National Aeronautics and Space Administration

Aircraft Loss of Control: Research and Technology Directions

Assuring Safe and Effective Control under Hazardous Conditions

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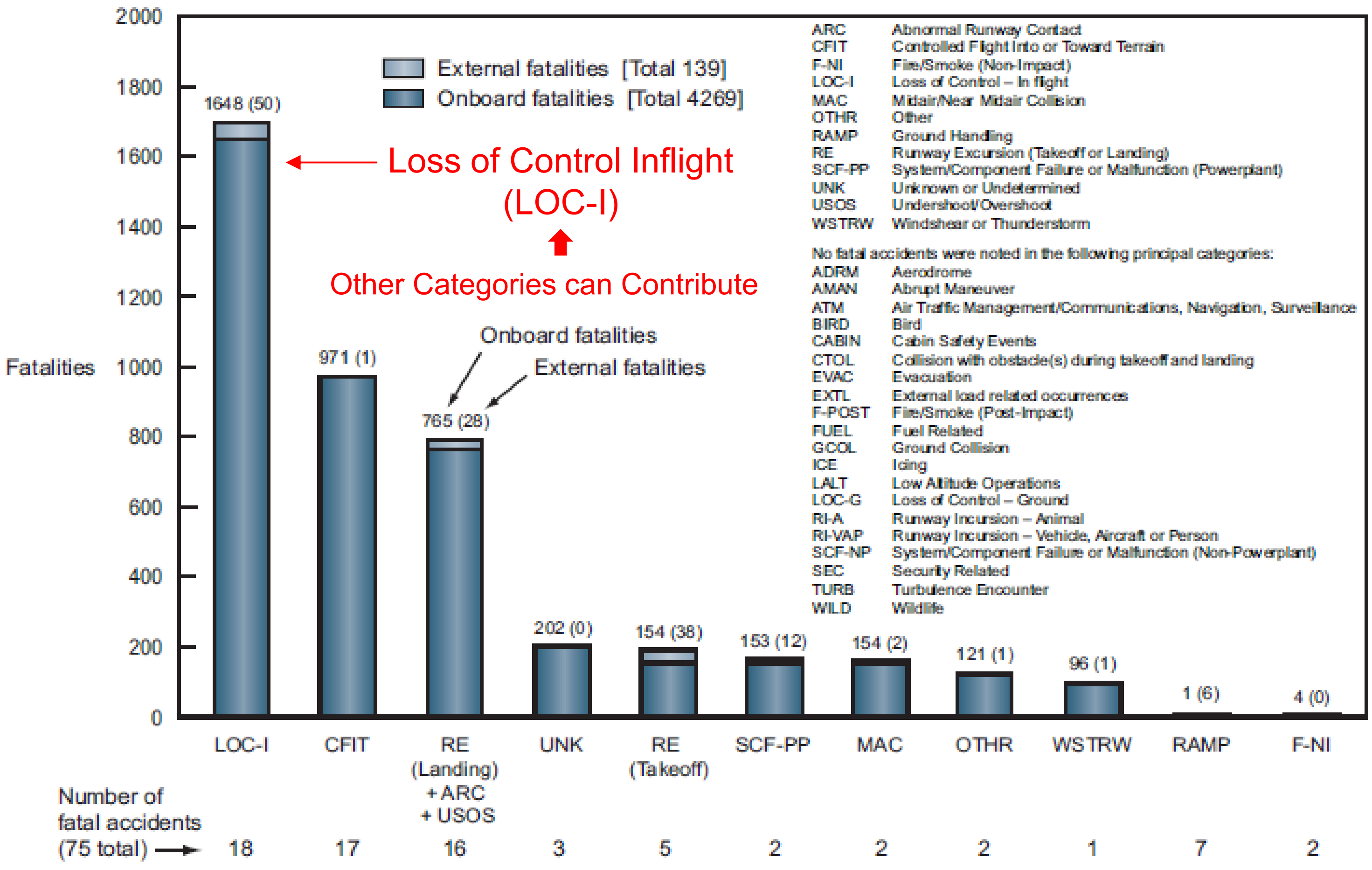
Outline

- Introduction: Aircraft Loss of Control (LOC)
- Research Approach
- Selected Research Results
  - LOC Hazards Analysis
  - Vehicle Dynamics Modeling
  - Guidance, Control, & Systems
  - Validation
- Future Research Directions
- Summary & Concluding Remarks

LOC Overview: Relevance to Accident Statistics

Fatalities by CAST/ICAO Common Taxonomy Team (CICTT) Aviation Occurrence Categories

Fatal Accidents – Worldwide Commercial Jet Fleet – 2003 Through 2012



Loss of Control Inflight (LOC-I)

Other Categories can Contribute

ARC	Abnormal Runway Contact
CFIT	Controlled Flight Into or Toward Terrain
F-NI	Fire/Smoke (Non-Impact)
LOC-I	Loss of Control – In flight
MAC	Midair/Near Midair Collision
OTHR	Other
RAMP	Ground Handling
RE	Runway Excursion (Takeoff or Landing)
SCF-PP	System/Component Failure or Malfunction (Powerplant)
UNK	Unknown or Undetermined
USOS	Undershoot/Overshoot
WSTRW	Windshear or Thunderstorm

No fatal accidents were noted in the following principal categories:

ADRM	Aerodrome
AMAN	Abrupt Maneuver
ATM	Air Traffic Management/Communications, Navigation, Surveillance
BIRD	Bird
CABIN	Cabin Safety Events
CTOL	Collision with obstacle(s) during takeoff and landing
EVAC	Evacuation
EXTL	External load related occurrences
F-POST	Fire/Smoke (Post-Impact)
FUEL	Fuel Related
GCOL	Ground Collision
ICE	Icing
LALT	Low Altitude Operations
LOC-G	Loss of Control – Ground
RI-A	Runway Incursion – Animal
RI-VAP	Runway Incursion – Vehicle, Aircraft or Person
SCF-NP	System/Component Failure or Malfunction (Non-Powerplant)
SEC	Security Related
TURB	Turbulence Encounter
WILD	Wildlife

Note: These statistics apply to jet transport aircraft ≥ 60,000 lbs.

CAST – Commercial Aviation Safety Team / ICAO – International Civil Aviation Organization

LOC Example: Colgan Air Flight 3407

- Crashed During Approach to Landing (instrument landing system approach)
- Aircraft: Bombardier DHC-8-400, N200WQ; Date: February 12, 2009
- Clarence Center, New York (Near Buffalo-Niagara International Airport)

NTSB

National Transportation Safety Board

Office of Research and Engineering

Flightpath

Loss of Control on Approach
Colgan Air, Inc., Operating as
Continental Connection Flight 3407
Bombardier DHC-8-400, N200WQ

Clarence Center, New York

February 12, 2009

DCA09MA027

Board Meeting

<u>Note</u>: This Aircraft (and many others involved in LOC accidents) < 60,000 lbs

What is Aircraft LOC and what Causes it?

LOC Problem Definition

LOC Characteristics

LOC: aircraft motion that is characterized by one or more of the following: [1, 2]

- outside normal envelopes (adjusted for flight phase)
- not predictably altered by pilot control inputs (i.e, aircraft response is no longer predictable to the pilot)
- characterized by nonlinear effects that degrade handling qualities
  - kinematic / inertial coupling
  - disproportionately large responses to small state variable changes,
  - oscillatory / divergent behavior
- likely to result in high angular rates / displacements,
- characterized by the inability to maintain heading, altitude, and wings-level flight
- flight path is outside of acceptable tracking tolerances and cannot be predictably controlled by pilot (or autoflight system) inputs

Note: LOC need not be unrecoverable

Primary Causes

1. Entry into vehicle upset condition (e.g., Stall / Departure)
2. Reduction or loss of control effectiveness
3. Changes to vehicle dynamic response and handling / flying qualities (including asymmetric effects)
4. Combinations of the above (1-3)

Causal & Contributing Factors

- **Adverse onboard conditions**:
  - **vehicle impairment**
    - » Inappropriate vehicle configuration, contaminated airfoil, improper loading, vehicle damage to airframe and engines
  - **system faults, failures, and errors**
    - » Control component, engine, sensor system, flight deck instrumentation, non-control component
  - **inappropriate crew action / inaction**
    - » Loss of aircraft attitude, energy, or system state awareness, aggressive maneuver, abnormal control input, ineffective recovery, improper procedure, crew fatigue / impairment
- **External hazards and disturbances**:
  - **inclement weather & atmospheric disturbances**
    - » wind shear, turbulence, rain / thunderstorms, snow / icing, wake vortices
  - **poor visibility** (fog / haze, night)
  - **obstacle** (fixed or moving)
- **Abnormal dynamics & vehicle upsets**:
  - abnormal vehicle dynamics & control response
  - abnormal attitude, airspeed, angular rates, asymmetric forces, or flight trajectory
  - uncontrolled descent (including spiral dive)
  - stall/departure from controlled flight

LOC Usually Results from Multiple Causal & Contributing Factors

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[1] Wilborn, J. E. and Foster, J. V., "Defining Commercial Aircraft Loss-of-Control: a Quantitative Approach," *AIAA Atmospheric Flight Mechanics Conference and Exhibit, Providence, Rhode Island, 16-19 August 2004.*

[2] Lambregts, A. A., Nesemeier, G., Wilborn, J.E., Newman, R. L., "Airplane Upsets: Old Problem, New Issues, AIAA Modeling and Simulation Technologies Confernece and Exhibit, Honolulu, Hawaii, 18-21 August 2008

LOC Research Approach

Holistic Approach to Breaking LOC Precursor Sequences:

Prevent | **Detect** | **Mitigate** | **Recover**

Normal Flight → **Vehicle Problem / External Hazard** → **Inappropriate Crew Response** → **Vehicle Upset** → Safe Flight

- Improved Crew Training under LOC Precursor Conditions

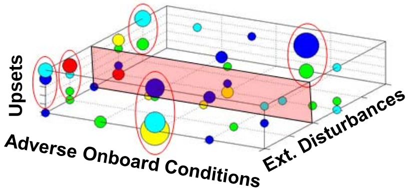
- Vehicle Impairment, Fault, Failure, Damage
- External Hazard / Disturbance

- Poor Situational Awareness / Distraction
- Spatial Disorientation (Poor Visibility)
- Mode Confusion (System Complexity)

- Abnormal Attitudes
- Abnormal Trajectory
- Stall/Departure

Problem Definition

LOC Hazards Analysis



- **Crew Action / Inaction**
- **Vehicle / System**
- **Environmental / Atmospheric**
- **Vehicle Upsets**

Vehicle Failure → **Inappropriate Crew Response** → **Vehicle Upset** →

New / Emergent Risks

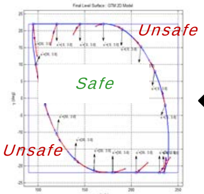
Technology Development & Evaluation

Vehicle Dynamics Modeling

Guidance, Control & Systems

Comprehensive Technology Evaluations

Analysis



Simulation

Testing

LOC Test Scenarios ↕ ***Evaluation Requirements***

LOC RWG (Industry, Government, Academia)

Technology Products

Improved Crew Training *under LOC Hazards*

Enhanced Representative Simulation Methods & Models

Improved Situational Awareness, Guidance & Control *under LOC Hazards*

Enhanced Onboard Systems Technologies

Technology Transition

LOC Hazards Analysis (1)

Objectives:

1. Establish Analysis Team (NASA, NTSB, NIA, STI, MIT)*
2. Define an extensive accident (and incident) set over a recent 15-year time period
   - Events that involved loss of control regardless of official classification
   - Wide spectrum of commercial transport aircraft (at or above 12,500 lbs, jets & props)
3. Perform a thorough analysis of this accident / incident set
   - Team consensus process
   - Evaluation of causal & contributing factors (or precursors) should include
     - individual precursors
     - worst-case precursor combinations
     - precursor sequencing
4. Identify future LOC risks
   - Based on current trends
   - Determined by CAST
5. Develop a comprehensive set of LOC test scenarios
   - Based on & correlated to accident / incident analysis & future risks
   - Any additional conditions needed for resilience testing

* LOC Analysis Team: C. Belcastro & J. Foster (NASA), L. Groff & D. Crider (NTSB), R. Newman (NIA), D. Klyde (STI), A. Huston (MIT)

LOC Hazards Analysis (2)

LOC Accident / Incident Data Set

- Data Sources
  - Aircraft Accident Reports on DVD (R. Dorsett, 2006)
  - Australian Transport Safety Bureau (ATSB)
  - Aviation Safety Network (ASN)
  - Canadian Transportation Safety Board (TSB)
  - Flightglobal (Ascend Database)
  - French Bureau d'Enquêtes et d'Analyses pour la sécurité de l'aviation civile (BEA)
  - German Bundesstelle für Flugunfalluntersuchung (BFU)
  - International Civil Aviation Organization (ICAO)
  - Irish Air Accident Investigation Unit (AAIU)
  - National Transportation Safety Board (NTSB)
- Search Criteria
  - "loss-of-control"
  - "upset"
  - "unusual attitude"
  - "stall"
  - "uncontrolled"

Resulted in Broader LOC Accident Set than LOC-I, Including Accidents & Incidents Involving:

- Failure by crew to maintain control,
- Weather encounters,
- Abrupt maneuvers, and
- Reduced control capability due to equipment malfunction or failure

LOC Hazards Analysis (3)

275 Accidents and Incidents (1996 – 2010)

7185 Onboard Fatalities, 235 Ground Fatalities

LOC Events by 5-Year Intervals:

Timeframe	Events	On-Board Fatalities
1996 to 2000	102	2938
2001 to 2005	99	2143
2006 to 2010	74	2104
Total	275	7185

LOC Events by Phase of Flight:

Flight Regime	Events	On-Board Fatalities
Takeoff	6	270
Initial Climb	79	1241
Climb	43	1697
Cruise	41	2008
Descent	17	156
Holding	22	0
Approach	34	1087
VFR Pattern	8	69
Circling	3	152
Final Approach	9	77
Landing	18	37
Go-around	8	15
Missed Approach	5	374
Maneuvering	2	2
Total	275	7185

LOC Events by Aircraft Classification:

Aircraft Classification	Events	On-Board Fatalities
Wide-body Turbojets	38	2224
Narrow-body Turbojets	96	3858
Business Jets	42	115
Turboprop Transports	44	615
Piston Transports	5	34
Commuter Airplanes	50	339
Total	275	7185

LOC Events by Type of Operation:

Operation	Events	On-Board Fatalities
Scheduled Airlines	143	5803
Non-Scheduled	87	1234
Non-Revenue Operations	28	78
Executive Transportation	17	70
Total	275	7185

Accident Set is Provided in Appendix A
of the 2014 SciTech Paper (see Refs in Backup)

LOC Hazards Analysis (4)

Adverse Onboard Conditions	External Hazards & Disturbances	Abnormal Vehicle Dynamics & Upsets
Vehicle Impairment	**Inclement Weather & Atmospheric Disturbances**	**Abnormal Vehicle Dynamics**
Inappropriate Vehicle Configuration	Thunderstorms / Rain	Uncommanded Motions
Contaminated Airfoil	Wind Shear	Oscillatory Vehicle Response
Improper Loading (Weight / CG)	Turbulence	Abnormal Control for Trim / Flight
Improper Loading (Cargo)	Wake Vortex	Abnormal / Counterintuitive Control Response
Airframe Structural Damage	Snow / Icing	
Engine Damage		
System & Component Failure / Malfunction	**Poor Visibility**	**Vehicle Upset Conditions**
System Operational Error	Fog / Haze	Abnormal Attitude
Control Component	Night	Abnormal Airspeed
Engine		Abnormal Angular Rates
Sensor		Undesired Abrupt Dynamic Response
Flight Deck Instrumentation		Abnormal Flight Trajectory
System / Sub-System (non-control)		Uncontrolled Descent
Ineffective Crew Action / Inaction	**Obstacle**	Stall / Departure
Loss of Attitude State Awareness	Fixed	
Loss of Energy State Awareness	Moving	
Lack of Aircraft / System State Awareness		
Aggressive Maneuver		
Abnormal / Inadvertent Control Input		
Improper / Ineffective Recovery		
Inadequate Crew Resource Monitoring		
Improper Procedure		
Crew Fatigue / Impairment		

Precursor Categories

Precursor Sub-Categories

Precursors / Hazards

LOC Hazards Analysis (5)

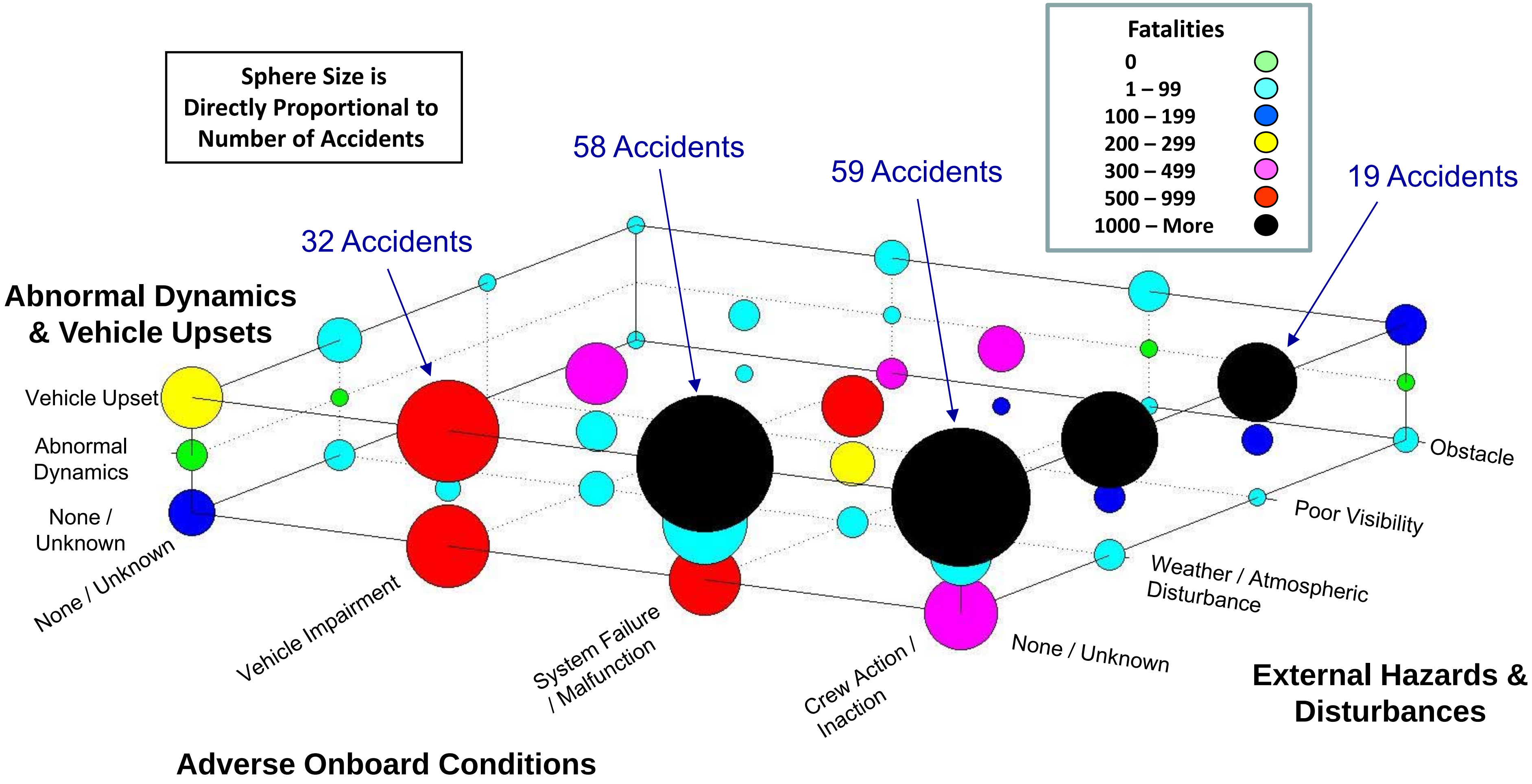
Individual LOC Hazards Statistics: Category & Sub-Category Level

Hazard Category / Sub-Category	Accidents / Incidents	%	Fatalities	%
Adverse Onboard Conditions	**240**	**87.3**	**6750**	**94.0**
Vehicle Impairment	86	31.3	2576	35.8
System & Component Failures / Malfunctions	117	42.6	3150	43.8
Inappropriate Crew Action / Inaction	160	58.2	4444	61.8
External Hazards & Disturbances	**101**	**36.7**	**3036**	**42.2**
Inclement Weather & Atmospheric Disturbances	65	23.6	1741	24.2
Poor Visibility	30	10.9	1324	18.4
Obstacle	16	5.8	601	8.4
Abnormal Dynamics & Vehicle Upset Conditions	**220**	**80.0**	**5416**	**75.4**
Abnormal Vehicle Dynamics	47	17.1	312	4.3
Vehicle Upset Conditions	188	68.4	5315	74.0

Individual Precursor Contributions are Provided in the 2014 SciTech Paper

LOC Hazards Analysis (6)

Worst-Case Hazards Combinations (1)

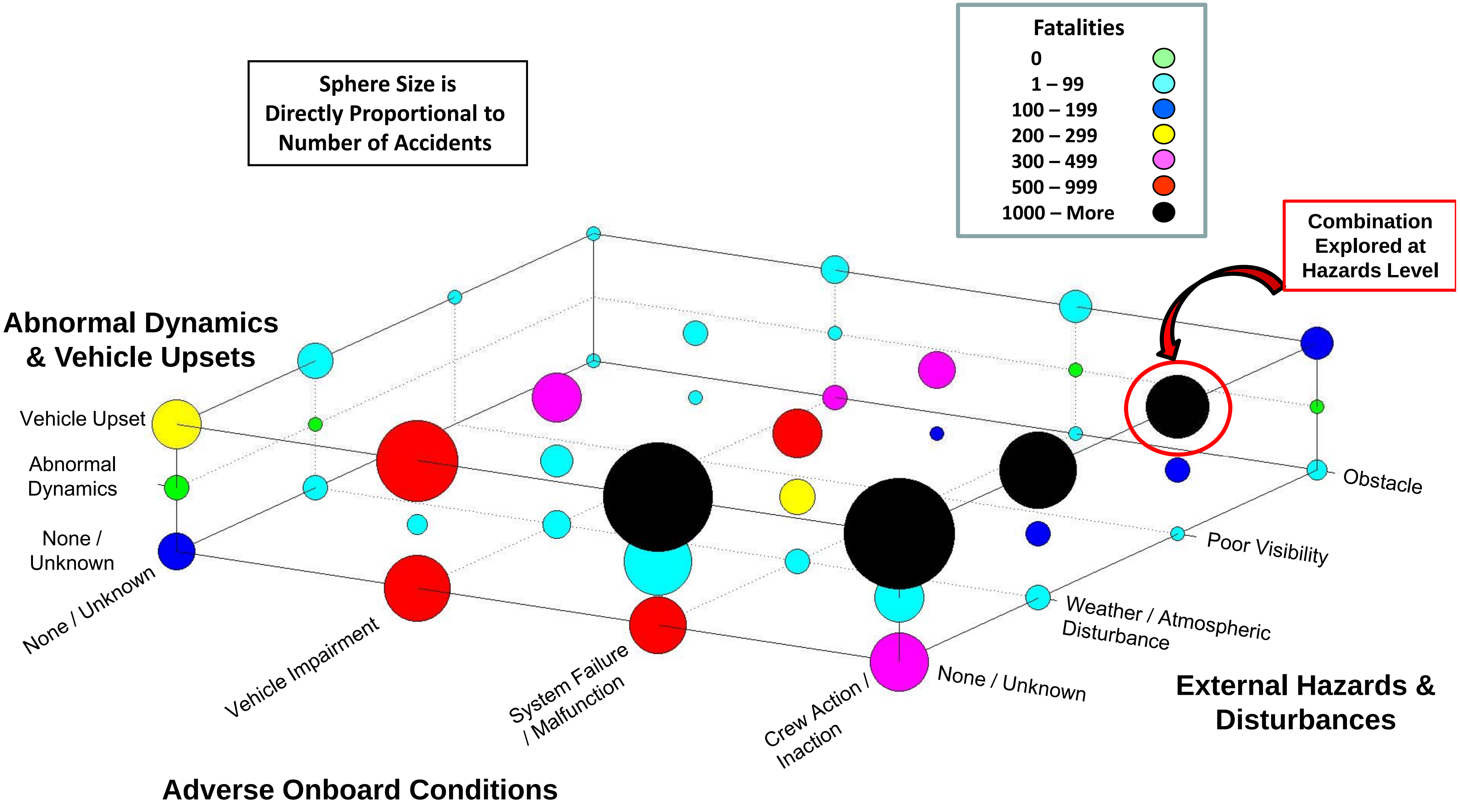


Sphere Size is Directly Proportional to Number of Accidents

Preliminary Worst-Case Analysis Performed at Sub-Category Level

LOC Hazards Analysis (7)

Worst-Case Hazards Combinations (2)



Sphere Size is Directly Proportional to Number of Accidents

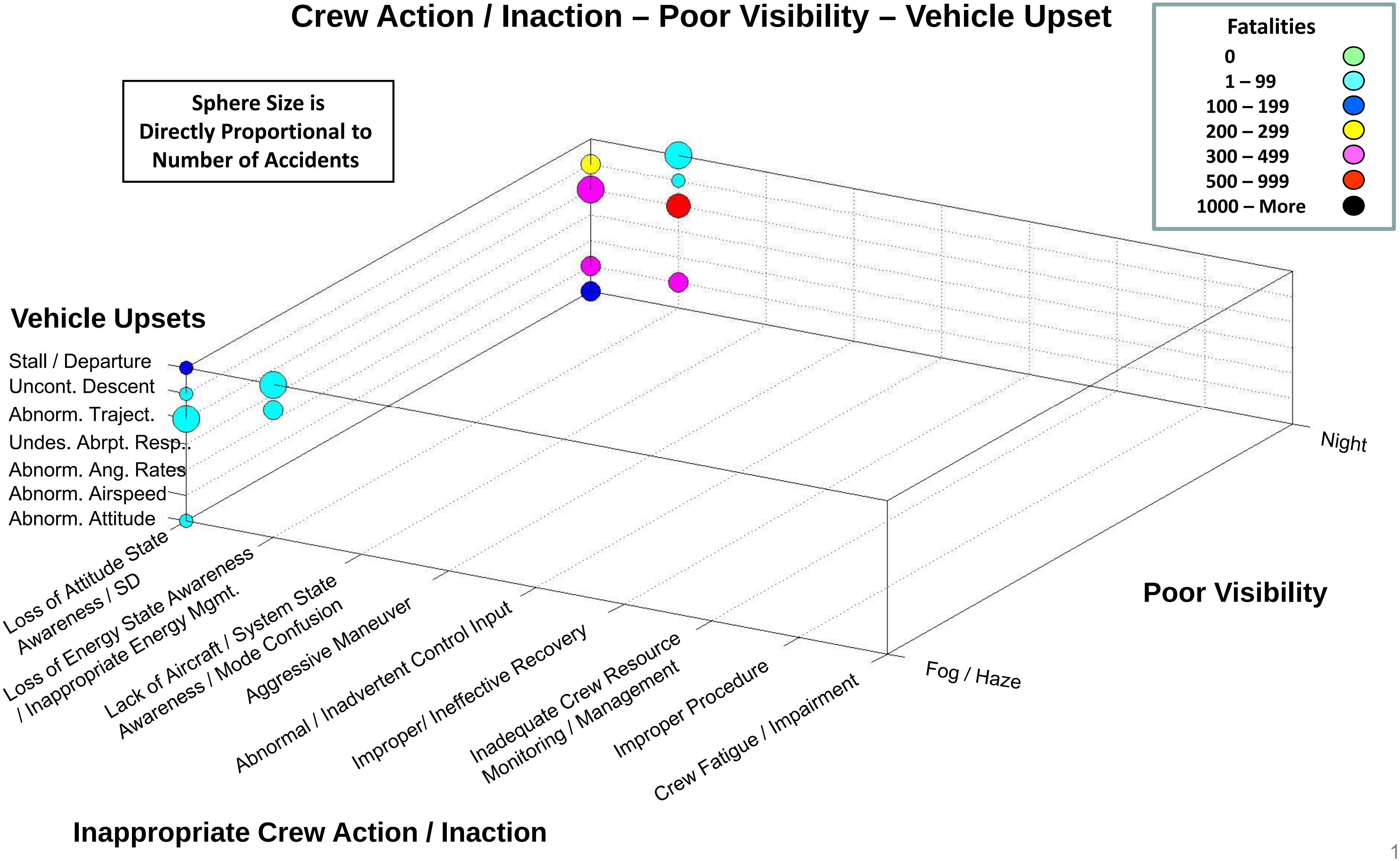
Fatalities

0 🟢
1 – 99 🔵
100 – 199 🔵
200 – 299 🟡
300 – 499 🟣
500 – 999 🔴
1000 – More ⚫

Combination Explored at Hazards Level

LOC Hazards Analysis (8)

Precursor Combinations for Crew Action / Inaction – Poor Visibility – Vehicle Upset



Sphere Size is Directly Proportional to Number of Accidents

LOC Hazards Analysis (9)

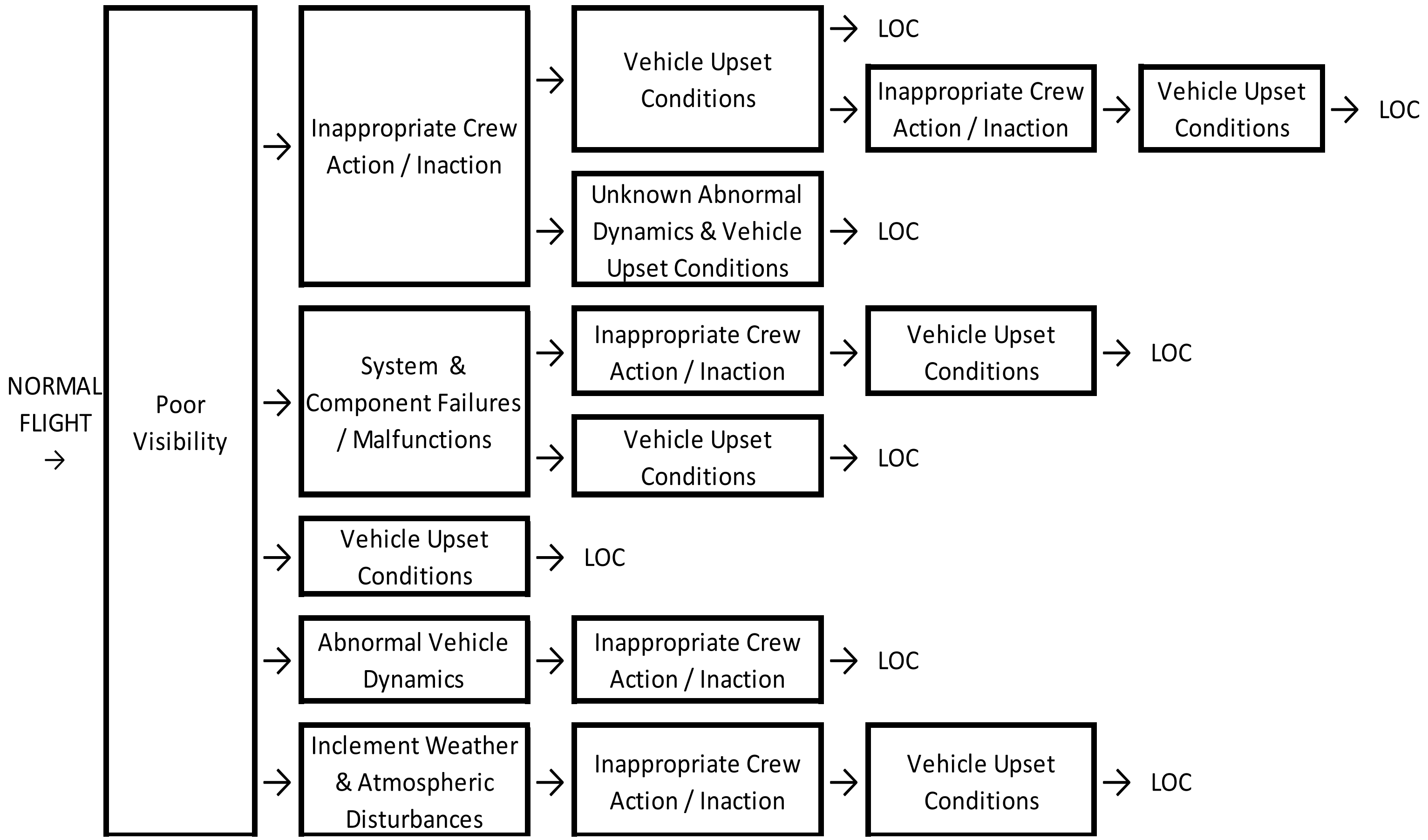
Temporal Sequencing: Category & Sub-Category Totals

Precursor	1st	2nd	3rd	4th	5th	6th	7th
Adverse Onboard Conditions	**167**	**153**	**88**	**39**	**10**	**3**	**0**
Vehicle Impairment	41	32	11	4	3	0	0
System & Component Failures / Malfunctions	84	35	10	5	1	0	0
Inappropriate Crew Action / Inaction	42	86	67	30	6	3	0
External Hazards & Disturbances	**86**	**16**	**4**	**2**	**0**	**1**	**0**
Inclement Weather & Atmospheric Disturbances	58	6	1	1	0	0	0
Poor Visibility	19	6	2	0	0	0	0
Obstacle	9	4	1	1	0	1	0
Abnormal Dynamics & Vehicle Upset Conditions	**0**	**89**	**78**	**55**	**33**	**11**	**3**
Abnormal Vehicle Dynamics	0	23	14	8	4	1	0
Vehicle Upset Conditions	0	66	64	47	29	10	3
Unknown Precipitating Events	**22**	**-**	**-**	**-**	**-**	**-**	**-**
TOTALS	**275**	**258**	**170**	**119**	**43**	**15**	**3**

Precursor Sequence Information is Provided in the 2014 SciTech Paper

LOC Hazards Analysis (10)

Sequence Diagrams – Example: Initiated by Poor Visibility

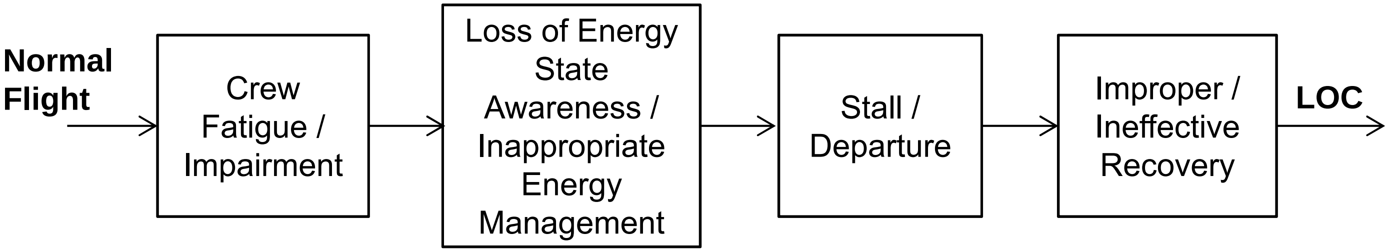


	Events	Fatalities
Poor Visibility Total	19	832
NORMAL FLIGHT → Poor Visibility → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	11	529
NORMAL FLIGHT → Poor Visibility → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	1	143
NORMAL FLIGHT → Poor Visibility → Inappropriate Crew Action / Inaction → Unknown Abnormal Dynamics & Vehicle Upset Conditions → LOC	1	3
NORMAL FLIGHT → Poor Visibility → System & Component Failures / Malfunctions → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	2	3
NORMAL FLIGHT → Poor Visibility → System & Component Failures / Malfunctions → Vehicle Upset Conditions → LOC	1	1
NORMAL FLIGHT → Poor Visibility → Vehicle Upset Conditions → LOC	1	1
NORMAL FLIGHT → Poor Visibility → Abnormal Vehicle Dynamics → Inappropriate Crew Action / Inaction → LOC	1	0
NORMAL FLIGHT → Poor Visibility → Inclement Weather & Atmospheric Disturbances → Inappropriate Crew Action / Inaction → Vehicle Upset Conditions → LOC	1	152

Sequence Diagrams at Category & Sub-category Level are Provided in Appendix B of the 2014 SciTech Paper

LOC Hazards Analysis (11)

Example Sequence at Precursor Level:
Colgan Air 3407 (2/12/2009)



Normal Flight

Crew Fatigue / Impairment

Loss of Energy State Awareness / Inappropriate Energy Management

Stall / Departure

Improper / Ineffective Recovery

LOC

LOC Hazards Analysis (12)

Example Detailed Precursor Sequence:

2/6/1996: Birgenair 301 (B-757) En Route,

Near Puerto Plata, Dom. Republic (189 Fatalities)

Improper Maintenance Action / Inaction	Night	Sensor / Sensor System Failure / Malfunction	System Operational Error / Inadequacy	Flight Deck Instrument Failure / Malfunction	Loss of Energy State Awareness / Inadequate Energy Management	Stall / Departure	Improper / Ineffective Recovery
Pitot tubes were left uncovered for 3-4 days prior to the flight	Unclear whether night conditions were a contributing factor	Pilot's air speed indicator (ASI) was not working properly and resulted in a falsely high ASI reading; Co-pilot's ASI seemed to be working; Incorrect ASI readings possibly caused by a blocked pitot tube (which was left uncovered for 3-4 days prior to this flight)	Autopilot / Autothrottle inappropriately increased pitch-up and reduced airspeed based on erroneous ASI of 350 kts (when actual ASI was 220 kts)	"Rudder ratio" and "Mach Airspeed" advisory warnings were issued to crew while Co-pilot ASI read 200 kts decreasing; excessive speed warning was followed by stick shaker indicating imminent stall	Pilots got confused due to the ASI mis-match between pilot and co-pilot, decreasing co-pilot ASI while getting an excessive speed warning, and excessive speed warning followed by stick shaker	Stick shaker activated	Crew realized too late that they were losing speed and altitude, disconnected the autopilot and applied full thrust; crew failed to execute procedures for recovery

LOC Hazards Analysis Summary

- Comprehensive Set of Accidents / Incidents Compiled for 1996 – 2010
  - 10 International Databases Searched for LOC
  - Commercial transports at or above 12,500 lbs
  - 275 accidents & incidents identified resulting in 7185 fatalities
- Preliminary Analysis Results Obtained
  - Based on Six Accident / Incident Subsets (45-46 Events)
  - Individual Precursor Statistics
  - Worst-Case Precursor Combinations
  - Temporal Sequencing
- Ongoing Research
  - Re-Evaluation Based on Team Consensus Approach (In Progress)
  - Definition of Future LOC Risks (To be Coordinated with CAST / ATLAS)
  - Development of LOC Test Scenarios
  - Final Results to be Submitted for NASA TP and Journal Publication

- Analysis results and test scenarios can be used in the development and evaluation of technology solutions for LOC prevention and recovery (e.g., Onboard Systems)
  - LOC test scenarios also provide engineering simulation requirements
- Potential for wider application of this research to broader LOC solutions

LOC Problem Publications

- "Statistical Summary of Commercial Jet Airplane Accidents, Worldwide Operations, 1959-2011", Boeing Commercial Airplanes, July 2012. URL: http://www.boeing.com/news/techissues/pdf/statsum.pdf
- Evans, Joni K., "An Examination of In Flight Loss of Control Events During 1988–2004", Alliant Techsystems, Inc., NASA Langley Research Center, Contract No.: TEAMS:NNL07AM99T/R1C0, Task No. 5.2, 2007.
- Wilborn, J. E. and Foster, J. V., "Defining Commercial Aircraft Loss-of-Control: a Quantitative Approach," *AIAA Atmospheric Flight Mechanics Conference and Exhibit, AIAA, Providence, Rhode Island, 16-19 August 2004*
- Belcastro, Christine M. and Foster, John V.: Aircraft Loss-of-Control Accident Analysis; *AIAA Guidance, Navigation and Control Conference*, Toronto, August 2-5, 2010
- Belcastro, Christine M., Groff, Loren, Newman, Richard L., Foster, John V., Crider, Dennis A., Klyde, David H., and Huston, A. McCall, "Preliminary Analysis of Aircraft Loss of Control Accidents: Worst Case Precursor Combinations and Temporal Sequencing", *AIAA Conference on Guidance, Navigation, and Control*, *SciTech Forum*, National Harbor, Maryland, January 2014.
- Belcastro, Christine M. and Jacobson, Steven: Future Integrated Systems Concept for Preventing Aircraft Loss-of-Control Accidents; *AIAA Guidance, Navigation and Control Conference*, Toronto, August 2-5, 2010.
- Belcastro, Christine M., "Loss of Control Prevention and Recovery: Onboard Guidance, Control, and Systems Technologies," *AIAA Conference on Guidance, Navigation and Control*, Minneapolis, Minnesota, August 2012.
- Belcastro, Christine M.: Validation and Verification of Future Integrated Safety-Critical Systems Operating under Off-Nominal Conditions; *AIAA Guidance, Navigation and Control Conference*, Toronto, 2010.
- Belcastro, Christine M., "Validation of Safety-Critical Systems for Aircraft Loss-of-Control Prevention and Recovery," *AIAA Guidance, Navigation, and Control Conference*, Minneapolis, Minnesota, August 2012.
- Belcastro, Christine M., Groff, Loren, Newman, Richard L., Foster, John V., Crider, Dennis A., Klyde, David H., and Huston, A. McCall, "Aircraft Loss of Control Analysis and Test Scenarios for Technology Development and Validation", *NASA Technical Paper*. (To be submitted in 2014)

Initial LOC Hazards Prioritization

Analysis of 64 Accidents with 2821 Fatalities from 2000 – 2009 (10 Years)

Multiple Hazards Guidance, Mitigation, & Upset Prevention / Recovery

Crew-Related Hazards

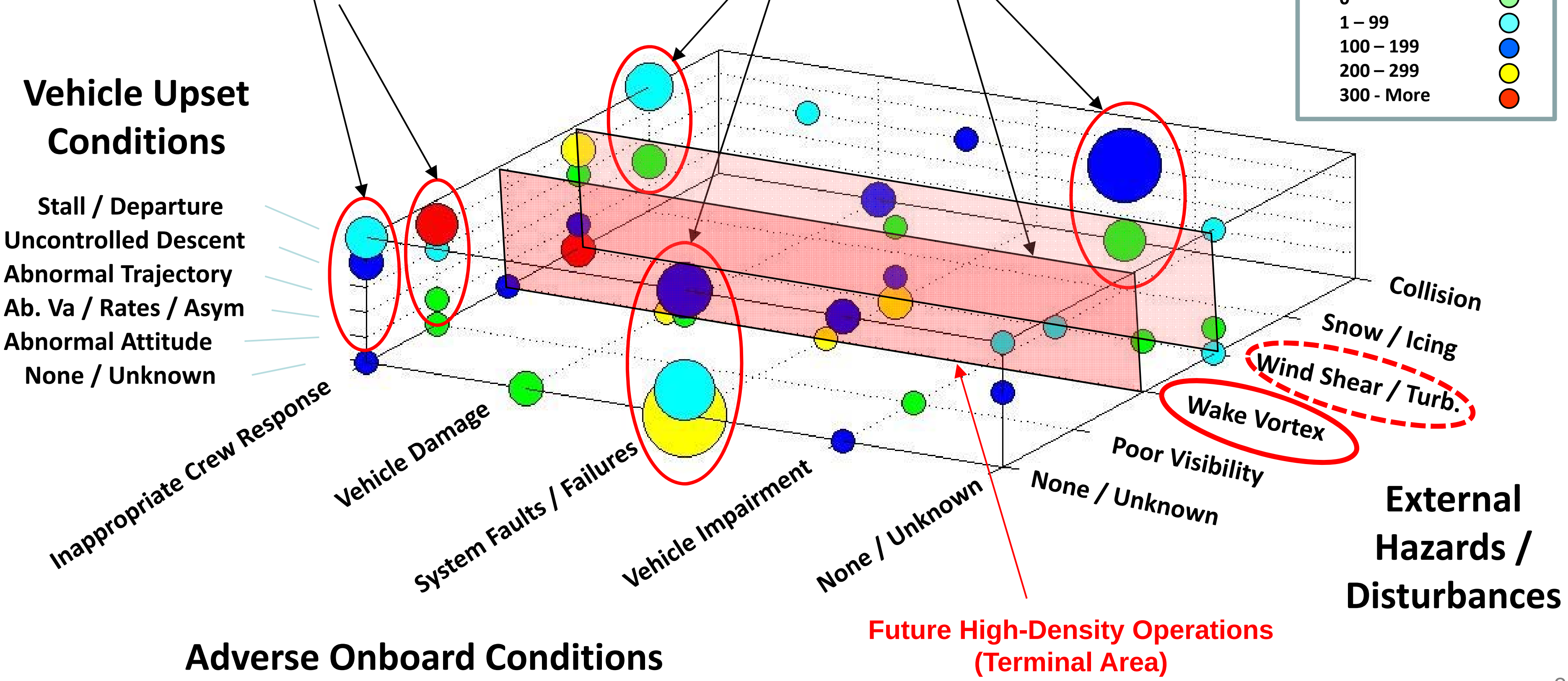
- Loss of Aircraft State Awareness
  - Attitude / Energy
- Spatial Disorientation

Vehicle/Environment-Related Hazards

- Control Component Failures
- Icing Effects
- Wakes / Wind Shear

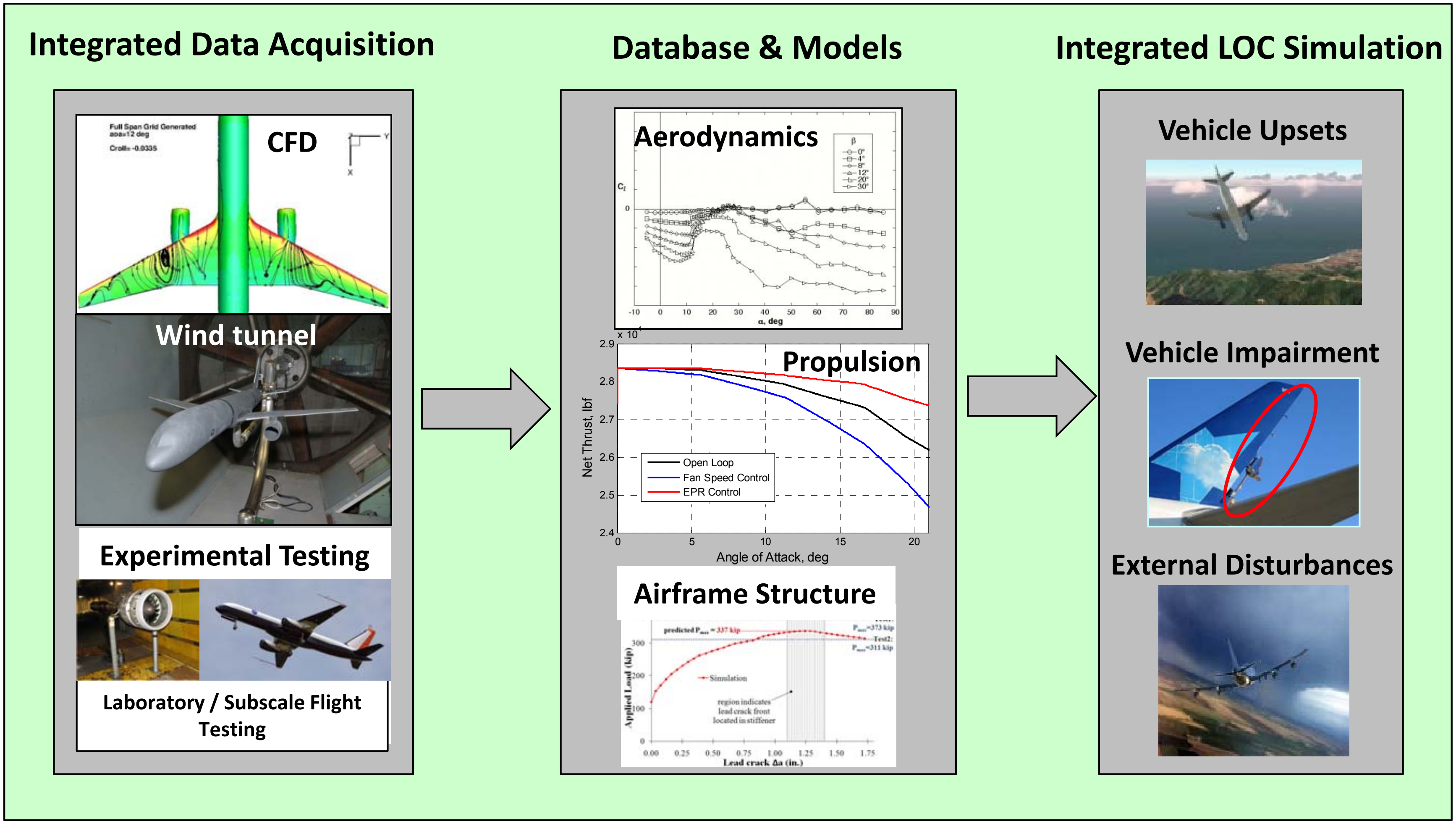
+/- Upsets & Crew Actions / Inactions

Sphere Size is Directly Proportional to Number of Accidents



Vehicle Dynamics Modeling Technologies (VDMT) for Characterizing Effects of LOC Hazards

Representative Modeling Research Approach



Integrated Data Acquisition

CFD

Wind tunnel

Experimental Testing

Laboratory / Subscale Flight Testing

Database & Models

Aerodynamics

Propulsion

Airframe Structure

Integrated LOC Simulation

Vehicle Upsets

Vehicle Impairment

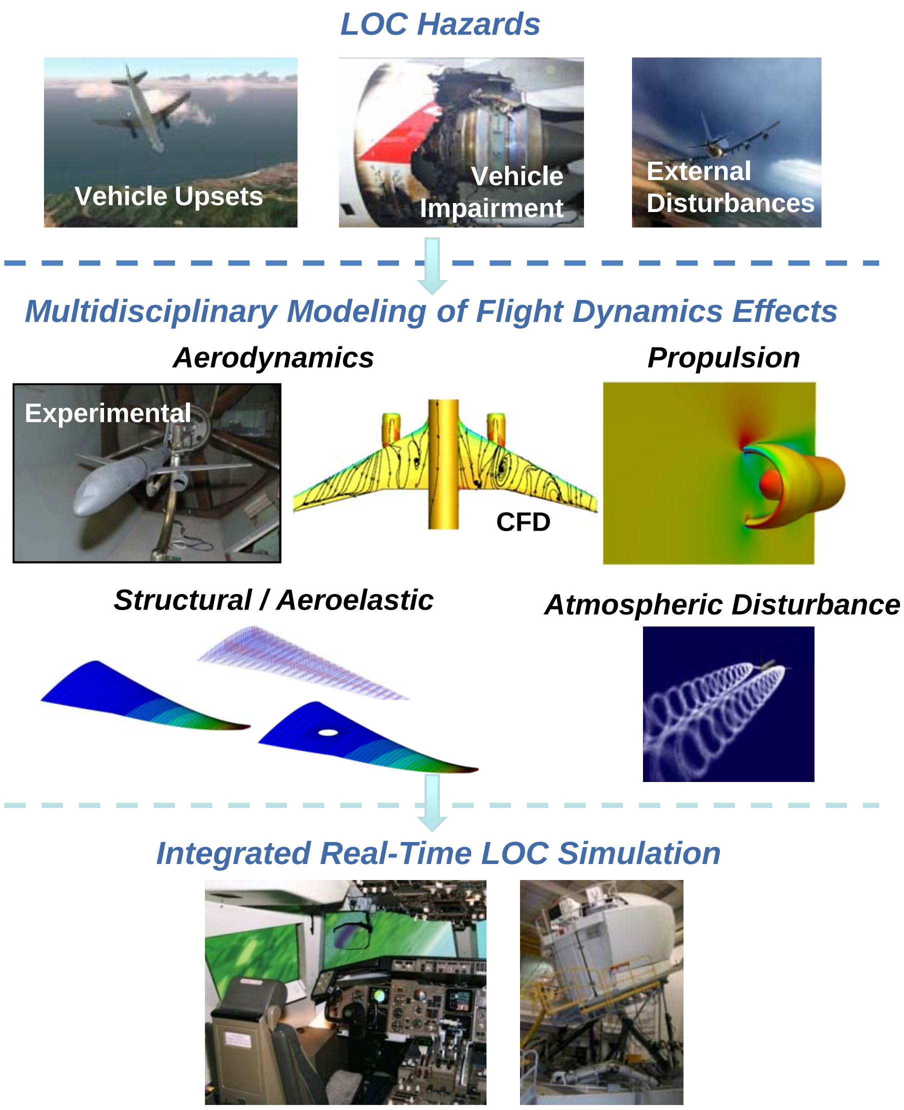
External Disturbances

Class-Representative Integrated LOC Simulations (Upsets, Impairment, External Disturbances)

NRA Partner: Boeing

VDMT Accomplishments Summary

- Vehicle Upset Modeling
  - Aerodynamic Effects
  - Engine Effects
  - Airframe Structure Effects
- Vehicle Impairment Modeling
  - Icing Effects (Partnered with AEST)
    - Airframe
    - Engine
  - Damage
    - Airframe (Partnered with MVS)
    - Engine
  - System Failures
    - Control Components
    - Collateral Damage Effects
    - Engine
- Integration of Existing Atmospheric Disturbance Models
  - Wind Shear
  - Wake Vortices
  - Turbulence
- Integrated Real-Time Simulation Development
  - Multidisciplinary Hazard Effects
  - Multiple Hazards that can Lead to LOC



LOC Hazards

Multidisciplinary Modeling of Flight Dynamics Effects

Integrated Real-Time LOC Simulation

Integrated Multidisciplinary Real-Time Simulation Provide Means of Capturing Vehicle-Level Effects

Guidance, Control, and Systems Technologies (GCST) for Safe & Effective Control under LOC Hazards

Research Objectives

- Goal: Develop and evaluate onboard systems technologies that provide improved real-time situational awareness, guidance, and control under hazards that can lead to LOC

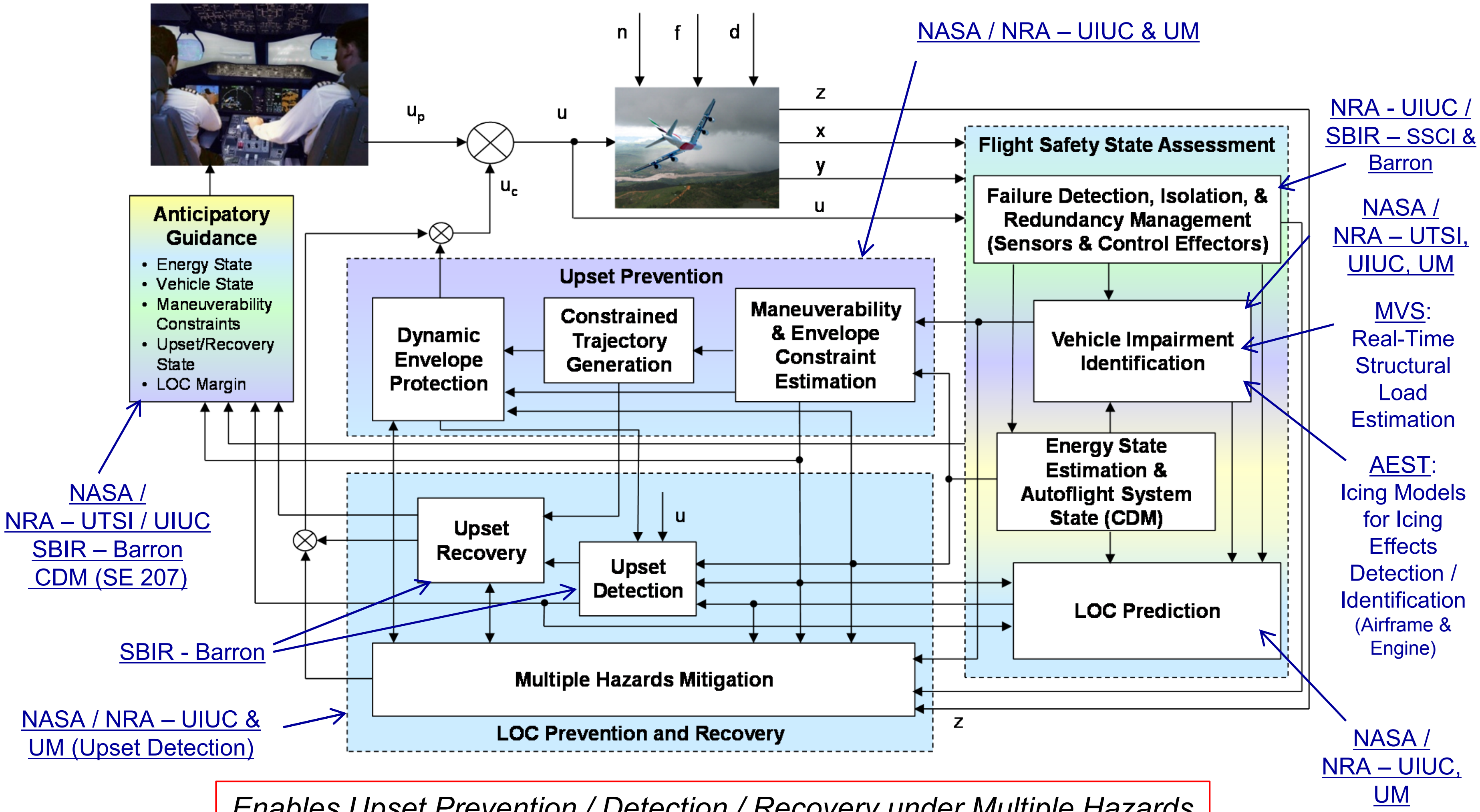
- Research Objectives:
  - Develop an integrated system architecture and technologies that provide
    - Hazards detection and flight safety impacts assessment
    - Upset prevention, detection and recovery
    - Multiple hazards mitigation (system failures, icing, wakes / wind shear)
  - Develop preliminary crew interface concepts that provide
    - Improved situational awareness specific to LOC
    - Anticipatory guidance for LOC prevention
    - Control cueing for recovery
  - Evaluate GCST technologies with support by CTE technologies
    - Analysis
    - Simulation
    - Experimental Testing

Guidance, Control, and Systems Technologies (GCST) for Safe & Effective Control under LOC Hazards

🟨 Crew Decision Making (CDM)

🟩 Maintaining Vehicle Safety (MVS)

🟦 🟪 Assuring Safe Control (ASC)



Anticipatory Guidance
- Energy State
- Vehicle State
- Maneuverability Constraints
- Upset/Recovery State
- LOC Margin

Upset Prevention

Dynamic Envelope Protection

Constrained Trajectory Generation

Maneuverability & Envelope Constraint Estimation

Flight Safety State Assessment

Failure Detection, Isolation, & Redundancy Management (Sensors & Control Effectors)

Vehicle Impairment Identification

Energy State Estimation & Autoflight System State (CDM)

LOC Prediction

Upset Recovery

Upset Detection

Multiple Hazards Mitigation

LOC Prevention and Recovery

NASA / NRA – UIUC & UM

NRA - UIUC / SBIR – SSCI & Barron

NASA / NRA – UTSI, UIUC, UM

MVS: Real-Time Structural Load Estimation

AEST: Icing Models for Icing Effects Detection / Identification (Airframe & Engine)

NASA / NRA – UIUC, UM

NASA / NRA – UTSI / UIUC SBIR – Barron CDM (SE 207)

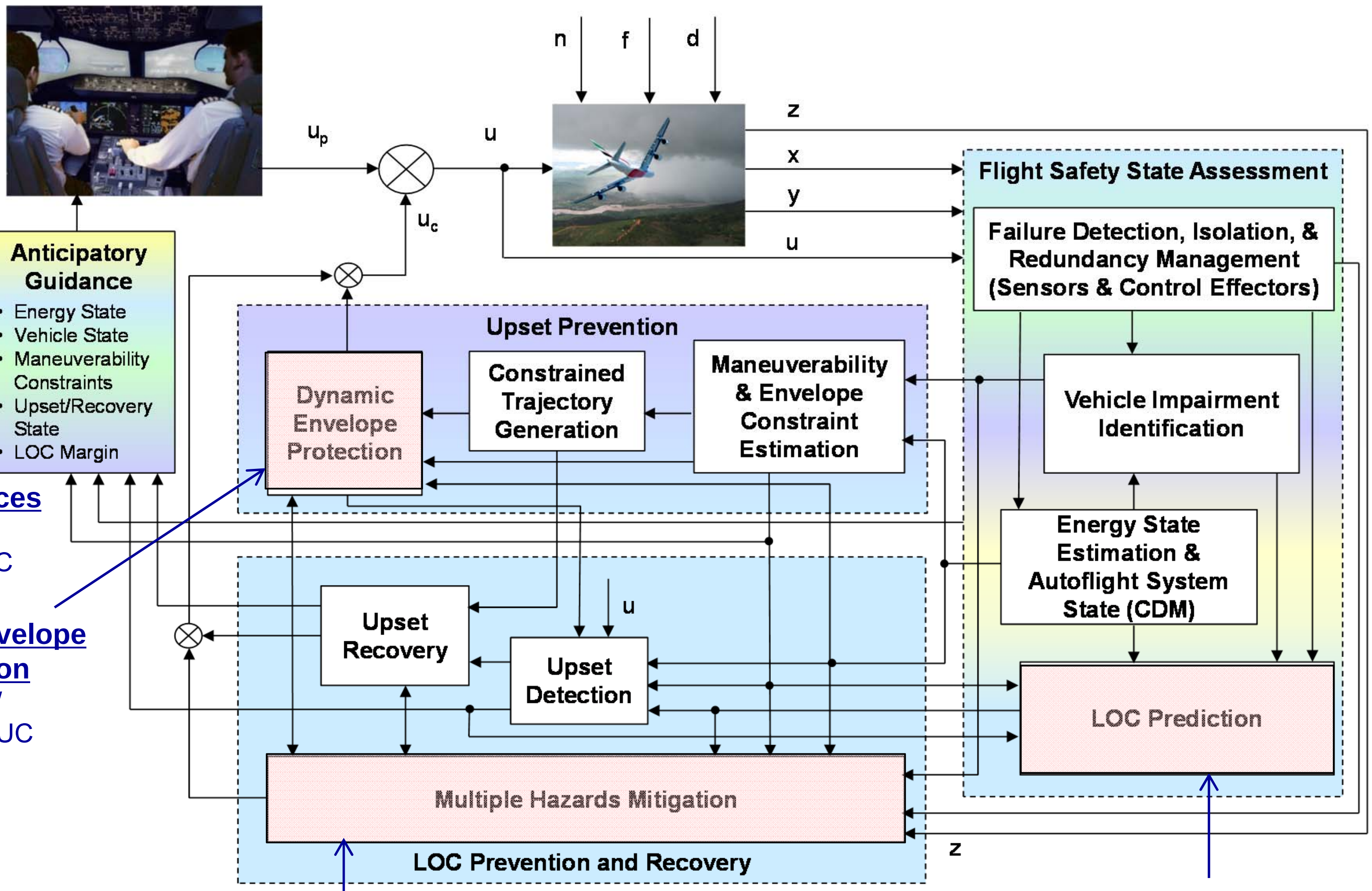
SBIR - Barron

NASA / NRA – UIUC & UM (Upset Detection)

Enables Upset Prevention / Detection / Recovery under Multiple Hazards

NRA: University of Illinois (UIUC), University of Michigan (UM), University of Tennessee (UTSI); SBIR: Scientific Systems (SSCI), Barron Associates (Barron)

Multiple Hazards Mitigation, LOC Prediction & Dynamic Envelope Protection



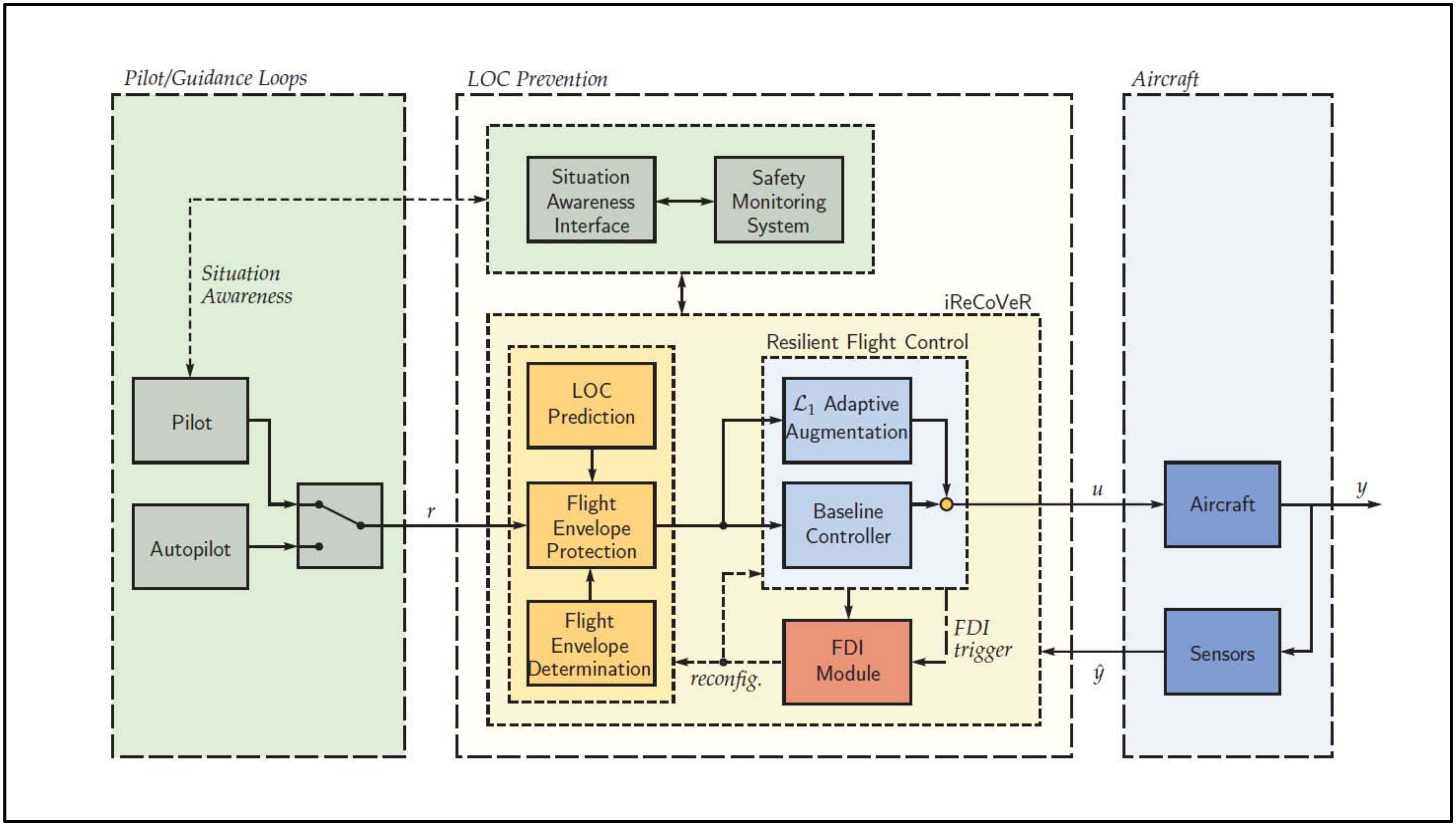
Pilot Interfaces
NASA /
NRA – UIUC

Dynamic Envelope Protection
NASA /
NRA – UIUC

Resilient Flight Control
NASA / NRA – UIUC

LOC Prediction
NASA /
NRA – UIUC

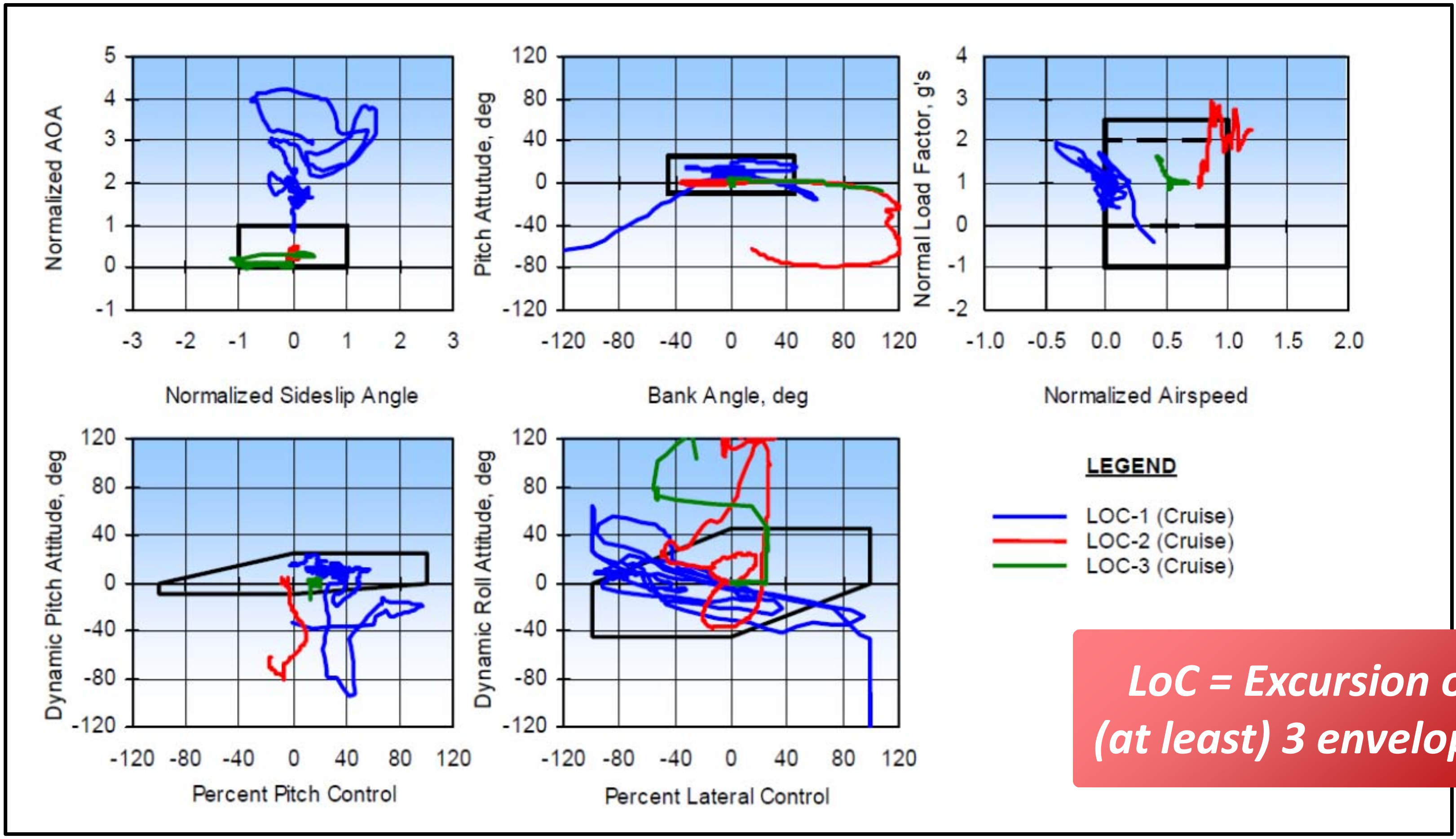
UIUC Technical Approach: iReCoVeR



UIUC Research Objectives

- *Dynamic Flight Envelope Protection (DFEP) and LOC Prediction:*
  - Ensure aircraft stays within its safe operational envelope
  - Automatically return the aircraft to the safe operational envelope if it is violated
- *Resilient Flight Control (RFC):*
  - Short-term stabilization with improved maneuverability margins under
    - Challenging flight conditions
    - Moderate faults/failures
    - Vehicle impairment conditions
  - Consisting of a baseline controller and an L1 adaptive control augmentation
- *Fault Detection and Isolation (FDI):*
  - Detect and isolate adverse conditions, e.g. vehicle impairment or ice accretion
  - Provide signal for reconfiguring RFC
- *Flight Envelope Determination (FED):*
  - Determine accurate estimate of the operational envelope of the possibly impaired aircraft
  - Provide estimate of envelope to DFEP

LOC Prediction & Flight Envelope Protection (1)

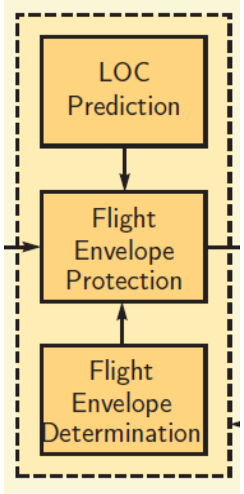


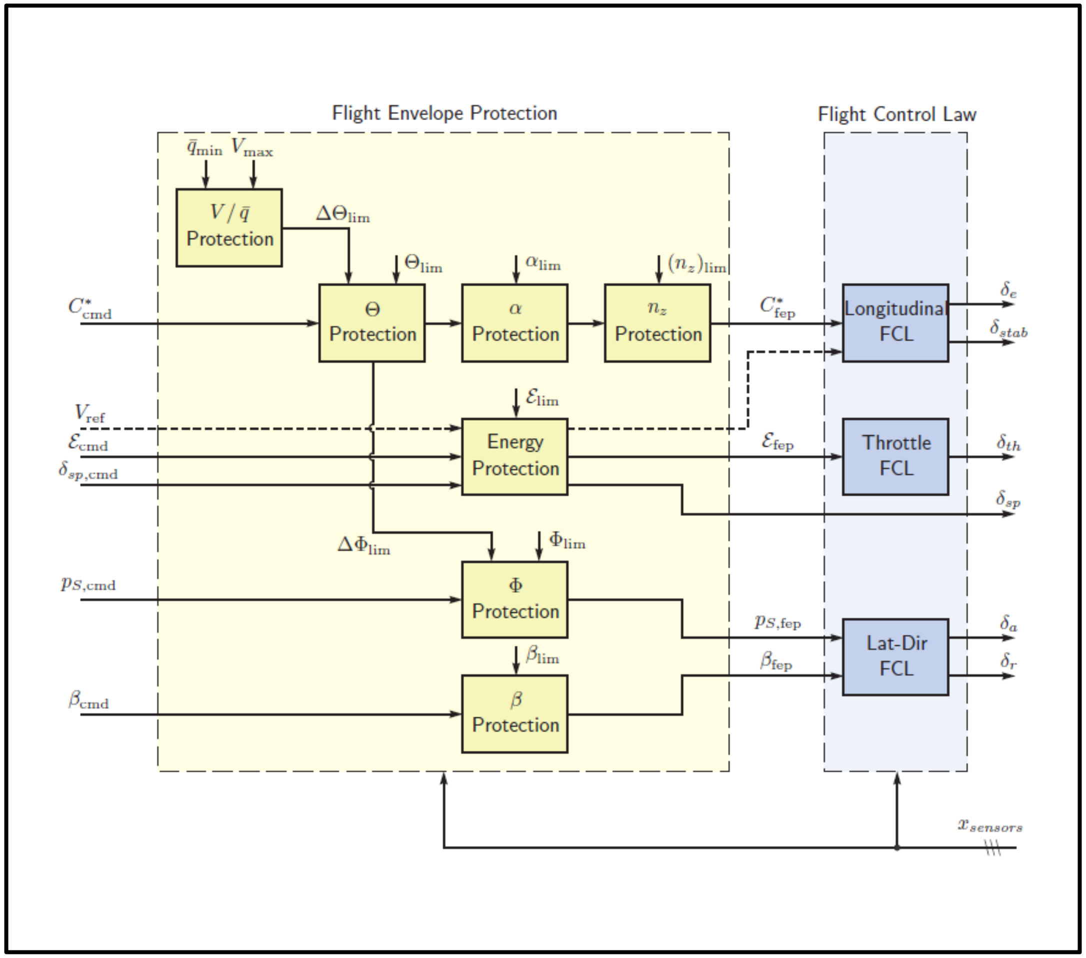
LoC = Excursion of (at least) 3 envelopes

[1] Wilborn, J. E. and Foster, J. V., "Defining Commercial Aircraft Loss-of-Control: a Quantitative Approach," *AIAA Atmospheric Flight Mechanics Conference and Exhibit*, Providence, RI, August 2004.

LOC Prediction & Flight Envelope Protection (2)

Control architecture for dynamic flight envelope protection (simplified):





- ***Command-limiting protection control laws;***

  C, p_s, β, & total specific energy*

- ***Dynamic FEP limits;***

  Limits can be adjusted online

- ***Hierarchical architecture for longitudinal protection system;***

  Load factor has the highest priority

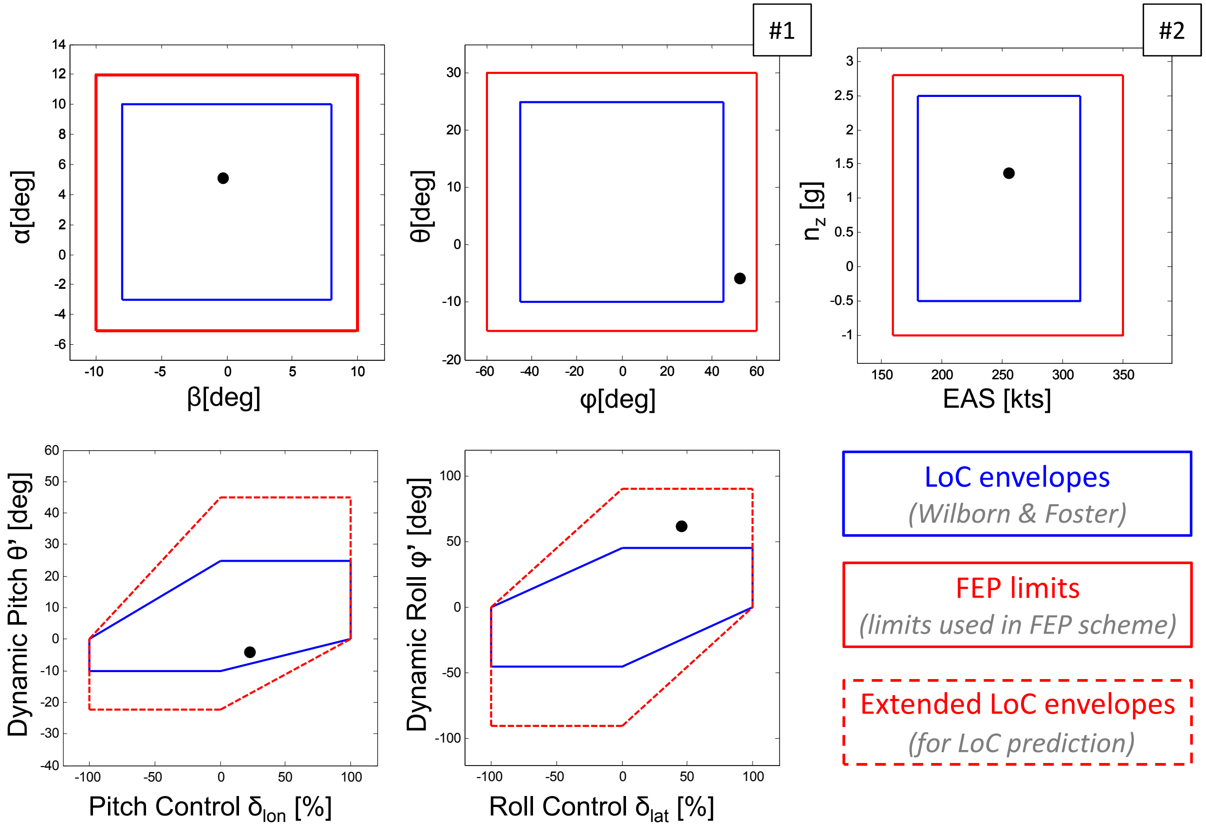
- ***Speed protection integrated with ϴ-protection.***

  Protect speed by modifying ϴ-limits

LOC Prediction & Flight Envelope Protection (3)

Illustrative Example

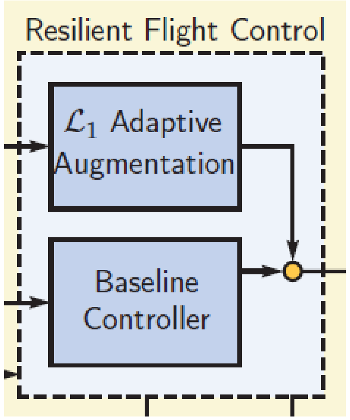
- **LoC Prediction:**
  - › *Keep count of the number of LoC and extended LoC envelope excursions.*
- **FEP-Limit Adjustment Logic:**
  - › *Adjust FEP limits depending on the number of exceeded LoC envelopes.*



Resilient Flight Control (1)

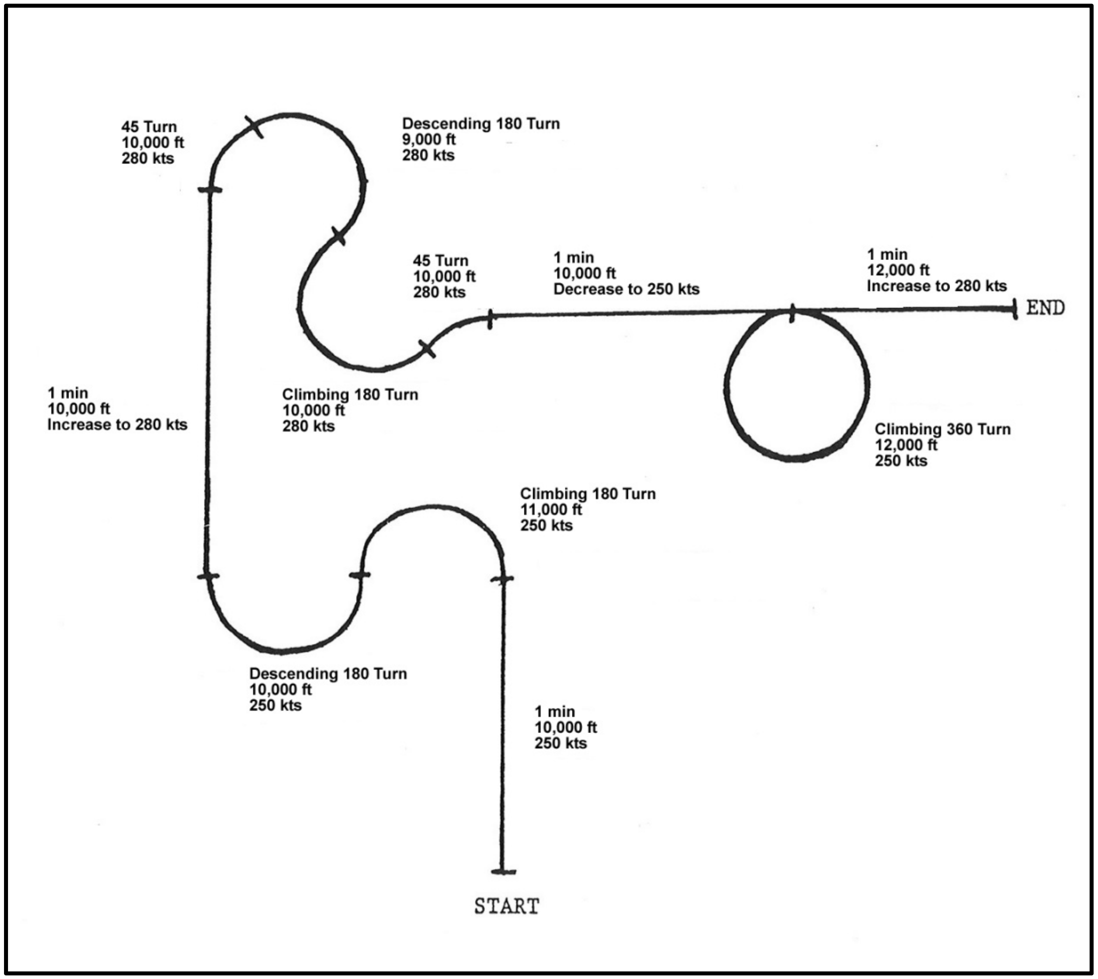
Baseline Robust Flight Control Law (Non-Adaptive)

- **Longitudinal Control Augmentation System:**
  - *C*U flight control law*
    - *precise flight-path control with long-term speed stability*
    - *commensurate with industry standard (e.g., Boeing)*
- **Lateral-Directional Control Augmentation System:**
  - *Integrated stability-axis roll-rate & AoSS flight control law*
    - *velocity-vector roll maneuvers without angle-of-sideslip build-up;*
    - *coordinated turns at zero sideslip and crosswind flight.*
- **Automatic Throttle Control System:**
  - *Total energy control law*
    - *Mode 0: Normal operational mode – pilot sets directly EPR;*
    - *Mode 1: Specific potential energy – pilot commands altitude changes;*
    - *Mode 2: Specific kinetic energy – pilot commands speed changes.*



Resilient Flight Control (9)

Piloted Simulation Results: Nominal Operations



- **Execution of standard maneuvers in normal flight operation:**
  - *Straight and level flight*
  - *25-deg bank turns*
  - *1,000-ft/min climbing turns and descents*
  - *Increase/Decrease airspeed*
- **Range of operation:**
  - *Alt: 9,000 – 12,000 ft.*
  - *Bank angle: 0 to 25 deg*
  - *Airspeed: 250 to 280 kts*

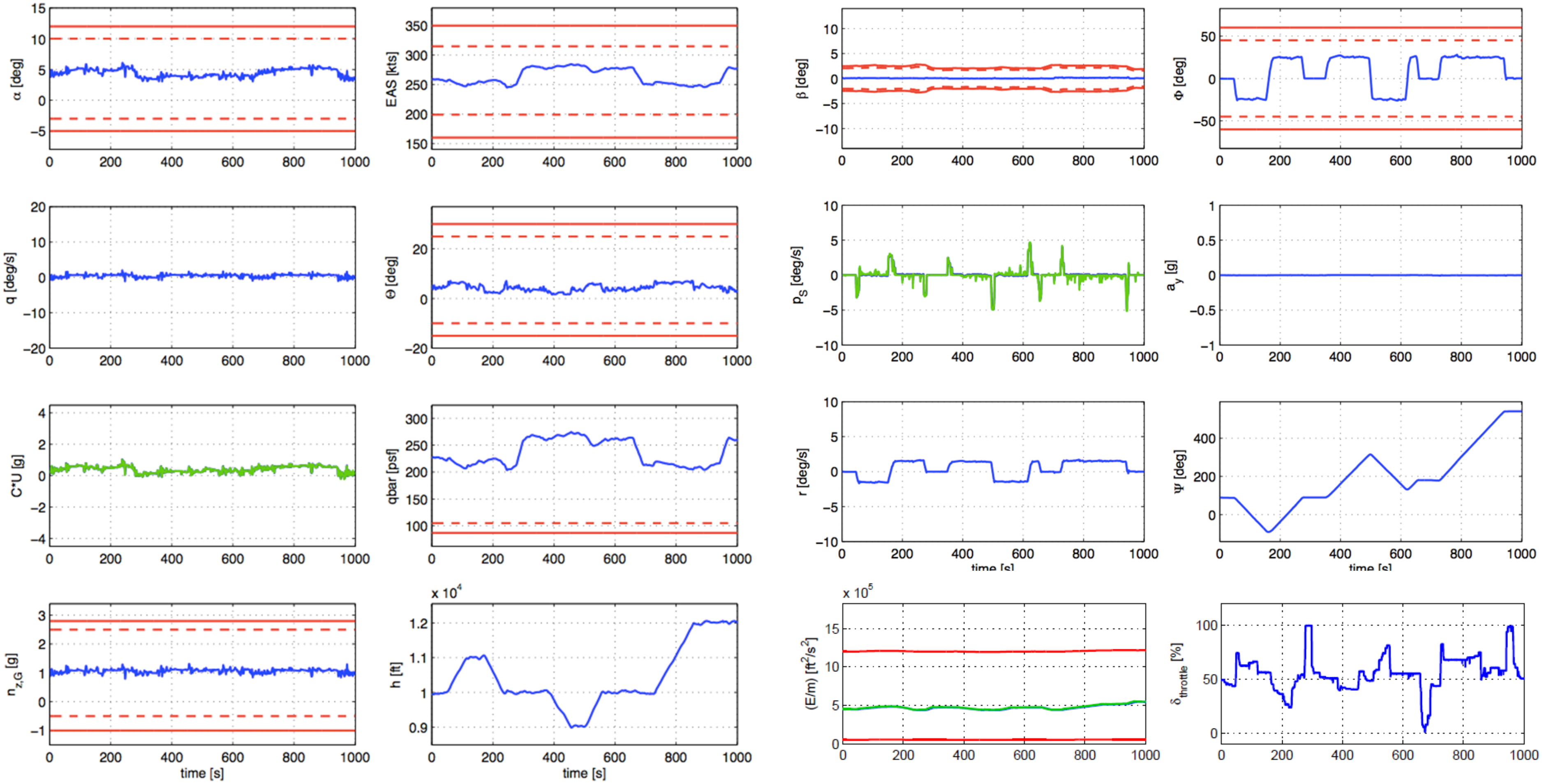
All of the tests are being performed by a transport category certificated pilot

Resilient Flight Control (10)

Piloted Simulation Results: Nominal Operations

LoC prediction & prevention ***active***

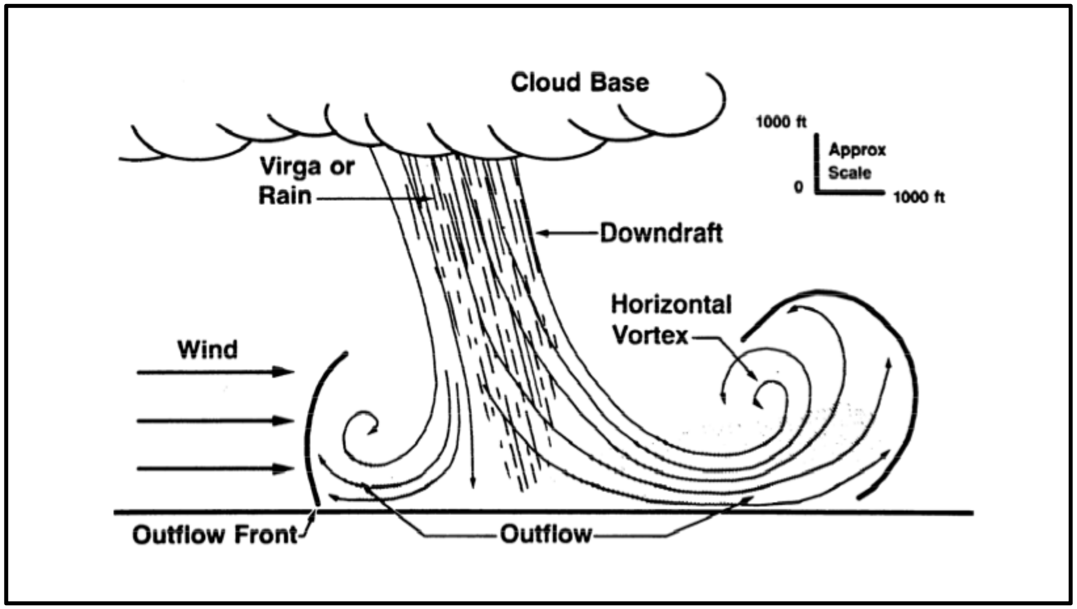
░ **1 excursion**
▒ **2 excursions**
▓ **>2 excursions**



Proposed System Does Not Appear to Affect Pilot Performance under Normal Operations

Resilient Flight Control (12)

Piloted Simulation Results: Microburst



<u>Tailwind</u>, <u>downdraft</u>, and <u>lateral gust</u> modeled as "(1−cos)-shaped" time-varying velocity fields fixed with respect to the NED frame.

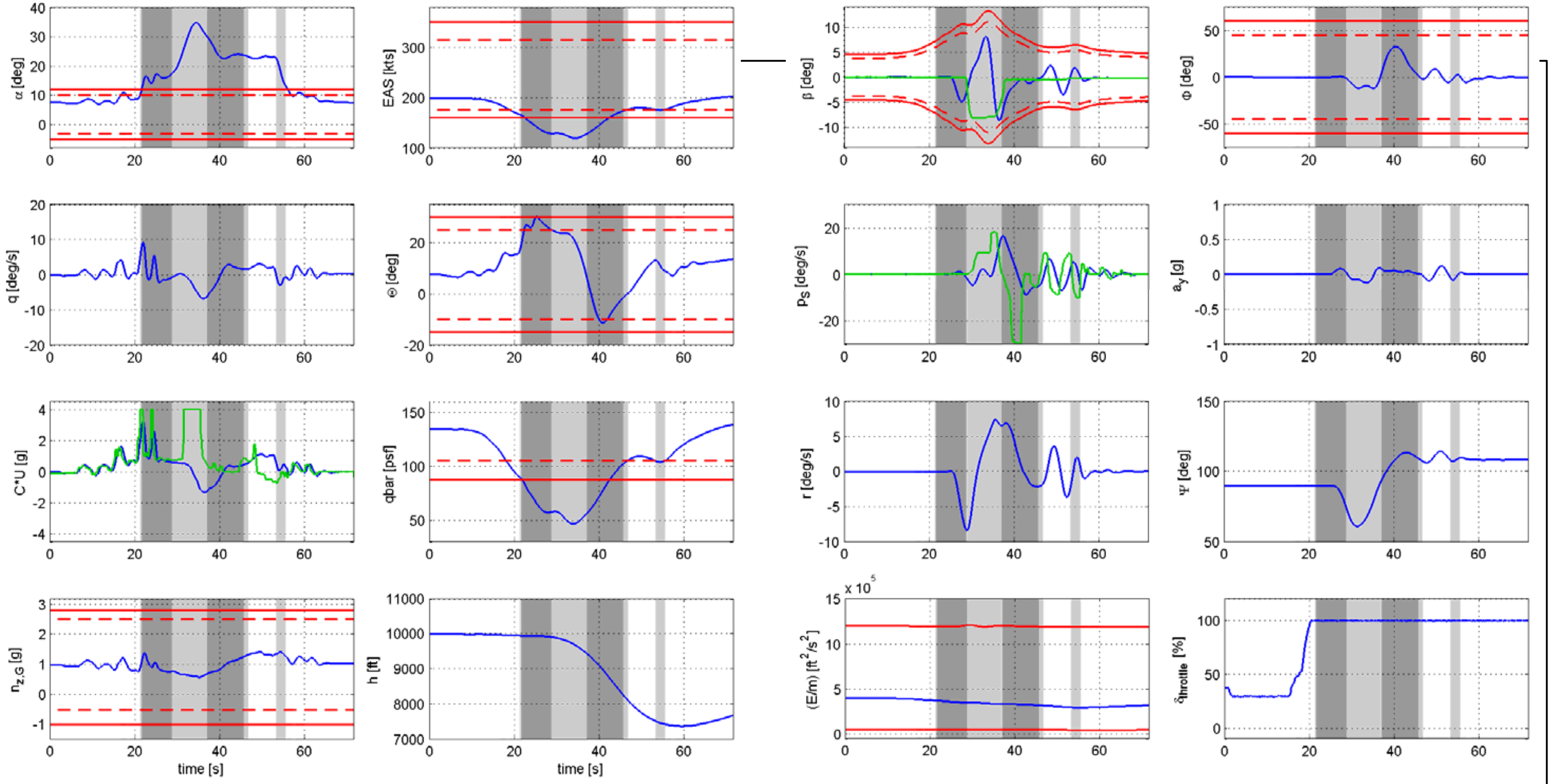
- **Test instructions:**
  - *Maintain wings level at 200 KCAS*
  - *Minimize altitude loss*
  - *Maintain initial heading*

Resilient Flight Control (12)

Piloted Simulation Results: Microburst

LoC prediction & prevention ***not active***

- ░ **1 excursion**
- ▒ **2 excursions**
- ▓ **>2 excursions**



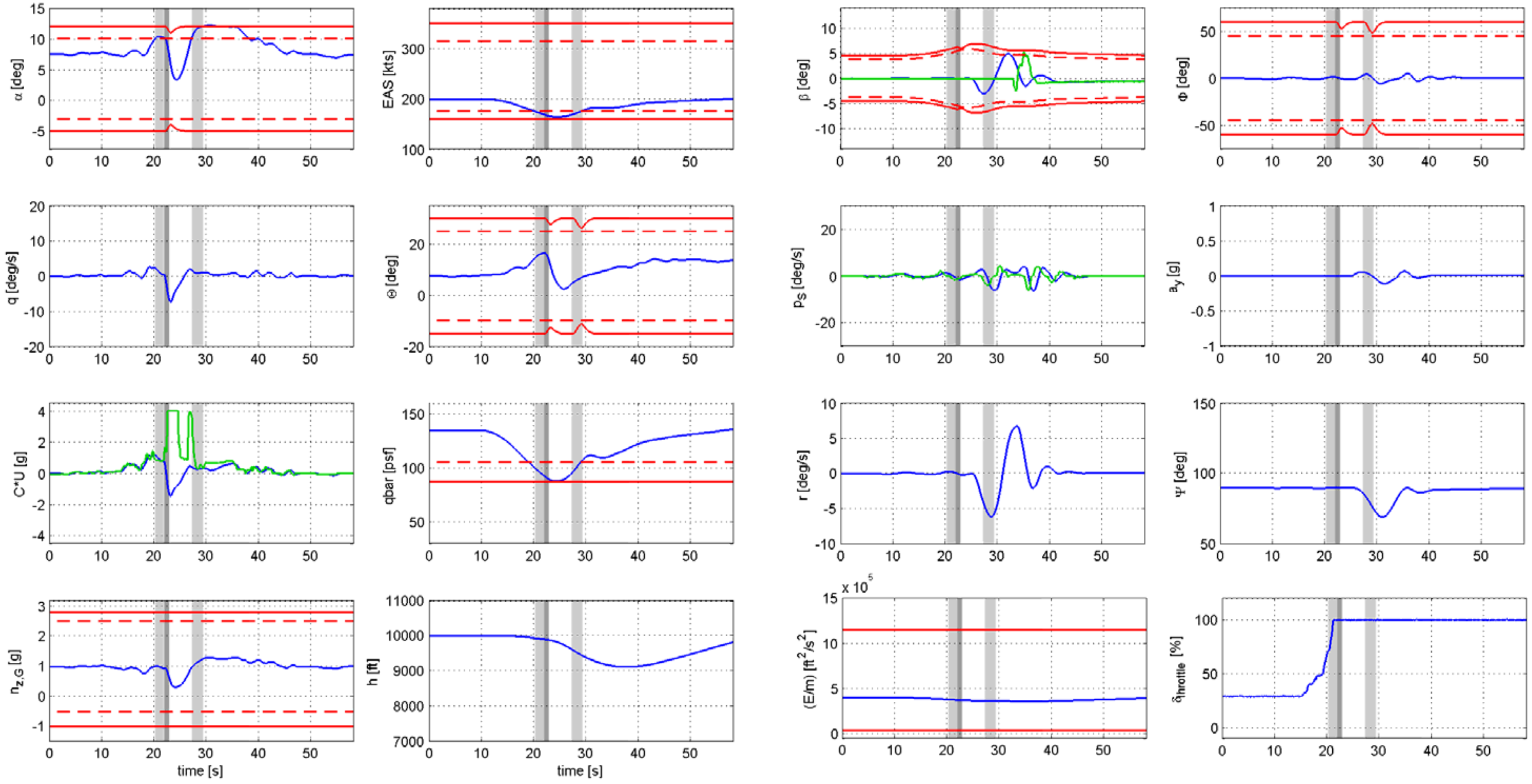
LOC Conditions Occur for Substantial Amount of Time; Pilot Recovered after 2500 ft Altitude Loss

Resilient Flight Control (13)

░ **1 excursion**
▒ **2 excursions**
▓ **>2 excursions**

Piloted Simulation Results: Microburst

LoC prediction & prevention ***active***



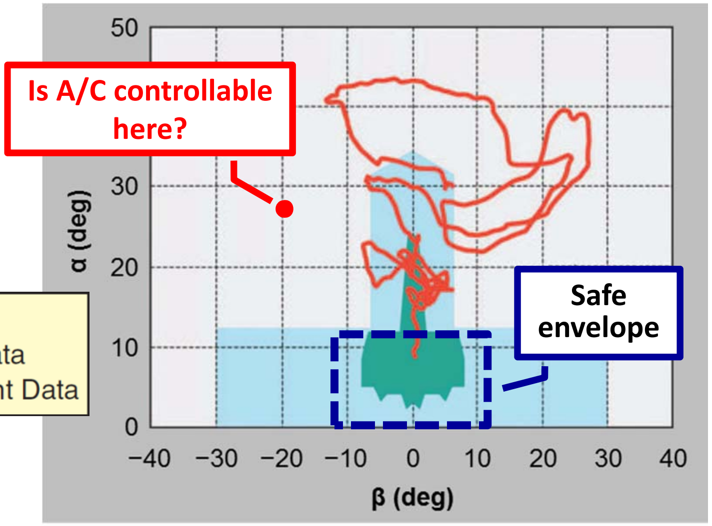
Significant Reduction in LOC Conditions; Pilot Recovered after < 1000 ft Altitude Loss

Resilient Flight Control (14)

Predictable :: Repeatable :: Testable :: Safe

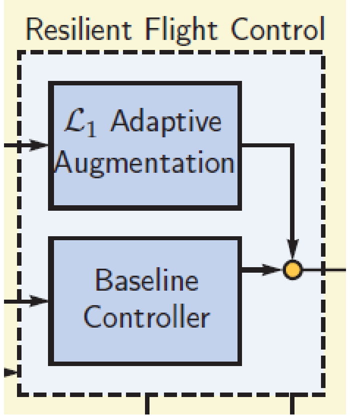
Control law objectives:

- Provide ***predictable aircraft response*** to help the pilot avoid excursions outside the *wind tunnel data envelope* ***in the presence of aircraft impairment.***



Source: NASA

High-risk flight conditions,
some unable to be tested in target application environment



10 publications directly related to work with AirSTAR GTM (2009-2012): conference proceedings, journal articles, magazine articles, book chapter

AirSTAR Testing under Vehicle Impairment

Example Result: Offset Landing with Emulated Destabilizing Failure:

- ➢ Initial offset: 90 ft. lateral, 1800 ft. downrange, 100 ft. above the runway
- ➢ Pitch Stability degraded by 2 inboard elevator segments → 50% reduction in pitch control effectiveness
- ➢ Roll Damping Stability degraded by spoilers
- ➢ Flying qualities ratings taken for nominal, neutrally stable, unstable airplane

Note: Subscale Test Vehicle Response is 4.25X Faster than Full-Scale Aircraft

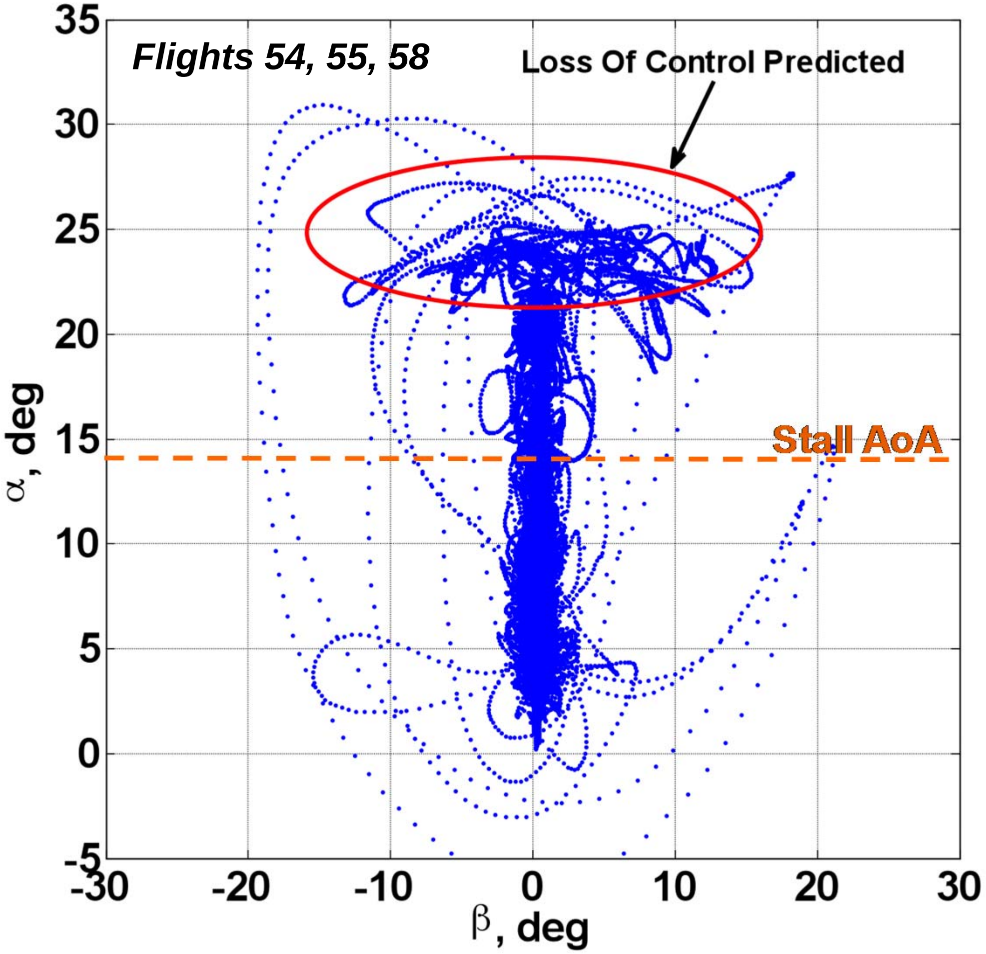
September 2010 Deployment, Ft. Pickett, VA

	Open-Loop Aircraft	L1 Adaptive Control System
Nominal	CHR 4 (FQ L2)	CHR 3 (FQ L1)
Neutrally Stable	CHR 10 (Uncontrollable)	CHR 5 (FQ L2)
Unstable		CHR 7 (FQ L3)

AirSTAR Testing under Upset Conditions

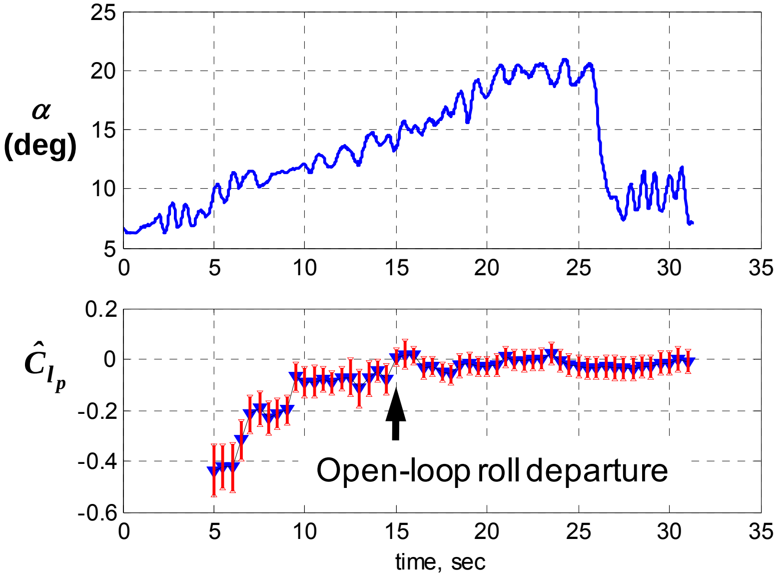
Example Result: Upset Test Condition - Stall / Departure (Pilot + Advanced Control System)

May 2011 Deployment, Ft. Pickett, VA



Demonstrated real-time stability and control characterization during approach to stall, through departure and recovery.

Example Result: T2 FLT 58 C14 WT02a



Applied L1 adaptive control to lengthen time on condition with stabilization that allowed slow transition through stall boundary and improved stall/departure recovery

UIUC Pilot Interfaces & Situational Awareness (1)

Objective

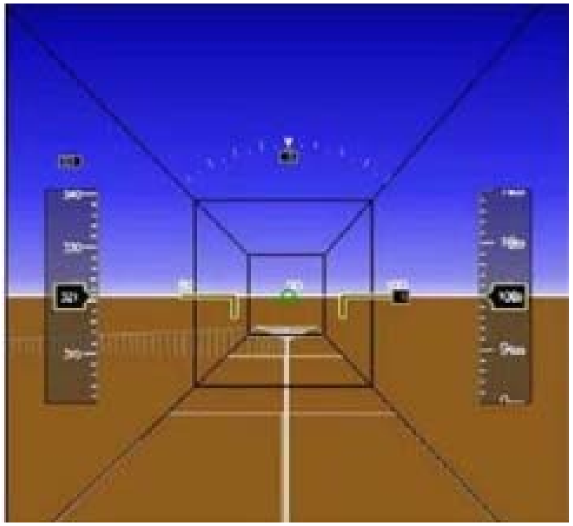
*Develop and validate **quantitative human performance modeling techniques** ensuring that **human-automation interaction interfaces** provide operators with the information for achieving high levels of **situation awareness**.*

- **D.A. Norman (1990):**
  - *"As automation increasingly takes its place in industry, especially high risk industry, it is often blamed for causing harm and increasing the chance of human error when failures do occur… **the problem is not the presence of automation**, but rather its inappropriate design… operations under normal operating conditions are performed appropriately, but there is **inadequate feedback and interaction with the humans** who must control the overall conduct of the task…"*

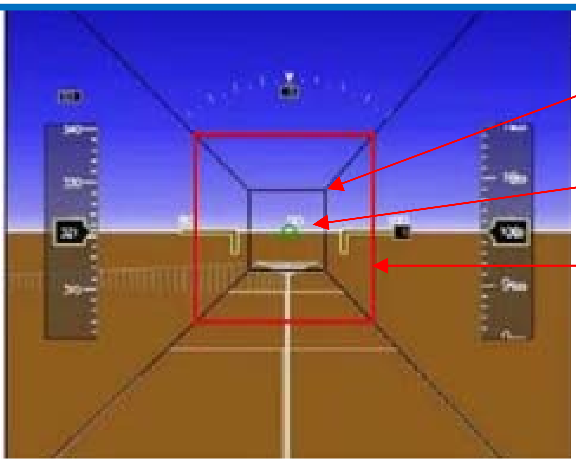
- **Examples of human-automation failures (in aviation):**
  - *American Airlines 4184 (Roselawn, IN): Automation returns control to pilots with no indication of current envelope for safe control input or recovery;*
  - *Scandinavian Airlines 751 (Gottröra, Sweden): Automation engages in actions not desired nor understood by the pilot;*
  - *AirFrance 447 (Atlantic Ocean): Automation fails to clearly disclose sensor inconsistencies as detected by the automation until autopilot disconnects.*

UIUC Pilot Interfaces & Situational Awareness (2)

Adaptive Tunnel Display Guides Pilot
(3-dimensional energy state display)



Conventional Tunnel

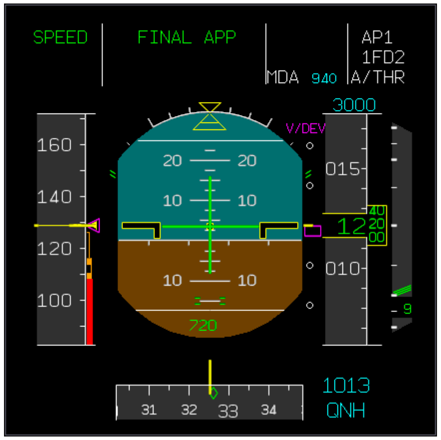


Adaptive Energy Tunnel

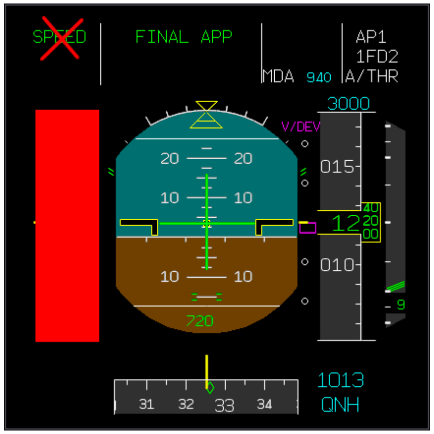
Desirable limit

Ownship

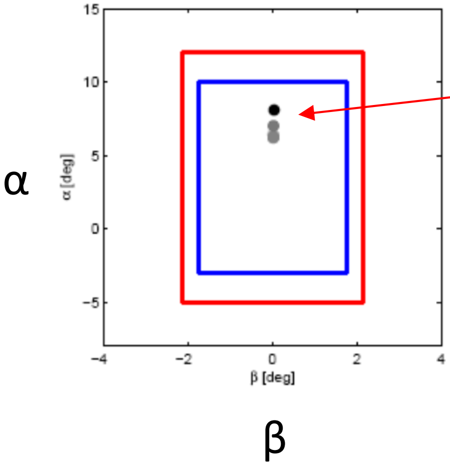
Absolute limit
(scales as
energy state
changes +
guides flight path)



before



after



ownship

Multiple Hazards Mitigation, LOC Prediction & Dynamic Envelope Protection: Summary

- **Preliminary control architecture for LOC prevention:**
  - *Based on the quantitative definition of loss of control proposed by Wilborn and Foster;*
  - *Critical flight parameters are maintained within desired limits;*
  - *Loss of control mitigated in the (reduced) set of test maneuvers considered;*
  - *The system does not seem to limit the ability of the pilot to perform aggressive, evasive maneuvers.*

- **Ongoing efforts:**
  - *Integrate FDI solutions into the control architecture;*
  - *Integrate ice accretion models;*
  - *Design and integrate pilot/aircraft/automation interfaces;*
  - *Expand the set of test scenarios;*
  - *Validate the developed technologies;*
  - *Investigate ‘optimal’ recovery procedures.*

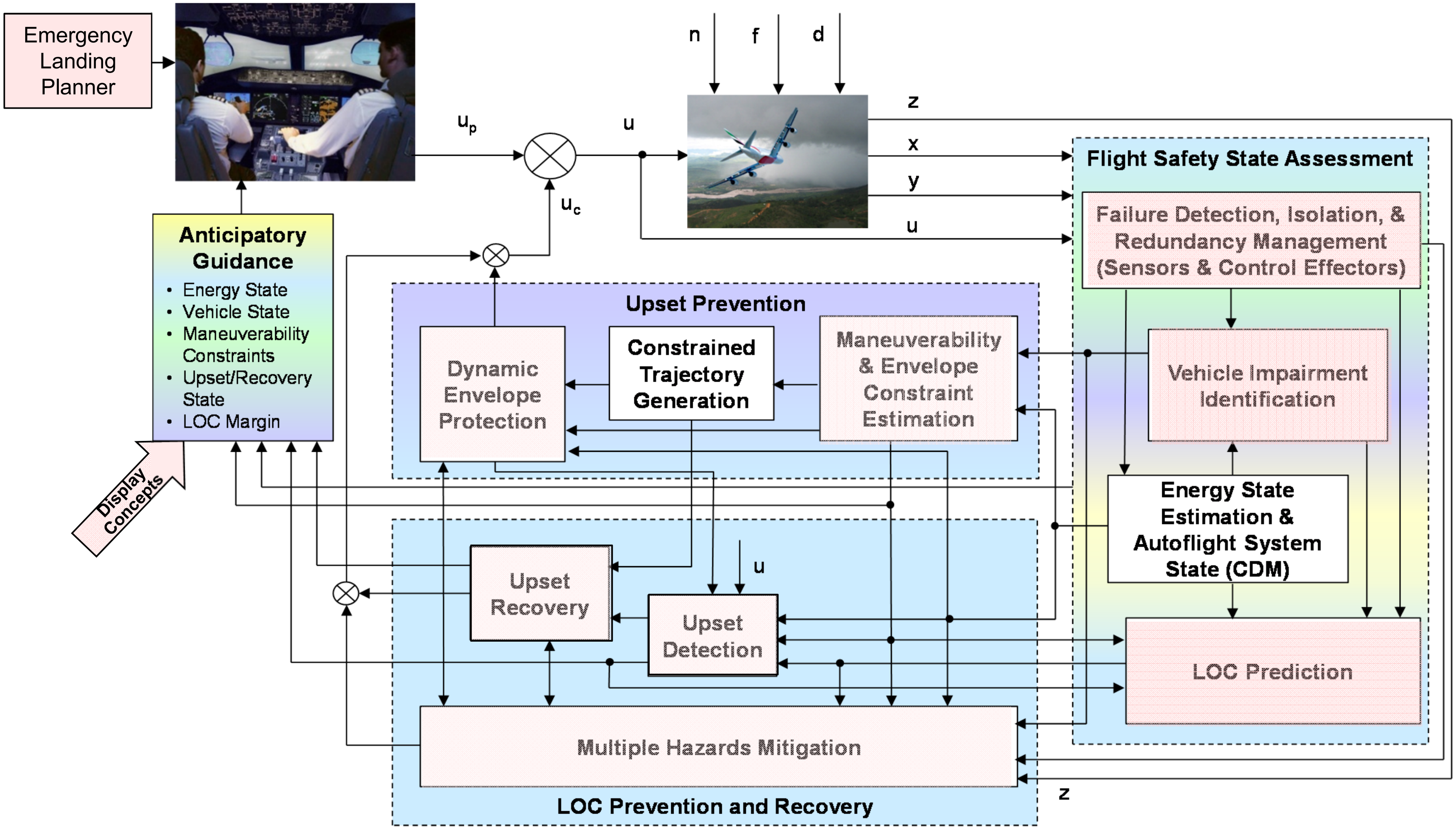
Multiple Hazards Mitigation, LOC Prediction & Dynamic Envelope Protection: Recent Publications

- **Theses**
  - N. Tekles, "***Pitch-Axis Flight Envelope Protection for NASA's GTM Research Aircraft,***" *Semester's Thesis*, Technical University of Munich, April 2013.
  - S. T. Pelech, "***Integration of the GTM T2 Model into a Full Size Simulator for Human-in-the-Loop Testing,***" *Master's Thesis*, University of Illinois at Urbana-Champaign, May 2013.
  - N. Tekles, "***Flight Envelope Protection, Loss-of-Control Prevention, and Upset Recovery Systems for NASA's Transport Class Model,***" *Master's Thesis*, Technical University of Munich, March 2014.
  - J. Chongvisal, "***Pilot-in-the-loop simulated flight tests of a Loss-of-Control Prediction and Prevention System for NASA's Transport Class Model,***" *Master's Thesis*, University of Illinois at Urbana-Champaign, May 2014. (to be submitted)
  - K. Ackermann, "**Flight Simulator Development for Pilot-in-the-Loop testing using NASA's Transport Class Model**," Master's Thesis, University of Illinois at Urbana-Champaign, August 2014. (to be submitted)

- **AIAA GNC 2014**
  - N. Tekles, E. Xargay, R. Choe, N. Hovakimyan, I. M. Gregory, and F. Holzapfel, "***Flight Enveloped Protection for NASA's GTM Research Aircraft***," in *AIAA Guidance, Navigation and Control*, National Harbor, MD, January 2014.
  - J. Chongvisal, N. Tekles, D. Talleur, A. Kirlik, N. Hovakimyan, and C. M. Belcastro, "***Loss-of-control prediction and prevention for NASA's Transport Class Model***," in *AIAA Guidance, Navigation and Control*, National Harbor, MD, January 2014.
  - H. Lee, S. Snyder, & N. Hovakimyan, "***An Adaptive Unkown Input Observer for Fault Detection and Isolation of Aircraft Actuator Faults***," in *AIAA Guidance, Navigation and Control*, National Harbor, MD, January 2014.
  - K. A. Ackerman, S. T. Pelech, R. S. Carbonari, N. Hovakimyan, and A. Kirlik, "***Integration of a Simulink Dynamics Model into a Full Sized Simulator for Human-in-the-Loop Testing***," in *AIAA Guidance, Navigation and Control*, National Harbor, MD, January 2014.
  - H. Felemban, J. Che, C. Cao, and I. M. Gregory, "***Estimation of Airspeed Using Continuous Polynomial Adaptive Estimator***," in *AIAA Guidance, Navigation and Control*, National Harbor, MD, January 2014.

- **At Least 10 Publications on L1 Adaptive Control Development with AirSTAR**
  - Conference papers, Journal articles, Magazine articles, Book chapter

GCST for Safe & Effective Control under LOC Hazards: Status



Enables Upset Prevention / Detection / Recovery & Safe Landing under Multiple Hazards

NRA: University of Illinois (UIUC), University of Michigan (UM), University of Tennessee (UTSI);
SBIR: Scientific Systems (SSCI), Barron Associates (Barron)

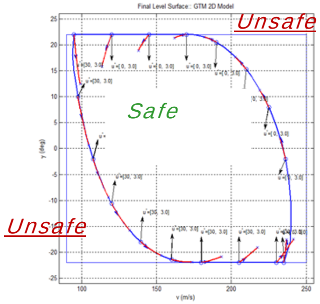
GCST Accomplishments Summary

- Hazards Effects Detection, Identification, & Mitigation (Dynamics and Control Effects)
  - System Failures
    - Sensors (Focus on Dynamics & Control)
    - Control Actuator Failures
    - Propulsion System
  - Vehicle Impairment
    - Icing
      - Airframe
      - Engine
    - Damage
      - Airframe Structure (Current Activity with MVS, Longer Term)
      - Propulsion System
  - External Hazards
    - Robustness under Turbulence
    - Wind Shear
    - Wake Vortices
  - Inappropriate Crew Actions / Inaction
    - Inappropriate / Ineffective Control Inputs
    - Ineffective Recovery
- Vehicle Level Effects Prediction / Detection
  - LOC Prediction
  - Upset Detection
  - Safe Flight Envelope Estimation
  - Flight Safety (Longer Term)

Comprehensive Technology Evaluation (CTE)

Comprehensive Technology Evaluation using Realistic Hazards Test Scenarios

Analysis



- Stability / Robustness
- Confidence Level Assessment

Identification of Potential Technology Problems

Simulation

- Vehicle Upsets/Impairment
- Vehicle Impairment

Guided Monte Carlo & Piloted Evaluations

Experimental Testing

- Ground-Based
- In-Flight

Integrated & High-Risk Evaluations

Real-Time Monitoring

- Fault Detection
- Real-Time Monitoring

Integrated System Evaluations under Multiple Hazards

Assess Effective Hazards Coverage, and Identify System Limitations & Weaknesses

NRA Partners: University of Minnesota, University of West Virginia, Georgia Institute of Technology (Bristol University and Drexel University)

CTE Accomplishments Summary

- Analysis Methods
  - Nonlinear Analysis Methods (Bifurcation, etc.)
  - Robustness Analysis for Nonlinear Uncertain Systems
    - Deterministic
    - Stochastic
  - Analysis for Fusion-Based Stochastic Estimation Systems
  - Analysis of Pilot-Vehicle Systems
  - Analysis of Pilot-Automation Systems
  - Analysis of Complex Integrated Systems
- Simulation Methods (Based on Enhanced LOC Hazards Simulation)
  - Batch / Monte Carlo
  - Real-Time Piloted Evaluations
- Experimental Test Methods
  - AirSTAR Testbed (Potential for Integrated System Vehicle-Level Testing)
    - Conventional Transports within Visual Range
    - T-Tail Transports (Developing research aircraft via SBIR I & II)
    - Beyond Visual Range (Developing capability in-house)
    - Test Vehicle with SHM Infrastructure (SBIR IIe ?)
  - SAFETI Lab (Potential for Integrated System Vehicle-Level Testing)
- LOC Test Scenarios Development
  - Preliminary Test Scenarios Developed (2012)
  - Final Set to be Developed (2014)

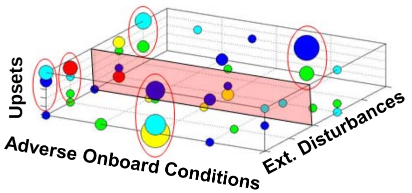
Approach for Developing LOC Test Scenarios

Hazards Analysis

Realistic Test Scenarios with Traceability to the Hazards Sets

Accident Data / Future Risks

Worst-Case Hazards Combinations

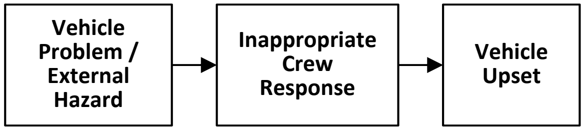


Crew Hazards
- Loss of Aircraft State Awareness
- Spatial Disorientation

Vehicle and Environmental Hazards
- Control Component Failures
- Icing Effects
- Wake Vortices

Abnormal Flight / Upset Hazards
- Extreme Attitudes
- Abnormal Energy States
- Abnormal Control Response
- Stall / Departure

Hazards Sequences


Vehicle Problem / External Hazard → Inappropriate Crew Response → Vehicle Upset

Unique & Generalized Sequences

Partners: NTSB & NIA (CAST / ATLAS)

Scenario Set Number	Recommended Evaluation Methods	Scenario Description	Flight Condition	Adverse Onboard Conditions	Inappropriate Crew Response	External Hazards & Disturbances	Vehicle Upset Conditions
Four Precursor LOC Scenarios: Vehicle Failure –> Inappropriate Crew Response –> Upset –> Vehicle Damage							
55	Analysis, Batch Simulation, Piloted Simulation	Engine Failure Followed by Crew Distraction Leading to Upset and Vehicle Damage	Cruise	1. Single Engine Failure (100% Thrust Loss); 4. Various Levels of Structural Damage with and without Loss of Control Effector	2. Crew Distraction Resulting in Delayed Response Followed by Excessive Response		3. Decreased Airspeed, Asymmetric Forces / Moments, Stall / Departure

Scenario Set Number	Generalized Sequence	Coverage of Hazards Based on Historical Data & Future Potential Risk Sets								
		Accidents from Data Set Covered by Scenario	Number of Accidents from Data Set Covered by Scenario	Future Risks Covered by Scenario	Number of Future Risks Covered by Scenario	% Coverage of Data Set		% Cumulative Coverage		
						Accidents	Future Risks	Accidents	Additional Future Risks Covered	Future Risks
1	D	56	1	3	1	0.79%	10%	0.79%	1	10%
2	D	62, 63	2	3	1	1.59%	10%	2.38%	0	10%
3	D	1, 15, 18, 41, 79	5	3	1	3.97%	10%	6.35%	0	10%
4	D, E	17, 20, 8, 113	4	3	1	3.17%	10%	9.52%	0	10%
5	D	13	1	3	1	0.79%	10%	10.32%	0	10%
6	D	7	1	3	1	0.79%	10%	11.11%	0	10%
7	D	3	1	10	1	0.79%	10%	11.90%	1	20%
8	D	2	1	3, 10	2	0.79%	20%	12.70%	0	20%
9	D	2, 110	2	3, 10	2	1.59%	20%	14.29%	0	20%
10	D	N/A	0	7	1	0.00%	10%	14.29%	1	30%
11	D	16	1	8	1	0.79%	10%	15.08%	1	40%
12	D	N/A	0	4	1	0.00%	10%	15.08%	1	50%

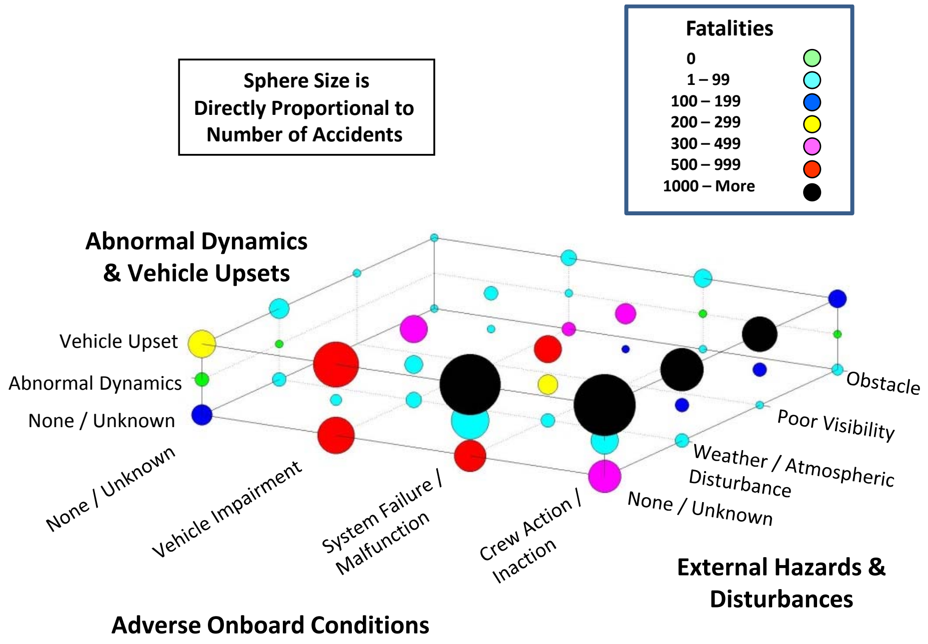
Status of LOC Hazards Analysis & Test Scenarios Development

- Comprehensive Set of Accidents / Incidents Compiled for 1996 – 2010
  - 10 International Databases Searched for LOC
  - Commercial transports at or above 12,500 lbs
  - 275 accidents & incidents identified resulting in 7185 fatalities
- Preliminary Analysis Results Obtained
  - Based on Six Accident / Incident Subsets (45-46 Events)
  - Individual Precursor Statistics
  - Worst-Case Precursor Combinations
  - Temporal Sequencing
- Ongoing Research
  - Re-Evaluation Based on Team Consensus Approach (In Progress)
  - Definition of Future LOC Risks (To be Coordinated with CAST / ATLAS)
  - Development of LOC Test Scenarios
  - Final Results to be Submitted for NASA TP and Journal Publication

Example Preliminary Analysis Results

275 LOC Accidents & Incidents (1996-2010)

Worst Case Precursor Combinations

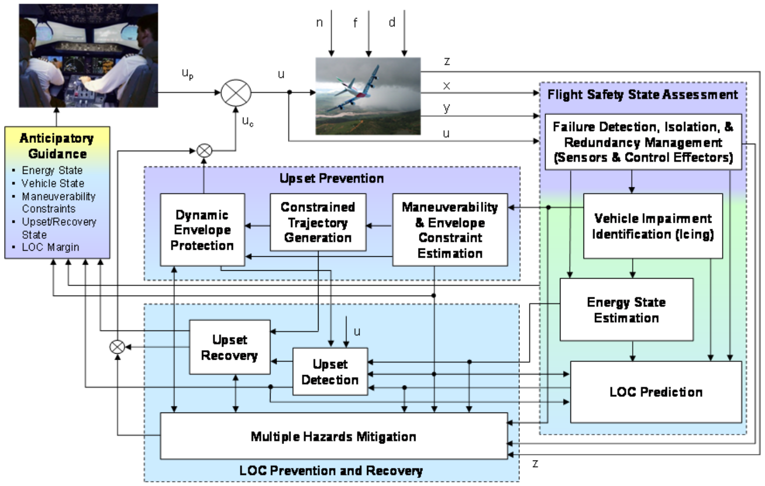


108 Unique Sequences Identified at Sub-Category Level;
237 Unique Sequences Identified at the Precursor Level

Ref: Belcastro, C. M., Groff, L., Newman, R. L., Foster, J. V., Crider, D. A., Klyde, D. H., and Huston, A. M., “Preliminary Analysis of Aircraft Loss of Control Accidents: Worst Case Precursor Combinations and Temporal Sequencing”, *AIAA Conference on Guidance, Navigation, and Control*, *SciTech Forum*, National Harbor, MD, January 2014.

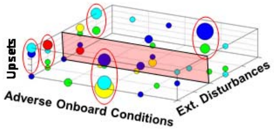
LOC Research Integration

Enhanced Onboard Systems Technologies for Improved Situational Awareness, Guidance & Control *under LOC Hazards*



LOC Hazards Analysis

Worst-Case Hazards Combinations



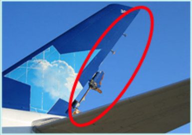
Hazards Sequences

Vehicle Problem / External Hazard → Inappropriate Crew Response → Vehicle Upset

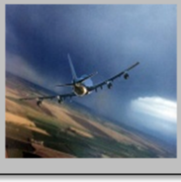
Integrated LOC Hazards Effects Simulation

Vehicle Upsets

Vehicle Impairment



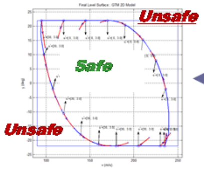
External Disturbances



Test Scenarios Based on Accident / Incident Analysis & Future Risks

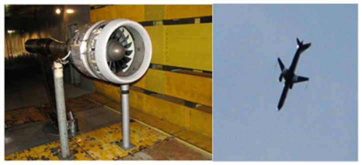
Comprehensive Technology Evaluation (CTE)

Analysis

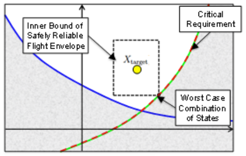


Simulation

Experimental Testing



Evaluation Methods, Tools, & Testbeds



AirSTAR

Level of Confidence in the Evaluation Results

Level of Hazards Coverage

Degree of Technology Effectiveness

Technology Limitations & Constraints

Future Research Directions: Safety-Assured Autonomy for Advanced Manned / Unmanned Aircraft

Safety-Assured Autonomy

Fully Autonomous Systems

Enable Safety-Assured Operations at All NAS Levels (Vehicles, Infrastructure, and Operations)

Pilot-Optional Aircraft

- *Real-Time Safety Assurance*
- *Resilient Control & Mission Management*

Variable Autonomy Systems

Enable Synergistic Dynamic Teaming Between Human and Intelligent Systems

Single-Pilot Operations

- *Resilient Control under LOC Hazards*
- *LOC Prediction, Prevention & Recovery*
- *Resilient Mission Planning*

Resilient Systems

Provide Safety Augmentation, Guidance & Emergency Intervention to Support Baseline Systems and Human Operator

Remotely Piloted UAS

- *Dynamic Envelope Protection*
- *Resilient Control under Off-Nominal Conditions*
- *Upset Detection & Recovery*
- *Automatic Collision Avoidance*
- *Emergency Landing Planning*

Baseline:

Technology Used to Automate Routine Operations under Nominal Conditions and Provide Information & Alerts

Current Operations

Baseline: Altitude Hold, Autoland, Nominal Envelope Protection, TCAS, EGPWS, No Significant Warnings or Guidance under LOC Hazards

Summary & Concluding Remarks

- Aircraft LOC Contributes Significantly to Accidents & Fatalities
  - Largest Fatal Accident Category
  - Most Complex Accident Category (Many Causal & Contributing Factors)
- NASA is Conducting Unique Hazards Analysis of LOC Problem to Enable Holistic Technology Solution
  - Large Accident / Incident Set
  - Worst-Case Hazards Combinations
  - Detailed Hazards Sequences
  - Comprehensive LOC Test Scenarios
- NASA is Conducting Research and Developing Technologies for LOC Prevention & Recovery
  - Vehicle Dynamics Modeling & Simulation of LOC Precursor Conditions
  - Guidance, Control, & Systems for LOC Prevention / Recovery
  - Improved Crew Situation Awareness, Guidance, & Cueing under LOC Hazards
  - Validation of Safety-Critical Technologies Developed for LOC Prevention / Recovery
- Future Research Direction towards Resilient Autonomous Aircraft
  - Resilient Systems
  - Variable Autonomy Systems
  - Fully Autonomous Systems

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Backup

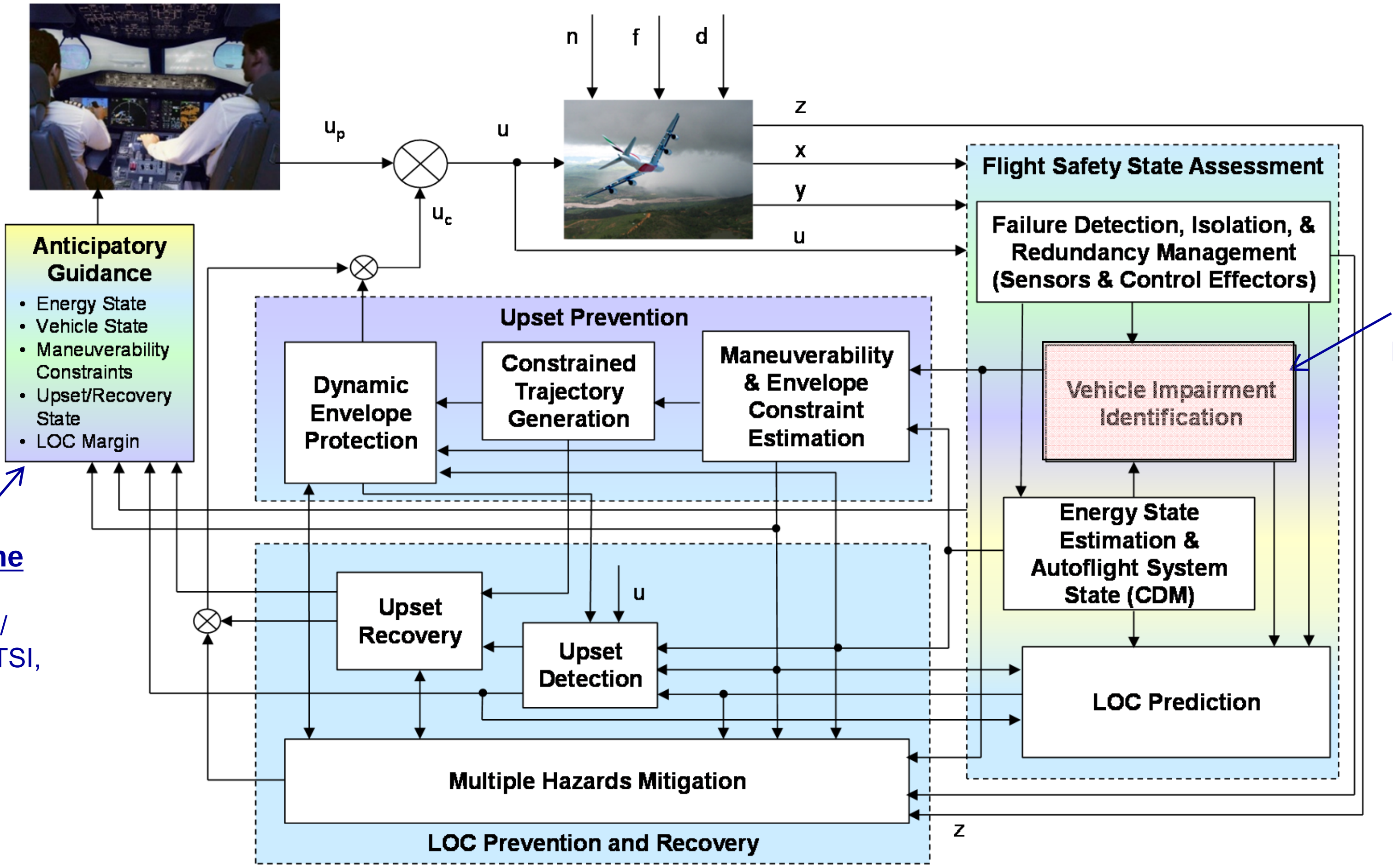
- Abstract
- Vehicle Impairment under Icing
  - Airframe
  - Engine
- Multiple Hazards Mitigation
  - Fast Engine Response
  - Integrated Flight / Propulsion Control

Abstract

Aircraft loss of control is a leading cause of fatal accidents across all transport airplane and operational classes. Aircraft loss-of-control (LOC) accidents are highly complex in that they can result from numerous causal and contributing factors acting alone or (more often) in combination. Hence, there is no single intervention strategy to prevent these accidents.

This presentation will define LOC as a dynamics and control problem, summarize LOC accident analysis results, and discuss recent NASA research that supports a holistic approach for significantly reducing aircraft LOC accidents for current and future aircraft. The approach includes onboard systems technologies for LOC prevention and recovery, as well as a parallel effort for their validation. The onboard systems technologies provide improved situational awareness, guidance, and control under realistic LOC hazards, and include: hazards effects detection and mitigation; upset detection, prevention and recovery; and multiple hazards mitigation. Validation technologies include analytical, simulation, and experimental methods, tools and testbeds as well as the development of a comprehensive set of realistic LOC test scenarios. Future research directions will also be discussed.

Vehicle Impairment Identification



Anticipatory Guidance
- Energy State
- Vehicle State
- Maneuverability Constraints
- Upset/Recovery State
- LOC Margin

Upset Prevention

Dynamic Envelope Protection

Constrained Trajectory Generation

Maneuverability & Envelope Constraint Estimation

Flight Safety State Assessment

Failure Detection, Isolation, & Redundancy Management (Sensors & Control Effectors)

Vehicle Impairment Identification

Energy State Estimation & Autoflight System State (CDM)

LOC Prediction

Upset Recovery

Upset Detection

Multiple Hazards Mitigation

LOC Prevention and Recovery

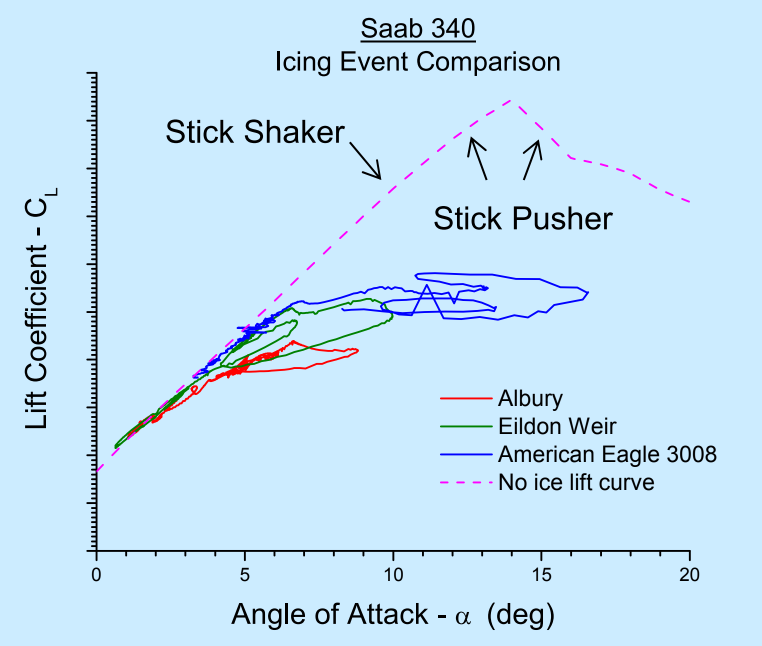
Airframe Icing
NASA /
NRA – UTSI,

Airframe Icing
NASA /
NRA – UTSI,

Vehicle Impairment Identification – Airframe Icing (1)

Airframe Icing Problem Relevance

- Control
  - American Eagle Flight 4184 ATR 72-212, October 31, 1994
    - » Loss of roll control, upset
    - » fatal accident
  - Air Canada Flight 457 & Air Canada Flight 1130; A321-211, December 7, 2002
    - » Roll oscillations
    - » Recovered with flap change
- Icing Stall
  - Stick shaker and pusher:
    - » May occur after stall, if at all
  - Crews may not respond to:
    - » Stall break (roll off and roll control)
    - » Post stall flight characteristics
  - Lack of stall recognition with nose low and banked.



Accident/Incident	Shaker	Pusher	Break
Saab 340A, VH-LPI, Eilden Weir, Victoria, Nov 11, 1998	ES	ES	NR
Saab 340A, VH-KEQ, Albury, New South Wales Australia, June 18, 2004	ES	ES	PR
Saab 340B, VH-OLM, Bathurst, New South Wales Australia, June 28 2002	ES	ES	NR
American Eagle 3008, Saab 340B+, January 2, 2006	ES	ES	NR
Air Canada Flight 646, Canadair CL-600-2B219, December 16, 1997	--	--	--
Cessna Citation 560, Pueblo, Colorado, February 16, 2005	UK	UK	UK
Comair Flight 3272, Embraer EMB-120RT, January 9, 1997	ES	--	NR
Skywest 3855, Bombardier CL-600-2B19, January 17, 2004	--	--	--
ComAir 5054, EMB-120, March 19, 2001	NR	NR	NR

Ref: Dennis Crider, NTSB, LOC RWG
Kickoff Meeting, August 16,2012

IO = Inoperative UK = Unknown PR = Proper response NR = Not responded to ES = Early stall

Vehicle Impairment Identification – Airframe Icing (2)

Airframe Icing Problem Relevance

- Summary of Airframe Icing Problem:
  - Pilots aren't familiar with what adverse effects can come from them, such as
    - Stall occurring before normal stall angles of attack
    - Changes in control effectiveness
  - Pilots don't realize they are in icing conditions, and do not receive advance warning of impending stall
  - Icing problem can build up slowly, then the aircraft can quickly get into an upset from a trigger event, such as maneuvering or a configuration change (e.g., flaps or power changes)
  - At that point, there is little time to think or react.

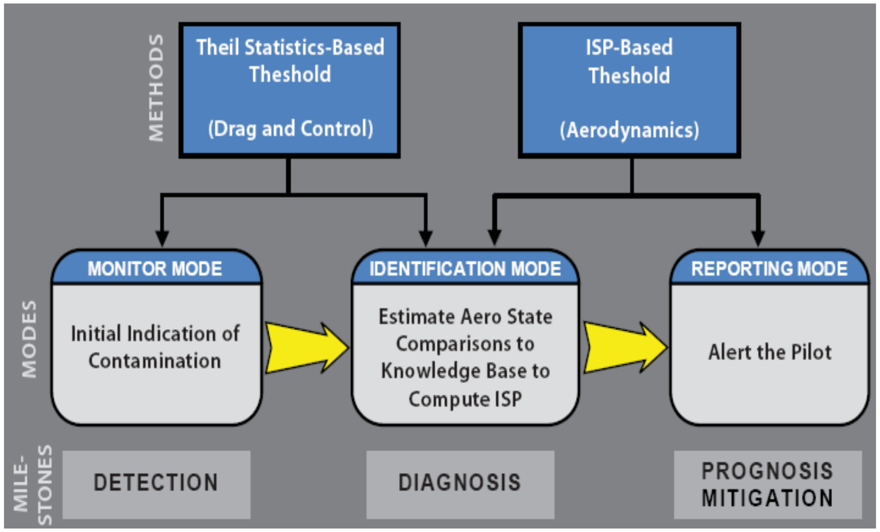
- Potential Technology Solution:
  - ICEPRO addresses this problem directly by
    - detecting icing and its effects on the aircraft stability and control,
    - giving the pilot specific warnings in advance (e.g., elevator control effectiveness is reduced right now), and
    - showing flight envelope restrictions based on the current aircraft condition.

ICEPRO System Description

1) Monitor Mode:
   - Utilizes Dynamic Inversion Control Evaluation System (D-ICES) to compare current aircraft state to a nominal baseline state.
   - ID mode triggered when control differences or drag degradation thresholds met

2) ID Mode:
   - Executes a series of optimally designed control excitations during periods of low pilot control activity
   - Utilizes Real-Time Parameter Identification (RTPID) to compute an icing severity parameter (ISP) based on comparisons of current stability and control to baseline

3) Reporting Mode:
   - Alert messages and cues displayed to the pilot to remain within safe flight envelope
   - Low speed cues are dynamically set to maintain the 5% stall margin based on icing severity



METHODS

Theil Statistics-Based Theshold (Drag and Control)

ISP-Based Theshold (Aerodynamics)

MODES

MONITOR MODE: Initial Indication of Contamination

IDENTIFICATION MODE: Estimate Aero State Comparisons to Knowledge Base to Compute ISP

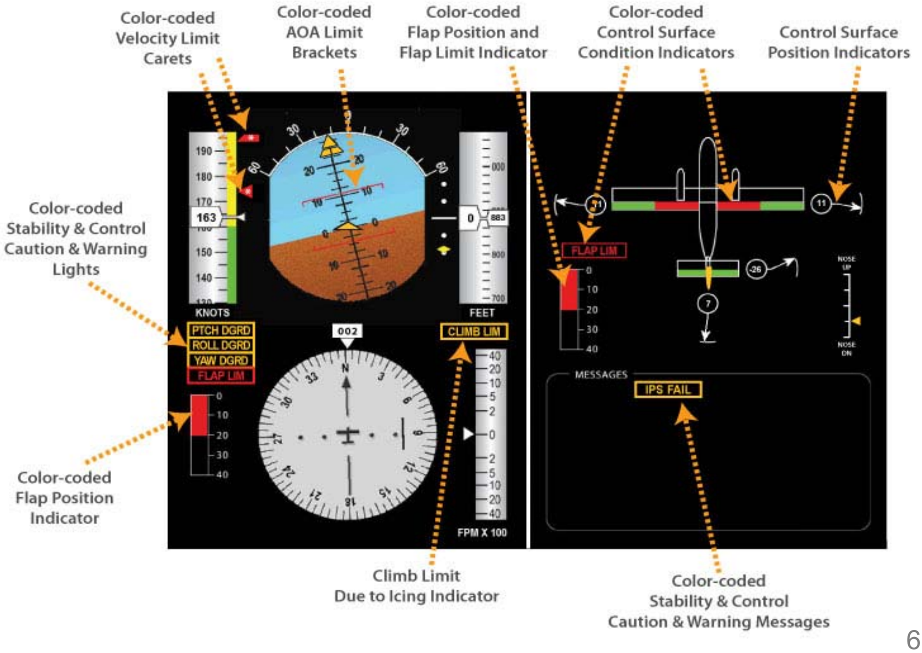
REPORTING MODE: Alert the Pilot

MILE-STONES

DETECTION

DIAGNOSIS

PROGNOSIS MITIGATION



Color-coded Velocity Limit Carets

Color-coded AOA Limit Brackets

Color-coded Flap Position and Flap Limit Indicator

Color-coded Control Surface Condition Indicators

Control Surface Position Indicators

Color-coded Stability & Control Caution & Warning Lights

Color-coded Flap Position Indicator

Climb Limit Due to Icing Indicator

Color-coded Stability & Control Caution & Warning Messages

ICEPRO System Evaluation (1)

- Portable, fixed-base FTD
  - Pilot seat, controls, and turbo-prop throttle quadrant
  - Column force system and elevator trim switch
  - 4 flat panel screens for out-the-window graphics
  - Multiple PC's hosting D-Six simulation model, drive graphics, and an electro-mechanical control loader
- Instructor's Workstation
  - Sets up initial conditions for each training block
  - Video recording & monitoring devices
  - Intercom for communications between pilot & instructor
  - Supplement FTD training with multi-media training

ICEPRO System Evaluation (2)

- ICEPRO was Evaluated by 30 Pilots During the 2007-2011 NASA NRA using
  - NASA GRC's ICEFTD
  - Simulated on-board excitation system (OBES)

- All pilots were constrained to fly a hazardous configuration. The ICEPRO pilot group showed
  - » Fewer incipient upsets
  - » Better Situation Awareness
  - » No increase in workload with ICEPRO

- By providing the pilot reliable cuing and messages, ICEPRO
  1. Raised situational awareness
  2. Assisted in flying the task
  3. Reduced the risk of upsets and eventual LOC from a hazardous icing encounter

Statistically Significant Results

Reference: Contractor Report Submitted to NASA GRC by UTSI

Airframe Icing Publications

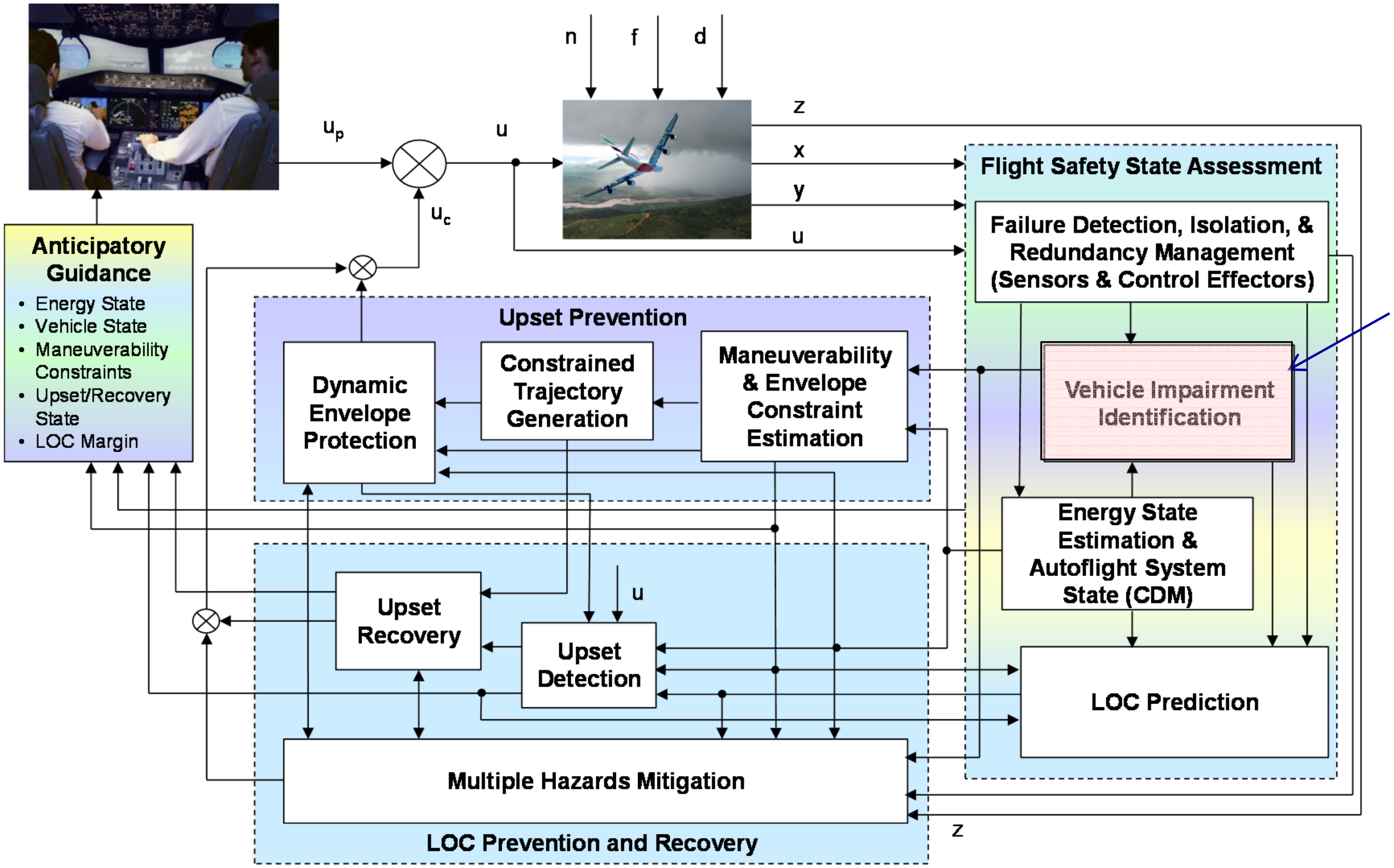
Dissertation:

- B. Martos, “Identifying and Correcting First Order Effects in Explanatory Variables for Longitudinal Real Time Parameter Identification Methods in Atmospheric Turbulence,” University of Tennessee, 2013.

Conference Publications:

- D. R. Gingras, R. Ranaudo, B. Barnhart, T. Ratvasky and E. Morelli, “Envelope Protection for In-Flight Ice Contamination," AIAA-2009-1458, 2009.
- D. R. Gingras, B. Barnhart, R. Ranaudo, B. Martos, T. Ratvasky and E. Morelli, "Development and Implementation of a Model-Driven Envelope Protection System for In-Flight Ice Contamination," AIAA-2010-8141, 2010.
- R. Ranaudo, B. Martos, B. Norton, D. Gingras, B. Barnhart, T. Ratvasky and E. Morelli, "Piloted Simulation to Evaluate the Utility of a Real Time Envelope System for Mitigating In-Flight Icing Hazards," AIAA-2010-7987, 2010.
- B. Martos and E. A. Morelli, "Using Indirect Turbulence Measurements for Real-Time Parameter Estimation in Turbulent Air," AIAA-2012-4651, 2012.
- Morelli, E.A. and Cunningham, K. “Aircraft Dynamic Modeling in Turbulence,” AIAA-2012-4650, *AIAA Atmospheric Flight Mechanics Conference*, Minneapolis, MN, August 2012
- B. Martos, R. Ranaudo, B. Norton, D. Gingras, B. Barnhart, T. Ratvasky and E. Morelli, "Final Report NASA Grant NNH06ZEA001N: Development, Implementation and Pilot Evaluation of a Model-Driven Envelope Protection System to Mitigate the Hazard of In-Flight Ice Contamination," NASA CR-2013-0000, (To be published in 2014).

Vehicle Impairment Identification: Engine Icing Effects



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Engine Icing
NASA

Vehicle Impairment Identification – Engine Icing

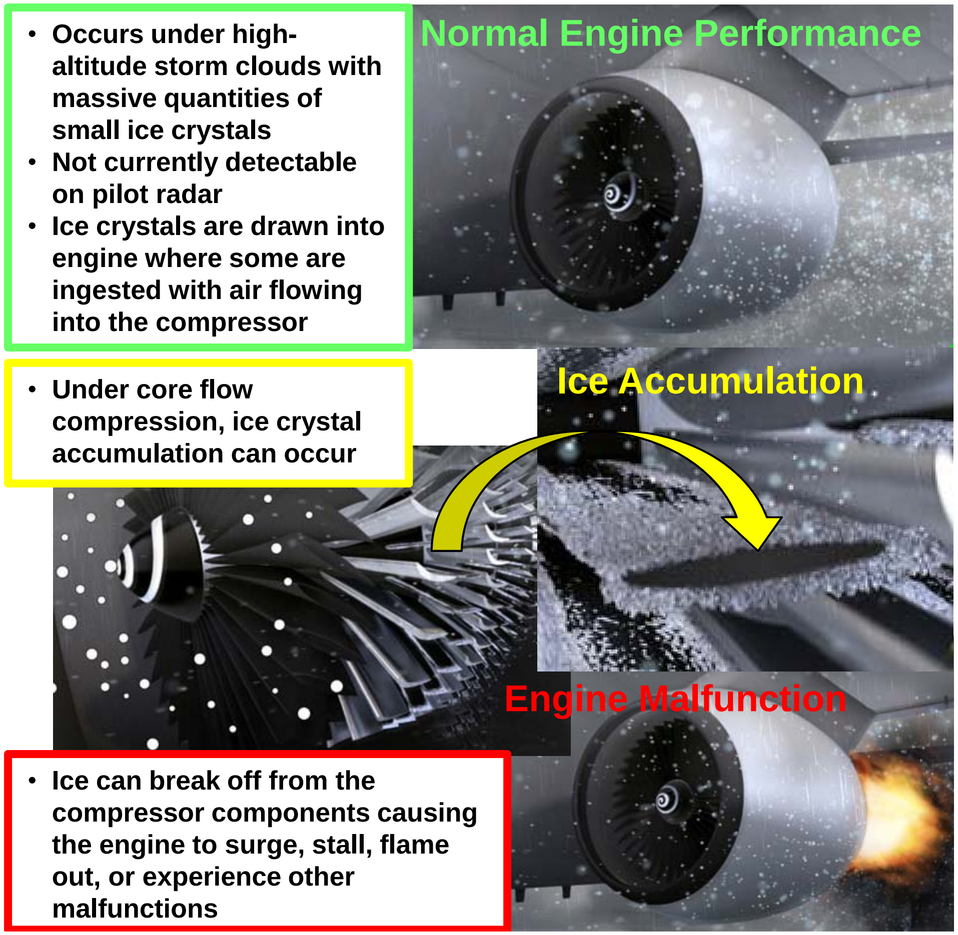
Engine Icing Problem Relevance

153 Power-Loss events 1988-2010 *

14 total power loss (all engines)

* Fisher, John, “Aircraft Turbine Engine Icing: Current Issues and Future Vision,” presentation at SAE International Aircraft Icing Conference, June 16th, 2011

- Ice has been found to accrete in the compressors of commercial aircraft engines during operations under High Ice Water Content (HIWC) conditions
- More than 150 power loss events reported in last 20 years
  - Temporary or sustained power loss, uncontrollability, engine shutdown
- Many possible causes for power losses
  - Compressor surge
  - Flame-out due to combustor ice ingestion
  - Sensor Icing
  - Engine Rollback



- **Occurs under high-altitude storm clouds with massive quantities of small ice crystals**
- **Not currently detectable on pilot radar**
- **Ice crystals are drawn into engine where some are ingested with air flowing into the compressor**

- **Under core flow compression, ice crystal accumulation can occur**

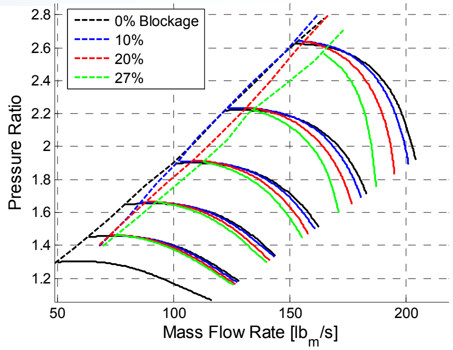
- **Ice can break off from the compressor components causing the engine to surge, stall, flame out, or experience other malfunctions**

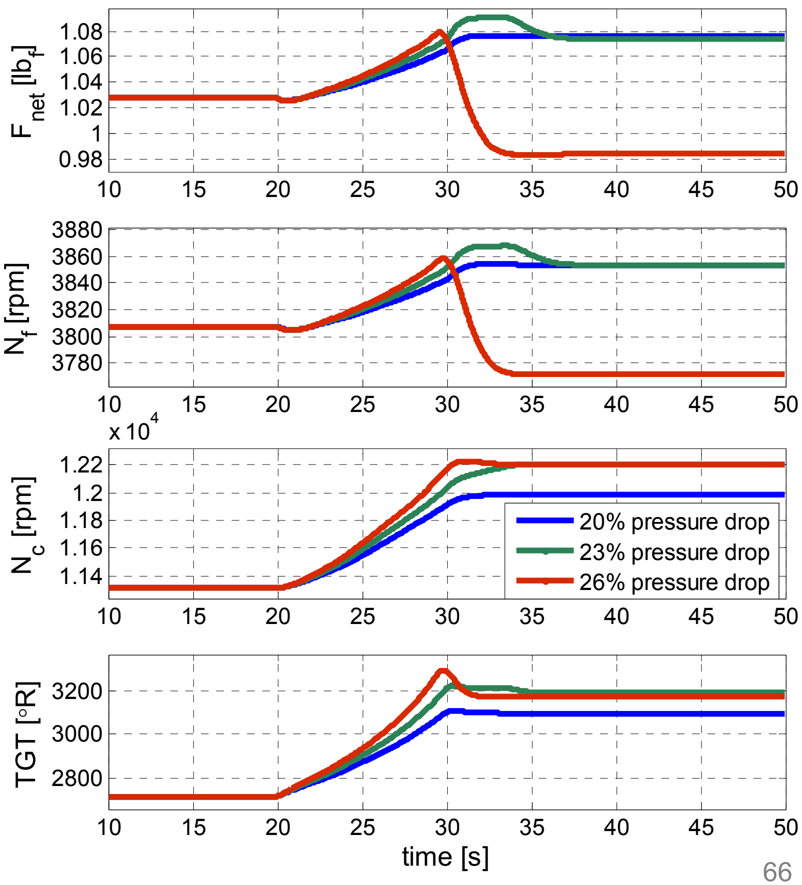
Engine Icing Effects Detection (1)

Engine Icing Effects Modeling & Simulation

- **Problem**: Engine Rollback Phenomena
  - Occurs once blockage become severe enough
  - Results in decreased thrust and fan speed, and increase in Turbine Gas Temperature (TGT)
  - Unresponsive to throttle commands
- **Approach**: Use NASA C-MAPSS40k simulation
  - Realistic controller, sensor noise, modular
    - Currently available for U.S. citizens
    - Open-source thermodynamic modeling platform under development
  - Modify Low Pressure Compressor (LPC) maps to include the effect of discrete levels of ice blockage
- **Accomplishment**: Successful simulation of Engine Rollback using LPC blockage map and dynamic controller
  - Caused by the engine controller limiting fuel when certain safety limits are reached
- **Significance**:
  - Enables technology evaluation under engine icing
  - Enables development of detection/mitigation methods

Ref: May, R.D., Guo, T-H., Veres J.P., Jorgenson, P.C.E., “Engine Icing Modeling and Simulation (Part 2): Performance Simulation of Engine Rollback Phenomena,” 2011-38-0026, SAE International Conference on Aircraft and Engine Icing and Ground Deicing, Chicago, IL, Jun 13-17, 2011. doi:10.4271/2011-38-0026

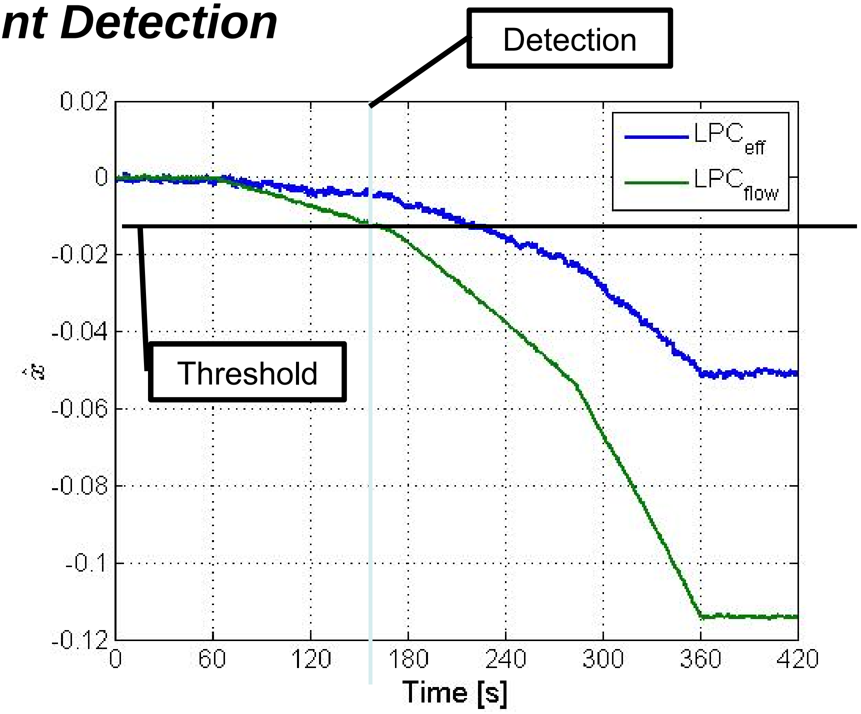




Engine Icing Effects Detection (2)

Engine Icing Impairment Detection

- **Approach**:
  - Estimate the change in LPC “health” (LPC efficiency and flow capacity) based on available sensors
  - Threshold Selected to
    - Balance false positive rate and detection time
    - Detect a decrease in the flow capacity
  - Linear estimator approach
    - Distance Measure (Dm) to determine deviation from expected sensor values
    - Low memory usage
    - Should be capable of operating real-time in typical FADEC
- **Accomplishments**:
  - Early results promising
  - Further improvements achievable using HIWC sensor
  - Development of mitigation strategies next step



- Early Results:
  - False-Positive = 0.2%
  - True-Positive = 99.6%
  - Average Blockage Level at Detection = 4.55%

Engine Icing Effects Detection (3)

- Assumptions:
  - No other component faults
  - This ensures that all changes in engine operation are due to ice accretion
  - Detection algorithm based on combination of LPC efficiency and LPC flow capacity

- Ongoing Research
  - Developing a technique for full envelope detection and transient operations

- Future Plans
  - Complete dynamic detection algorithm for full envelop and transient operations
  - Follow up on work done in NASA PSL
    - » Complete development of model of Honeywell engine using T-MATS software
    - » Implement & test detection algorithms on simulated engine
    - » Verify against experimental data
  - Develop mitigation strategies – iterate with the NASA GRC icing code to determine how the change in operating point impacts the accretion of ice & possible testing in PSL

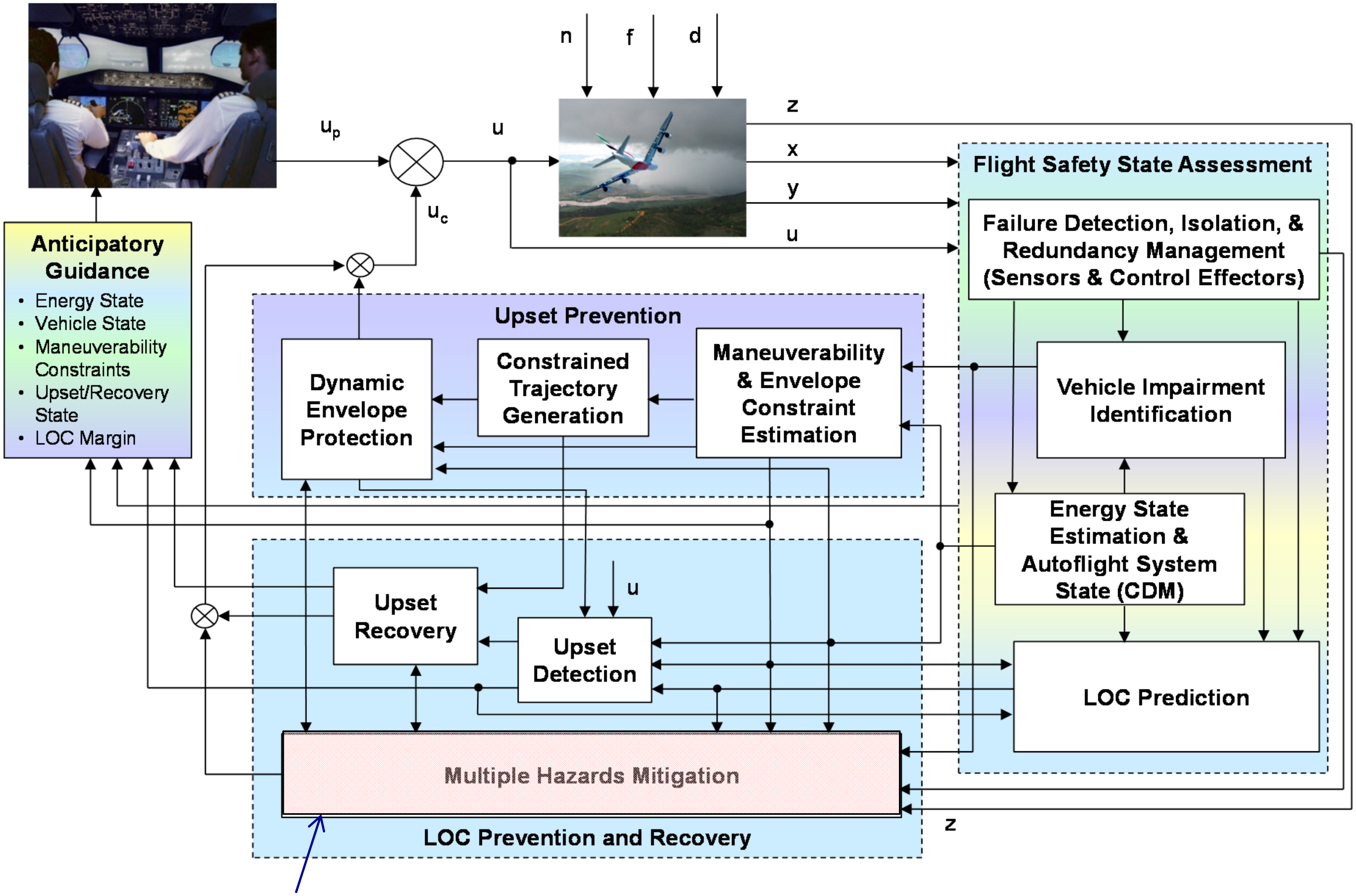
- Engine Icing Effects Detection Technology Status: TRL 1 → 3

Engine Icing Effects Detection (4)

Publications

- May, R.D., Simon, D.L., Guo, T-H., “Modeling and Detection of Ice Particle Accretion in Aircraft Engine Compression Systems,” AIAA Atmospheric Flight Mechanics Conference, Minneapolis, MN, Aug 13-16, 2012.
- May, R.D., Guo, T.H., Simon, D.L., “An Approach to Detect and Mitigate Ice Particle Accretion in Aircraft Engine Compression Systems,” ASME-GT2013-95049, ASME TurboExpo 2013, San Antonio, TX, June 3-7, 2013.
- May, R. D., Guo, T-.H., Simon, D. L., “Detection of the Impact of Ice Crystal Accretion in an Aircraft Engine Compression System During Dynamic Operation,” AIAA 2014-0270, AIAA Guidance, Navigation, and Control Conference, National Harbor, MD, January 13-17, 2014
- R. May, J.W. Chapman, J.P. Veres, T. Guo, M.J. Oliver, “Development and Validation of an Aircraft Engine Simulation Including the Impact of Engine Ice Accretion, “Propulsion and Energy 2014 Forum, Cleveland, OH, July 28-30, 2014. (To Appear)

Fast Engine Response & Integrated Flight-Propulsion Control (IFPC)



Anticipatory Guidance

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Fast Engine Response / Integrated Flight-Propulsion Control

NASA GRC / LaRC

NRA – P&W

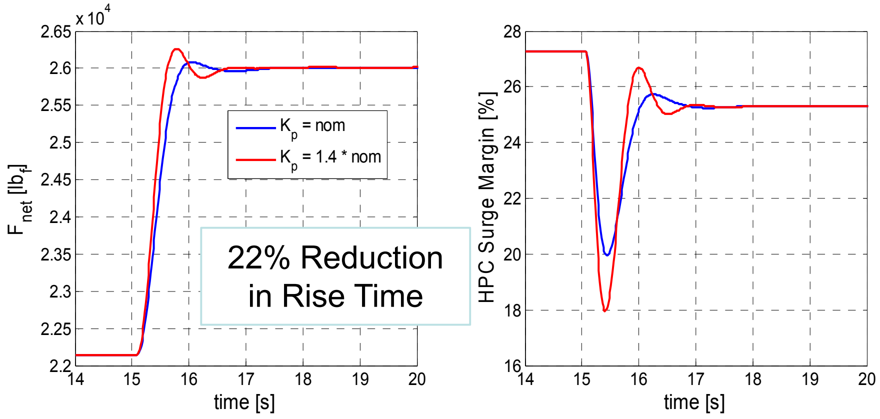
Fast Engine Response Research (1)

- Fast response engine can increase the likelihood of recovering the aircraft from loss of control scenarios
- Challenges:
  - Engine behavior is highly non-linear depending on operation conditions
  - Involving risk of engine failures
- Approaches:
  - Increase controller bandwidth
  - Relax engine limits
  - Off-nominal operation
  - C-MAPSS40k simulation
- Results:
  - Engine response time can be improved with only changes to gains and limits and by using existing actuators in novel ways
  - Any change will increase the risk of engine failure
  - Pilot based evaluations of the fast response engine are very favorable

Fast Engine Response Research (2)

Control gain modification

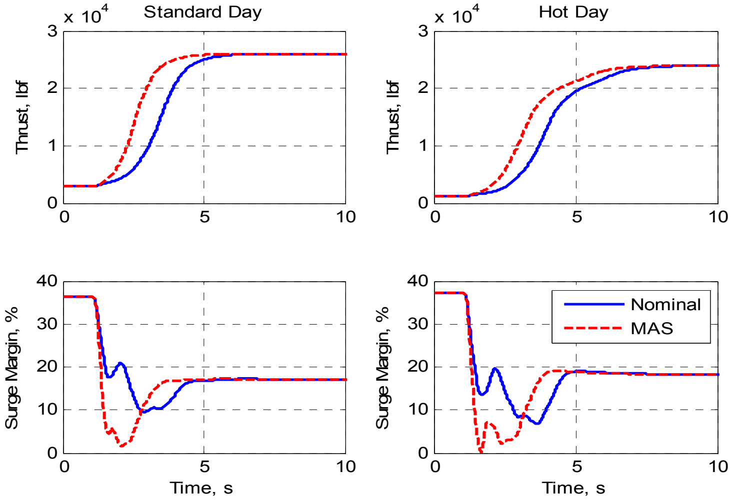
- Changing the setpoint controller’s gain will improve response during small transients
- Increase in gain reduces stability margins
- Marginal impact on HPC Surge Margin



22% Reduction in Rise Time

Risk-based limit modification

- Relax acceleration limits
- Reduced compressor surge margin
- Engine condition considered to minimize the risk
- Rise time reduction depending on the engine health condition

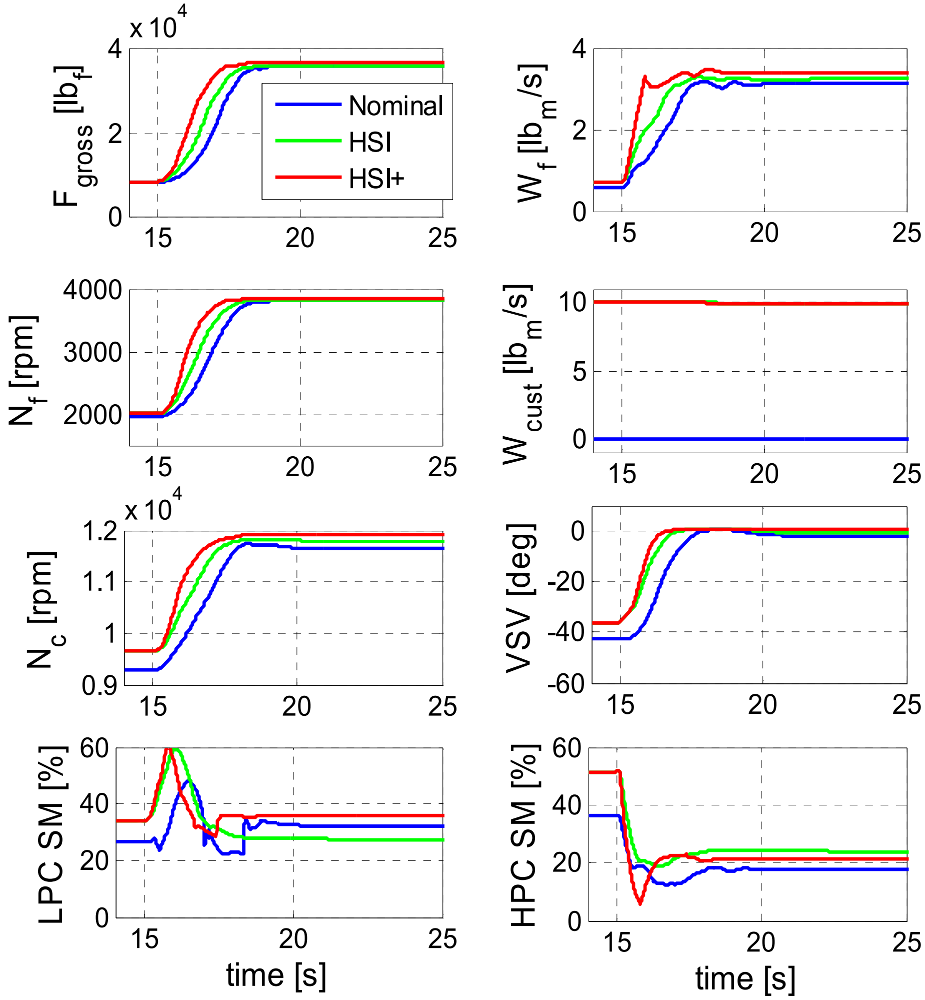


Fast Engine Response Research (3)

High Speed Idle Operation

- Designed to improve engine response during approach
- Operate at higher shaft speeds
- Reduces the potential fan/core mismatch
- Higher speeds lead to more thrust
- During approach/landing it is critical to balance the aircraft's energy
- Engine can be operated in an off-schedule manner to reduce excess thrust
  - Move compressor vanes off-nominal
  - Bleed air from engine components
  - Extract power from shafts

Control Law	Time Constant
Nominal	2.28 s
HSI	1.81 s
HSI+	1.36 s



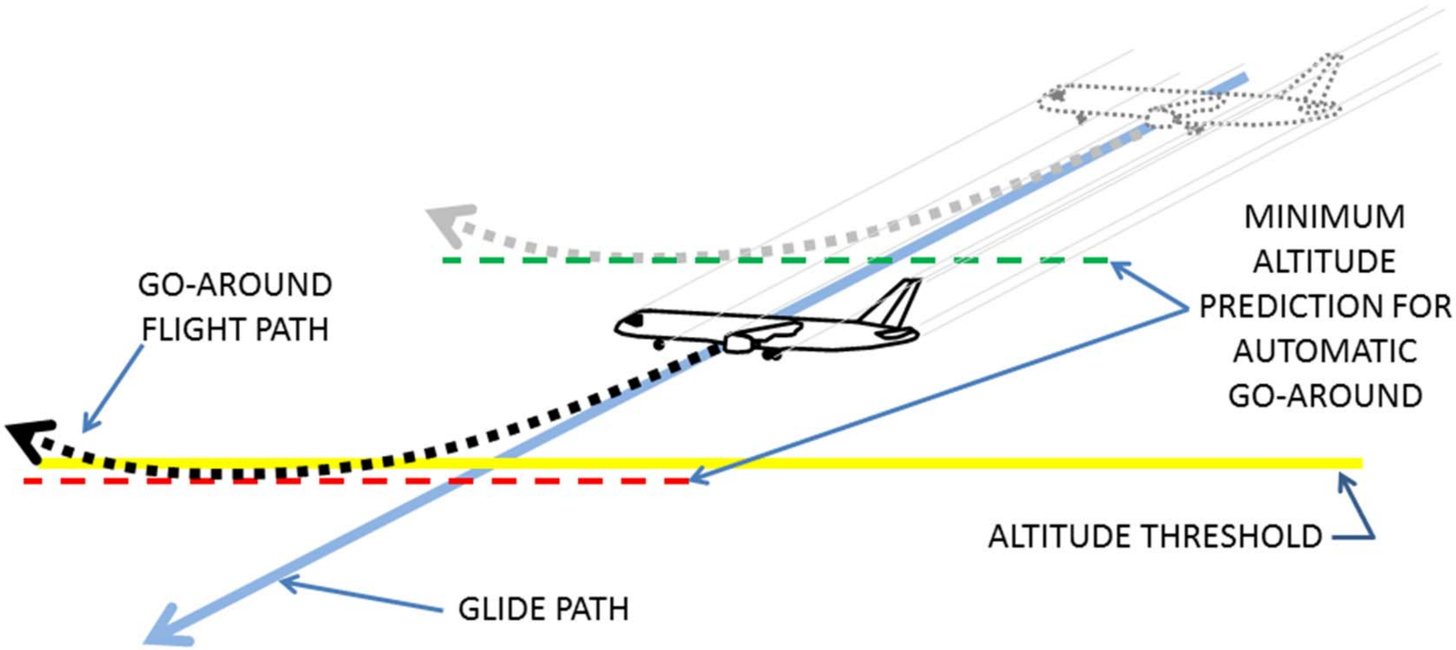
Integrated Flight-Propulsion Control (1)

Model-Predictive Automatic Recovery System (M-PARS)

- Proof of concept as an example of the Integrated Flight and Propulsion Control
- Objective:
  - Prevent unintended/premature ground contact during approach phase of flight
  - Automatic aggressive recovery maneuver of collision is otherwise inevitable
- Approaches:
  - Define protected envelop of the flight landing path
  - Continuous prediction of altitude loss during maneuver
  - Define recovery control commands
  - Determine trigger point for necessary recovery
  - Can not interfere with normal landing procedure
- Results:
  - Model-predictive automatic recovery system to prevent unintended ground contact during landing
  - Automatic application of recovery maneuver through flight and propulsion control override
  - Very successful pilot evaluations for approach/landing in different scenarios

Integrated Flight-Propulsion Control (2)

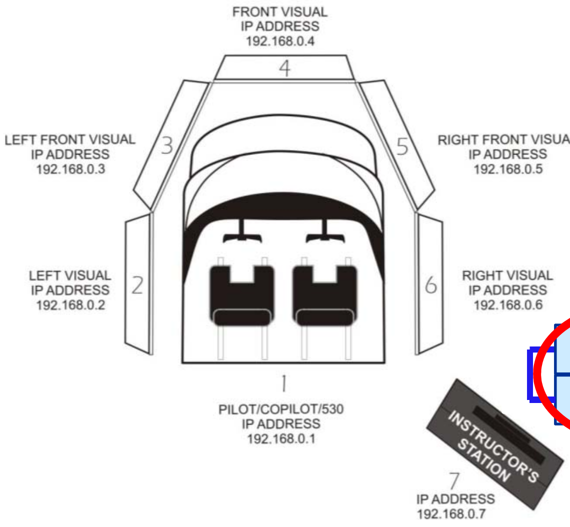
Automatic Recovery System

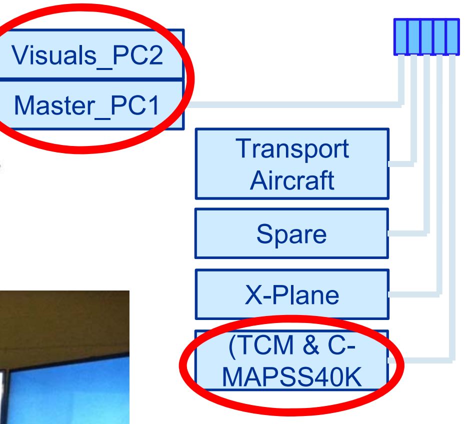


- Define aggressive recovery control commands (e.g., autopilot GA mode, full power and pitch up, etc.)
- Continuous prediction of altitude loss due to maneuver
- If prediction violates threshold, initiate recovery maneuver

Integrated Flight-Propulsion Control (3)

NASA GRC Simulation Testbed





Visuals_PC2

Master_PC1

Transport Aircraft

Spare

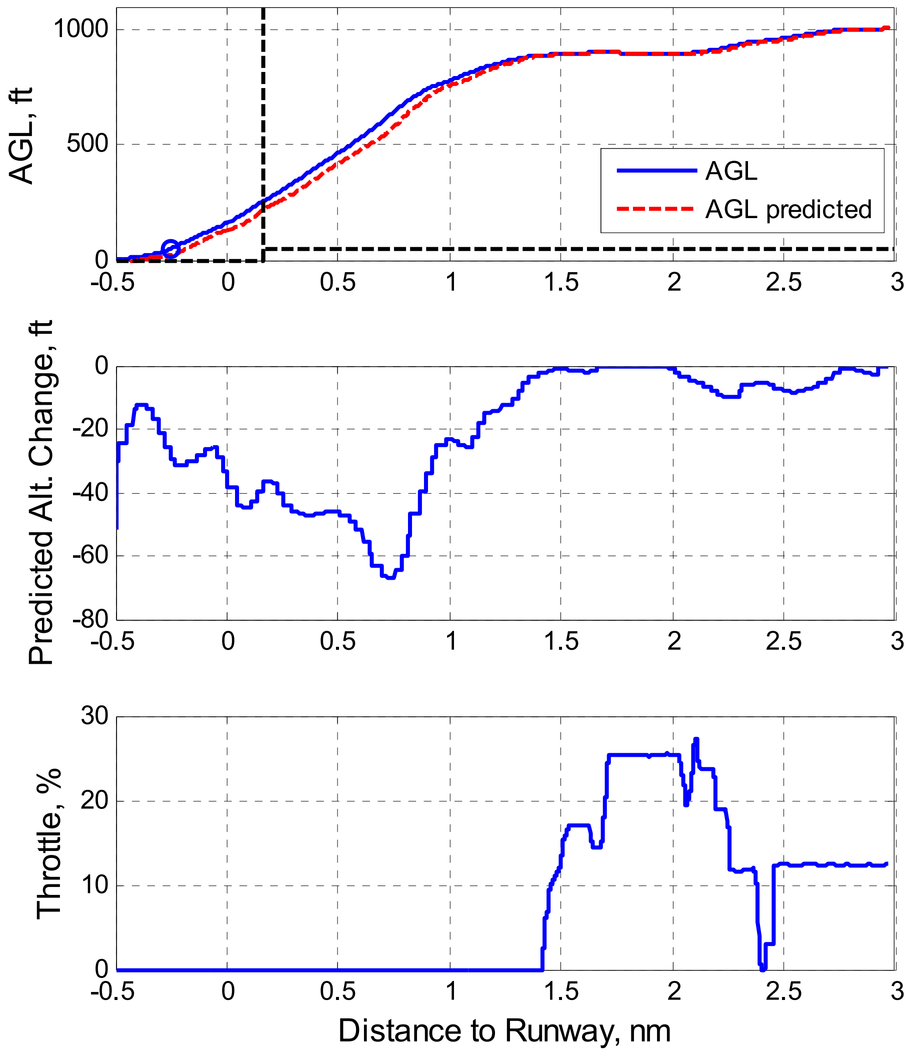
X-Plane

(TCM & C-MAPSS40K

- Full cockpit with standard pilot/copilot controls and instrumentation
- PC 1: X-Plane
- PC 2: Displays
- PC 3: Everything else
  - Models and control systems for aircraft and engines (TCM + C-MAPSS40k)
  - Flight path predictor
  - MPARS flight/propulsion control override algorithms

Integrated Flight-Propulsion Control (4)

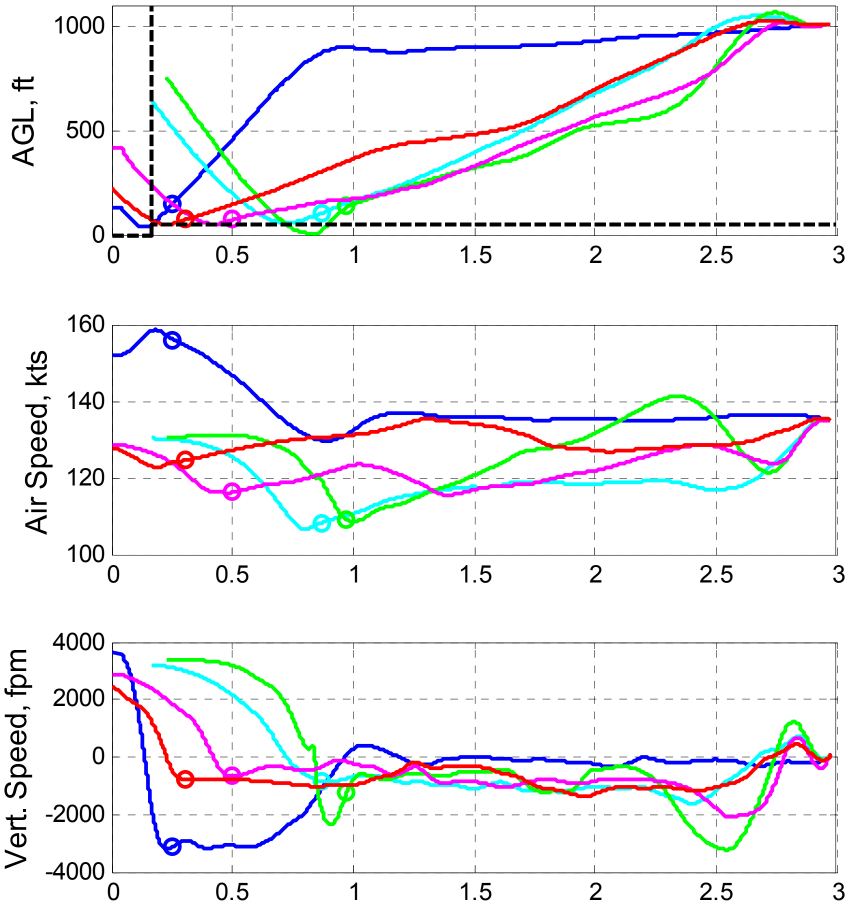
Successful Landing

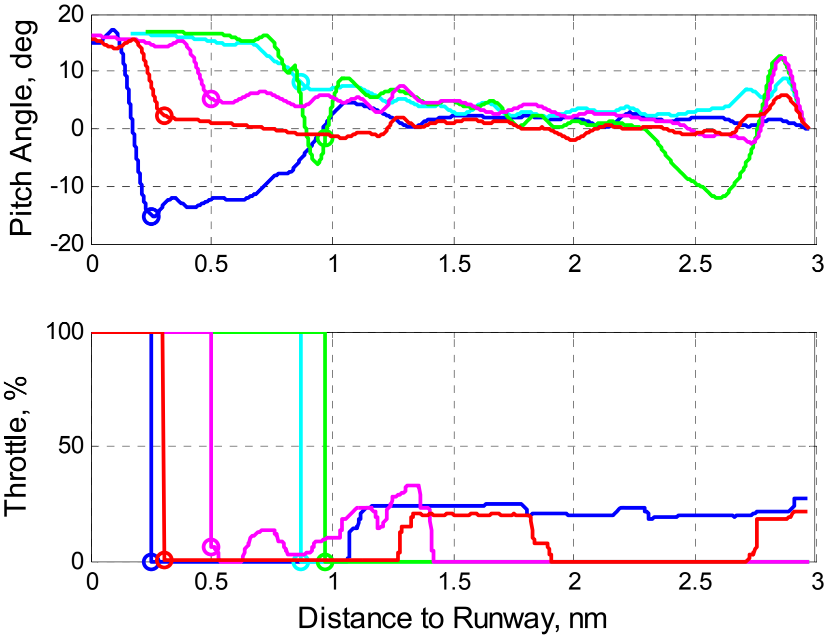


- **Flight path is from right to left**
- Altitude threshold set to 50 feet AGL
- 1000 feet from runway: altitude threshold set to 0 feet
- 50 feet AGL: protection system deactivates
- Simple rules work well unless trying to touchdown at runway edge

Integrated Flight-Propulsion Control (5)

Failed Approaches





- Variety of failed approaches to stress test recovery system
- All cases would have touched down short of runway
- Circular point denotes MPARS activation (notice throttle change)

Fast Engine Response & Integrated Flight-Propulsion Control Summary (1)

- Status
  - Model-predictive automatic recovery system developed to prevent unintended ground contact
  - Primary application: low-speed, low-altitude
  - Automatic application of aggressive recovery maneuver (flight/propulsion controls override)
  - Continuous flight path prediction to ensure “last-second” activation
- Ongoing & future work:
  - Forward distance prediction & sloping threshold
  - Uncertainty analysis of flight path predictor
  - Incorporation of risk-based enhanced engine performance control modes

Fast Engine Response & Integrated Flight-Propulsion Control Summary (2)

Publications (1)

- McGlynn, G. E., Litt, J.S., Lemon, K.A., and Csank, J.T., “A Risk Management Architecture for Emergency Integrated Aircraft Control,” AIAA-2011-1568, Infotech@Aerospace 2011, St. Louis, Missouri, Mar. 29-31, 2011. also NASA/TM—2011-217143, December 2011.
- Csank, J.T., Chin, J.C., May, R.D., Litt, J.S., and Guo, T.-H., “Implementation of Enhanced Propulsion Control Modes for Emergency Flight Operation,” AIAA-2011-1590, Infotech@Aerospace 2011, St. Louis, Missouri, Mar. 29-31, 2011.
- Avishai Weiss, Ilya Kolmanovsky, Walter Merrill, "Incorporating Risk into Control Design for Emergency Operation of Turbo-Fan Engines," AIAA-2011-1591, Infotech@Aerospace 2011, St. Louis, Missouri, Mar. 29-31, 2011.
- Chuan Wang, Reza Sharifi, Chengyu Cao, "L1 Adaptive Control of Uncertain Nonlinear Systems in the Presence of Output Limits," AIAA-2011-1400, Infotech@Aerospace 2011, St. Louis, Missouri, Mar. 29-31, 2011
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- Csank, J. T., May, R. D., Guo, T-H., Litt, J.S., “The Effect of Modified Control Limits on the Performance of a Generic Commercial Aircraft Engine,” AIAA 2011-5972, 47th AIAA/ASME/SAE/ASEE Joint Propulsion Conference & Exhibit, July 31-August 3, 2011, San Diego, CA. Also NASA/TM--2012-217261, January 2012.

Fast Engine Response & Integrated Flight-Propulsion Control Summary (3)

Publications (2)

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- Lemon, Kimberly A., Litt, Jonathan S., and May, Ryan D., “An Emergency Engine Response Requirement Analysis Tool for Lateral-Directional Dynamic Aircraft Stability,” AIAA 2011-6308, AIAA Guidance, Navigation & Control Conference, Portland, OR, August 8-11, 2011.
- May, Ryan D., Lemon, Kimberly A., Csank, Jeffrey T., Litt, Jonathan S., and Guo, Ten-Huei, “The Effect of Faster Engine Response on the Lateral Directional Control of a Damaged Aircraft,” AIAA 2011-6307, AIAA Guidance, Navigation & Control Conference, Portland, OR, August 8-11, 2011. Also NASA/TM--2012-217216. March 2012.
- Litt, Jonathan S., Sowers, T. Shane, Owen, A. Karl, Fulton, Chris, Chicatelli, Amy, “Flight Simulator Evaluation of Enhanced Propulsion Control Modes for Emergency Operation,” AIAA 2012-2604, Infotech@Aerospace 2012, Garden Grove, CA, June 19-21, 2012.
- Litt, Jonathan S., Guo, Ten-Huei, Sowers, T. Shane, Chicatelli, Amy K., Fulton, Christopher E., May, Ryan D., and Owen, A. Karl, "Pilot-in-the-Loop Evaluation of a Yaw Rate to Throttle Feedback Control with Enhanced Engine Response," AIAA-2012-5027, AIAA Guidance, Navigation, and Control Conference, Minneapolis, Minnesota, Aug. 13-16, 2012.
- Zaretsky, Erwin V., Litt, Jonathan S., Hendricks, Robert C., Soditus, Sherry M., "Determination of Turbine Blade Life From Engine Field Data," JOURNAL OF PROPULSION AND POWER, Vol. 28, No. 6, November-December 2012, pp. 1156-1167, also NASA/TP—2013-217030, April 2013.
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Fast Engine Response & Integrated Flight-Propulsion Control Summary (4)

Publications (3)

- Litt, Jonathan S., Liu, Yuan, Sowers, T. Shane, Owen, A. Karl, Guo, Ten-Huei, “Piloted Simulation Evaluation of a Model-Predictive Automatic Recovery System to Prevent Vehicle Loss of Control on Approach,” AIAA 2014-0036, AIAA ATMOSPHERIC FLIGHT MECHANICS CONFERENCE, National Harbor, MD, January 13-17, 2014, also NASA/TM—2014-216644, March 2014.
- Liu, Yuan, Litt, Jonathan S., Sowers, T. Shane, Owen, A. Karl, Guo, Ten-Huei, “Application and Evaluation of Risk-Based Performance Enhancing Engine Control Modes,” Propulsion and Energy 2014 Forum, Cleveland, OH, July 28-30, 2014. (To Appear)

New Technology Disclosures

- “High Speed Idle Engine Control Mode” non-provisional utility patent application filed on 12/13/2012. Co-inventors are Jeff Csank, Ryan May, Jonathan Litt, and Ten-Huei Guo
- “Model-Predictive Automatic Recovery System,” Co-inventors are Jonathan Litt, Yuan Liu, T. Shane Sowers, and A. Karl Owen.

Invited Presentations

- Ten-Huei Guo, “Enhanced Engine Control Overview,” 4th NASA GRC Aeronautics Propulsion Control and Diagnostics Research Workshop, Dec. 11-12, 2013, Cleveland, OH
- James Liu, “Controller Design for Enhanced Engine Response,” 4th NASA GRC Aeronautics Propulsion Control and Diagnostics Research Workshop, Dec. 11-12, 2013, Cleveland, OH
- Jonathan Litt, “Using Propulsion System for Loss of Control Prevention and Mitigation,” 4th NASA GRC Aeronautics Propulsion Control and Diagnostics Research Workshop, Dec. 11-12, 2013, Cleveland, OH
- James Liu, “Piloted Simulation of a Model-Predictive Automated Recovery System,” at Aerospace Control and Guidance Systems Committee Meeting #113, March 12-14, 2014, Englewood, CO.