High-Level Modeling and Analysis of TCAS

Carl Livadas

Theory of Distributed Systems Group
Laboratory for Computer Science
MIT

Joint work with: John Lygeros and Nancy A. Lynch

Outline of Talk

I. Introduction

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III. TCAS Model

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I. Introduction

Goal: Model, analyze, and design hybrid systems.

- Develop abstract system models.
- Prove high-level theorems about system safety.
- Refine models.
- Use refinement to infer lower-level theorems.

Framework: Input/Output Automaton models

- Precise notion of behavior at component interfaces.
- Invariant assertion proofs.
- Compositional reasoning.
- Levels of abstraction (simulation proofs).
- Asynchronous [Lynch, Tuttle]
  Timed [Lynch, Vaandrager]
  Hybrid [Lynch, Segala, Vaandrager, Weinberg]

Hybrid System Case Studies

Hybrid System Benchmark Problems:

- Railroad Crossing Problem [Heitmeyer, Lynch 94]
- Steam Boiler Controller [Leeb, Lynch 95]

Personal Rapid Transit Systems:

- Raytheon's PRT 2000™
  [Weinberg, Lynch 95], [Weinberg, Lynch, Delisle 96], [Weinberg 96]
  [Livadas 97], [Livadas, Lynch 98]

Automated Highway Systems:

- California PATH Project
  [Branicky, Dolginova, Lynch 96], [Dolginova, Lynch 97], [Dolginova 98]

Air Traffic Management Systems:

- Traffic Alert and Collision Avoidance System (TCAS)
  [Lygeros, Lynch 97], [Livadas, Lynch, Lygeros 99]

Traffic Alert and Collision Avoidance System (TCAS)

- On board conflict detection/resolution system
- Safety critical but very complex
- Humans in the loop
- Developed through a series of revisions:
  - TCAS I: Traffic Advisories (TAs)
    (implemented, 1983)
  - TCAS II-6: TAs and vertical Resolution Advisories (RAs)
    (implemented, 1990)
  - TCAS II-7: TAs and vertical RAs with reversals
    (developed, 1997)
  - TCAS III: TAs and horizontal/vertical RAs
    (abandoned)
  - TCAS IV: TAs and horizontal/vertical RAs using GPS
    (conceptual)

More about TCAS II-7

TCAS II-7 uses:

- Range and range rate data (radar).
- Own and intruder altitude data (*Mode_S* transponder).
- Simple aircraft dynamics ($\ddot{x} = u$).
- Simple intruder intent assumptions ($u = 0$).

To:

- Alert pilot to potential collision threats.
- Determine maneuver to resolve conflict.
  - Sufficient vertical separation at closest approach.
  - "Climb" or "Descend" only.
- Issue resolution advisories to pilot.
  - Consistent for TCAS-equipped aircraft.
  - Can reverse resolution advisories (once).

Validation for TCAS

Extensive simulation:

- MIT Lincoln Labs [Drumm 97–98]
  - Provides no absolute guarantees.
  - Number of test cases very large (approx. 2 million).
  - Changes involve extensive regression testing.
  - Hard to provide conditional guarantees.

Software specification methods:

- StateCharts [Harel 97]
- RSML [Leveson, Heimdahl, Hildreth, Reese 94, 96]
- SpecTRM-RL [Leveson, Heimdahl, Reese, Brown 98, 99]
- Intent Specifications [Leveson 98]

Probabilistic modeling:

- [Kuchar 95]

Drawbacks of these approaches:

- Primarily software (not hybrid).
- Complete, detailed, low-level.
- Validation: Static checking, e.g., all cases covered.

What Else is Needed?

Better models for TCAS systems:

- Include continuous and discrete system components.
- Model and analyze systems at higher level of abstraction.
  - Capture intuitions of software designers, application users.
  - Suitable for informal communication/documentation.
  - Suitable for formal reasoning.
- Allow nondeterminism, incorporate uncertainty.
- Use formal notions of composition and refinement.
  - Support successive model refinement down to code level.
  - Connect with lower-level verification approaches.

Short-Term Goals for TCAS:

- Safety guarantees (Conditional but absolute).
- Qualitative evaluation of system limitations.
- Propose suggestions for the design of TCAS IV.

Long-Term Goals for TDS:

- Develop practical verification approach for hybrid systems:
  - Improve the hybrid system model and proof methods.
  - Develop practical tools for designing hybrid systems.

II. Hybrid Input/Output Automata

[Lynch, Segala, Vaandrager, Weinberg 96, 99]

$\boldsymbol{A = (U, X, Y, \Sigma^{in}, \Sigma^{int}, \Sigma^{out}, \Theta, \mathcal{D}, \mathcal{W})}$:

- Variables V
  (Input U/Internal X/Output Y; External $E = U \cup Y$)
- Discrete Actions Σ
  (Input Σ^{in}/Internal Σ^{int}/Output Σ^{out})
- Initial States Θ
- Discrete Transitions $\mathcal{D}$ (discrete behavior)
- Trajectories $\mathcal{W}$ (continuous behavior)

Axioms: input-enabling, closure of trajectories, *etc.*

Execution

- $\alpha = w_0 a_1 w_1 a_2 w_2 \cdots$, where $\alpha.\mathit{fstate} \in \Theta$, $w_i \in \mathcal{W}$, and $a_i \in \Sigma$
- Admissible: $\alpha.\mathit{ltime} = \infty$

Traces (external behavior)

- $\gamma = (w_0 \downarrow E)\mathit{vis}(a_1)(w_1 \downarrow E)\mathit{vis}(a_2)(w_2 \downarrow E) \cdots$

HIOA model admits:

- Parallel composition
- Successive refinement (levels of abstraction)

Composition of HIOAs

Let A_1 and A_2 be two compatible HIOA. The composition of A_1 and A_2 is defined as $A_1 \times A_2 = (U, X, Y, \Sigma^{in}, \Sigma^{int}, \Sigma^{out}, \Theta, \mathcal{D}, \mathcal{W})$, where:

- $X = X_1 \cup X_2$
  $Y = Y_1 \cup Y_2$
  $U = (U_1 \cup U_2) - (Y_1 \cup Y_2)$

- $\Sigma^{int} = \Sigma_1^{int} \cup \Sigma_2^{int}$
  $\Sigma^{out} = \Sigma_1^{out} \cup \Sigma_2^{out}$
  $\Sigma^{in} = (\Sigma_1^{in} \cup \Sigma_2^{in}) - (\Sigma_1^{out} \cup \Sigma_2^{out})$

- $s \in \Theta$ iff $s \lceil V_1 \in \Theta_1 \ \wedge \ s \lceil V_2 \in \Theta_2$

- $(s, a, s') \in \mathcal{D}$ iff $s \lceil V_1 \xrightarrow{\pi_{A_1}(a)}_{A_1} s' \lceil V_1 \ \wedge \ s \lceil V_2 \xrightarrow{\pi_{A_2}(a)}_{A_2} s' \lceil V_2$

- $w \in \mathcal{W}$ iff $w \downarrow V_1 \in W_1 \ \wedge \ w \downarrow V_2 \in W_2$

Levels of Abstraction/Simulation Relations

Simulation relation from A to B (same external signature):

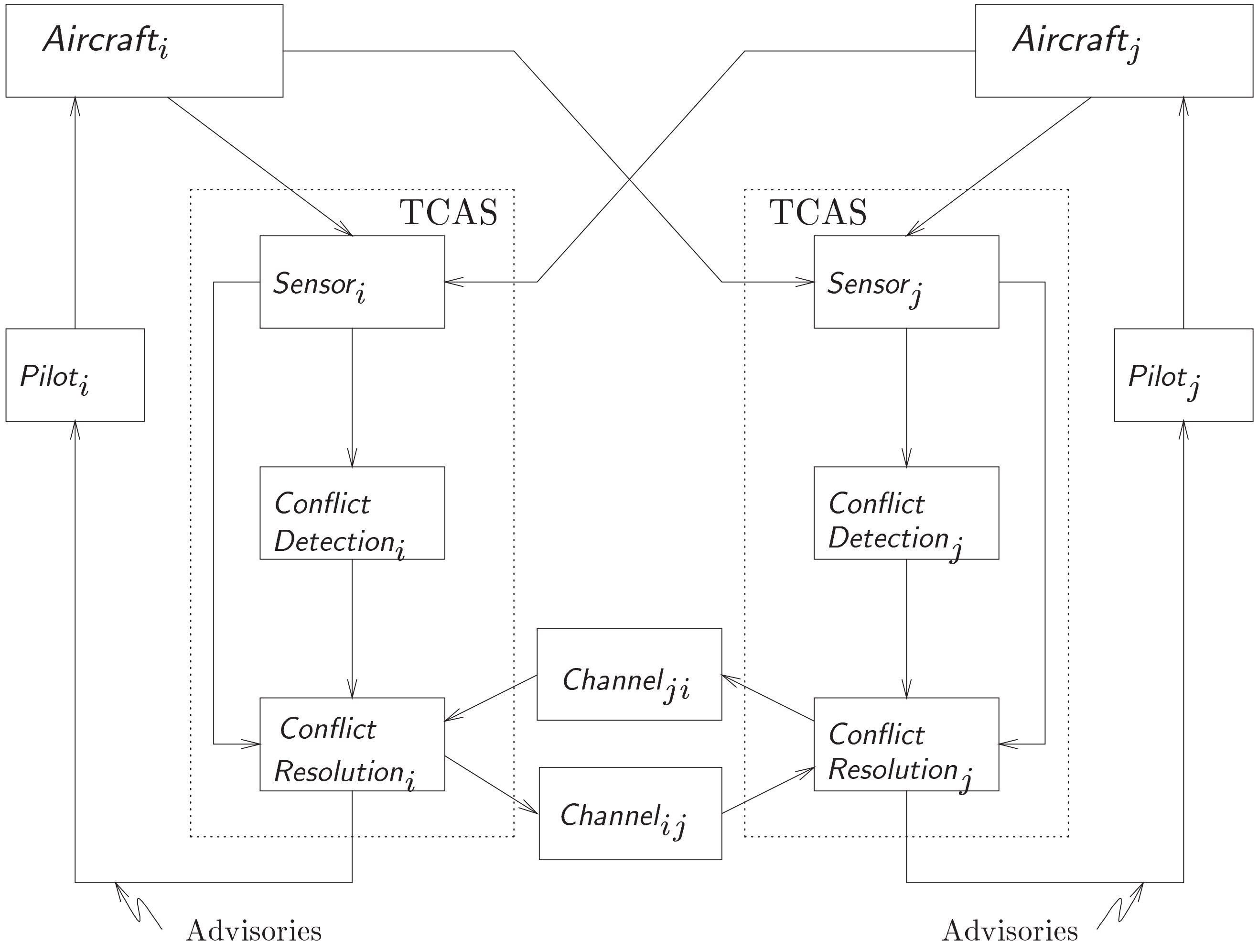
1. If $r \in \Theta_A$, then B has start state s with $r \; R \; s$.

2. If $r \; R \; s$ and $r \xrightarrow{a}_A r'$ then
   B has a finite execution fragment α from s to s', with the same trace, and with $r' \; R \; s'$.

3. If $r \; R \; s$ and w is a trajectory of A from r to r' then
   B has finite execution fragment α from s to s', with the same trace, and with $r' \; R \; s'$.

Theorem.
If there is a simulation from A to B, then traces$(A) \subseteq$ traces(B).

III. TCAS Model



TCAS Components

Aircraft Automaton A_i

- Variables representing transponder number and equipment.
- Simple aircraft dynamics.

Sensor Automaton S_i

- Senses available signals and schedules conflict resolutions.

Conflict Detection Automaton D_i

- Senses available information and declares/undeclares threats.

Conflict Resolution Automaton R_i

- Resolves threats.

Communication Channel Automaton C_{ij}

- Sends messages between aircraft.

Pilot Automaton P_i

- Maintains velocity and acceleration within acceptable bounds.
- Follows/ignores advisories within alloted time.

Aircraft Automaton A_i

Variables:

Input: $a_i \in \mathbb{R}^3$, aircraft acceleration

Output: $Mode\_S_i \in \mathbb{N}$, unique transponder number

$Equipment_i \in \{\text{None}, \text{Report}, \text{TCAS}\}$

$p_i \in \mathbb{R}^3$, position

$v_i \in \mathbb{R}^3$, velocity

Discrete Actions:

None.

Trajectories:

Input variables arbitrary.

$Mode\_S_i$, $Equipment_i$ constant.

$$\begin{bmatrix} \dot{p}_i(t) \\ \dot{v}_i(t) \end{bmatrix} = \begin{bmatrix} v_i(t) \\ a_i(t) \end{bmatrix}$$

Sensor Automaton S_i

Variables:

Input: p_j, v_j, for all j

Output: $R_{ij} \in \mathbb{R}^+, \dot{R}_{ij} \in \mathbb{R}$, for all other j, range and range rate

$h_{ij} \in \mathbb{R}^+, \dot{h}_{ij} \in \mathbb{R}$, for all j, relative altitude and vertical velocity

Internal: A timer.

Actions:

Output: Sample_i

Trajectories:

Input variables arbitrary.

Output variables constant, calculated from inputs.

Trajectories stop when Sample_i action enabled (after time T).

Discrete Transitions:

Sample_i occurs every T seconds.

Conflict Detection Automaton D_i

Variables:

Input: $R_{ij}, \dot{R}_{ij}$, for all other j
$h_{ij}, \dot{h}_{ij}$, for all j

Derived: $\mathit{Range\_Test}_{ij} \in \texttt{Bool}$, for all other j
$\mathit{Altitude\_Test}_{ij} \in \texttt{Bool}$, for all other j

Actions:

Output: $\mathit{Declare}_{ij}$, for all other j
$\mathit{Undeclare}_{ij}$, for all other j

Trajectories:

Input variables arbitrary.
Trajectories stop when any output action enabled.

Discrete Transitions:

- $\mathit{Declare}_{ij}$ occurs when aircraft j poses a threat (satisfies range, altitude tests).
- $\mathit{Undeclare}_{ij}$ occurs when aircraft j moves out of range (fails range test).

Details of range, altitude tests extracted from TCAS specifications.

Conflict Resolution Automaton R_i

Variables:

Input: h_{ij}, $\dot{h}_{ij}$, R_{ij}, $\dot{R}_{ij}$, *Mode_S*$_j$, *Equipment*$_j$

Output: *Sense*$_i \in \{\text{Climb}, \perp, \text{Descend}\}$, initially $\perp$

Strength$_i \in \{2500, 1500, 0, -500, -1000, -2000\}$ (units of ft/min)

Actions:

Input: *Sample*$_i$

Declare$_{ij}$, *Undeclare*$_{ij}$

Receive$_{ji}$(dir)

Output: *Send*$_{ij}$(dir)

Discrete Transitions:

- Sense selected initially (upon *Declare*$_{ij}$ or *Receive*$_{ij}$(dir)), may be reversed later (upon *Receive*$_{ij}$(dir) or *Sample*$_i$).
- Sense changes communicated to intruder (*Send*$_{ij}$(dir)).
- After *Declare*$_{ij}$, strength selected upon every *Sample*$_i$.
- *Sense*$_i$, *Strength*$_i$ told to the pilot.
- Conflict ends for j upon *Undeclare*$_{ij}$.

Sense Selection $[N = 2]$

- Initial selection upon $\mathit{Declare}_{ij}$:
  - If only one sense OK, choose it.
  - If both senses OK, choose non-crossing.
  - If neither sense OK, choose the one that leads to greater separation.
- Initial selection upon $\mathit{Receive}_{ij}(\mathrm{dir})$:
  - If $\mathit{Mode\_S}_i > \mathit{Mode\_S}_j$ comply.
  - If $\mathit{Mode\_S}_i < \mathit{Mode\_S}_j \wedge$ dir non-crossing, comply.
  - If $\mathit{Mode\_S}_i < \mathit{Mode\_S}_j \wedge$ dir crossing, choose as above.
- Subsequent sense selection upon $\mathit{Receive}_{ij}(\mathrm{dir})$:
  - If $\mathit{Mode\_S}_i > \mathit{Mode\_S}_j$ comply.
  - If $\mathit{Mode\_S}_i < \mathit{Mode\_S}_j$ ignore.
- Subsequent sense selection upon Sample_i:
  - If $\mathit{Mode\_S}_i > \mathit{Mode\_S}_j$ do nothing.
  - If $\mathit{Mode\_S}_i < \mathit{Mode\_S}_j$ reverse if current sense not OK and reversed sense OK and non-crossing.
  - Reverse at most once.

Communication Channel and Pilot Automata

Communication Channel Automaton C_{ij}: Messages from i to j

- Input Action: *Send*$_{ij}$
- Output Action: *Receive*$_{ji}$
- All messages delivered, in order, within time d_c.

Pilot Automaton P_i:

- Generates $a_i \in [\underline{a}_x, \overline{a}_x] \times [\underline{a}_y, \overline{a}_y] \times [\underline{a}_z, \overline{a}_z]$.
- Maintains vertical velocity in $[\underline{v}_z, \overline{v}_z]$.
- May follow or ignore an advisory (*Follow*$_i$).
- If *Follow*$_i$ $=$ False, may apply any allowable a_i.
- If *Follow*$_i$ $=$ True, responds within time d_p by applying $a_{zi} = \sigma a$ until $\sigma \dot{h}_{ii} \geq$ *Strength*$_i$, where $\sigma = 1$, if *Sense*$_i$ $=$ Climb, and $\sigma = -1$, otherwise. Before then, apply any allowable a_i.

IV. Results So Far

Verification Approach:

- Start with simple/idealized cases.
  - Only two aircraft, both TCAS equipped, limited uncertainty,...
- Consider various execution assumptions.
  - Both pilots follow advisories, within certain time.
  - One follows, one keeps going as before,...
- Obtain conditional claims, conditioned on execution assumptions.
- Gradually add complexity.

Verification Goal:

Theorem. *TCAS ensures that aircraft maintain sufficient separation.*

Proof Outline

Proof Approach:

1. Define "well-behaved aircraft system", *WBS*.
2. Classify *WBS* executions into three categories.
   - Non-crossing
   - Crossing
   - Reversing
3. Prove safety for each execution category.
4. Combine per-category safety results to obtain overall safety results.

Proof Goal:

Theorem. *If safety condition P holds when a conflict is declared then TCAS ensures that "well-behaved" aircraft maintain sufficient separation.*

Well-Behaved Aircraft System (WBS)

- Only two aircraft.
- Aircraft 1 has higher priority.
- Communication channels C_{12} and C_{21} are FIFO.
- Both aircraft TCAS equipped.
- Both pilots follow RAs.
- No sensor uncertainty.
- Use nominal strength only.
- Constant horizontal velocity.
- Pilots do not oppose RAs.
- Sufficient time to implement RAs.
- When threat is first detected, at least one sense appears to be ok.

Well-Behaved Aircraft System (WBS)

- Only two aircraft.
- Aircraft 1 has higher priority: $\mathit{Mode\_S}_1 < \mathit{Mode\_S}_2$.
- Communication channels C_{12} and C_{21} are FIFO.
- Both aircraft TCAS equipped: $\mathit{Equipment}_1 = \mathit{Equipment}_2 = \text{TCAS}$.
- Both pilots follow RAs: $\mathit{Follow}_1 = \mathit{Follow}_2 = \text{True}$.
- No sensor uncertainty.
- Use nominal strength only: $\mathit{Strength}_1 = \mathit{Strength}_2 = 1500$.
- Constant horizontal velocity: $\underline{a}_x = \overline{a}_x = \underline{a}_y = \overline{a}_y = 0$.
- Pilots do not oppose RAs: $\mathit{Sense}_i \neq \perp \implies \sigma_i a_{zi} \geq 0$,
  where $\sigma_i = 1$, if $\mathit{Sense}_i = \text{Climb}$, and $\sigma_i = -1$, otherwise.

Well-Behaved Aircraft System (WBS), cont'd

- Sufficient time to implement RA: Initially, $T > 2d_c + d_p$.
- When threat is first detected, at least one sense appears OK: Initially $SEP_{ij}(\sigma) \geq ALIM$, for some $\sigma \in \{-1, 1\}$.

T, Time to closest horizontal approach:

$$T = -\frac{\Delta x \Delta v_x + \Delta y \Delta v_y}{\Delta v_x^2 + \Delta v_y^2}$$

τ, Estimated time to closest approach:

$$\tau = -\frac{R_{ij}}{\min\{\dot{R}_{ij}, -10\}}$$

SEP_{ij}, Estimated vertical separation at closest approach:

$$SEP_{ij}(\sigma) = \begin{cases} \sigma\left[\Delta z_{ij} + \Delta v_{zij}\tau\right], \text{ if } (\tau \leq d) \vee (\sigma v_{zi} \geq 1500), \\ \sigma\left[\Delta z_{ij} + \Delta v_{zij} d + (1500\sigma - v_{zj})(\tau - d)\right], \text{ else.} \end{cases}$$

where $\sigma \in \{-1, 1\}$, sense of aircraft i and
$d \in \mathbb{R}^+$, RA implementation delay assumed by TCAS.

WBS Execution Categories

Non_Crossing_Execs

- TCAS protocol invoked
- Non-crossing RA issued initially
- Non-crossing RA maintained throughout conflict

Crossing_Execs

- TCAS protocol invoked
- Crossing RA issued initially
- Crossing RA maintained throughout conflict

Reversing_Execs

- TCAS protocol invoked
- Crossing RA issued initially
- Non-crossing RA issued subsequently
- Non-crossing RA maintained thereafter throughout conflict

Per-Category Results

Definition. *Safe_Execs is the set of executions of WBS in which the aircraft are sufficiently separated in altitude (ALIM) at closest horizontal approach.*

Lemma 1.
If $\alpha \in$ Non_Crossing_Execs and P_{NC} holds initially, then $\alpha \in$ Safe_Execs.

Lemma 2.
If $\alpha \in$ Crossing_Execs and P_C holds initially, then $\alpha \in$ Safe_Execs.

Lemma 3.
If $\alpha \in$ Reversing_Execs and P_R holds initially, then $\alpha \in$ Safe_Execs.

Lemma 1: Safety of Non-Crossing Executions

P_{NC}:
$S \geq$ *ALIM*, where $S =$ projected smallest altitude separation at time T (time of closest horizontal approach), based on non-crossing RA, nominal strength.

Calculating S:

- Initial altitude separation, minus
- Potential loss in altitude separation due to RA implementation delay D_{NC}, plus
- Altitude separation gained by following nominal strength non-crossing RA from when it is implemented until T.

$S = |\Delta z| + V_{NC} D_{NC} + 3000(T - D_{NC})$, where
$\sigma = \text{sign}(z_1 - z_2)$,
$D_{NC} = 2d_c + d_p$, and
$V_{NC} = \max(\underline{v}_z, \sigma v_{z1} - \overline{a}_z d_c) + \max(\underline{v}_z, -\sigma v_{z2} - 2\overline{a}_z d_c)$.

Lemma 2: Safety of Crossing Executions

P_C:

$S \geq$ *ALIM*, where $S =$ projected smallest altitude separation at time T, based on crossing RA, nominal strength.

Calculating S:

- Initial altitude separation, minus
- Potential loss in altitude separation due to RA implementation delay D_C, plus
- Altitude separation gained by following nominal strength crossing RA from when it is implemented until T.

$S = -|\Delta z| + V_C D_C + 3000(T - D_C)$, where

$\sigma = \text{sign}(z_1 - z_2)$,

$D_C = 2d_c + d_p$, and

$V_C = \max(\underline{v}_z, -\sigma v_{z1} - \overline{a}_z d_c) + \max(\underline{v}_z, \sigma v_{z2} - 2\overline{a}_z d_c)$.

Lemma 3: Safety of Reversing Executions, $T_R \leq D_C$

P_R:
$S \geq$ *ALIM*, where S = projected smallest altitude separation at T, based on reversing just prior to implementing a crossing advisory, then following non-crossing RA, nominal strength.

Calculating S:

- Initial altitude separation, minus
- Potential loss in altitude separation due to reversed RA implementation delay $D_C + D_R$, plus
- Altitude separation gained by following nominal strength non-crossing RA from the time of implementing the reversal until T.

$S = |\Delta z| + V_R(D_C + D_R) + 3000(T - D_C - D_R)$, where
$\sigma = \text{sign}(z_1 - z_2)$,
$D_R = d_c + d_p$, and
$V_R = \max(\underline{v}_z, \sigma v_{z1} - \overline{a}_z D_C) + \max(\underline{v}_z, -\sigma v_{z2} - \overline{a}_z(D_C + d_c))$.

Lemma 3: Safety of Reversing Executions, $T_R > D_C$

- At time of reversal, both aircraft have implemented the crossing RA, $i.e.$, $-\sigma v_{z1} \geq 1500$ and $\sigma v_{z2} \geq 1500$.
- In order to reverse, crossing RA must not be OK and non-crossing RA must be OK, $i.e.$, $\mathit{Sep}_{12}(-\sigma) < \mathit{ALIM}$ and $\mathit{Sep}_{12}(\sigma) \geq \mathit{ALIM}$.

$\Longrightarrow \ \sigma \Delta z \geq \mathit{ALIM}$

Lemma 3: Safety of Reversing Executions, $T_R > D_C$

P_R:
$S \geq \mathit{ALIM}$, where S = projected smallest altitude separation at T, based on reversing just prior to the $\sigma\Delta z = \mathit{ALIM}$ mark, then following non-crossing RA, nominal strength.

Calculating S:

- Initial altitude separation ($\sigma\Delta z = \mathit{ALIM}$), minus
- Potential loss in altitude separation due to RA implementation delay D_R, plus
- Altitude separation gained by following nominal strength non-crossing RA from the time of implementing the reversal until T.

$S = \mathit{ALIM} + V_R D_R + 3000(T - \overline{T}_R - D_R)$, where
$\sigma = \mathrm{sign}(z_1 - z_2)$,
$D_R = d_c + d_p$,
$V_R = \max(\underline{v}_z, \sigma v_{z1} - \overline{a}_z \overline{T}_R) + \max(\underline{v}_z, -\sigma v_{z2} - \overline{a}_z(\overline{T}_R + d_c))$, and
$\overline{T}_R$, upper bound on reversing time, given by:
$-|\Delta z| + V_C D_C + 3000(\overline{T}_R - D_C) = -\mathit{ALIM}$.

Overall Safety Results

Goal: Find condition P such that:
For any execution α of *WBS*, if P holds initially, then $\alpha \in$ *Safe_Execs*.

Sample Results:

1. **Conjunction of Safety Conditions**

2. **Ruling out Crossing RAs**

3. **Aircraft Close in Altitude**

Overall Safety Results, cont'd

Conjunction of Safety Conditions:

- $P = P_{NC} \wedge P_C \wedge P_R$
- Simple but conservative.

Ruling out Crossing RAs:

- $P = P_{NC} \wedge \mathit{Crossing\_Impossible}$, where

$$\sigma = \mathrm{sign}(z_1 - z_2), \text{ and}$$

$$\begin{aligned}\mathit{Crossing\_Impossible} = &(\mathit{Sep}_{12}(\sigma) \geq \mathit{ALIM} \vee \mathit{Sep}_{12}(-\sigma) < \mathit{ALIM}) \\ &\wedge (\mathit{Sep}_{21}(-\sigma) \geq \mathit{ALIM} \vee \mathit{Sep}_{21}(\sigma) < \mathit{ALIM}).\end{aligned}$$

Overall Safety Results, cont'd

Aircraft Close in Altitude:

$P = P(K) = (S \geq \mathit{ALIM}) \wedge |\Delta z| \leq K$,
where $S =$ projected smallest altitude separation at T, based on reversing at the latest possible time $\overline{T}_R$, then following non-crossing RA, nominal strength.

Calculating $\overline{T}_R$: Latest possible time of reversal, dictated by $|\Delta z| \leq K$ initially (possibly time of crossing in altitude).

Calculating S: Similar to reversing execution case.

V. Future Research

- **Remove Restrictions:**

  1. Uncertainty in sensor values, in aircraft flight dynamics.
  2. Unrestricted horizontal aircraft dynamics.
  3. Variable resolution strengths, not just nominal.
  4. Different assumptions on pilots' behavior, e.g.:
     – Follow RAs, but with larger delay.
     – One pilot doesn't follow RAs.
  5. One of the planes not TCAS-equipped.
  6. Multiple aircraft, $N > 2$.

- **Challenge Problem 1: (For hybrid systems formal methods community)**
  Thoroughly analyze this problem, and others like it, using formal techniques.

- **Challenge Problem 2: (For ATM design/validation community)**
  Incorporate high-level formal modeling/analysis into design process.

VI. Conclusions

Contributions:

- With respect to TCAS:
  - Extracted simplified high-level TCAS model.
  - Obtained safety conditions for TCAS's execution categories.
  - Combined per-category guarantees into overall safety conditions.
- With respect to formal analysis and verification:
  - Demonstrated use and practicality of high-level modeling and analysis techniques.