Egg-shaped conflict envelopes with Fuzzy logic for airspace Collision Risk Modelling

Hee Wei Gary FOO
Zhao-Wei ZHONG
Nanyang Technological University
Acknowledgment

• This research was partially aided by ATMRI of NTU and CAAS via ATMRI Project No. 2014-D2-ZHONG for Regional Airspace Capacity Enhancement – ASEAN Pilot.
Motivation

• To increase airspace capacity, aircraft separation can be reduced.
• Therefore, how are the current separation standards derived?
• Can a different conflict envelope lead to the acceptance of a reduced separation requirement?
Target Level of Safety (TLS)

• TLS is specific to type of flight (recreational, military, commercial, etc.), and phase of flight (cruise, approach, etc.).
• TLS is usually defined as number of accidents per flight hour.
• There are multiple TLS around the world. Generally, they are in the order of $10^{-8}$ to $10^{-9}$ accidents per flight hour.
Collision Risk Models

• No single unified CRM
• EUROCONTROL
  – CRM developed by Mathematical Drafting Group
  – Includes ADS-B and 4D radar information
• Africa & Middle-East
  – CRM based on ICAO’s Rice Formula
Conflict Envelope (or Region of Conflict)

- Existing 3D conflict envelopes
  - Cylindrical
  - Cuboid
Egg-shaped Conflict Envelopes

- 2D Conflict Envelope of similar geometry derived from the shape of an egg
- Gives conflict attention to forward direction
- Conflict status is not transposable \((A \cap B \Leftrightarrow B \cap A)\)

- Inspired from the collision cone in automobile collision detection technology
Geometrical formulation

• Standard ellipse
  \[
  \frac{(x - k)^2}{a} + \frac{(y - m)^2}{b} = 1
  \]

• Modified ellipse with asymmetric x-values
  \[
  \frac{(x - k)^2}{a} + \frac{(y - m)^2}{b} \cdot g(x) = 1
  \]
  \[
  g(x) = 1 - px
  \]

• Parametrized
  \[
  x = t + k
  \]
  \[
  y = \pm \sqrt{\frac{b(a - t^2)}{a(1 - pt)}}
  \]
  \[
  a, b > 0, k \geq 0, t^2 \leq a
  \]
Some early results

• Simulated using entry and exit points on the circumference of a circular 2D airspace.

• 300 runs, each with randomized entry/exit points and time
Non-transposable conflict logic

\[ (A \cap B \Leftrightarrow B \cap A) \]

Aircraft B is in conflict with aircraft A.

Aircraft A is NOT in conflict with aircraft B.
Some results

Percentage of total flight time in conflict

Scenario number
Percentage of total flight time in conflict

Sorted ascending
Histogram fit using Laplace distribution

<table>
<thead>
<tr>
<th></th>
<th>Mean $\mu$</th>
<th>Std Dv $\sigma$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Egg</td>
<td>26.3</td>
<td>9.9</td>
</tr>
<tr>
<td>Circle</td>
<td>25.8</td>
<td>11.9</td>
</tr>
</tbody>
</table>
Tilt of Conflict Envelope

- Conflict envelope tilts with aircraft intention
- Intention may be acquired from flight plan or ATC queries
- Reflects where a conflict is more likely to happen

\[ y' = y + \alpha x^n, \ x > 0 \]
Fuzzy Logic vs Boolean Logic

• Boolean Logic: Yes (1) or No (0)

• Fuzzy Logic: Yes (1), No (0), or any real value between 1 and 0.
  – Infinite number of values

• Logical output = \( f \) (inputs)
Membership Functions (MF) in Fuzzy Logic

- MFs are functions that assign an input to a degree of membership between 0 to 1. Common functions include:
  - Trapezoid
  - Gaussian
  - Cauchy
  - Laplace
  - Logistic (Sigmoid) ← Used for implementation
Conflict Status at the Boundary

- *Conflict* [1 or 0] will change from Boolean to Fuzzy \( \rightarrow \) *Degree of Conflict* [1,0]

![Graph 1](image1)

![Graph 2](image2)
Heatmap of Fuzzy Conflict Envelope
Between Fuzziness and Randomness

- Both concepts can easily be confused since they take on values between 0 and 1.
  - Fuzziness: Degree to which an event occurs
  - Randomness: Certainty of an event occurring

- Eg:
  - Fuzziness: Will it be a thunderstorm, or a light shower, or anything in between.
  - Randomness: How likely will it rain
Challenges

• How can the *level of safety* parameter be
  – **Evaluated** in a simulation,
  – **Compared** with existing standards/models,
  – **Verified** in a real-world setting.

• How can the optimal shape/size of the egg-shape be determined, such that it does not over or under estimate the collision probabilities

• What concept in reality can the *degree of conflict* parameter really represent?
Conclusion

• Presented a non-symmetrical conflict enveloped which prioritizes forward of aircraft.
• Briefly demonstrated a tilted conflict envelope which may vary with the aircraft intent
• Integrated Fuzzy logic to the boundary of the conflict envelope
Thank you for your attention!