Surviving the Improbable
Upset Prevention and Recovery in Flight Control

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Outline

• Introduction

• Upset Prevention:
  – Safe Flight Envelope Estimation
  – Safe Flight Envelope Protection: Concept Demonstration

• Upset Recovery: Stall Recovery Guidance
Introduction: Who am I?

History:
• 1998 – 2004: Aerospace Engineering, Delft University of Technology, NL
• 2004 – 2010: lecturer and PhD researcher in Delft
  2009: visiting scientist at DLR in Germany during 4 months
• 2010 – 2016: scientific researcher at DLR in Germany
  2012 – 2014: Visiting Marie Curie Fellow at NASA Ames
• 2016 – today: senior aerospace research engineer at NASA Ames

Interests:
• Aircraft state estimation and Kalman filtering
• Aerodynamic model identification: structure selection and parameter identification, fault detection
• Adaptive control and nonlinear dynamic inversion, Pseudo Control Hedging
• Control Allocation
• Handling qualities and pilot workload analysis
Introduction

- Loss of control in flight (LOC-I) remains the most frequent primary cause of accidents
- 40% of all accidents is LOC-I related and this category involves most fatalities
- Increasing trend over the last decades

Upset Prevention and Recovery

Research subtopics, based on CAST directives on safety enhancements:

1. **Upset prevention**
   - Adaptive safe flight envelope estimation
   - Adaptive envelope protection

2. **Upset recovery**
   1. Stall recovery guidance
   2. Unusual attitude recovery

Upset recovery training aspect
Estimation of the envelope boundaries

Trim envelope: all the sets of stable equilibrium conditions $(V, \gamma)$ within the input limits.

Aircraft variables:
- Airspeed $V$
- Flight path angle $\gamma$

Inputs:
- Angle of attack $\alpha$
- Thrust $T$

Max thrust constraint
Max angle of attack constraint
Set of stable trim points
Balanced min thrust and drag
Min angle of attack constraint, or max velocity

ACT Simulation Model at 15000 feet.
Estimation of the envelope boundaries

Safe maneuverability envelope is defined as intersection between forward and backward reachable sets.

Intersection of 5 second forwards and backwards reachable sets.

Based on ACT Simulation Model at 15000 ft.
Estimation of the envelope boundaries
trim and maneuvering envelope variation

Full Flaps at 15000 ft.
Nominal at 15000 ft.
Nominal at 30000 ft.
Full Flaps, Gear, Spoilers at 13000 ft.
Estimation of the envelope boundaries

maximum roll angle

\[ L \cos \gamma \cos \phi = W \]

maximum achievable roll angle at current airspeed and flight path angle before stall occurs

\[ V_{IAS} = 222 \text{ kts}, \phi_{\text{max}} > 60^\circ \]

\[ V_{IAS} = 161 \text{ kts}, \phi_{\text{max}} = 45^\circ \]

\[ V_{IAS} = 142 \text{ kts}, \phi_{\text{max}} = 20^\circ \]
Additional information provided to the pilot over the cockpit displays
Experiment overview:
Advanced Concepts Flight Simulator

- **Objective**
  Explore how crews manage their energy state, both with and without new technology

- **Overview**
  - 10 commercial flight crews
  - 4 descent and landing scenarios in Memphis airspace
  - Workload assessment, questionnaires

- **New technology:**
  - Maneuver envelope limits displayed on the primary flight display (PFD)
  - Others (not discussed here)
Experiment overview: Icing scenario

- Aircraft is initialized in an icing condition:
  - modified flight dynamics: less lift, more drag, $\alpha_{\text{stall}}$ smaller

![Graphs showing lift and drag curves with and without ice](chart.png)
Results

Icing scenario

Impact of icing on the safe flight envelope

Introduction – Envelope Estimation – Envelope Protection – Concept Demonstration – Upset Recovery
Results

Icing scenario

Margins to limits for icing scenario

Flap deployment strategy for icing scenario

margins for all crews

flap deployment strategy
Implementation of the protections in the closed loop architecture

Protections are implemented in:
- Flight control laws
- Cockpit displays
- Haptic feedback

<table>
<thead>
<tr>
<th>Envelope boundary</th>
<th>Protection in controller</th>
<th>Displayed in PFD</th>
<th>Haptic feedback</th>
</tr>
</thead>
<tbody>
<tr>
<td>max roll</td>
<td>X</td>
<td>X</td>
<td>X</td>
</tr>
<tr>
<td>max $\alpha$</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>min airspeed</td>
<td>via max $\alpha$</td>
<td>X</td>
<td>via max $\alpha$</td>
</tr>
<tr>
<td>max load factor</td>
<td>X</td>
<td></td>
<td>X</td>
</tr>
<tr>
<td>min/max flight path angle</td>
<td>X</td>
<td></td>
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</tbody>
</table>
Experiment method: Simona Research Simulator

• Research hypotheses
  – Will envelope protection prevent loss of control and reduce workload?
  – Will modified PFD improve situational awareness about flying capabilities?
  – Will haptic feedback improve situational awareness about protective action?

• Overview
  – 7 commercial pilots
  – Icing scenario in approach near Amsterdam Schiphol Airport
  – Workload assessment and questionnaires

• New technologies
  – Adaptive envelope protection in flight control laws
  – Extended primary flight display
  – Haptic feedback on stick
Results: icing scenario

- Gradual ice accretion on the wings, starts around FL30
- Wind gusts make effect on envelope less obvious
- Speed and bank angle margins improve with new tech
- No increase in workload
Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen

DLR Robotic Motion Simulator: overview

Simulator cab of Robotic Motion Simulator
Concept demonstration of envelope protection in Robotic Motion Simulator at DLR Oberpfaffenhofen
Conclusions of upset prevention

• Adaptive safe flight envelope estimation and protection algorithms were designed and evaluated by several airline pilots in various simulators.

• Safe envelope bounds estimated in real time taking into account malfunctions and upsets, used for three kinds of protections:
  – Extended Primary Flight Display
  – Hard protections in the flight control laws
  – Haptic feedback on sidestick

• Significant performance changes detected in icing scenario.

• Observations with new technology:
  
  **ACFS experiments:**
  – pilots adapted strategy based on information
  – Icing scenario:
    – higher $V_{\text{min}}$
    – flap deployment for higher speeds

  **Simona experiments:**
  – larger safety margins to envelope boundaries prevent loss of control in off-nominal conditions,
  – reduced workload (objective and subjective ratings),
  – improved situational awareness (subjective ratings).
Stall Recovery Guidance
# Sequence of events for stall recovery

<table>
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<tr>
<th>Onset to Stall</th>
<th>Stall Occurrence</th>
<th>Stall Recovery</th>
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<tbody>
<tr>
<td>Decreasing airspeed, increasing angle of attack</td>
<td>Speed below stall speed, alpha exceeds stall value</td>
<td>Accelerating dive, trade altitude for speed, potential → kinetic energy</td>
</tr>
<tr>
<td><strong>FAA stall recovery template:</strong></td>
<td>1. Disconnect autopilot and autothrottle/autothrust</td>
<td>2. Nose down until stall indications eliminated, 3. Bank wings level, 4. Apply thrust as needed, 5. Retract speed brakes and spoilers</td>
</tr>
<tr>
<td></td>
<td>6. Return to the desired flightpath</td>
<td>Establish level flight or climb</td>
</tr>
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- **Onset to Stall:**
  - Decreasing airspeed, increasing angle of attack

- **Stall Occurrence:**
  - Speed below stall speed, alpha exceeds stall value

- **Stall Recovery:**
  - Accelerating dive, trade altitude for speed, potential → kinetic energy
  - Pitch up, transition to level flight, avoiding secondary stalls or overstressing structure
  - Out of stall, establish level flight or climb

- **FAA Stall Recovery Template:**
  1. Disconnect autopilot and autothrottle/autothrust
  2. Nose down until stall indications eliminated
  3. Bank wings level
  4. Apply thrust as needed
  5. Retract speed brakes and spoilers
  6. Return to the desired flightpath
Upset recovery: stall recovery guidance

Strategy: exchange potential energy (altitude) for kinetic energy (speed), taking into account energy dissipation (drag) and energy inflow (thrust)

Constraints:
- Secondary stalls ($\alpha$)
- Structural loads ($n_z$)
- Pitching moment ($T_{\text{max}}$)

Pilot guidance through flight director ($\theta_c$) and throttle tape ($T_c$) in PFD
Evaluated in 3 different simulators

- Vertical Motion Simulator at NASA Ames
- Research Flight Deck at NASA Langley
- Level D A330 simulator at FAA
Experiment results

Traffic avoiding maneuver in cruise phase:

Performance improvements with guidance:
• Fewer and less severe secondary stalls
• Less total altitude loss during recovery
• No violations of maximum/minimum load factor limits
• On average shorter time to recover
• Better buffer to overspeed limit
Conclusions and remarks

• Overall, stall recovery guidance algorithms evaluated in 3 simulators
  – NASA Ames
  – NASA Langley
  – FAA.

• 2 dissimilar aircraft configurations

• 65 participating flight crews:
  – 40 at NASA Ames (of which 10 test pilots)
  – 13 at NASA Langley (Boeing pilots)
  – 12 at FAA (Airbus pilots)

• Different scenarios: cockpit display malfunctions, autothrottle failure, sensor faults, windshear, traffic avoiding maneuvers in all phases of flight.

• Satisfactory performance, well received by pilots.
Thank you for your attention

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