Switched Systems and Motion Coordination: Combinatorial Challenges

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Outline

• Air Traffic Management (ATM): a rich source of switched systems problems
  – ATM as motion coordination in a route network
  – Scales of processes in ATM
  – Motion coordination as a switching system

• Related literature and the gaps

• Other challenges

• What is desirable at higher Technology Readiness
Air Traffic Management (ATM) as Motion Coordination in a Route Network


Switched Systems can help with automation in ATM!
Air Traffic Operations in U. S. Airspace: Scales

- Flights simultaneously airborne: 6,000 – 7,000 at peak hours
- Traffic Flow Management (TFM) time scales:
  - Strategic routing: ~2-6 hrs
  - Tactical routing: <~2 hrs
  - Separation assurance: ~10 mins
- Terminal space size 60-80 nmi around the airport
- Human controller workload (~15-20 aircraft in sector)
Constraints:
An Operational View

• Distance separation requirements
• Merging routes
• Division of responsibility for safety (human vs. automation) – today, mostly human
• Airspace restrictions
• Performance bounds (acceleration, pitch, etc.)
Physical airspace

State space
Physical airspace

State space

states losing separation
Physical airspace

State space
Physical airspace

State space

different orders of precedence on (3, 4)

switching surfaces

apparently, nice geometry…
Physical airspace

State space
(only part of)
Physical airspace

State space
(only part of)
Physical airspace

State space
(only part of)
Physical airspace

State space (only part of)
Physical airspace

State space
(still only part)
A 3-aircraft example

Sadovsky et. al.,
## Related literature and the gaps

<table>
<thead>
<tr>
<th>source(s)</th>
<th>content</th>
<th>assumptions absent in ATM</th>
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<tr>
<td>Dmitruk et. al.: Systems and Control Letters 57(11)</td>
<td>get hybrid Maximum Principle from classical sequence of discrete modes is given</td>
<td></td>
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<tr>
<td>Bengea et. al.: Automatica 41(1)</td>
<td>optimal control of switching systems by embedding system has no memory</td>
<td></td>
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<tr>
<td>R. Ghrist et. al., papers on “coordination”</td>
<td>multi-agent coordination in a route network routes known</td>
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<td>Passenberg et. al.: 49th IEEE Conference on Decision and Control Issue 0191-2216</td>
<td>maximum principle for hybrid systems with partitioned state space</td>
<td>partitioned state space (regional dynamics)</td>
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</table>
| Rezaei et. al.: AIAA Journal of Guidance, Control, and Dynamics doi: 10.2514/1.G001779 | algorithm for feasible hybrid control of arrival flights, with proof of correctness and bounds on computational cost | • all flights fully routed  
• only arrivals  
• only one landing runway  
• piecewise speed profiles  
• no wind |
Other Challenges: Proprietary Data

• **Question:** How to model aircraft control realistically for non-local, strategic navigation in terminal airspace?

• **Challenge(s):** Standard Operating Procedures, Flight Management Systems, and Flight Management Computers (brains of FMS) vary by airline and by manufacturer, and are *proprietary*.

  FAA guidance on developing SOPs: FAA document AC-120-71a. For FMS, some specifications are in ARINC 424.
Other Challenges: Regulation-imposed Constraints on Air Traffic Ops

• **Question:**
  How to model airspace and separation constraints realistically?

• **Challenge(s):**
  – Constraints vary discontinuously by:
    aircraft type, airspace type, and specific airspace.
  – Boundary of safety envelope generally not smooth.

Other Challenges: State Space Geometry

• **Question:** How to (or should one) parameterize a route network for multi-agent motion?

• **Challenge(s):** When one agent reaches the end of its route segment, another is in the middle of its segment. State space *not* a surface.

Other Challenges:
Uncertainty (weather, facility malfunctions, control execution)

• **Question:**
  How to model uncertainty?

• **Challenge(s):**
  Limitations of probability theory.

What is desirable at higher Technology Readiness Levels (TRL)

• Transparent analysis for:
  – Correctness
  – Reliability
  – Regulation compliance

• Real-time computation

• Solutions physically executable

• Feasible cost to industry
Summary

• Air Traffic Management research offers many problems in switched systems
• Multiple spatial and temporal scales; e.g., distinguish:
  – En Route airspace
    (prescribed routes, high altitude, room to hold, strategic planning)
  – Terminal airspace
    (sometimes procedures instead of routes, may not have room, many merging routes, more tactical in nature)

• Publications and other information at:

  www.aviationsystemsdivision.arc.nasa.gov/
• Thanks to D. Isaacson, NASA ARC

• Thank you for your attention
Backup Slides
The geometry of a dynamical system

\[ v \text{ is tangent to the surface at } x \]

Solving for such a \( \xi(t) \) on \( S \) that:

\[ \frac{d}{dt} \bigg|_{t=0} (t) = v(x) \text{ when } (\ ) = x \]
Example: a double pendulum with no inertia

fixed endpoint

$\theta_1$

$\theta_2$

$S$

$2\pi$

$0$

$2\pi$

$\frac{2\pi}{2}$

$\frac{\pi}{2}$
The geometry of control

Solving for such a $u(t)$ (or $u(x)$) that:
the resulting $\xi(t)$ goes where and how we want.

wind
land

switching

wind
land