16.422 Alerting Systems

Prof. R. John Hansman

Acknowledgements to Jim Kuchar
Consider Sensor System

- Radar
- Engine Fire Detection
- Other
Decision-Aiding / Alerting

System Architecture

- Environment
- Process
- Information Transduction
- Decision Making
- Control / Actuation

Sensors
Displays
Automation
Human
Actuator

Courtesy: Jim Kuchar
Fundamental Tradeoff in Alerting Decisions

- **When to alert?**
  - Too early 
    - Unnecessary Alert
    - Operator would have avoided hazard without alert
    - Leads to distrust of system, delayed response
  - Too late
    - Missed Detection
    - Incident occurs even with the alerting system

- **Must balance** Unnecessary Alerts and Missed Detections

Courtesy: Jim Kuchar
The Alerting Decision

- Examine consequences of alerting / not alerting
  - Alert is not issued: Nominal Trajectory (N)
  - Alert is issued: Avoidance Trajectory (A)

Compute probability of Incident along each trajectory

Courtesy: Jim Kuchar
Threshold Placement

Probability of False Alarm $P(FA)$ vs. Probability of Successful Alert $P(SA)$

Ideal Alerting System

Example Alerting Threshold Locations

Courtesy: Jim Kuchar
Threshold Placement

- Use specified $P(FA)$ or $P(MD)$
- Alerting Cost Function: Define $C_{FA}$, $C_{MD}$ as alert decision costs

\[ J = P(FA) C_{FA} + P(MD) C_{MD} \]
\[ = P(FA) C_{FA} + (1 - P(CD)) C_{MD} \]

Minimize Cost:
\[ \frac{dJ}{dP(FA)} = C_{FA} \]
\[ \frac{dP(CD)}{dP(FA)} = \frac{C_{FA}}{C_{MD}} \]

Slope of SOC curve = cost ratio

Courtesy: Jim Kuchar
Engine Fire Alerting

- C(FA) high on takeoff
- Alerts suppressed during TO

Now let's take a quick look at non-normal checklists. The 777 EICAS message list is similar to other Boeing EICAS airplanes. [For 747-400 operators: It doesn’t use the “caret” symbol to indicate a checklist with no QRH items, like the 747-400s do.] But it has an additional feature, called the “checklist icon”. The icon is displayed next to an EICAS message whenever there is an ECL checklist that needs to be completed. Once the checklist is fully complete, the icon is removed from display next to the message. This helps the crew keep track of which checklists remain to be completed.
Crew Alerting Levels

Non-Normal Procedures

Time Critical Operational condition that requires immediate crew awareness and immediate action

Warning Operational or system condition that requires immediate crew awareness and definite corrective or compensatory action

Caution Operational or system condition that requires immediate crew awareness and possible corrective or compensatory action

Advisory Operational or system condition that requires crew awareness and possible corrective or compensatory action

Alternate Normal Procedures

Comm Alerts crew to incoming datalink communication

Memo Crew reminders of the current state of certain manually selected normal conditions

Source: Brian Kelly Boeing

Don't have time to discuss these levels. Important thing to know is that we rigorously define and defend these levels. We apply them across all the systems. The indications are consistent for all alerts at each level. Thus the pilots instantly know the criticality and nature of an alert even before they know what the problem is.
### Boeing Color Use Guides

- **Red**: Warnings, warning level limitations
- **Amber**: Cautions, caution level limitations
- **White**: Current status information
- **Green**: Pilot selected data, mode annunciations
- **Magenta**: Target information
- **Cyan**: Background data

Again, we don’t have time to describe these definitions in detail. The important thing to note is that our philosophy is definite, and as simple as practical. It fits on one page, in big font no less.
When an alert message is displayed, the pilot simply pushes the CHKL button and the correct non-normal checklist is displayed. This prevents the crew from accidentally choosing the wrong checklist. The non-normal checklists have priority over the normal checklists.
Non-Normal Checklists

- Checklist specific to left or right side
- Exact switch specified
- Memory items already complete
- Closed-loop conditional item
- Page bar

This is what a typical normal checklist looks like. This is the Preflight checklist.

There are two kinds of line items, which we call open-loop and closed-loop items. The open-loop items have a gray check-box in front of them. These are items that the airplane systems cannot sense. The pilot determines whether the items have been completed and clicks the CCD thumbswitch when each item is complete.

Closed-loop items are for switches and selectors that are sensed by the airplane systems. They automatically turn green when the switch has been positioned correctly. If the crew actuates the wrong switch, the closed-loop item will not turn green and the crew will catch their error. In this example, the procedure was already complete, so the last two items are shown in green as soon as the checklist is displayed.

The white current line item box leads the pilot through the checklist and prevents accidentally skipping a line item. Color is used to indicate line item status. Incomplete items are displayed white and complete items are displayed green. Cyan (or blue) indicates an inapplicable item, or an item that has been intentionally overridden by the crew using the ITEM OVRD button. In this example, the flight is dispatching with autobrakes inoperative, so the crew has overridden the AUTOBRAKE item. Overriding the item allows the checklist to be completed.

Fire is detected in the right engine.

- RIGHT AUTOTHROTTLE ARM SWITCH ............... OFF
- RIGHT THRUST LEVER ............................CLOSE
- RIGHT FUEL CONTROL SWITCH ...............CUTOFF
- RIGHT ENGINE FIRE SWITCH ................. PULL

If FIRE ENG R message remains displayed:

- RIGHT ENGINE FIRE SWITCH ............... ROTATE
  Rotate to the stop and hold for 1 second.

ITEM OVRD

Checklist specific to left or right side

Exact switch specified

Memory items already complete

Closed-loop conditional item

Page bar
Internal vs External Threat Systems

- **Internal**
  - System normally well defined
  - Logic relatively static
  - Simple ROC approach valid
  - Examples (Oil Pressure, Fire, Fuel, …)

- **External**
  - External environment may not be well defined
    - Stochastic elements
  - Controlled system trajectory may be important
    - Human response
  - Need ROC like approach which considers entire system
  - System Operating Characteristic (SOC) approach of Kuchar
  - Examples (Traffic, Terrain, Weather, …)
Enhanced GPWS Improves Terrain/Situational Awareness

EFIS map display color legend

+ 2,000-ft high density (50%) red

+ 1,000-ft high density (50%) yellow

Reference altitude

- 250/-500-ft medium density (25%) yellow

- 1,000-ft medium density (25%) green

- 2,000-ft medium density (12.5%) green
Aircraft Collision Avoidance

human

experience, training

diagnosis and control

curator: "terrain"
warning: "pull up"

GPWS alert and decision aid

terrain data

automation

displays

aircraft

controls

human senses

sensors

other info. (e.g. window view)

other sensor information

altitude and altitude rate

terrain data
Conflict Detection and Resolution Framework

Environment → Intent → Dynamic Model → Metric Definition → Conflict Detection → Conflict Resolution → Human Operator → Environment

- Current States
- Projected States
- Metrics
- State Estimation
- Intent
- Dynamic Model
- Metric Definition
- Conflict Detection
- Conflict Resolution
- Human Operator

Courtesy: Jim Kuchar
Trajectory Modeling Methods

- Nominal
- Worst-case
- Probabilistic

Courtesy: Jim Kuchar
Nominal Trajectory Prediction-Based Alerting

- Alert when projected trajectory encounters hazard

- Look ahead time and trajectory model are design parameters
- Examples: TCAS, GPWS, AILS

Courtesy: Jim Kuchar
Airborne Information for Lateral Spacing (AILS)
(nominal trajectory prediction-based)

Endangered aircraft vectored away

Alert occurs with prediction of near miss in given time interval

Courtesy: Jim Kuchar
Alert Trajectory Prediction-Based Alerting

- Alert is issued as soon as safe escape path is threatened
- Attempt to ensure minimum level of safety
- Some loss of control over false alarms
- Example: Probabilistic parallel approach logic (Carpenter & Kuchar)

Courtesy: Jim Kuchar
Monte Carlo Simulation Structure

Current state information
(position, velocity)

Protected Zone size

Intent information:
Waypoints (2D, 3D, 4D)
Target heading
Target speed
Target altitude
Target altitude rate
Maneuvering limitations

Uncertainties
(probability density functions)
Current states
Along- and cross-track error
Maneuvering characteristics
Confidence in intent information

Monte Carlo Simulation Engine

Probability of conflict

Implemented in real-time simulation studies at NASA Ames
Computational time on the order of 1 sec

Courtesy: Jim Kuchar
Example State Uncertainty Propagation

Computed via Monte Carlo

along-track $\sigma = 15$ kt
cross-track $\sigma = 1$ nmi
(from NASA Ames)

Courtesy: Jim Kuchar
Generating the System Operating Characteristic Curve

Example Alerting Threshold Locations

Probability of False Alarm $P(FA)$

Probability of Successful Alert $P(SA)$

Courtesy: Jim Kuchar
Multiple Alerting System Disonance

- Already occurred with on-board alerting system & air traffic controller
  - mid-air collision and several near misses
    - Germany, July 1st, 2002; Zurich, 1999; Japan, 2001
- Potential for automation/automation dissonance is growing

Adapted from Jim Kuchar and Lixia Song.
Example: Russian (TU154) and a DHL (B757) collide over Germany on July 1st, 2002

TCAS: on-board collision avoidance system
ATC: Air Traffic Controller
Dissonance

• Indicated Dissonance: mismatch of information between alerting systems
  - alert stage
  - resolution command

• Indicated dissonance may not be perceived as dissonance
  - Human operator knows why dissonance is indicated

• Indicated consonance may be perceived as dissonance
Causes of Indicated Dissonance

- Different alerting threshold and/or resolution logic
  - Alerting Thresholds $T_i$
  - Resolution Logic $R_i$
  - Resolution commands or guidance $c_i$
  - Attention-getting and urgency $\hat{y}_i, a_i$

- Different sensor error or sensor coverage
  - Sensor systems
  - $x$
  - $G_i$
  - $n_i$
  - $\hat{y}_i$
Example Perceived Dissonance

- Influenced by other factors
  (system dynamics, trend data, nominal information, human mental model, etc.)
Current Mitigation Methods

- **Prioritization**

  - Alerting system for traffic
  - Alerting system for terrain
  - The alert for traffic is inhibited or only displayed passively

- **Procedures for responding to dissonance**
  - Human operator can be trained to know how the alerting systems work and how to deal with dissonance
  - Training may be inadequate
    - 2 B-757 accidents in 1996, dissonant alert from airspeed data systems
Terrain Alerting

TAWS Look-Ahead Alerts
(Terrain Database)

“Terrain, Terrain, Pull Up…”
approx 22 sec.

“Caution Terrain”
approx 45 sec

Basic GPWS modes
(radar altitude)

Courtesy: Brian Kelly, Boeing
• Threat terrain is shown in solid red
• “Pull up” light or PFD message
• Colored terrain on navigation display

Courtesy: Brian Kelly, Boeing
Current Mitigation Methods (2)

- Modify procedures to avoid dissonance

- AILS --- Airborne Information for Lateral Spacing parallel approach
  - Special alerting system for closely-spaced runway approaches

- TCAS --- Traffic alert and Collision Avoidance System
  - Warns the pilots to an immediate collision with other aircraft

- Modify air traffic control procedures to reduce the likelihood of a simultaneous TCAS alert and parallel traffic alert

- Changing operation procedure may largely reduce the efficiency of the airspace around the airport
Multiple Alerting System Representation

System 1

System 2

Sensor systems

Resolution logic

Alerting threshold

Resolution commands or guidance

Attention-getting and urgency

Displays

Process

Human

Control

Uncertainties

experience, training, etc.

$\xi$

$\dot{x}$

$\int x$

$F$

$G_1$

$G_2$

$G_{nom}$

$y_1$

$y_2$

$y_{nom}$

$\hat{y}_1$

$\hat{y}_2$

$\hat{y}_{nom}$

$n_1$

$n_2$

$\hat{n}_1$

$\hat{n}_2$

$\tilde{e}_1$

$\tilde{e}_2$

$z_1$

$z_2$

$z_{nom}$

$D_1$

$D_2$

$D_{nom}$

$T_1$

$T_2$

$R_1$

$R_2$

nominal information sources

direct observation

Multiple Alerting System

Sensors

Direct Observation

Uncertainties

$\xi$

$\dot{x}$

$\int x$

$F$

$G_1$

$G_2$

$G_{nom}$

$y_1$

$y_2$

$y_{nom}$

$\hat{y}_1$

$\hat{y}_2$

$\hat{y}_{nom}$

$n_1$

$n_2$

$\hat{n}_1$

$\hat{n}_2$

$\tilde{e}_1$

$\tilde{e}_2$

$z_1$

$z_2$

$z_{nom}$

$D_1$

$D_2$

$D_{nom}$

$T_1$

$T_2$

$R_1$

$R_2$

nominal information sources

experience, training, etc.
SIMPLE REPRESENTATION OF CONFORMANCE MONITORING

Observed behavior

Non-Conformance Region

Conformance Region

Clearance

e.g. assigned trajectory, heading vector, altitude, etc.

CONFORMING AIRCRAFT

NON-CONFORMING AIRCRAFT

Cross-track deviation (nm)

Time (mins)

A320
(1990s)

B737-200
(1960s)

Cross-track deviation (nm)

Time (mins)
CORE RESEARCH APPROACH

- Conformance Monitoring as “fault detection”
  - Aircraft non-conformance a “fault” in ATC system needing to be detected
  - Existing fault detection techniques can be used for new application

MODEL OF SYSTEM

COMMAND INPUT

ACTUAL SYSTEM

FAULT DETECTION FUNCTIONS
- Residual Generation Scheme
- Decision-Making Scheme

EXPECTED STATE BEHAVIORS

OBSERVED STATE BEHAVIORS
- Fault detection framework tailored for conformance monitoring

CONFORMANCE MONITORING ANALYSIS FRAMEWORK

**ACTUAL SYSTEM REPRESENTATION**

- PILOT INTENT
- A/C INTENT
- CONTROL SYSTEM
- AIRCRAFT DYNAMICS

**SURVEILLANCE**

- Observed state behaviors
- Expected state behaviors

**CONFORMANCE MONITORING FUNCTIONS**

- Conformance Residual Generation Scheme
- Decision-Making Scheme

**CONFORMANCE MONITORING MODEL**

- PILOT INTENT MODEL
- A/C INTENT MODEL
- CONTROL SYSTEM MODEL
- AIRCRAFT DYNAMICS MODEL

**SURVEILLANCE MODEL**

- Trajectory Destination
- Target states
- Guidance e.g. ANP mode
- Nav. accuracy
- Control A/c
- Surface property
- Velocity
- Position

**EXTERNAL DISTURBANCES**

- e.g. winds

**CONFORMANCE BASIS**

- Actual system representation

- External disturbance model

- Fault detection framework tailored for conformance monitoring
Intent formalized in “Surveillance State Vector”

Surveillance State Vector, $X(t)$

\[
X(t) = \begin{bmatrix}
\text{Position states, } P(t) \\
\text{Velocity states, } V(t) \\
\text{Acceleration states, } A(t) \\
\text{Current target states, } C(t) \\
\text{Planned trajectory states, } T(t) \\
\text{Destination states, } D(t)
\end{bmatrix}
\]

Accurately mimics intent communication & execution in ATC
DECISION-MAKING SCHEME

- Consider evidence in Conformance Residual to make best determination of conformance status of aircraft
- Simple/common approach uses threshold(s) on Conformance Residuals

![Diagram showing scalar and vector residuals](image)

**Scalar residual**

- Conformance Residual vs Time
- Example threshold
- Non-conforming region
- Conforming region

**Vector residual**

- States observed from nominal system operation
- Non-conforming region
- State $x_1$
- State $x_2$
Use “figures of merit” to examine trade-offs applicable to application:

- Time-To-Detection (TTD) of alert of true non-conformance
- False Alarms (FA) of alert when actually conforming
- FA/TTD tradeoff analogous to inverse System Operating Characteristic curve

### FIGURE OF MERIT TRADEOFFS

**Increasing decision threshold**

**Ideal operating point**

**Time-To-Detection (TTD) of true non-conformance of a particular type**
OPERATIONAL DATA EVALUATION

- **Boeing 737-400 test aircraft**
  - Collaboration with Boeing ATM
  - Two test flights over NW USA
  - Experimental configuration not representative of production model

- **Archived ARINC 429 aircraft states**
  - Latitude/longitude (IRU & GPS)
  - Altitude (barometric & GPS)
  - Heading, roll, pitch angles
  - Speeds (ground, true air, vertical, ...)
  - Selected FMS states (desired track, distance-to-go, bearing-to-waypoint)

- **Archived FAA Host ground states**
  - Radar latitude/longitude
  - Mode C transponder altitude
  - Radar-derived heading & speed
  - Controller assigned altitude
  - Flight plan route (textual)
LATERAL DEVIATION TEST
SCENARIO

<table>
<thead>
<tr>
<th>Nominal flight</th>
<th>Deviation</th>
<th>Recovery</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cross-track error (nm)</td>
<td>Heading angle (degs)</td>
<td>Roll angle (degs)</td>
</tr>
</tbody>
</table>

- **Databus data (0.1 sec)**
- **GPS data (1 sec)**
- **Radar data (12 sec)**
LATERAL DEVIATION FALSE ALARM / TIME-TO-DETECTION (2)

Note: results are for a simple deviation from straight flight under autopilot control. Shifted curves would result for different operating modes and environments: demonstrated through extensive simulation studies in thesis.
LATERAL TRANSITION NON-CONFORMANCE SCENARIO

Flight test trajectory

Fillet to correct route

Fillet to incorrect route

Approx. 10° heading non-conformance

Correct route

Incorrect route
LATERAL TRANSITION FALSE ALARM / TIME-TO-DETECTION

Observed Probability of False Alarm

10° non-conformance from straight flight (low fidelity CMM)
10° non-conformance during transition (medium fidelity CMM)
10° non-conformance during transition (low fidelity CMM)

Ideal operating point

Time-To-Detection (secs)
Design Principles for Alerting and Decision-Aiding Systems for Automobiles

James K. Kuchar
Department of Aeronautics and Astronautics
Massachusetts Institute of Technology
- Alert time: \( t_{\text{alert}} = \frac{(r - d)}{v} \)

\( t_{\text{alert}} = 0 \rightarrow \) braking must begin immediately

\( t_{\text{alert}} = \tau \rightarrow \) alert is issued \( \tau \) seconds before braking is required

- Determine \( P(UA) \) and \( P(SA) \) as function of \( t_{\text{alert}} \)
Example Human Response Time Distribution

Lognormal distribution (mode = 1.07 s, dispersion = 0.49) [Najm et al.]
Case 3: Add Response Delay
Uncertainty
Case 4: Add Deceleration Uncertainty

\[ \sigma_a = 3 \text{ ft/s}^2 \]
Conformance Monitoring for Internal and Collision Alerting

- Simple Sensor Based Collision Alerting Systems Do Not Provide Adequate Alert Performance due to Kinematics
  - SOC Curve Analysis
    - P(FA), P(MD) Performance
- Enhanced Collision Alerting Systems Require Inference or Measurement of Higher Order Intent States
  - Automatic Dependent Surveillance (Broadcast)
  - Environment Inferencing
    - Observed States
Aircraft Surveillance State Vector, $X(t)$ containing uncertainty & errors $\delta X(t)$ is given by:

- Traditional dynamic states
- Intent and goal states

\[
X(t) = \begin{bmatrix}
\text{Position, } R(t) \\
\text{Velocity, } V(t) \\
\text{Acceleration, } A(t) \\
\text{Intent, } I(t) \\
\text{Goals, } G(t)
\end{bmatrix}, \quad \delta X(t) = \begin{bmatrix}
\delta R(t) \\
\delta V(t) \\
\delta A(t) \\
\delta I(t) \\
\delta G(t) \\
\vdots
\end{bmatrix}
\]
• Intent State Vector can be separated into current target states and subsequent states

\[ I(t) = \begin{cases} 
\text{Current target states} \\
\text{Subsequent planned trajectory}
\end{cases} \quad \text{(Eqn. 3)} \]
Automobile Lateral Tracking Loop

External Environment

- Strategic Factors
- Hazard Monitoring
- Threats
- Disturbances

Goal Selection
- Default
- Open Loop
- Optimized
- Commanded
- Prior History
- Instructed
- Wander

Route Selection
- Best Line
- Lane Switching
- Traffic
- Speed

Lane/Line Selection
- Desired Line

Lane/Line Tracking
- Steering Command
- Wheel Position (force)

Vehicle
- Acceleration
- Velocity
- Position

Vehicle States

X = (Goal, Subsequent Planned Trajectory, Current Target State, Acceleration, Velocity, Position)
Intent Observability States

- Roadway
- Indicator Lights
  - Break Lights
  - Turn Signals
  - Stop Lights
- Acceleration States
- GPS Routing
- Head Position
- Dynamic History
- Tracking Behavior
Fatal Accident Causes

Fatalities by Accident Categories

Note: Accidents involving multiple non-onboard fatalities are included. Accidents involving single, non-onboard fatalities are excluded.

CFIT†
Loss of control in flight
Midair collision
Inflight fire
Fuel tank explosion
Landing
Ice/snow
Fuel exhaustion
Wind shear
Takeoff configuration
Runway incursion
Other
RTO††
Unknown

36 31 2 2 2 12 4 7 2 4 13 2 5

Total fatalities = 6,792 (6,566 onboard)
1997 fatalities = 684 (all onboard)

†CFIT  Controlled flight into terrain
††RTO  Refused takeoff

Adapted from The Boeing Company
Prototype MIT Terrain Alerting Displays
Alerting System Research

- **Kuchar, 1995**
  - Method for setting alert thresholds to balance False Alarms and Missed Detections

- **Yang, 2000**
  - Use of dynamic models to drive alerting criteria

- **Tomlin, 1998**
  - Hybrid control for conflict resolution

- **Lynch and Leveson, 1997**
  - Formal Verification of conflict resolution algorithm

- **Pritchett and Hansman, 1997**
  - *Dissonance* between human mental model and alerting system
    - Information that suggests different timing of alerts and actions to resolve the hazard
  - Suggested display formats to reduce dissonance