



Criteria Approach to Separation Assurance

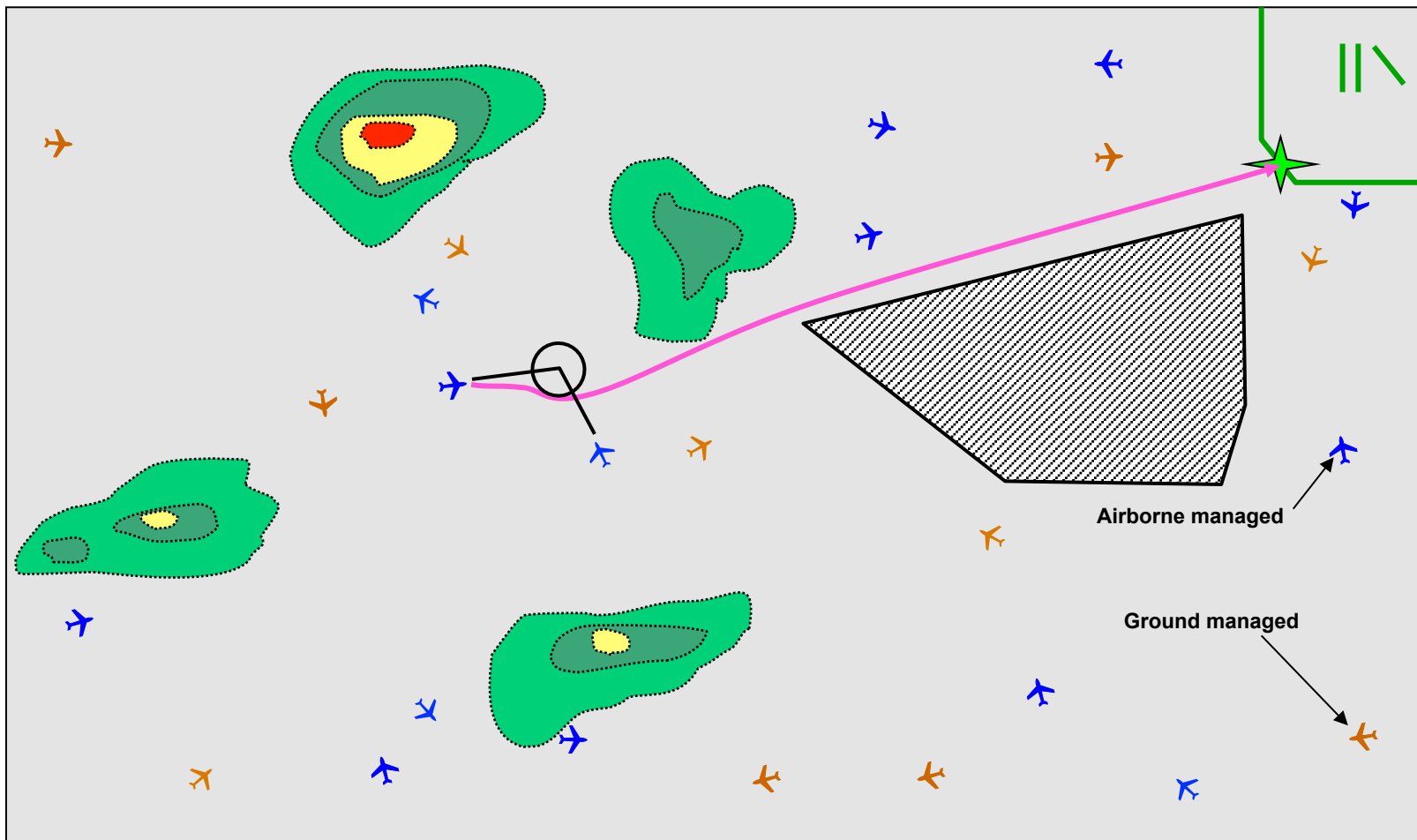
Jeffrey Maddalon,

Rick Butler, George Hagen, Cesar Muñoz, and
Anthony Narkawicz

March 26th, 2015



Self Separation Concept





Separation and Automation

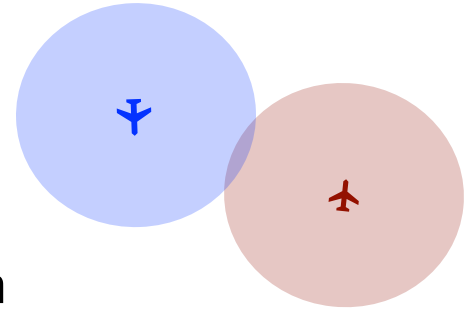
- Collision

- Scrape paint
- Avoid through pilot, controller, and TCAS



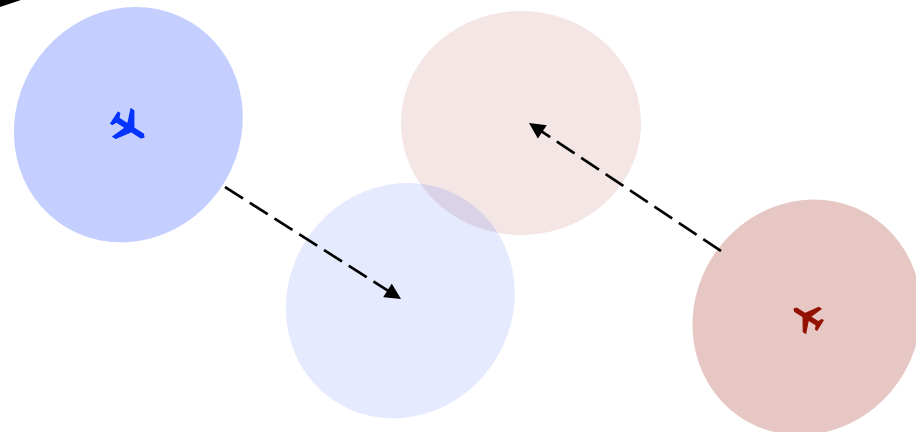
- Loss of Separation

- Separation standards are violated (5nmi, 1000ft)
- Avoid through human and/or automation decisions



- Conflict

- Predicted loss of separation

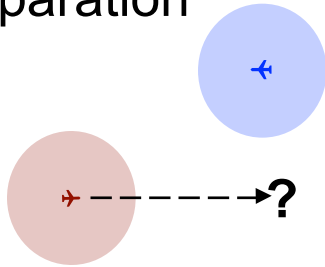




Separation Algorithms

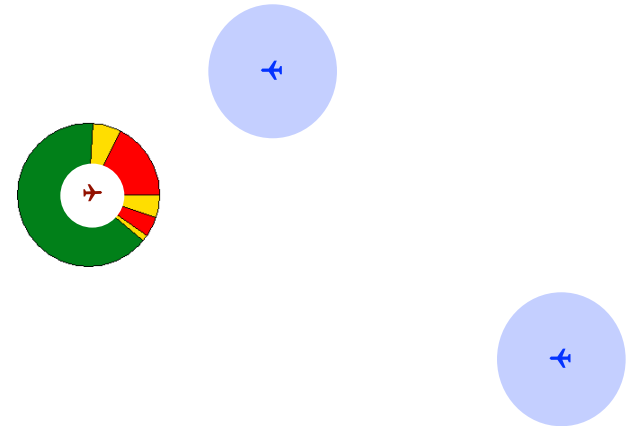
Conflict Detection

- Detect future loss of separation



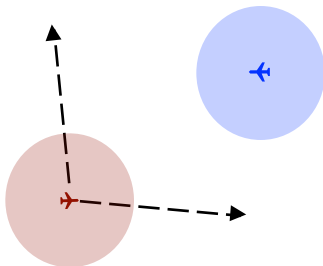
Conflict Prevention

- Provide conflict-free maneuvers



Conflict Resolution

- Suggest maneuvers to avoid a conflict

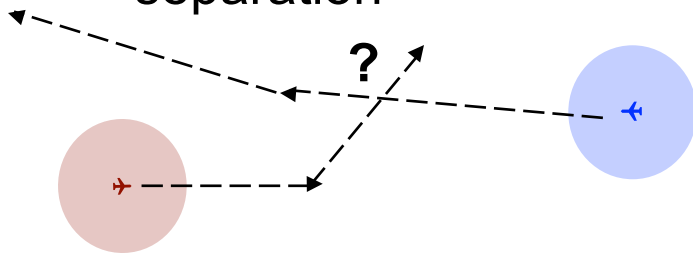




Trajectory Algorithms

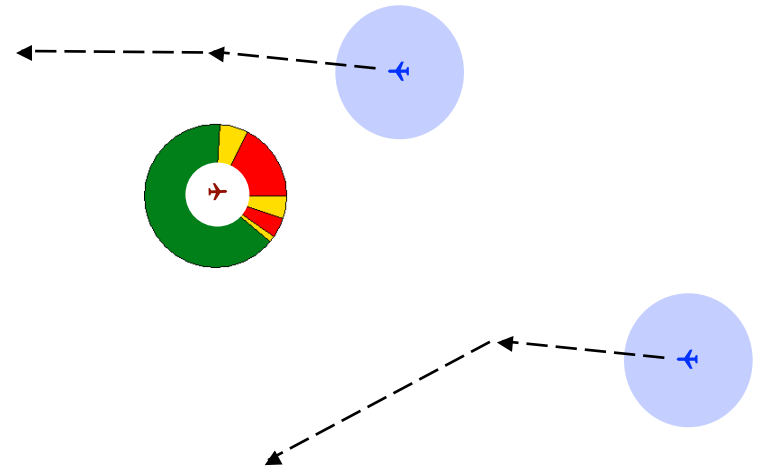
Conflict Detection

- Detect future loss of separation



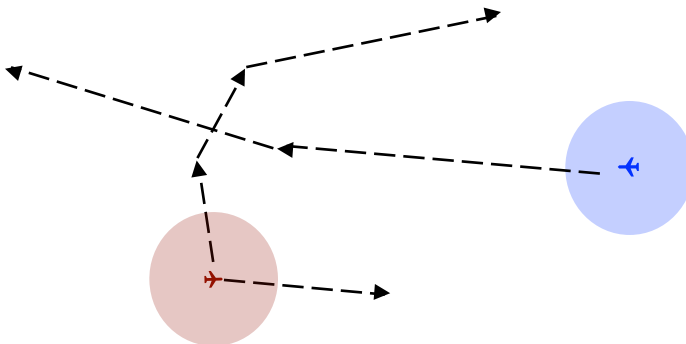
Conflict Prevention

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Conflict Resolution

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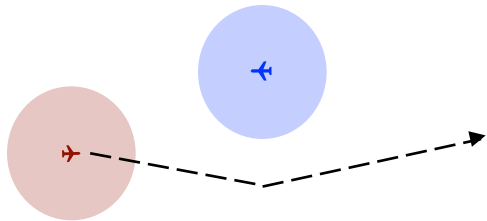




Recovery Algorithms

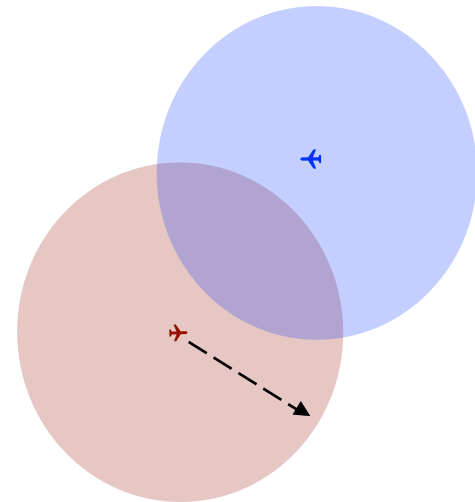
Conflict Recovery

- Suggest maneuvers to regain desired path



Loss of Separation Recovery

- For a variety of reasons separation may be lost
- Suggest a maneuver to regain separation





Research Goal

Develop a mathematical framework for the verification that such algorithms are correct (i.e., maintain safety properties)

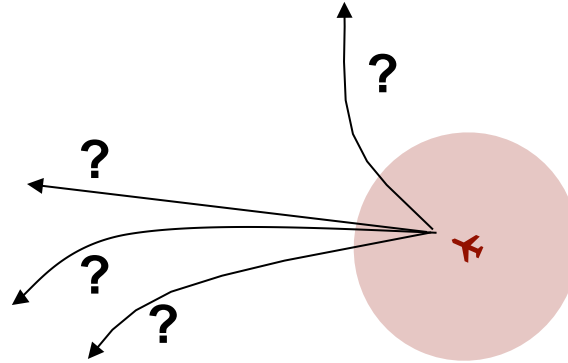
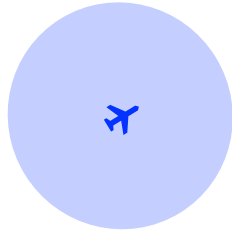


Outline

- Introduction
- **Example: Resolution**
- Criteria Approach to Coordination
- Using Criteria
- Criteria Details
- Summary



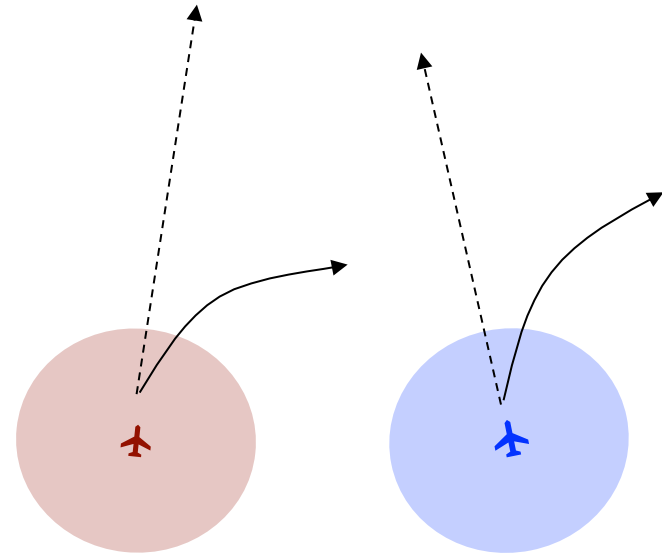
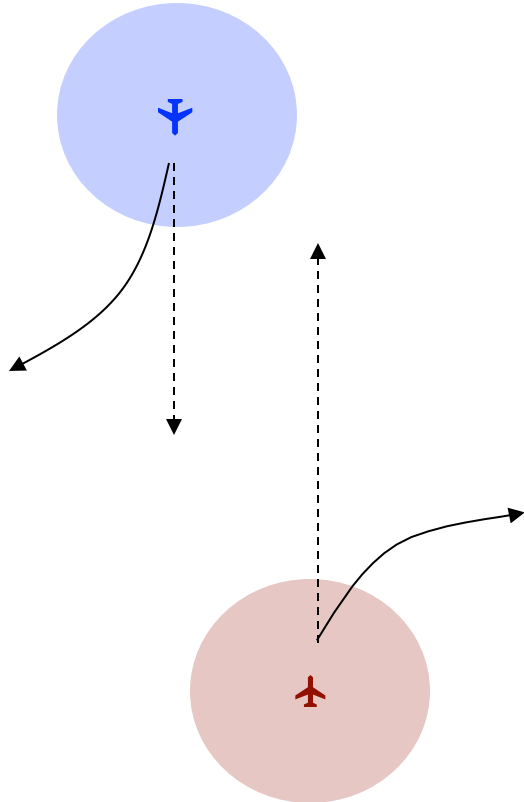
Resolution



- Each aircraft determines its own set of maneuvers to avoid the other aircraft
 - Go right/left
 - Speed up/slow down
 - Go up/down
- Safety Properties
 - Independence: free of conflicts if one aircraft maneuvers
 - **Coordination: free of conflicts if both aircraft maneuver**
- Customer Desires
 - No specific communication between aircraft
 - No unfair rules: lower aircraft ID goes first, etc.



Coordination Examples



Uh, oh...



Coordination

- Correctness
 - When both aircraft maneuver, is the combined maneuver safe?
 - Relies on “knowing” what the other aircraft is going to do
- How to achieve this knowledge?
 - Single algorithm
 - Multiple algorithms



Single Algorithm

- Single algorithm needs a single verification that the algorithm is coordinated with itself
 - For example, TCAS
- But this algorithm must
 - Accommodate aircraft with widely different performance envelopes
 - Have the entire fleet upgraded at one time
 - When new versions come out
 - Be used by everyone...
 - Competing airlines
 - Military traffic
 - International traffic



Multiple Algorithms

- Avoid the difficulties with a single algorithm
 - Multiple versions of TCAS are an example
- But multiple algorithms require
 - Each algorithm to be verified with every other algorithm
 - Costly $N \times N$ verification
 - This cost grows as new algorithms are added
 - and possibly exclude correct new algorithms



Multiple Algorithms

- Avoid the difficulties with a single algorithm
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 - Each algorithm to be verified with every other algorithm
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We have developed an approach that allows **multiple algorithms** with a verification cost close to a single algorithm

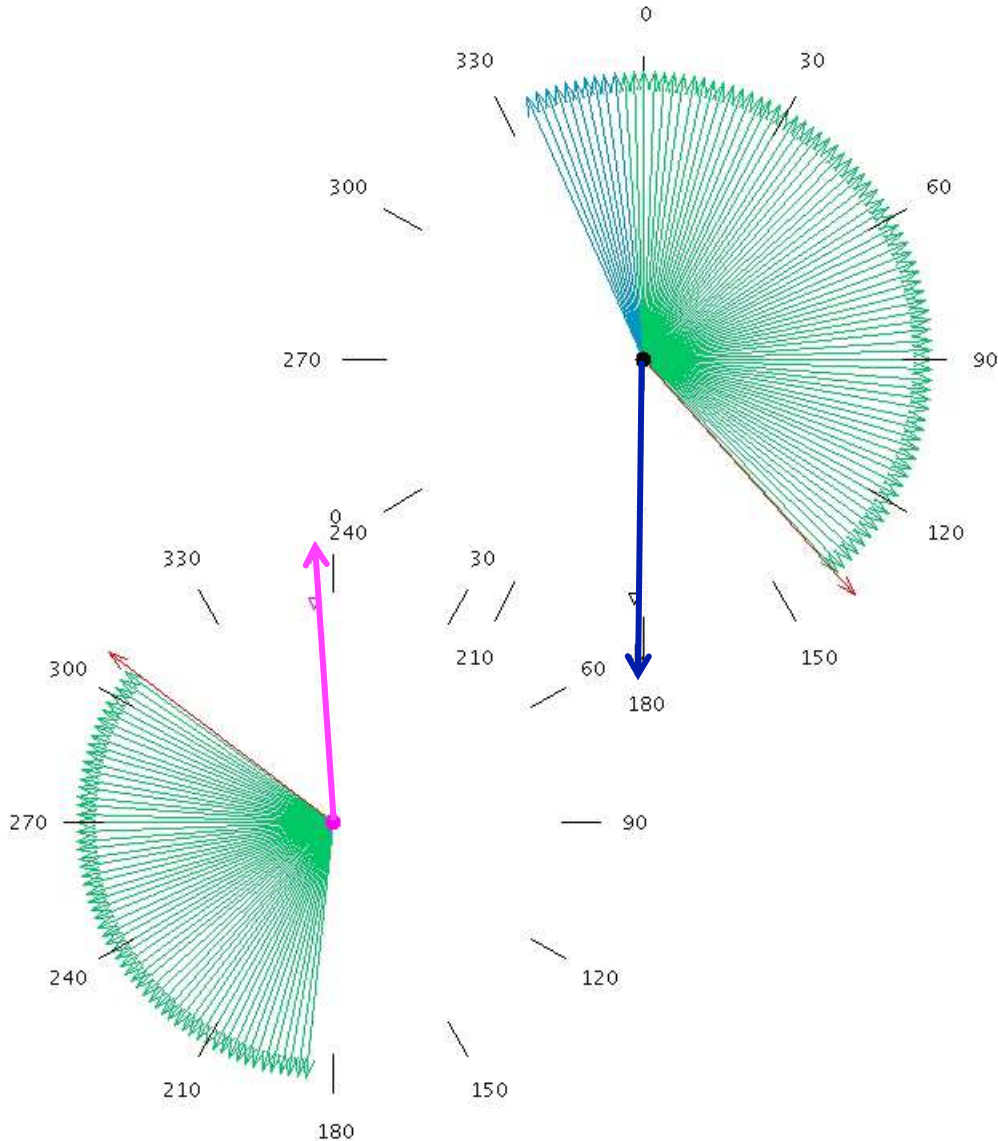


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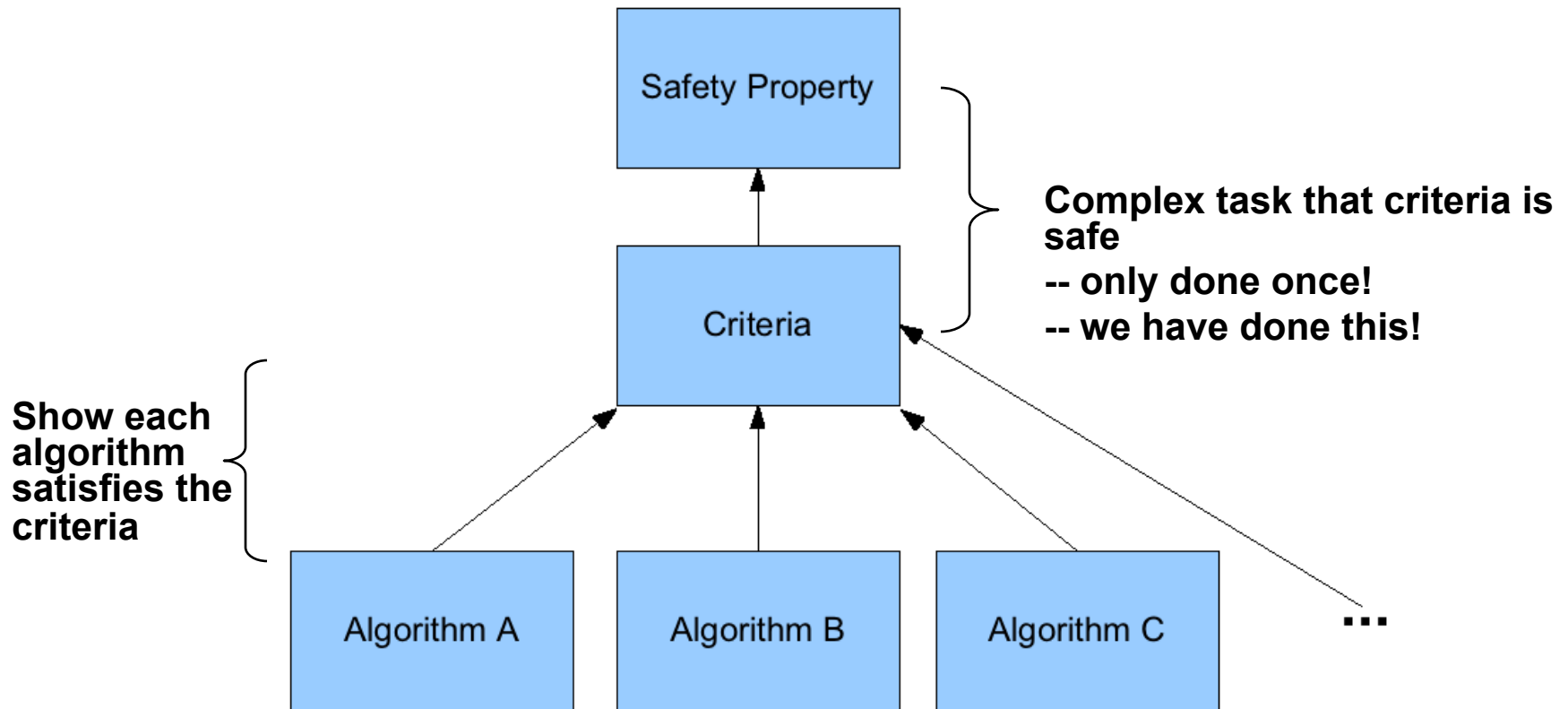
What is Criteria?



- Criteria is a range of resolutions
 - Each aircraft chooses any resolution within the criteria
 - The joint maneuver is coordinated
- Criteria is simple so algorithms can be checked in a straight-forward way



Multiple Algorithms



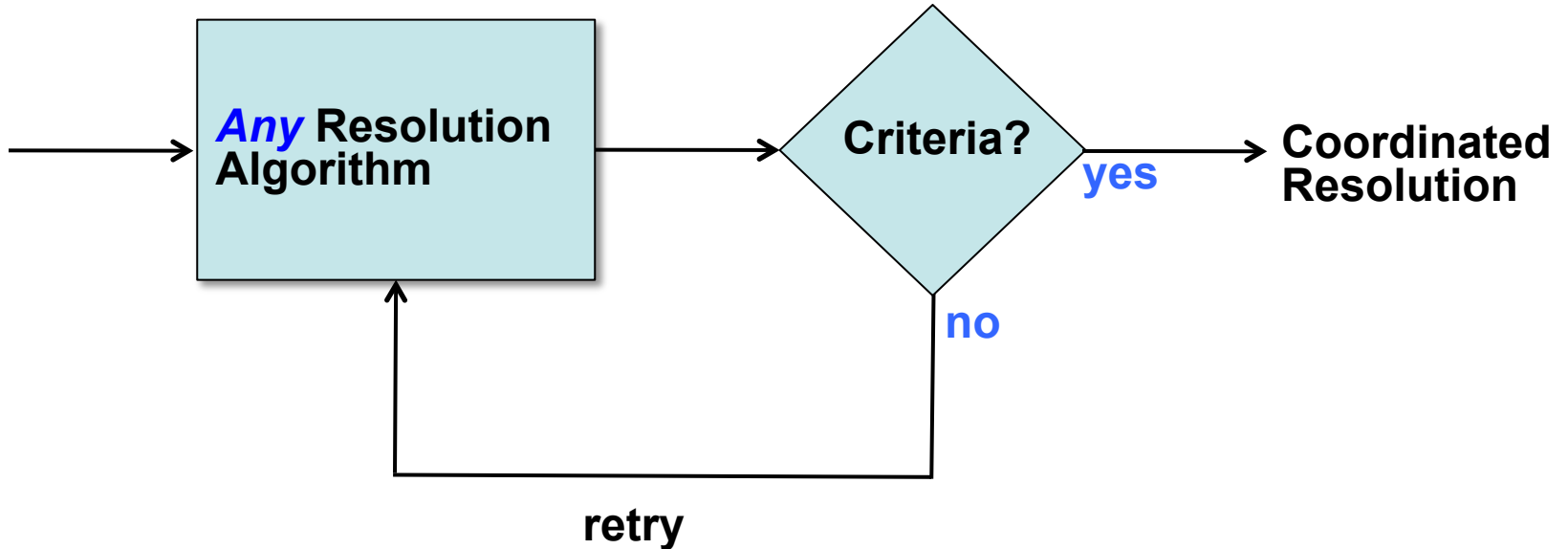


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Criteria “Filtering”



Theunissen and Uijt de Haag, “Towards a seamless integration of awareness support and alerting systems: Why and how” 30th Digital Avionics Systems Conference (DASC), 2011



Integrated Criteria

- Alternately, one can check if an algorithm **inherently** satisfies the criteria
 - Perform a mathematical/software verification that resolutions **always** satisfy the criteria
 - We have done this for several algorithms
 - Anthony Narkawicz and César Muñoz. State-Based Implicit Coordination and Applications, NASA TP-2011-217067, March 2011.

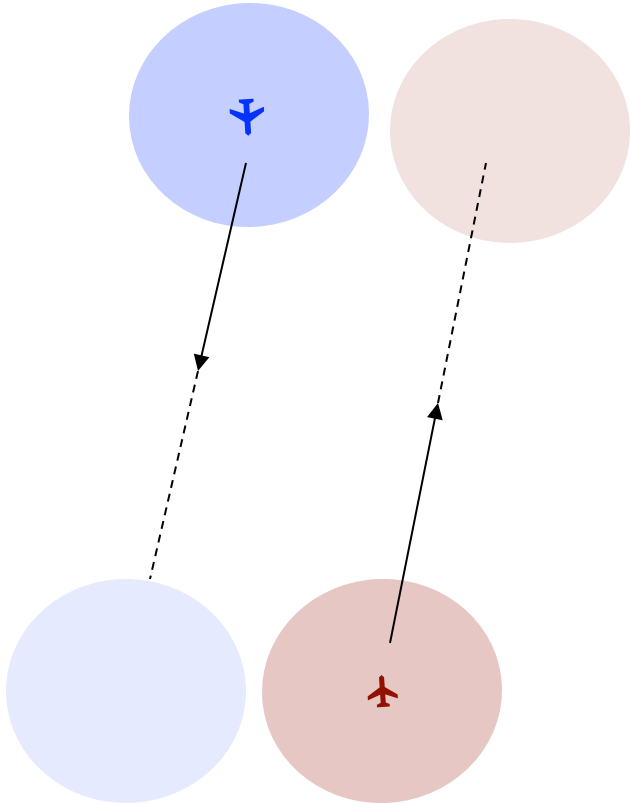


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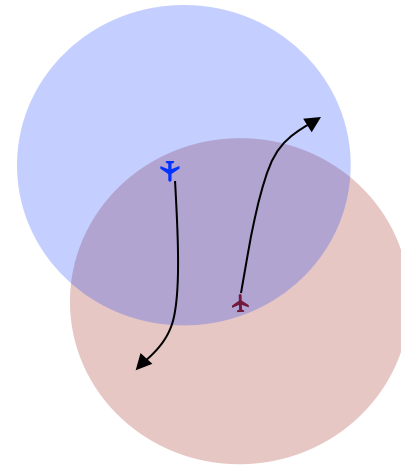


What is Safe?



Conflict-free

For all $t \geq 0 : \|s + t\mathbf{v}\| \geq D$



In Loss of Separation

$\|s + \tau\mathbf{v}'\| > \|s + \tau\mathbf{v}\|$, where τ is the time of closest approach



Criteria

in Conflict

in Loss of Separation

horizontal

$$(\mathbf{s} \cdot \mathbf{v}') \geq \epsilon R(\mathbf{s}^\perp \cdot \mathbf{v}')$$

$$(\mathbf{s} \cdot \mathbf{v}') > \mathbf{s} \cdot \mathbf{v} \text{ AND} \\ (\mathbf{s} \cdot \mathbf{v}') \geq \|\mathbf{s}\| \frac{(D - \|\mathbf{s}\|)}{T_h}$$

vertical

$$\Delta > 0 \text{ AND } t > 0 \text{ AND} \\ \delta = 1 \text{ AND } s_z v_z \geq 0 \\ \text{OR} \\ |s_z + t v_z| \geq H \text{ AND} \\ \delta |s_z + t v_z| v_z \leq 0$$

$$v'_z \neq 0 \text{ AND } s_z v'_z \geq 0 \text{ AND } s_z v_z \geq 0 \\ \text{IMPLIES} \\ \text{IF } v_z = 0 \text{ THEN} \\ \text{break_sym}(\mathbf{s})(v'_z) > 0 \\ \text{ELSE} \\ \text{sign}(v_z) v'_z \geq 0$$

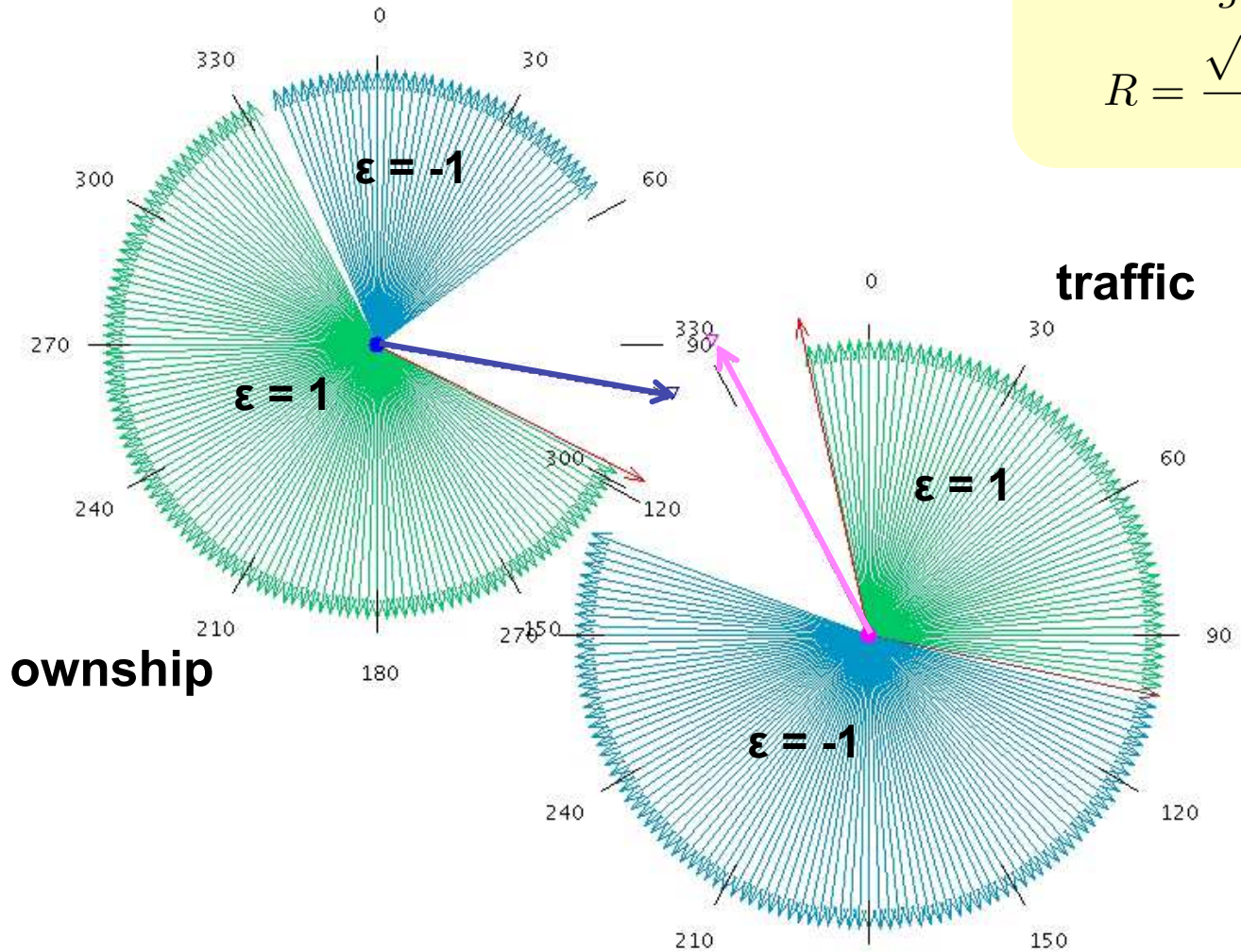


Horizontal Criterion

$$(\mathbf{s} \cdot \mathbf{v}) \geq \epsilon R(\mathbf{s}^\perp \cdot \mathbf{v})$$

where,

$$\epsilon = \text{sign}(\mathbf{s}^\perp \cdot \mathbf{v})$$
$$R = \frac{\sqrt{\mathbf{s}^2 - D^2}}{D}$$





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Summary

- Multiple algorithms and one criteria solves **practical** problems
 - Specialized algorithms for different aircraft performance envelopes
 - Algorithms can evolve
 - » don't have to upgrade the fleet at one time
 - Different algorithms from different vendors
 - » Different avionics suppliers
 - » Customize algorithms for different airlines
 - » International vendors
 - No **costly** NxN verification
- All coordinated solutions are really proposing a criteria
 - Complexity of criteria: “use my algorithm” vs. equations