Airborne Required Time of Arrival (RTA) Control and Integration with ATM

Michael R. C. Jackson, PhD
Honeywell Labs
Minneapolis, Minnesota, USA
Outline

• Motivation

• Single Waypoint RTA

• Multiple Waypoint RTA

• 4D Trajectory Negotiation
Motivation for Airborne Time-based Speed Control

- Many concepts for ATM Automation include Trajectory Based Operations, based on time.

- There are fundamental limits to accuracy using ground-based speed control to achieve time-based operations.
  - Typical concept is use FMS for 3D path with speed clearances from ground
  - Measurement of aircraft state
    - Radar accuracy limits
    - Time delays on measurements
  - Modeling of aircraft performance is generic to type
    - Dash models, engine types, derate settings, etc. are missing
  - Control actuation limitations
    - Inherent time-delays from measurement of disturbance to control action by pilot
  - Controller workload
    - Frequency of clearances by controller are limited by workload

- Airborne feedback control of speed to track time objectives can drastically reduce the trajectory dispersion.
Example from Tailored Arrivals results

Enroute Descent Advisor – Along Track Prediction Accuracy - 23 min time horizon

Acknowledgement: from Rich Coppenbarger, NASA Ames Research Center

In terms of time:
- Mean = 3 sec late
- Max Early = 34 sec
- Max Late = 38 sec
- Std Dev (σ) = 22 sec

Mean = -1.3 nmi
Max = 2.3 nmi
Min = -4.8 nmi
Std Dev = 1.5 nmi
Time-based Aircraft Control - RTA

- Onboard speed adjustment to meet waypoint time-of-arrival constraints
- Based on trajectory predictions function in Flight Management System
- Periodic recalculation of ETA and adjustment of airspeed commands.
  - Off Idle descent planned to allow for automatic throttle changes
  - Prior to Top-of-Descent, the T/D point may move with descent speed changes.
  - When in descent, path is frozen but speed command updated to meet the RTA.
  - If throttle hits idle, pilot must add drag to maintain path and speed.
**Basic RTA Algorithm**

- Consider a simplification of the FMS Trajectory Predictor

\[
ETA = \sum_{wpts} \frac{LegDist}{GndSpd} + Current\_Time
\]

- Speed profile hooked to a speed adjustment parameter (SAP), “speed control knob”
  - For example,

\[
Spd\_cmd_i = Spd\_default_i \times (1 + SAP\times gain_i)
\]

where, \(i \in \text{climb\_cas, climb\_mach, cruise\_mach, des\_mach, des\_cas, etc.}\)

- Differentiating the first equation w.r.t. SAP produces

\[
\frac{\partial ETA}{\partial SAP} = \sum \frac{-\text{LegTime} \times \partial GndSpd}{GndSpd} \frac{\partial GndSpd}{\partial SAP}
\]

- This sensitivity is used to estimate a speed adjustment to null the time error.
  - SAP computed iteratively by observing time error on each pass of trajectory predictions.

\[
\Delta SAP = \frac{RTA - ETA}{\frac{\partial ETA}{\partial SAP}}
\]
**Enhanced RTA Algorithm**

- Non-linearities in the models affect convergence of the algorithm
  - primary issue is the effect of speed limits near minimum and maximum speed
  - Second order partial derivative accounts for nonlinearities

\[
\frac{\delta^2 ETA}{\delta SAP^2} = \sum_{WPTS} \left[ \frac{2 \text{LegDist}}{\text{GndSpd}^3} \left( \frac{\delta \text{GndSpd}}{\delta SAP} \right)^2 - \frac{\text{LegDist}}{\text{GndSpd}^2} \frac{\delta^2 \text{GndSpd}}{\delta SAP^2} \right]
\]

- Solution for speed profile requires a quadratic equation

\[
\frac{1}{2} \frac{\delta^2 ETA}{\delta SAP^2} \Delta SAP^2 + \frac{\delta ETA}{\delta SAP} \Delta SAP + TimeError = 0
\]

- This algorithm converges more quickly than the 1st order algorithm

Preliminary Lab Testing Results

• Tested this RTA system in two of Honeywell’s hardware-in-the-loop validation facility (VALFAC) labs (757 and Gulfstream IV)

• Introduced unmodeled disturbances to observe system reaction
  — Wind prediction error
    › 20 knot headwind error
    › 10 knot tailwind error
  — Effect of turn radius changes with speed
  — Changes to RTA while in descent
  — Unplanned level-off during descent due to traffic
  — Modified vertical constraint while in descent

• In all cases the aircraft crossed the fix within +/- 6 seconds of the RTA

• Caveat – this was limited testing of a prototype system, not a fully certified system.
Linear Analysis Results


- RTA Reduces Trajectory Error
  - Nominal FMS trajectory sensitivity shown with a given set of disturbances
    › Very similar results to Tailored Arrivals
    › My error sources appear to be about 50% worse (2.6 mile vs. 1.5 mile St Dev)
  - RTA control reduces trajectory sensitivity most dramatically at end, but also through whole trajectory.

- Conclusion: ATM system doesn’t need to worry about FMS RTA speed maneuvers causing problems – resulting trajectory better matches the one used in conflict probe than “open-loop” FMS trajectory.
Multiple Waypoint RTA

- Single waypoint RTA may leave open too much uncertainty for some ATM concepts

- Multiple waypoint RTA allows ATM to specify multiple time constraints
  - Each RTA can be
    - AT constraint
    - AT/Before
    - AT/After

- FMS can solve this as a sequence of single waypoint RTAs
  - Earlier RTAs have priority if they cannot all be achieved

Diagram:

1. Initialize each RTA waypoint to Active or Inactive based on waypoint type or last pass.
2. Loop until active RTA waypoints are not changed.
3. Loop over RTA legs.
4. Compute SAP for each active RTA leg.
5. At last RTA wpt?
   - Yes
   - No
5.1. Must any inactive waypoints be activated, or can any active waypoints be deactivated?
   - Yes
   - No
5.1.1. Done.
Multiple Waypoint RTA Example

Legend
- Reference Traj.
- Latest Time
- Earliest Time
- RTA speed

- At/Before RTA
- At/After RTA
- At RTA

RTA Waypoints
AAA
BBB
CCC
DDD
EEE

Minimum Speed Profile
Maximum Speed Profile
Nominal Trajectory
RTA speed profile

Earliest Time
Latest Time
Earliest Time
Latest Time
Earliest Time
Latest Time
Earliest Time
Latest Time
Earliest Time
Latest Time

Delta Time
Distance

+ Later
- Earlier

Reference Traj. 3:10ZB + Later
Earliest Time 3:00ZA - Earlier
Nominal Trajectory 2:30ZB
RTA speed profile 4:40Z

Legend

3:10ZB + Later
- Earlier
Reference Traj.
RTA speed
RTA speed profile
Multiple RTA Effect on Uncertainty

- This is notional based on previous results

![Diagram showing the effect of RTA on uncertainty over time. The diagram illustrates the along-track error with time on the x-axis and along-track error on the y-axis. It compares cases with no RTA control, 1 RTA, 2 RTAs, and a 4D contract. The graph shows a reduction in uncertainty with the implementation of RTAs.]
Air/Ground Trajectory Negotiation

• 4-D trajectory tracking can further improve predictability of flight.
  — FMS actively tracks the trajectory used in ATM’s conflict probe

• Trajectory negotiated between controller and pilot using automation
  — ATM uplinks trajectory constraints (waypoints and RTAs)
  — FMS generates a compliant trajectory (using RTA capability) and downlinks it
  — ATM performs conflict probe and issues clearance
  — FMS uses feedback to track the predicted trajectory
    › Can request new clearance if/when the trajectory is no longer optimal or feasible

• Trajectory generation need on ground and airborne
  — Ground system required for unequipped aircraft and to iterate on solution
  — Airborne system required to assure trajectory is feasible to fly and to improve fuel efficiency

• Data exchange (via ADS-B & FIS-B) increases accuracy of both ground and airborne trajectory prediction systems.
Air/Ground Trajectory Negotiation - detail

FMS/AOC action | FMS downlink / ATM uplink | ATM action
---|---|---
8. Conflict Detection
9. Conflict?
10. Conflict Resolution (determine constraints using trajectory prediction)
11. Trajectory Constraints (Crossing altitudes, flyover waypoints, airspeeds, RTAs, etc.)
12. Trajectory Optimization subject to constraints (Trajectory change feasibility assessment)
14. Determine tracking accuracy requirements
15. Clearance and tracking tolerance requirements
17. Clearance Acknowledgement
19. Trajectory update (periodic)
20. Monitor compliance with contract.
21. Updated Atmosphere Forecasts
22. Predicted bubble violation?
23. Reopen trajectory negotiation process

Acknowledgement – this work was done with Seagull Technologies (now Sensis) on the NASA VAMS Point-to-Point Project

September 2007
Summary

• Airborne FMS control to time in terminal area is feasible
  – But, we only recommend applying time constraints as needed to solve ATM problems
    › Single RTA may solve majority of issues
    › Multiple RTA may be required for crossing traffic situations or airspace boundaries
    › 4D trajectory negotiation may provide additional information to ATM for high density ops

• Benefits
  – Improved accuracy and predictability of trajectories
  – Reduced controller workload
    › No need for several speed clearances to achieve arrival time – FMS generates internally
  – Helps enable Continuous Descent Approach & Tailored Arrivals
    › Reduced fuel burn and emissions
    › Reduced noise
    › Reduced flight time delay

• Challenges
  – Shared separation responsibility between ATM & pilot
    › Requires ATM tools & culture shift
  – Mixed equipage issues
  – Chicken & Egg problem: ATM system <> Airplane Capability <> Airline Investment …
Questions?
Modern aircraft have capable control systems

Flight Management Systems accurately measure, model, and control flight

Also:

TCAS, EGPWS