Autonomous Flight: Challenges and the Path Ahead

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A Brief History of Powered Flight

- 1903: The Wright Brothers flew at Kitty Hawk.
  - Model aircraft flights prior to Kitty Hawk flight saved their lives.
- Over the next decades, manned aircraft proliferated for passenger/cargo transport, defense, and recreational uses
- The "drone" emerged in defense applications to provide target practice and deliver munitions.
- A low-key model aircraft community grew alongside the manned aviation community, most commonly for hobby, education, and research applications
- Commercial Transport Flight Management Systems offer aviators and passengers a wealth of displays to augment autopilot and triply-redundant hardware.
- The modern UAS (Unmanned Aircraft System) has capitalized on Aerospace, power systems, sensing, and computing advances
- Regulators struggle to keep pace

Who Flies in the 21st Century?

- Passengers on "Tin Cans with Wings"
- Cargo on similar planes (FedEx, etc.)

- Manned Military Aircraft
  - Modern fighters have more autonomy than commercial transport and most UAS…

- General and Business Aviation
  - Equipage ranges from no radios and VFR only to full IFR-certified glass cockpits
  - Velcro'ed tablets are increasingly popular

- Unmanned Military UAS (small to large)
- Civil UAS (mostly small)
  - **ALREADY THE DOMINANT 21st CENTURY CATEGORY BY NUMBER OF PLATFORMS**

Autonomy + Flight: Part I

- Passenger Transport
  - FMS were designed to assist pilots
  - Passengers trust pilots more than autonomy
  - Economic, psychology concerns are dominant

- Cargo Transport
  - Economics: Use passenger transport designs
  - Integration: Must share airspace and airports with passenger transport

- Military Manned Aircraft
  - Unclear "next-generation" fighter will be manned
  - Legacy platform upgrades may involve "robot pilots" (DARPA ALIAS)

- Military Unmanned Aircraft
  - Air Force: RPAS (remotely piloted aircraft system)
  - Others: RPAS plus Autonomous (small) UAS

Autonomy + Flight: Part II

- **General Aviation**
  - Flight for fun and training: Pilots want to retain the ability to manually fly
  - Personal Air Vehicles (PAV): Non-pilots fly point-to-point -- pilotless planes would be welcome
  - Pilots can’t afford certified avionics but are increasingly “velcroing” tablets to their controls

- **Civil UAS**
  - High-altitude persistent flight: Autonomy is essential
  - Low-altitude delivery / surveillance:
    - Low-integrity UAS OK for LOS (line of sight) flight over unpopulated areas
    - High-integrity UAS (link + onboard intelligence) essential for urban applications and flight in mixed-use airspace

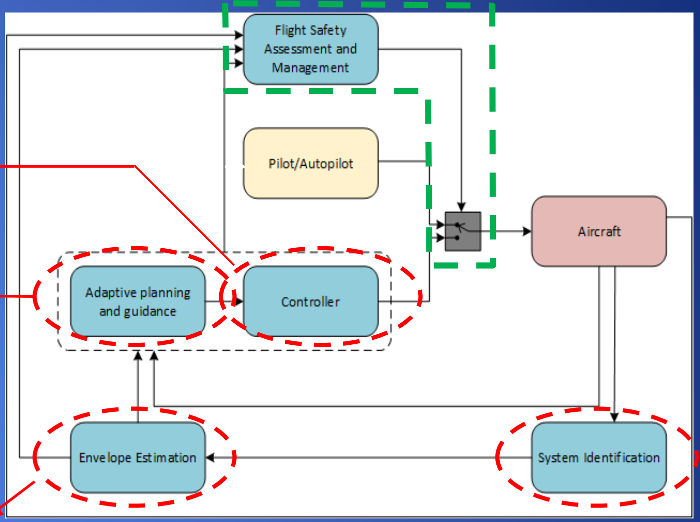
Autonomous Flight Research (Atkins)

- Emergency (Adaptive) Flight Planning
  - Automation to select a reachable nearby landing site and build a landing flight plan
  - Nominal, loss-of-thrust, control surface jam, structural damage cases studied
- Envelope-Aware Flight Management
  - Automatically override crew/automation when LOC (loss of control) is imminent
- Small UAS Risk Analysis → High-integrity Geofencing for Small UAS
  - Trigger, Guidance, Navigation, Control
  - Options: Integrated in autopilot, add-on
  - Focus: Resilience to tampering
    - GPS denial, data entry error, failures/faults

Adapt to changing aircraft dynamics

Compute low risk flight trajectories through icing conditions

Estimate degraded envelope parameters



Keep-In

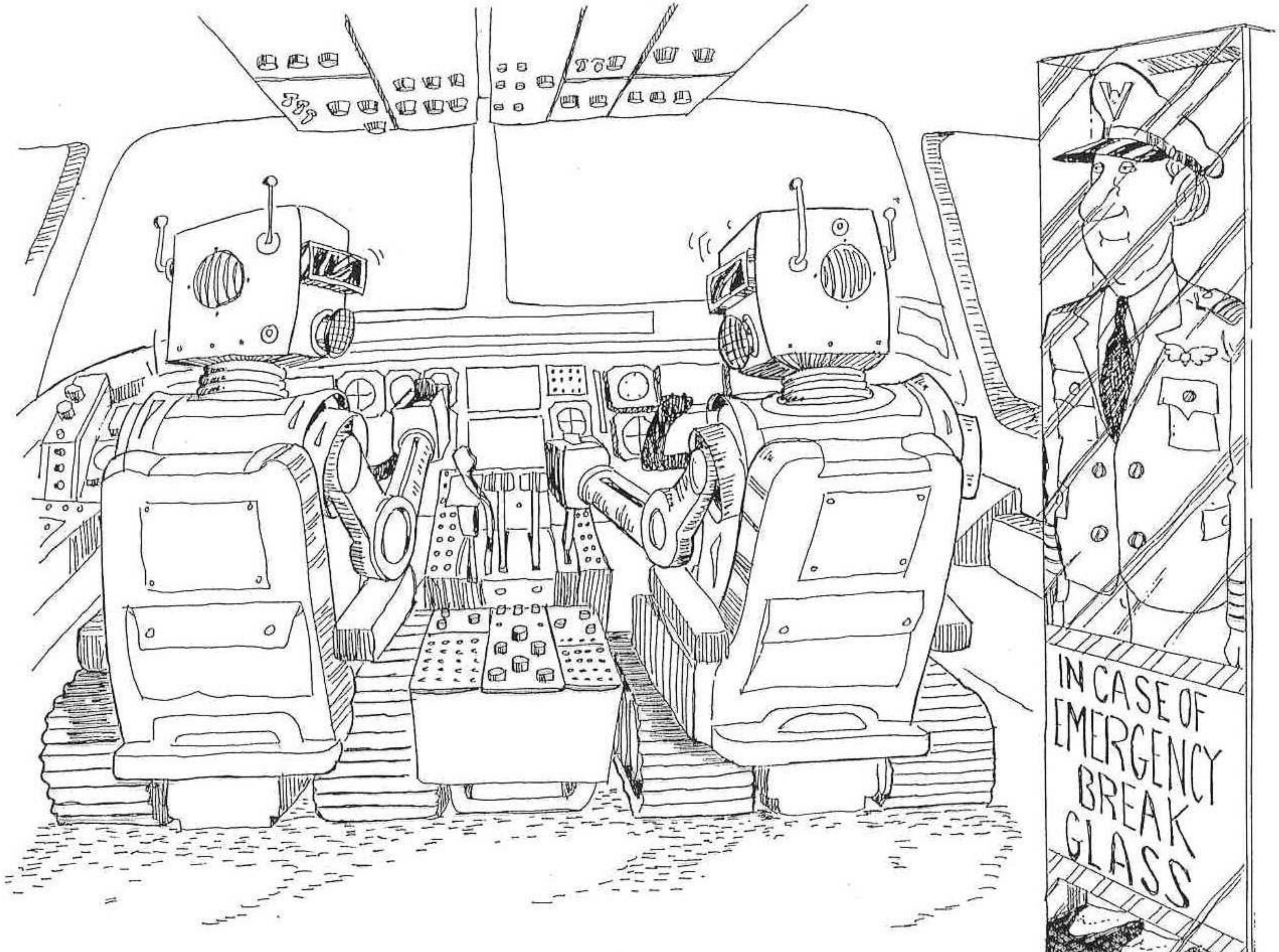
Keep-Out

Autonomous Flight: Technology / Community Needs

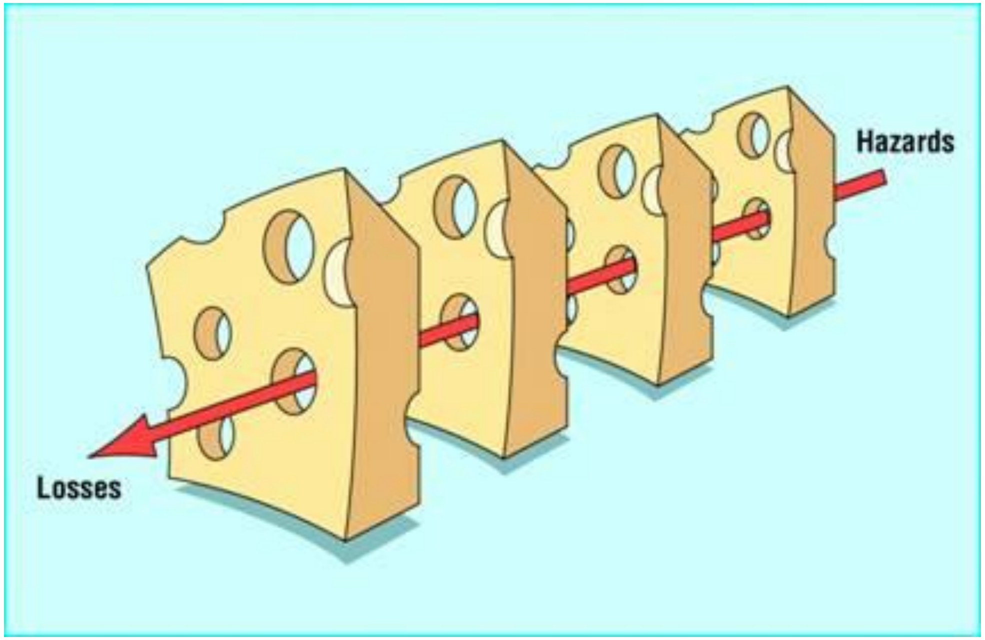
- **Certification and Licensing:**
  - The FARs (Federal Aviation Regulations) are out of date and hard to change.
  - Modern systems engineering and certification (V&V) need to be linked to actual safety and risk not legacy regulations → Formal methods to specify/update regs?
  - Complex, adaptive autonomy can be "licensed" like human pilots to end the stalemate → Build/test sequences to license UAS autonomy?
- Metrics:
  - Safety: How do we assess & assure safety given UAS flying over populated areas and in shared airspace?
  - Economics: How do we trade access to airspace for UAS v. manned operations, and how do UAS negotiate low-altitude airspace access?
- Complex, Adaptive Systems:
  - We can deploy automation that knows the rules and how to fly.
  - How do we assure the system-of-systems is correct and complete even to expected situations?
  - We cannot guarantee the autonomous aircraft will be safe – we also cannot guarantee this for a piloted aircraft – collaborative assessment of "which solution will work best" is essential.

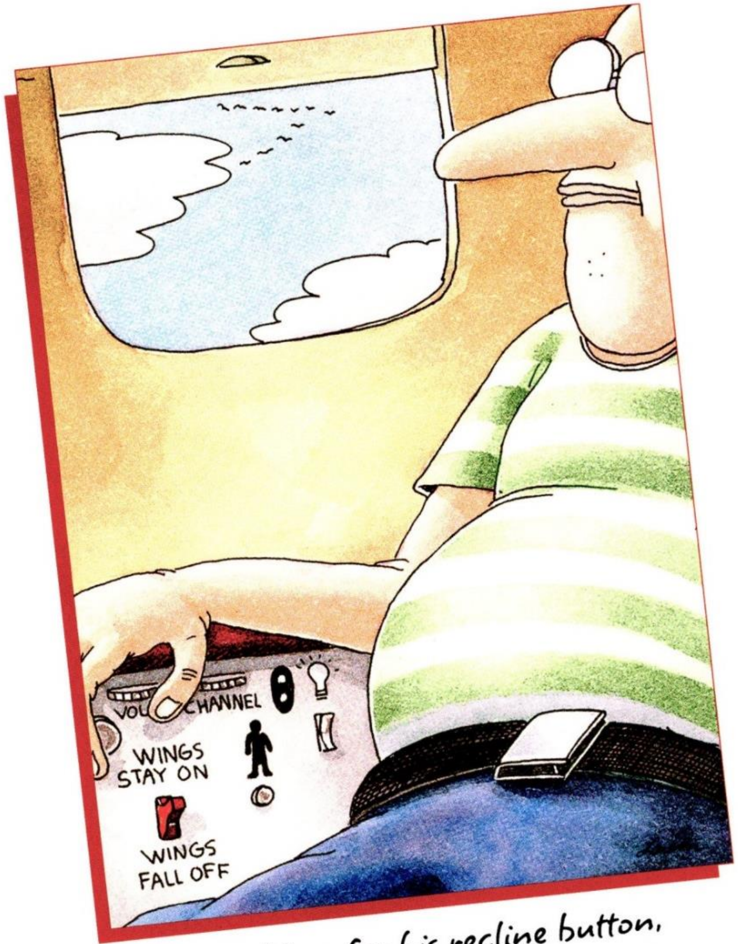
“Autonomy” in Aviation

AMY PRITCHETT
GEORGIA TECH
FEBRUARY 16, 2016


IN CASE OF
EMERGENCY
BREAK
GLASS

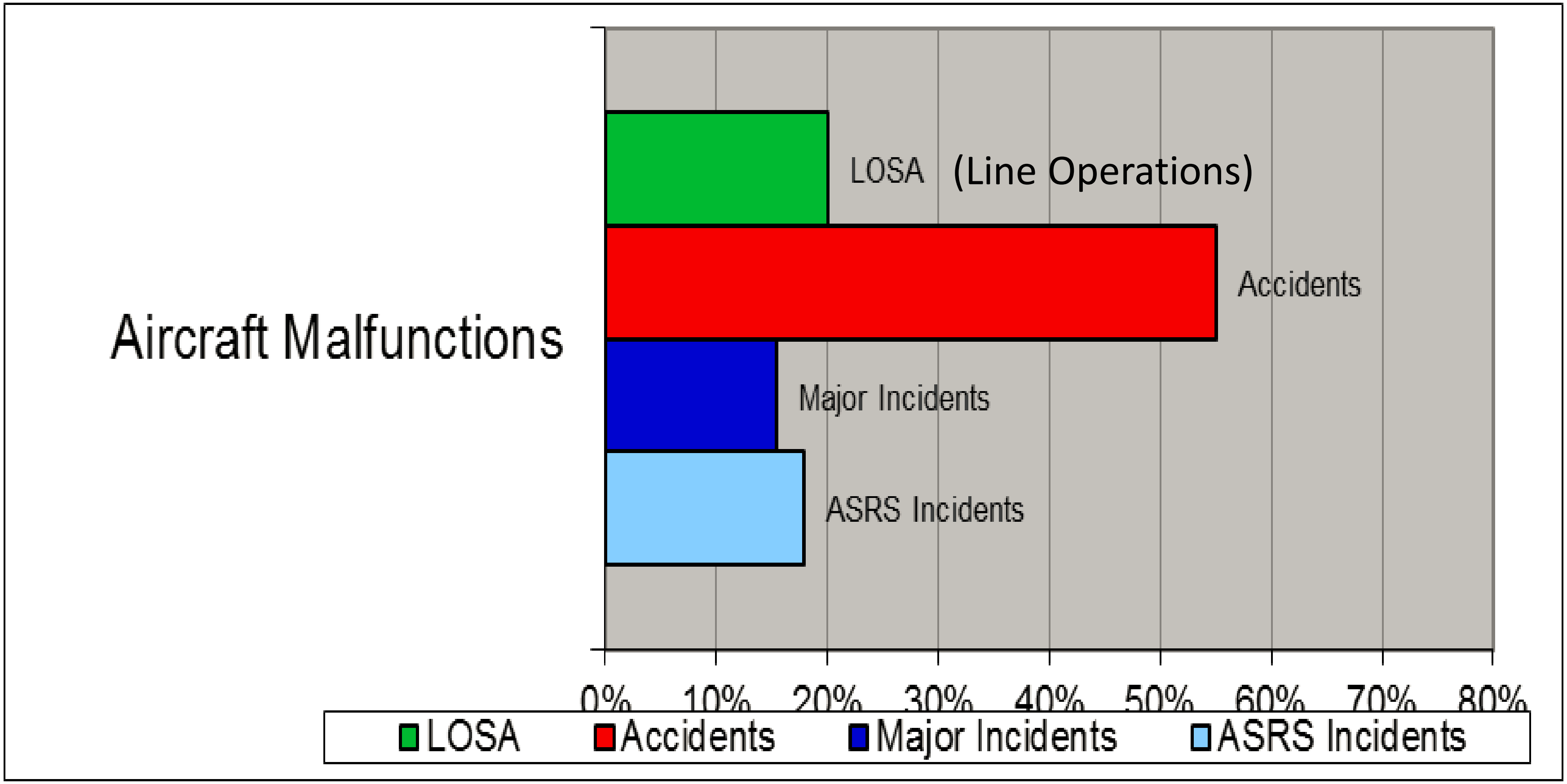
Aviation Can't Allow for Single-Point Failures





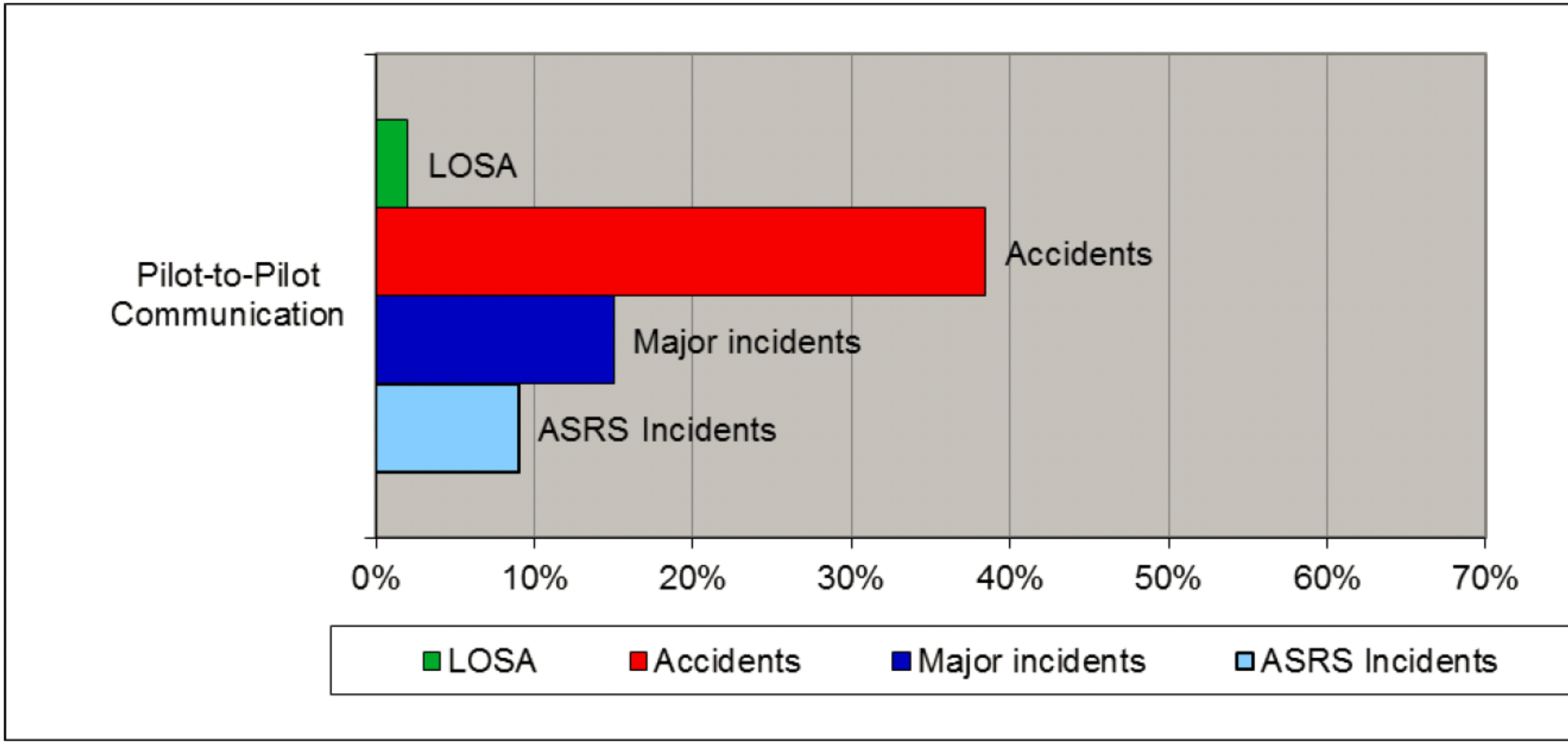
Fumbling for his recline button, Ted unwittingly instigates a disaster.

Humans Capture More Failures Than They Cause



Operational Use of Flight Path Management Systems: Final Report of the Performance-based operations Aviation Rulemaking Committee / Commercial Aviation Safety Team Flight Deck Automation Working Group, September 5, 2013

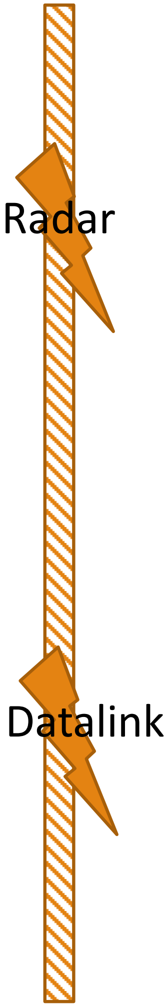
Accidents Tend to Involve Breakdowns in Communication and Coordination



Operational Use of Flight Path Management Systems: Final Report of the Performance-based operations Aviation Rulemaking Committee / Commercial Aviation Safety Team Flight Deck Automation Working Group, September 5, 2013

The Turing Test for Aviation

What would one aviation agent expect from another?



Ability to do a task

Ability to report when it can't do a task

Ability to flex the task structure to achieve desired ends

Ability to adapt its goals to the situation

Ability to communicate and coordinate in manner that makes sense to other agent

Ability to ignore other agent when necessary

Ability to recognize and use interdependencies in inter-agent activities

Ability to operate at many levels of abstraction simultaneously

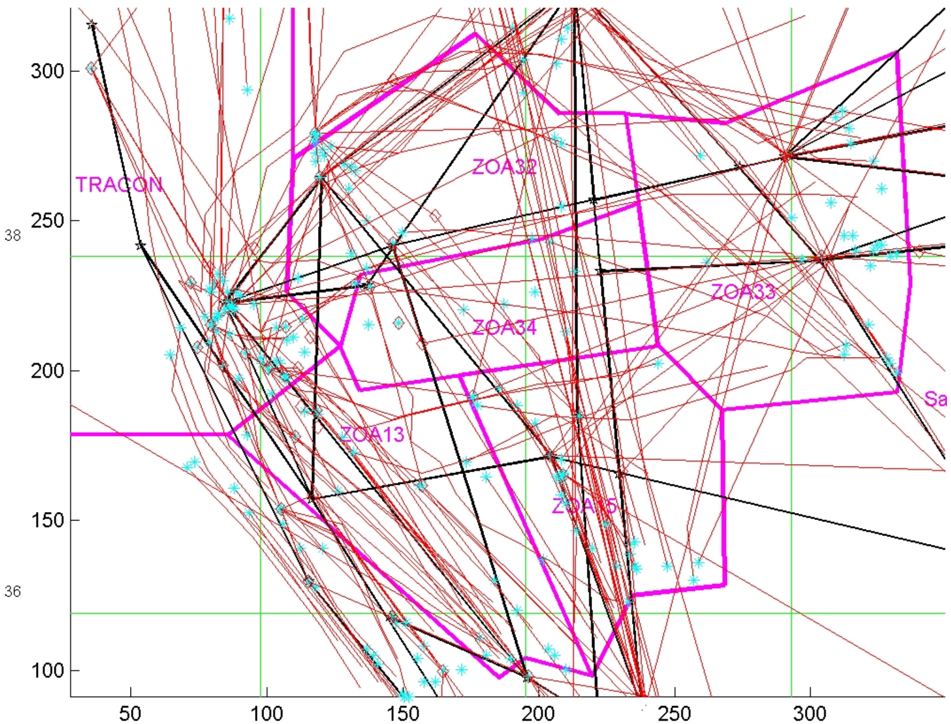
Autonomy in UAS Traffic Management

Claire Tomlin

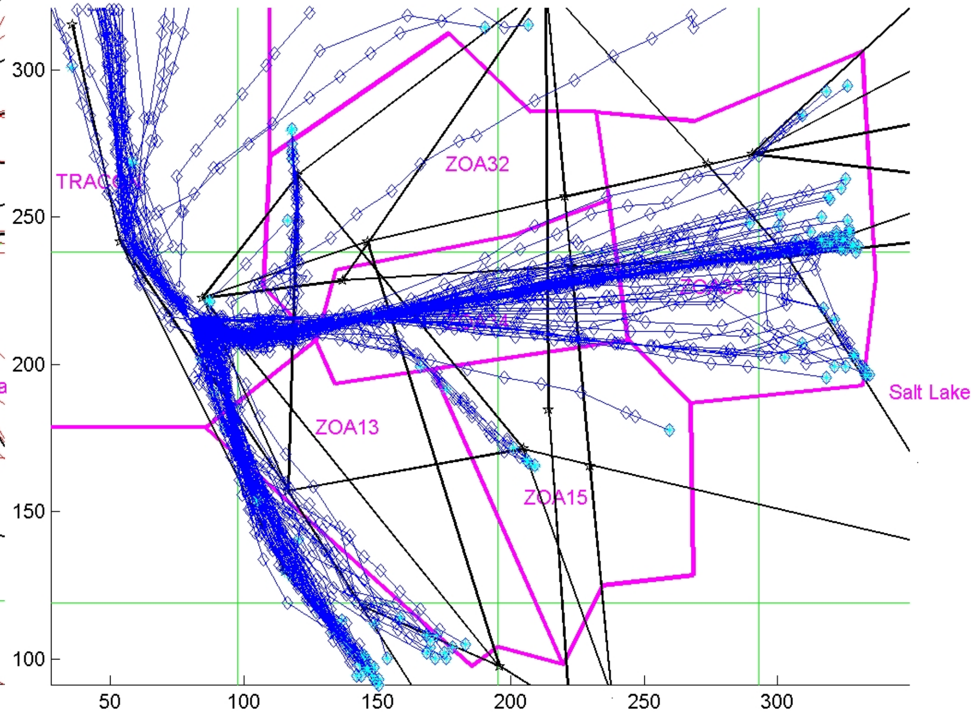
Department of Electrical Engineering and Computer Sciences
University of California at Berkeley

February 16 2016

Air traffic in Oakland Center



cross traffic

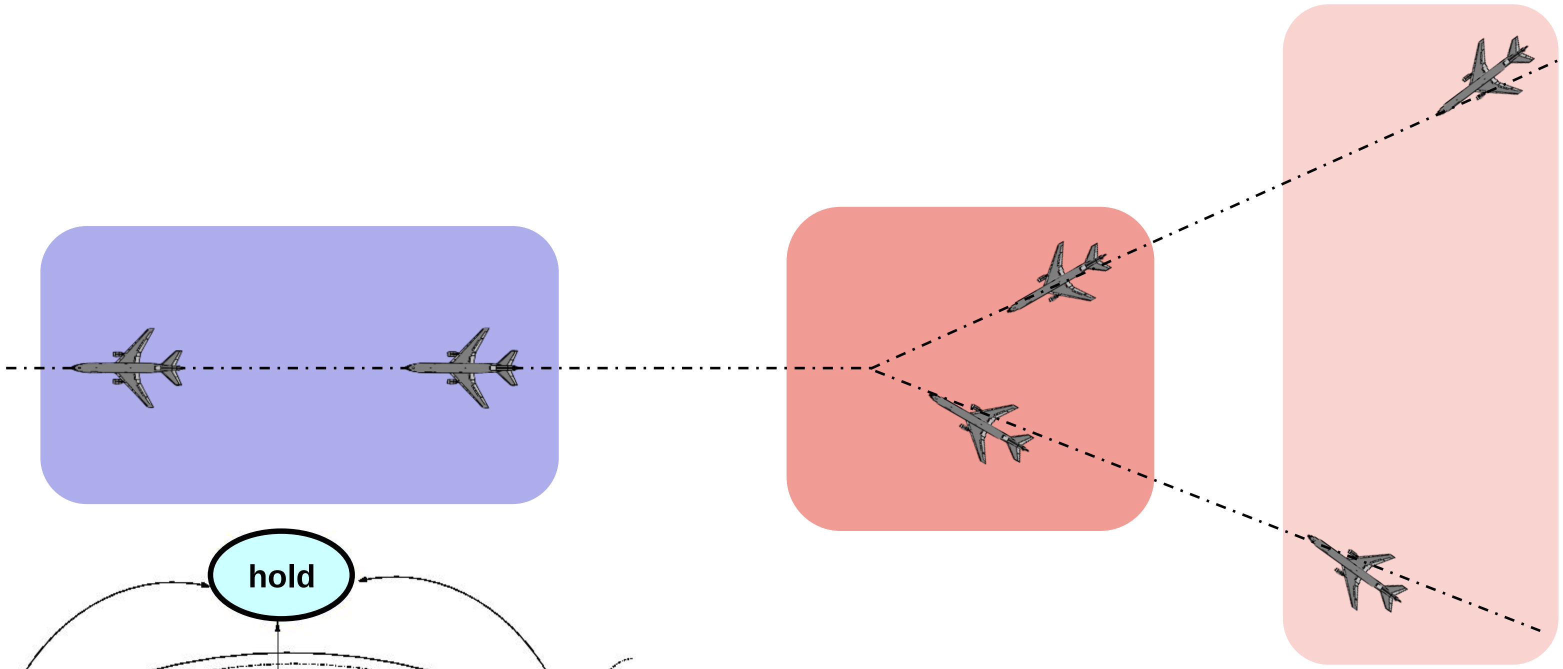


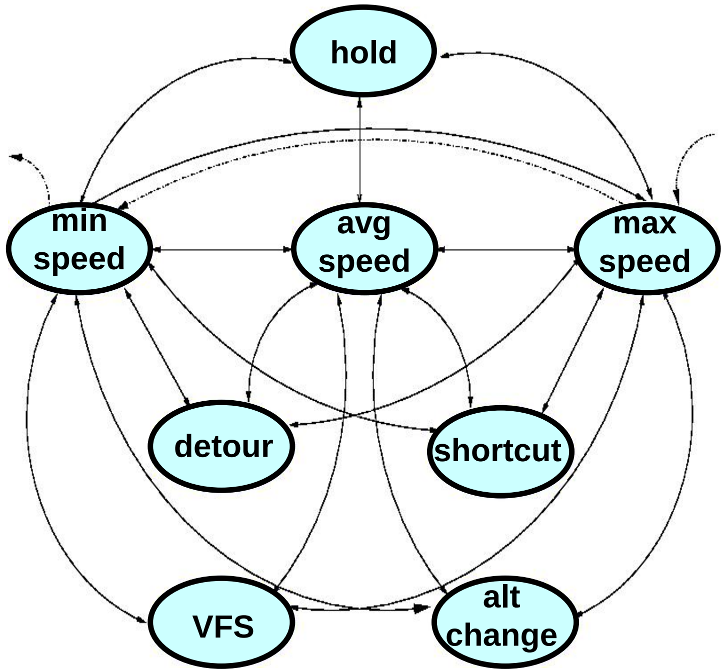
merging traffic

- Safety critical: 1000 ft, 5 nmi separation
- Standard corridors of well-travelled routes

[NASA ETMS, FACET]

Controller must keep aircraft separated



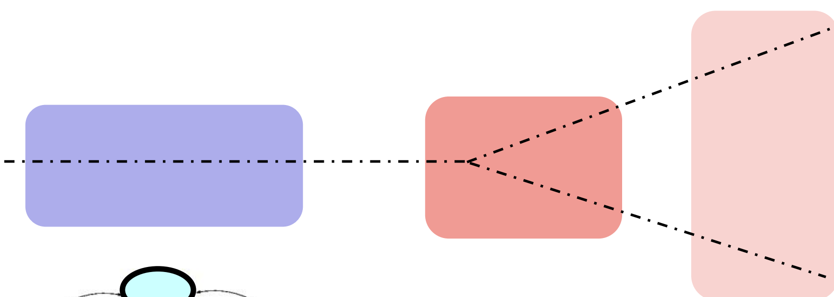


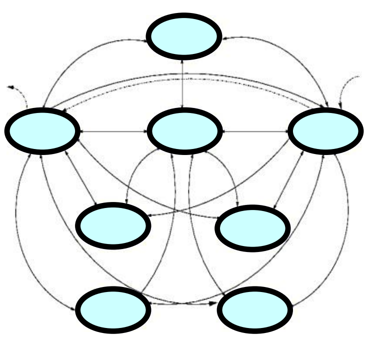
- Small set of control actions
- Infrequent deviations from nominal
- Grouping by potential conflict

Growing numbers of UAV applications

[Amazon]

[Google]



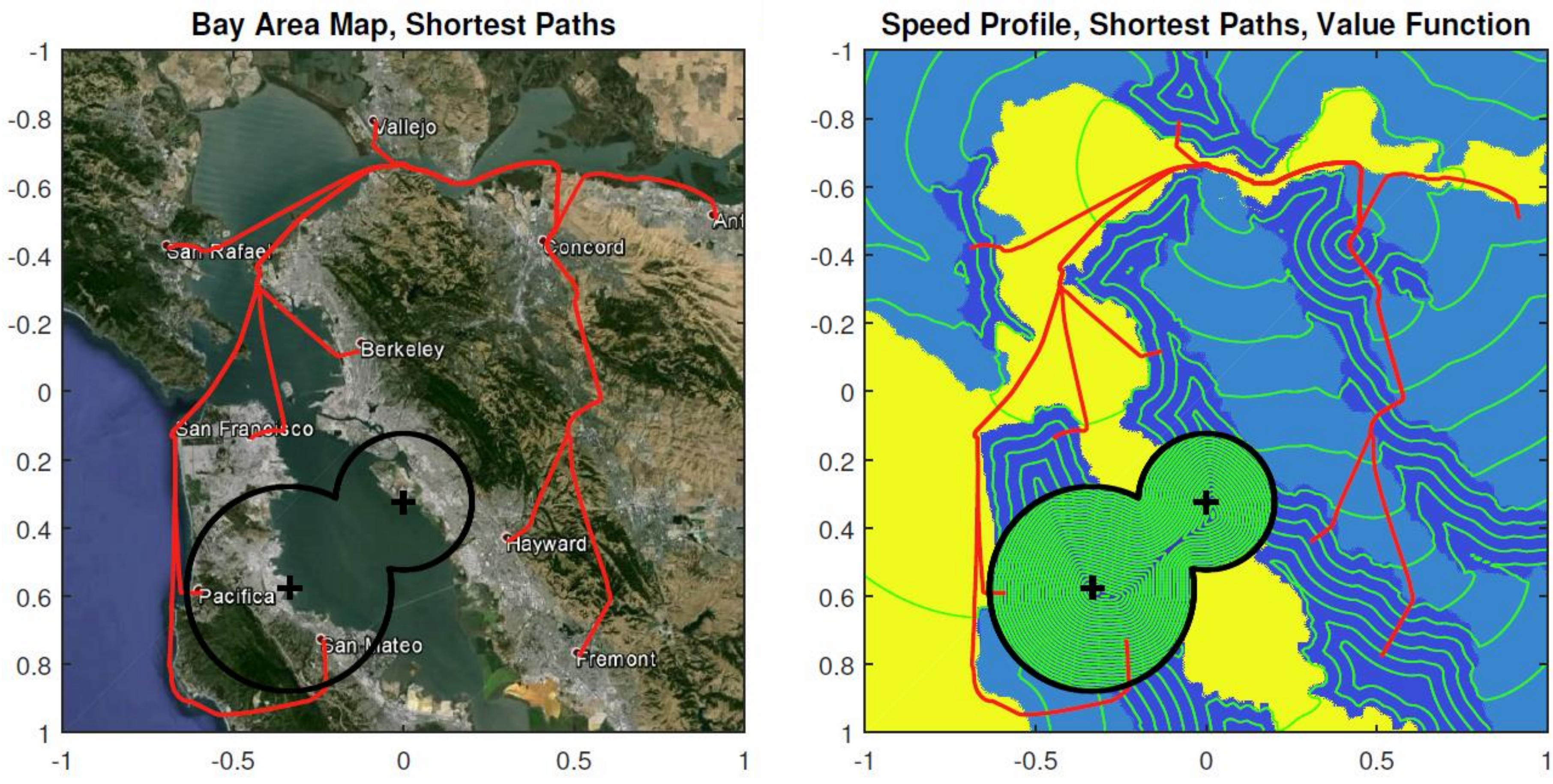


1. Safety
2. Simplicity
3. Ability to adapt to new information

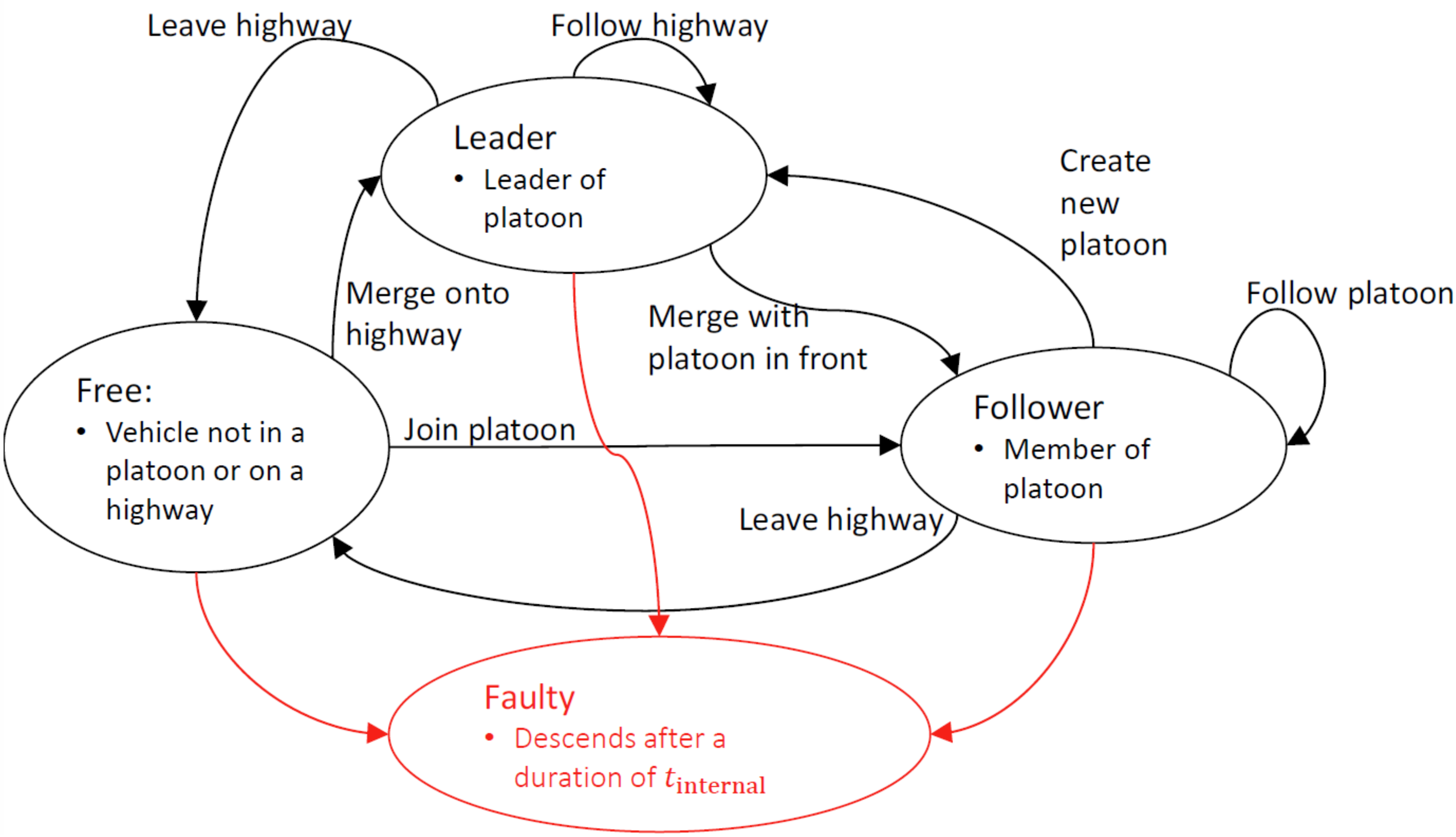
[NASA]

- Collision avoidance system
- Forced landing system

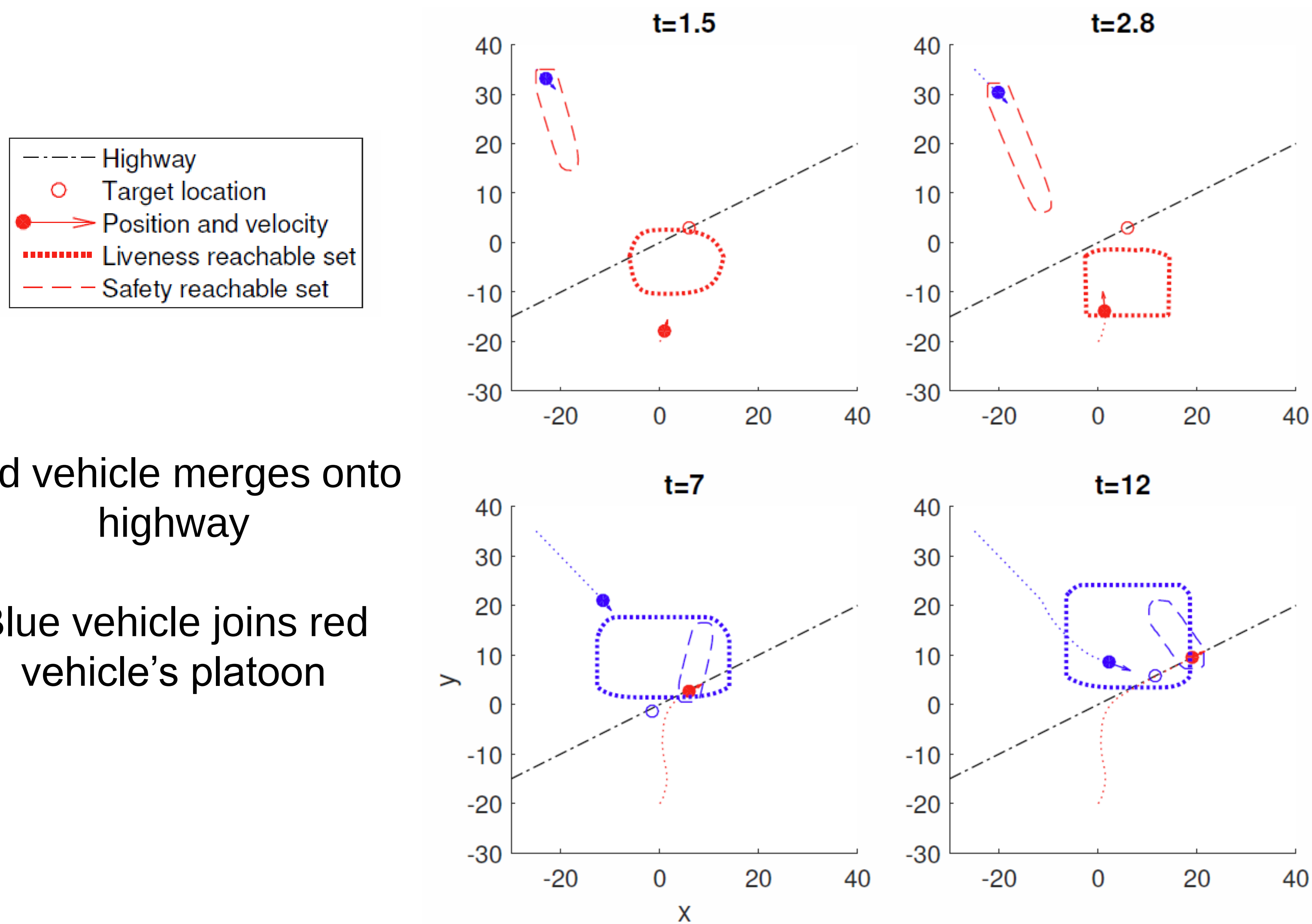
Example: Platooning UAVs



Example: Platooning UAVs



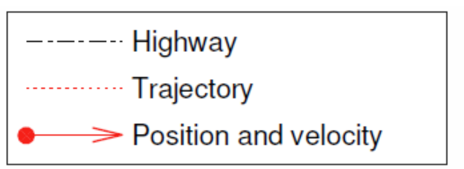
Merging onto highway and joining platoon



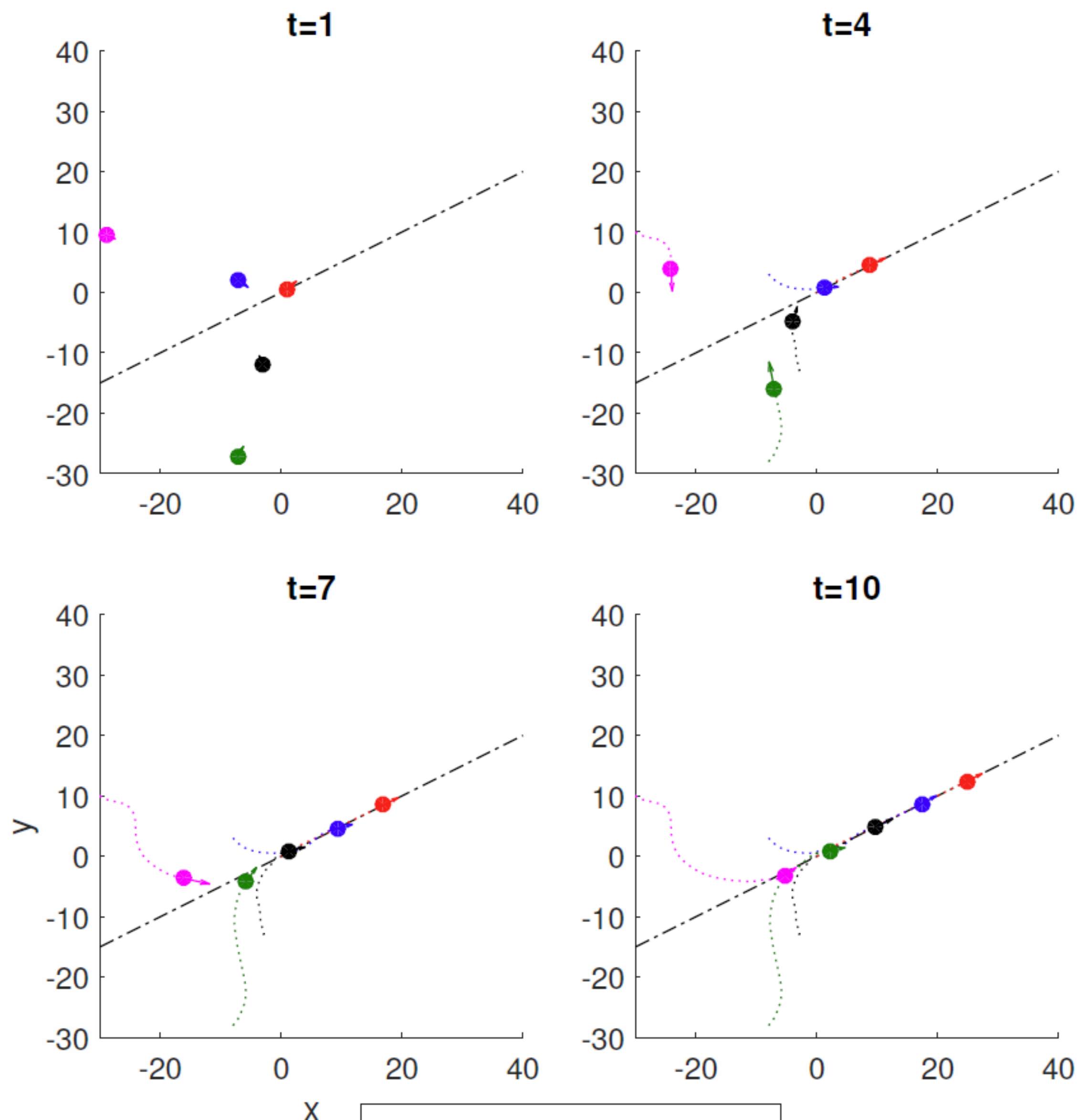
Red vehicle merges onto highway

Blue vehicle joins red vehicle's platoon

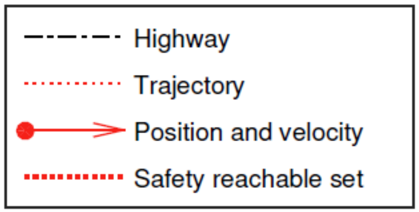
Merging onto highway and joining platoon

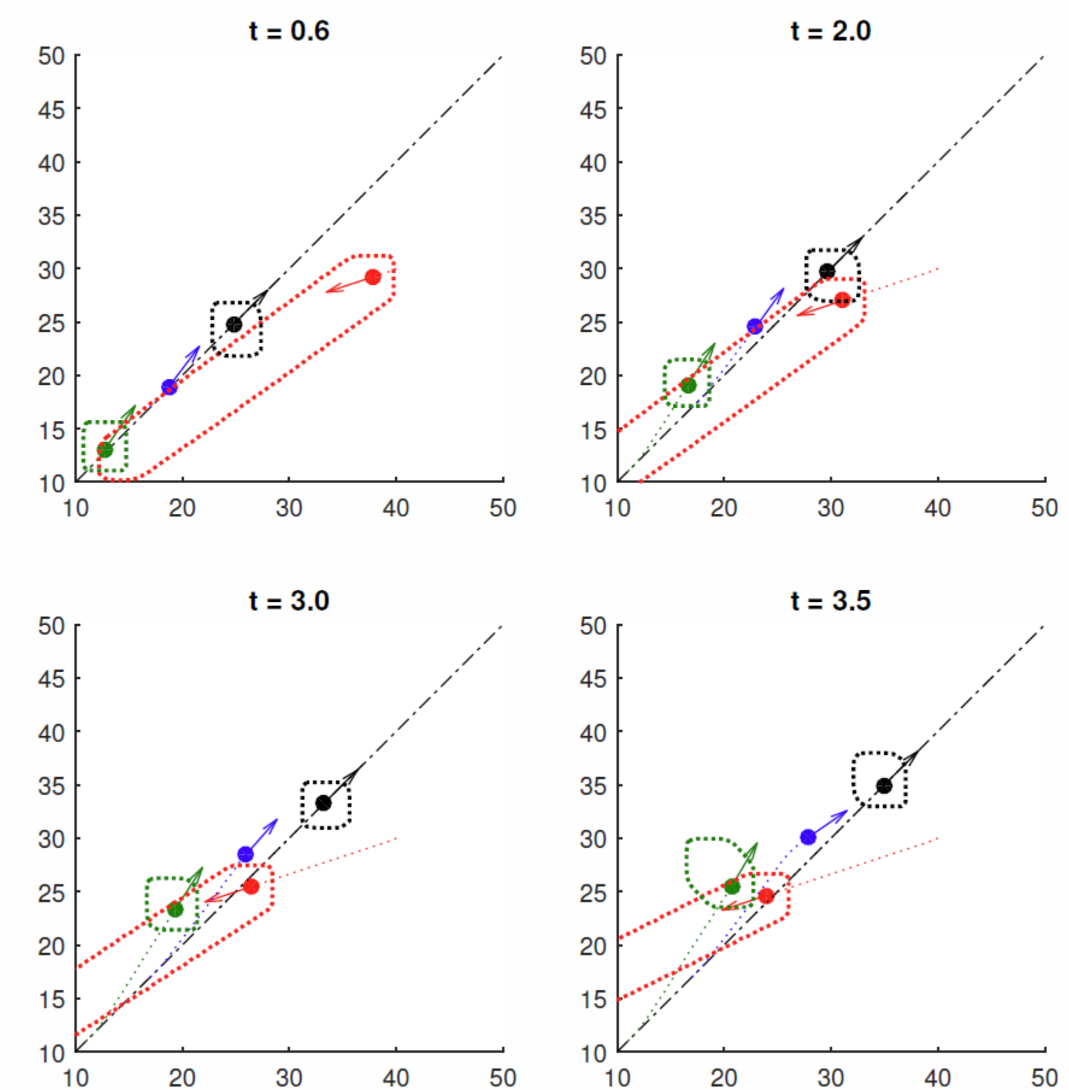


4 vehicles join platoon following red vehicle



Intruder vehicle

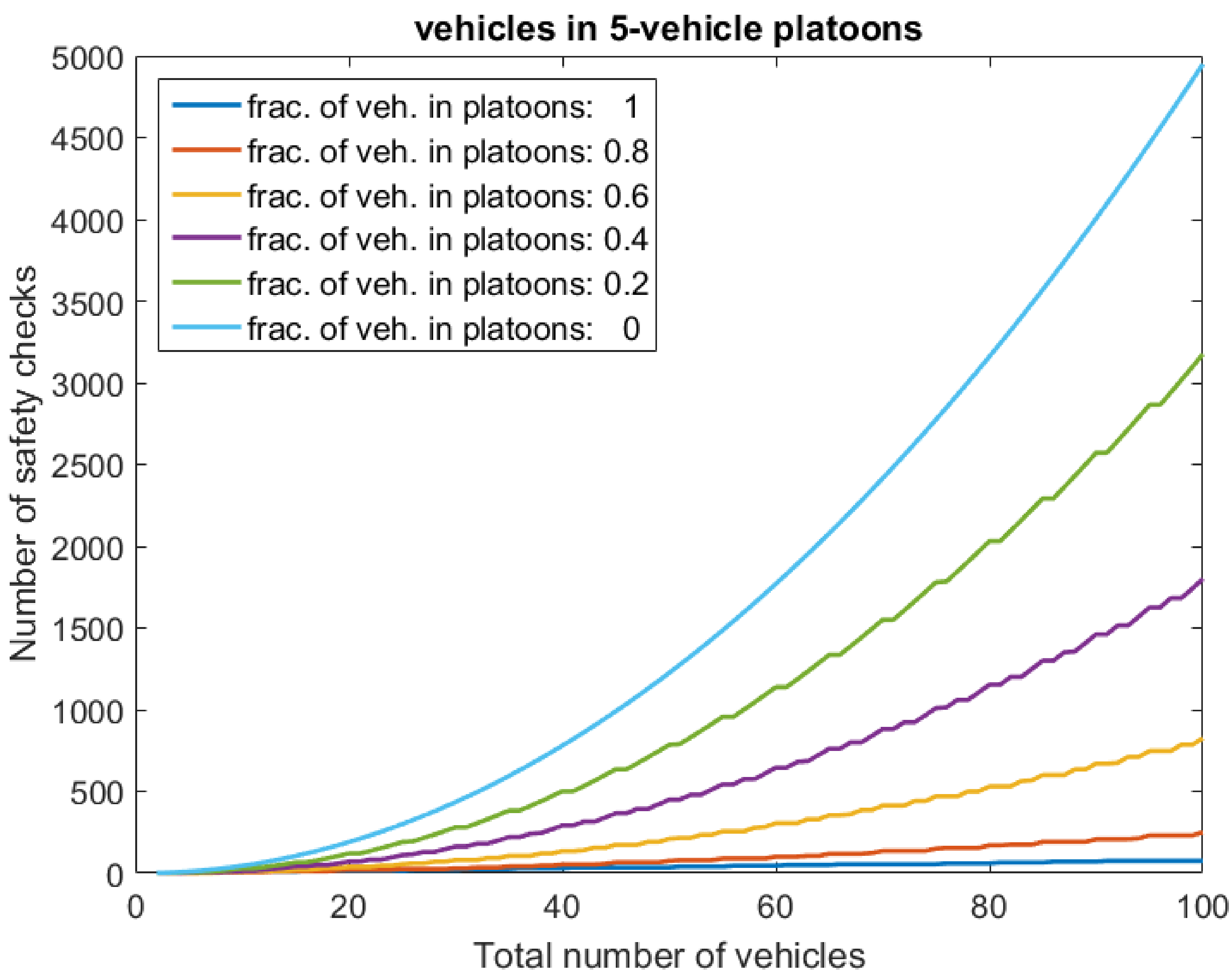




Platoon responding to intruder (red vehicle)

Reachable sets for blue vehicle are shown

Blue vehicle must stay outside of all dotted boundaries


vehicles in 5-vehicle platoons
frac. of veh. in platoons: 1
frac. of veh. in platoons: 0.8
frac. of veh. in platoons: 0.6
frac. of veh. in platoons: 0.4
frac. of veh. in platoons: 0.2
frac. of veh. in platoons: 0
Number of safety checks
Total number of vehicles
0
500
1000
1500
2000
2500
3000
3500
4000
4500
5000
20
40
60
80
100

Mykel J. Kochenderfer
Stanford

The World's Forum for Aerospace Leadership

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1. 100% **Allocation of Air Resources Against an Intelligent Adversary**

Eric Zarybnisky United States Air Force, El Segundo, CA, UNITED STATES; Andrew Armacost Department of Management, USAF Academy, CO, UNITED STATES; Stephan Kolitz Draper Lab, Cambridge, MA, UNITED STATES; Cynthia Barnhart Department of Civil and Environmental Engineering, Cambridge, MA, UNITED STATES; Leslie Kaelbling Department of Electrical Engineering and Computer Science, Cambridge, MA, UNITED STATES
AIAA-2007-2803
AIAA Infotech@Aerospace 2007 Conference and Exhibit, Rohnert Park, California, May 7-10, 2007

2. 100% **Collision Avoidance for Unmanned Aircraft using Markov Decision Processes***

Selim Temizer Massachusetts Institute of Technology, Lexington, MA; Mykel Kochenderfer MIT Lincoln Laboratory, Lexington, MA; Leslie Kaelbling Massachusetts Institute of Technology, Lexington, MA; Tomas Lozano-Perez Massachusetts Institute of Technology, Lexington, MA; James Kuchar MIT Lincoln Laboratory, Lexington, MA
AIAA-2010-8040
AIAA Guidance, Navigation, and Control Conference, Toronto, Ontario, Aug. 2-5, 2010

3. 99% **Hazard Alerting Using Line-of-Sight Rate**

Mykel Kochenderfer MIT Lincoln Laboratory, Lexington, MA, UNITED STATES; J Griffith MIT Lincoln Laboratory, Lexington, MA, UNITED STATES; James Kuchar MIT Lincoln Laboratory, Lexington, MA, UNITED STATES
AIAA-2008-6630
AIAA Guidance, Navigation and Control Conference and Exhibit, Honolulu, Hawaii, Aug. 18-21, 2008

4. 97% **Accounting for State Uncertainty in Collision Avoidance**

James Chryssanthacopoulos, Lincoln Laboratory, Massachusetts Institute of Technology; Mykel Kochenderfer, Lincoln Laboratory, Massachusetts Institute of Technology
Journal of Guidance, Control, and Dynamics 2012
0731-5090 vol.34 no.4 (951-960)
doi: 10.2514/1.53172

5. 96% **Robust Model-based Execution of Critical Spacecraft Sequences**

Michel Ingham Jet Propulsion Laboratory, Pasadena, CA, UNITED STATES
AIAA-2004-6352
22710
AIAA 1st Intelligent Systems Technical Conference, Chicago, Illinois, Sep. 20-22, 2004

6. 87% **Human Intent Prediction Using Markov Decision Processes**

Catharine McGhan University of Michigan, Ann Arbor, Ann Arbor, MI; Ali Nasir University of Michigan, Ann Arbor, Ann Arbor, MI; Ella Atkins University of Michigan, Ann Arbor, Ann Arbor, MI
AIAA-2012-2445
Infotech@Aerospace 2012, Garden Grove, California, June 19-21, 2012

7. 87% **Information-Rich Path Planning with General Constraints Using Rapidly-Exploring Random Trees**

Daniel Levine Massachusetts Institute of Technology, Cambridge, MA, UNITED STATES; Brandon Luders Massachusetts Institute of Technology, Cambridge, MA, UNITED STATES; Jonathan How Massachusetts Institute of Technology, Cambridge, MA, UNITED STATES
AIAA-2010-3360
AIAA Infotech@Aerospace 2010, Atlanta, Georgia, Apr. 20-22, 2010

8. 85% **Application of a General Index Heuristic to Road Surveillance using Multiple UAVs**

Derek Kingston Air Force Research Laboratory, Wright-Patterson AFB, OH; Thomas Temple Massachusetts Institute of Technology, Cambridge, MA
AIAA-2011-6388
AIAA Guidance, Navigation, and Control Conference, Portland, Oregon, Aug. 8-11, 2011

9. 82% **Decomposition Methods for Optimized Collision Avoidance with Multiple Threats**

James Chryssanthacopoulos, Massachusetts Institute of Technology; Mykel Kochenderfer, Massachusetts Institute of Technology
Journal of Guidance, Control, and Dynamics 2012
0731-5090 vol.35 no.2 (398-405)
doi: 10.2514/1.54805

10. 82% **Airspace Encounter Models for Estimating Collision Risk**

Mykel Kochenderfer, Massachusetts Institute of Technology; Matthew Edwards, Massachusetts Institute of Technology; Leo Espindle, Massachusetts Institute of Technology; James Kuchar, Massachusetts Institute of Technology; J. Griffith, Massachusetts Institute of Technology
Journal of Guidance, Control, and Dynamics 2010
0731-5090 vol.33 no.2 (487-499)
doi: 10.2514/1.44867

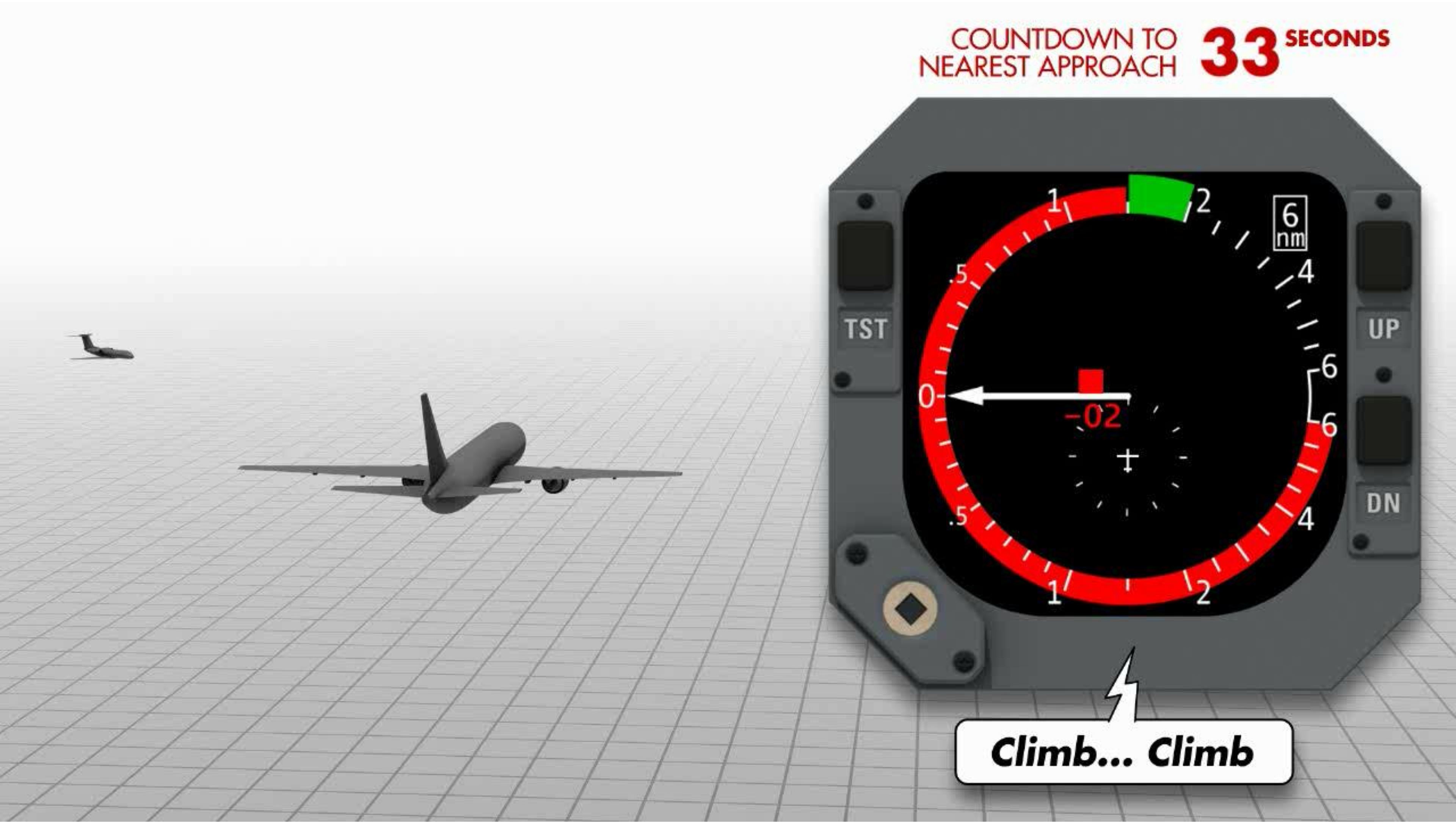
markov decision process: 70 hits; milp: 193 hits

TCAS

TCAS


COUNTDOWN TO NEAREST APPROACH
46 SECONDS
TST
UP
DN
6 nm
-02
Traffic... Traffic

TCAS


COUNTDOWN TO NEAREST APPROACH
33 SECONDS
6 nm
TST
UP
DN
-02
Climb... Climb

```
PROCESS Reversal_modeling;

    Default modeled separation for current RA is 0 if current RA is negative;
    Set own altitude and own rate to own tracked altitude and own tracked rate;

    IF (own does not follow his RAs)
        THEN  Model separation achieved assuming RA not followed;
              IF (current RA is a climb RA)
                  THEN  CLEAR flag indicating the sense of the RA after a reversal;
                  ELSE  SET flag indicating the sense of the RA after a reversal;
              IF (modeled separation achieved by continuing current RA greater than 1.2 *
                  P.CROSSTHR)
                  THEN  CLEAR reversal flag in ITF
        ELSE
        <Begin own is assumed to follow its RA>
              IF (current RA is positive)
                  THEN  model response to current RA;
                        <model maximum displayable rate for climb if current rate exceeds
                        maximum displayable rate or minimum displayable rate for descent if
                        current rate is less than minimum displayable rate>

                        IF (tracked response lags modeled response in RA direction AND
                            time since RA less than a parameter time AND
                            own's rate has not changed by more than P.MODEL_ZD since the
                            RA was first issued)
                            THEN  set own altitude and own rate to modeled altitude and rate
                                  for use in reversal modeling;
                        Model separation achieved by continuing current RA;
              Set delay time to greater of pilot delay time remaining for last advisory against a
                  new threat, and the pilot quick reaction time;

              IF (considering a reversal from a descend RA to a climb RA)
                  THEN  set own goal rate to greater of own tracked rate (or maximum
                        displayable rate, whichever is less) and nominal climb rate;
                  ELSE  IF (own too close to ground to descend)
                            THEN  set own goal rate to zero;
                            ELSE  set own goal rate to lesser of own tracked rate (or minimum
                                  displayable rate, whichever is greater) and nominal descent
                                  rate;
              IF (vertical chase, low VMD geometry was not the reason for considering
                  reversal)
                  THEN  IF (intruder causing crossing OR (intruder level AND own crossing
                            from above) OR intruder rate and own modeled rate are opposite in sign)
                            THEN  use outer rate bound to model intruder;
                            ELSE  use inner rate bound to model intruder;
                  ELSE  use intruder's tracked vertical rate to model intruder;
              CALL MODEL_SEP
                  IN (delay, goal rate, own altitude, own rate, acceleration response, sense after
                      reversal, intruder altitude, modeled intruder rate, ITF entry)
                  OUT (predicted separation for sense reversal);

              IF (Predicted separation for sense reversal is not positive OR
                 modeled separation achieved by continuing current RA GE G.ALIM)
                  THEN  CLEAR reversal flag in ITF;
        <End own is assumed to follow its RA>

END Reversal_modeling;
```



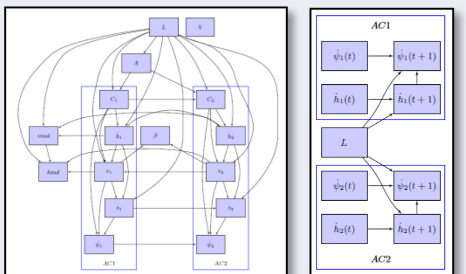
```
PROCESS Reversal_modeling;

    NOMINAL_SEP = 0;
    Z = G.ZOWN;
    ZD = G.ZDOWN;
    DELAY = 0;

    IF (G.OWN_FOLLOW EQ FALSE)
        THEN  CALL MODEL_SEP
                  IN (DELAY, ZD, Z, ZD, P.VACCEL, OWNTENT(7), ITF.ZINT, ITF.ZDINT, ITF entry)
                  OUT (NOMINAL_SEP);
              IF (OWNTENT(7) EQ $TRUE)
                  THEN  NEW_SENSE = $FALSE;
                  ELSE  NEW_SENSE = $TRUE;
              IF (NOMINAL_SEP GT 1.2 * P.CROSSTHR)
                  THEN  CLEAR ITF.REVERSE;
        ELSE
        <Begin own is assumed to follow its RA>
            IF (OWNTENT(5,6) EQ '00')
                THEN  DELAY = MAX(P.TV1 - (G.TCUR - G.TPOSRA), 0);
                      IF (OWNTENT(7) EQ $FALSE)
                          THEN  ZDGOAL = MAX(MIN(G.ZDOWN, P.MAXDRATE), P.CLMRT);
                          ELSE  ZDGOAL = MIN(MAX(G.ZDOWN, P.MINDRATE), P.DESRT);
                      CALL PROJECT_VERTICAL_GIVEN_ZDGOAL
                          IN ((G.TCUR - G.TPOSRA), G.ZTV, G.ZDTV, ZDGOAL, P.TV1, P.VACCEL)
                          OUT (ZPROJ, ZDPROJ);
                      IF  (((OWNTENT(7) EQ $FALSE AND ZPROJ GT G.ZOWN AND
                          (G.ZDOWN GE G.ZDTV - P.MODEL_ZD)) OR
                          (OWNTENT(7) EQ $TRUE AND ZPROJ LT G.ZOWN AND
                          (G.ZDOWN LE G.ZDTV + P.MODEL_ZD))) AND
                          G.TCUR – G.TPOSRA LT P.MODEL_T)
                          THEN  Z = ZPROJ;
                                ZD = ZDPROJ;
                      CALL MODEL_SEP
                          IN (DELAY, ZDGOAL, Z, ZD, P.VACCEL, OWNTENT(7),
                              ITF.ZINT, ITF.ZDINT, ITF entry)
                          OUT (NOMINAL_SEP);
            IF (OWNTENT(7) EQ $TRUE)
                THEN  NEW_SENSE = $FALSE;
                ELSE  NEW_SENSE = $TRUE;
            DELAY = MAX(P.TV1 - (G.TCUR - G.TLASTNEWRA), P.QUIKREAC);

            IF (NEW_SENSE EQ $FALSE)
                THEN  ZDGOAL = MAX(P.CLMRT, MIN(G.ZDOWN, P.MAXDRATE));
                ELSE  IF (G.NODESCENT EQ $TRUE)
                          THEN  ZDGOAL = 0;
                          ELSE  ZDGOAL = MIN(P.DESRT, MAX(G.ZDOWN,          P.MINDRATE));
            IF (G.REV_CONSDRD EQ FALSE)
                THEN  IF ((ITF.INT_CROSS EQ $TRUE) OR (ITF.ZDINT EQ 0 AND
                          ITF.RZ GT 0) OR (ITF.ZDINT * G.ZDMODEL LT 0))
                          THEN  MZDINT = ITF.ZDOUTR;
                          ELSE  MZDINT = ITF.ZDINR;
                ELSE  MZDINT = ITF.ZDINT;

            CALL MODEL_SEP
                IN (DELAY, ZDGOAL, Z, ZD, P.RACCEL, NEW_SENSE, ITF.ZINT, MZDINT, ITF entry)
                OUT (ZMP);

            IF (ZMP LE 0 OR NOMINAL_SEP GE G.ALIM)
                THEN  CLEAR ITF.REVERSE;
        <End own is assumed to follow its RA>
END Reversal_modeling;
```


RTCA DO-185B Volume 1 (1799 pages)

Building Trust in AI for Aviation

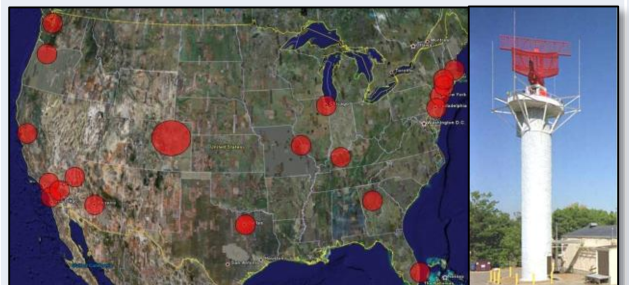
Airspace Encounter Models	Recorded Radar Tracks	Formal Methods

Airspace Encounter Models



Generate many encounters representative of airspace

Recorded Radar Tracks



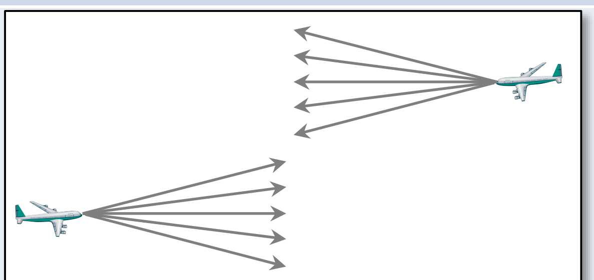
Recorded radar tracks with known TCAS intervention

Formal Methods

$$
\begin{aligned}
& r_p \geq 0 \wedge h_p > 0 \wedge r_v \geq 0 \wedge a_r > 0 \wedge a_d \geq \wedge d_p \geq 0 \wedge d_\ell \geq 0 \\
& \wedge (w = -1 \vee w = 1) \wedge D_{\text{impl}}(r, h, \dot{h}_0, d) \rightarrow \\
& [((?\text{true} \cup \dot{h}_f := *; (w := -1 \cup w := 1); \\
& \qquad (d := d_p; ?D_{\text{impl}}(r, h, \dot{h}_0, d); \text{advisory} := (w, \dot{h}_f) \cup \\
& \qquad d := d_p + d_\ell; ?D_{\text{impl}}(r, h, \dot{h}_0, d); \text{advisory} := \text{COC})); \\
& \quad a := *; ?(wa \geq -a_d); t_\ell := 0; \\
& \quad \{r' = -r_v, h' = -\dot{h}_0, \dot{h}_0' = a, d' = -1, t_\ell' = 1 \,\& \\
& \quad (t_\ell \leq d_\ell) \wedge (d \leq 0 \rightarrow w\dot{h}_0 \geq w\dot{h}_f \vee wa \geq a_r)\} \\
&)^*] (|r| > r_p \vee |h| > h_p)
\end{aligned}
$$

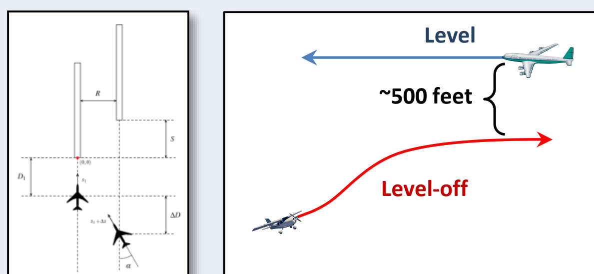
Apply hybrid system theorem provers to approximate models

Stress Testing



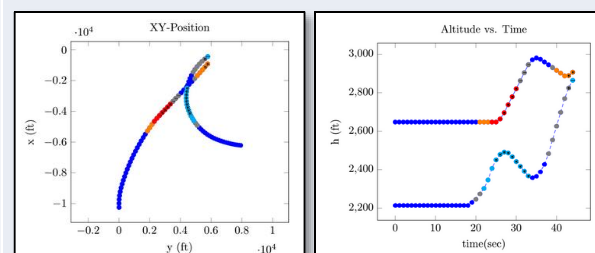
Exhaustive variations of certain classes of encounters

Scenario Specific Mini-Models



Focused models constructed from expert knowledge and data

Most Likely Failure Condition



Use black box sampling to find most likely failure

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