane Creation
e.g., SLC (above roads)
Strategic Deconfliction: Space-Time Lane Diagram

(a) Scheduled Flight (with headway time)

(b) Proposed Flights
Lane-Based Reservation System

Scheduled Flights
Possible Flight

Third Lane in Sequence

Second Lane in Sequence

First Lane in Sequence (i.e., launch lane)
Space Time Lane Diagram

Proposed Flight
Time Interval

Existing Flight

Headway Times
Strategic Deconfliction: Labels

- Label: A
- Label: B
- Label: C
- Label: D
- Label: E

The diagram illustrates the timeline with segments labeled from 0 to $q_1$, $[0, q_1)$, $q_1$ to $(q_1, q_2)$, $q_2$ to $(q_2, \infty)$.

- Label 1
- Label 2
- Label 3
- Label 4
- Label 5
Examples

1A,1A $[q_1, q_2]$

1A,1B $[q_1, q_2]$

1A,1C $[p_3 - ts, q_2]$

1A,1D $[q_2, q_2]$

1A,1E $[]$

1A,2A $[q_1, q_2]$

1A,2B $[q_1, q_2]$

1A,2C $[p_3 - ts, q_2]$

1A,2D $[q_2, q_2]$

1A,2E $[]$

1A,3A $[p_2, q_2]$

1A,3B $[p_2, q_2]$

1A,3C $[p_3 - ts, q_2]$

$s < s_r$

1A,3C $s = s_r$

1A,3C $[p_2, q_2]$
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<th>Intervals</th>
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This is a complete table of all possible proposed flight versus scheduled flights with resulting intervals.
Algorithm SD (Strategic Deconfliction)

On input:
- lanes: lane sequence for requested flight
- \([q_1, q_2]\): requested launch interval
- \(n_c\): number of lanes
- flights: flights per lane
- \(h_t\): maximum required headway time

On output:
- Safe time intervals to launch

begin
possible\_intervals \leftarrow [q_1, q_2]
for each lane \(e \in \) lanes
  \text{time\_offset} \leftarrow \text{time to get to lane } e
  \text{possible\_intervals} \leftarrow \text{possible\_intervals} + \text{time\_offset}
for each flight, \(f\), in lane \(e\)
  \text{new\_intervals} \leftarrow \emptyset
  for each interval in possible\_intervals
    \([t_1, t_2]\) \leftarrow \text{interval } i
    \text{label} \leftarrow \text{get\_label}(f, t_1, t_2, s_f, t_1, t_2, s, h_t)
    \text{f\_int} \leftarrow \text{get\_interval}(\text{label}, f, t_1, t_2, s_f, t_1, t_2, s, h_t)
    \text{new\_intervals} \leftarrow \text{merge}(\text{new\_intervals}, \text{f\_int})
  end
  possible\_intervals \leftarrow \text{new\_intervals}
end
possible\_intervals \leftarrow possible\_intervals - \text{time to last lane}

Computational Complexity: (in terms of interval operator, \(I\))

\(\#I op_s \leq \sum_{k=1}^{n} f_k + \sum_{i \neq j} f_i f_j\)

\(\text{Big } O: O(f^2)\)
where \(f = \sum_{k=1}^{n} f_k\)
Beyond SD: Contingencies!

If every UAS follows its nominal flight plan:

→ there are no problems!

But, there are contingencies:

“something that might possibly happen in the future, usually causing problems or making further plans and arrangements necessary”
(Cambridge Dictionary)
Example - Communication Outage

Lanes give us the ability to deal with contingencies in a deterministic way.
Real-Time Tactical Deconfliction (UAS Behavior)

• Uses the Closest Point of Approach (CPA) method
• “In-between” strategic deconfliction and sensor-based methods

If a flight, $f_1$, has a conflict with flight $f_2$, then the two flights can be deconflicted as follows:

$Deconflict_Pair$

while conflict($f_1, f_2$)
    reduce speed, $s_1$, of $f_1$
    if $s_1 < s_{min}$
        then flight $f_1$ fails
This allows the definition of the Closest Point of Approach Deconfliction (CPAD) algorithm:

Algorithm 1: Closest Point of Approach
1. ∀ active flight, $f$
2. if $f$ enters a new lane
3. OR a neighboring flight has slowed
4. OR $f$ has reduced speed on its own
5. then call $Deconflict_Pair$ for all flights in neighboring lanes
6. if $f$ has reduced speed
7. then $f$ broadcasts this information.
Real-Time Tactical Deconfliction (UAS Behavior)

- Uses the Closest Point of Approach (CPA) method
- “In-between” strategic deconfliction and sensor-based methods

Communications are not required

The Lane Based network enables efficient storage of local lane maps

Sensors provide a fallback option and a second opinion on the state of the system

More options to handle nefarious contingencies

If a flight, $f_1$, has a conflict with flight $f_2$, then the two flights can be deconflicted as follows:

\begin{align*}
Deconflict\_Pair
\end{align*}

\begin{algorithmic}
\While{\text{conflict}($f_1, f_2$)}
\State reduce speed, $s_1$, of $f_1$
\If{$s_1 < s_{min}$}
\State then flight $f_1$ fails
\EndIf
\EndWhile
\end{algorithmic}

This allows the definition of the Closest Point of Approach Deconfliction (CPAD) algorithm:

\begin{algorithm}
\caption{Closest Point of Approach}
\begin{algorithmic}[1]
\State $\forall$ active flight, $f$
\State if $f$ enters a new lane
\State OR a neighboring flight has slowed
\State OR $f$ has reduced speed on its own
\State then call Deconflict\_Pair for all flights in neighboring lanes
\State if $f$ has reduced speed
\State then $f$ broadcasts this information.
\end{algorithmic}
\end{algorithm}
Approximate Global Deconfliction

• Global deconfliction achieved by each UAS running the CPAD algorithm
• Limited data exchanged between vehicles
• Violations of safe separation only possible in certain contingency scenarios like communication issues
  • Agents can fallback to sensor based tactical deconfliction
  • Contingency information propagates throughout network in affected lanes
Experiments - Discrete Event Simulation

- Simulation Parameters:
  - tmax - simulation time
  - nf - number of flights
  - smax - maximum speed allowed

- Simulation process
  - Each new flight selects a sequence of lanes
  - Event triggered by time-of-arrival for each lane
  - Flights advanced in position and speed

- Performance Metrics
  - Total delay (in simulation units)
  - Average Speed
  - Failures to schedule (due to safe-separation constraint)

Fig. 1: Set of UAS on Airways during Discrete Event Simulation. Red dots represent UAS in Flight; blue lanes are launch lanes.
Simulation Results

Table 1: Delays and Failures in Experimental Simulations

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<th>$n_f$</th>
<th>$s_{\text{max}}$</th>
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- Two aspects simulated:
  - $t_{\text{max}}$:\{100,200\}, $s_{\text{max}}$:\{5,9\}
  - $n_f$ chosen to launch approximately one flight per minute on average
- Five runs of simulation for each parameter
- Only one flight failed to schedule due to separation constraints
- Average speed near max indicates efficient absorption of contingent events (new flights entering the network)
Contributions

• DDDAS Paradigm for Unmanned Air Traffic Control
• Real-time conflict/contingency management protocol
• Lane-based model for airspace structure
Future Work

• Broader experiments that explore lane-configuration
• Sensitivity analysis
• Experiments with real vehicles in flight
• Characterize communication requirements for CPAD protocol