CAST Safety Enhancement Research on Airplane State Awareness and Prediction Technologies

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SAE/NASA Autonomy and the Next Generation Flight Deck

Moffett Field, CA
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Team

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American Airlines
Rockwell Collins
SAAB Sensis
Georgia Tech
Boeing
The University of Iowa
George Mason University
Ohio University
Decision Research
Honeywell

Outline

- Motivation
- Technologies
  - Trajectory Prediction
  - Safe Flight Envelope Estimation
  - Predictive Alerting
  - Synoptic Displays
  - Stall Recovery Guidance
- Concluding remarks

Motivation

CAST | The Commercial Aviation Safety Team

CAST-recruited gov't-industry team (2010-2014)

- Analyzed 18 events from ~10 years prior; Identified 12 recurring problem themes; Suggested >270 intervention strategies

- Assessed each intervention strategy for effectiveness & feasibility; Recommended
  - **13** safety enhancements (SEs), no research req'd
  - **5 research** safety enhancements (SEs)
  - **1 design** SE where research is critical to implementation

- Published plans to achieve each safety enhancement

NASA's contribution (2014-2019)

NASA ARMD
Airspace Operations & Safety (AOSP) Program

Airspace Technology Demonstrations (ATD) Project

Technologies for Airplane State Awareness (TASA) Sub-Project

Invalid Source Data	Distraction	Systems Knowledge	Crew Resource Management	Automation Confusion / Awareness	Ineffective Alerting	Inappropriate Control Actions	Total
	x	x	x		x		7
x	x		x		x		6
	x		x	x	x	x	8
	x	x	x	x	x	x	9
	x		x	x	x	x	7
	x	x	x	x	x	x	11
	x		x		x	x	6
	x		x	x	x	x	6
	x		x	x	x	x	8
x	x	x	x	x	x	x	9
x	x		x		x	x	7
	x	x	x	x	x	x	10
	x			x	x	x	6
	x			x	x		7
	x	x	x	x	x	x	9
x	x	x	x	x	x		10
x	x		x	x	x		8
	x		x	x	x		7
5	18	7	16	14	18	12	

Virtual Day-VMC Displays (SE-200)

Attitude & Energy State Techs (SE-207)

Systems State Technologies (SE-208)

Simulator Fidelity (SE-209)

Flight Crew Performance (SE-210)

Training for Attention Management (SE-211)

Desired Outputs and Schedule

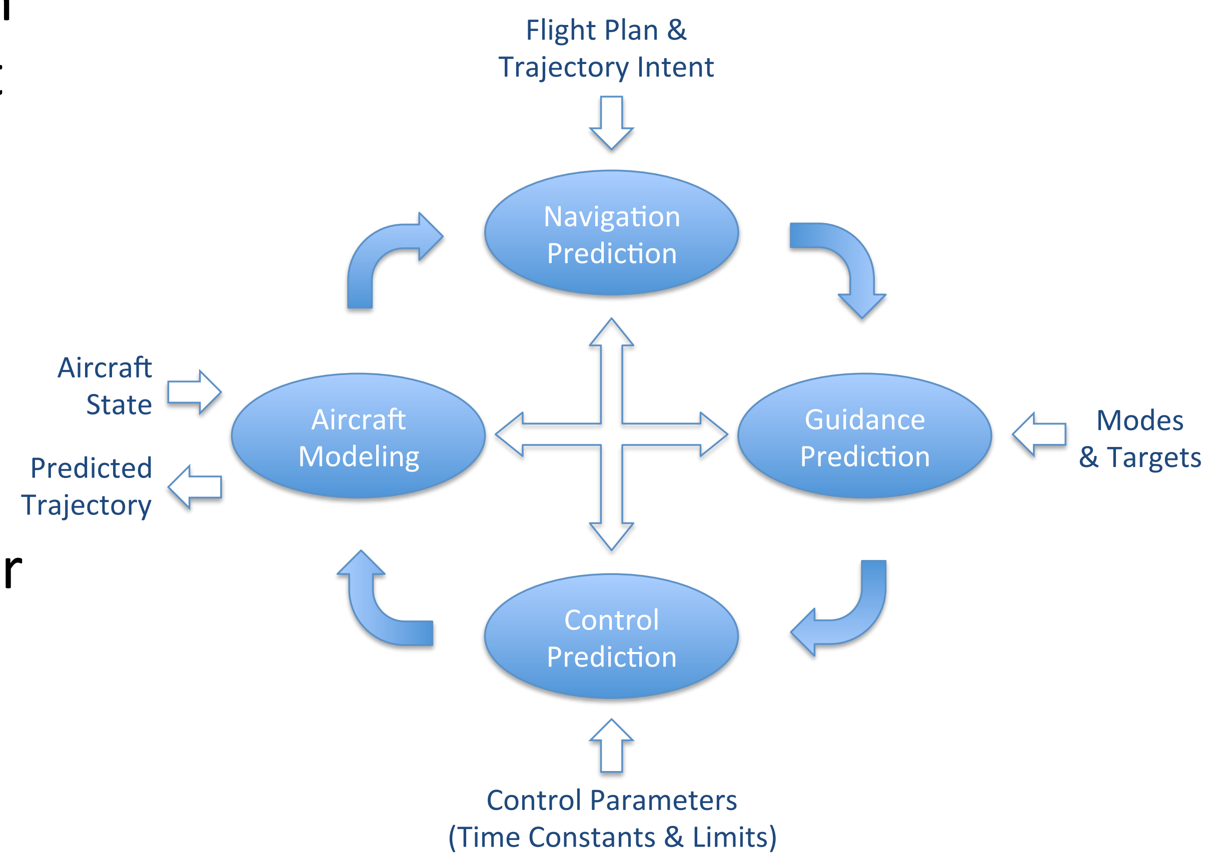
http://www.skybrary.aero/bookshelf/books/2999.pdf
http://www.skybrary.aero/bookshelf/books/3000.pdf

TECHNOLOGIES

Trajectory Prediction
Safe Flight Envelope Estimation
Predictive Alerting
Synoptic Displays
Stall Recovery Guidance

Trajectory Prediction

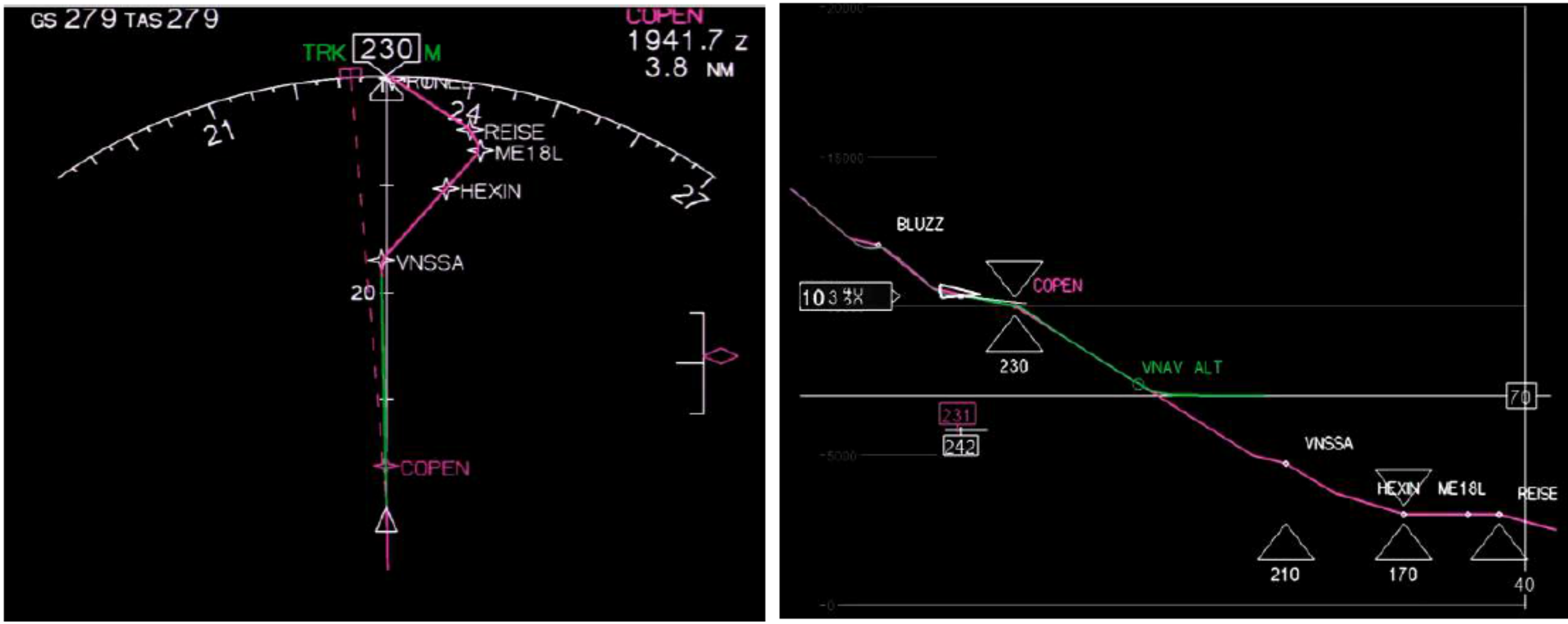
- Fast-time simulation of simplified aircraft dynamics
- Models behavior of FMS, APS, ATS
- Bank, flight path angle, thrust commands (1st order system with rate limits)
- 5 minute prediction horizon



Kimberlee Shish, et al., "Aircraft Mode and Energy-State Prediction, Assessment, and Alerting," Journal of Guidance, Control, and Dynamics, Online: August 26, 2016

Trajectory Prediction

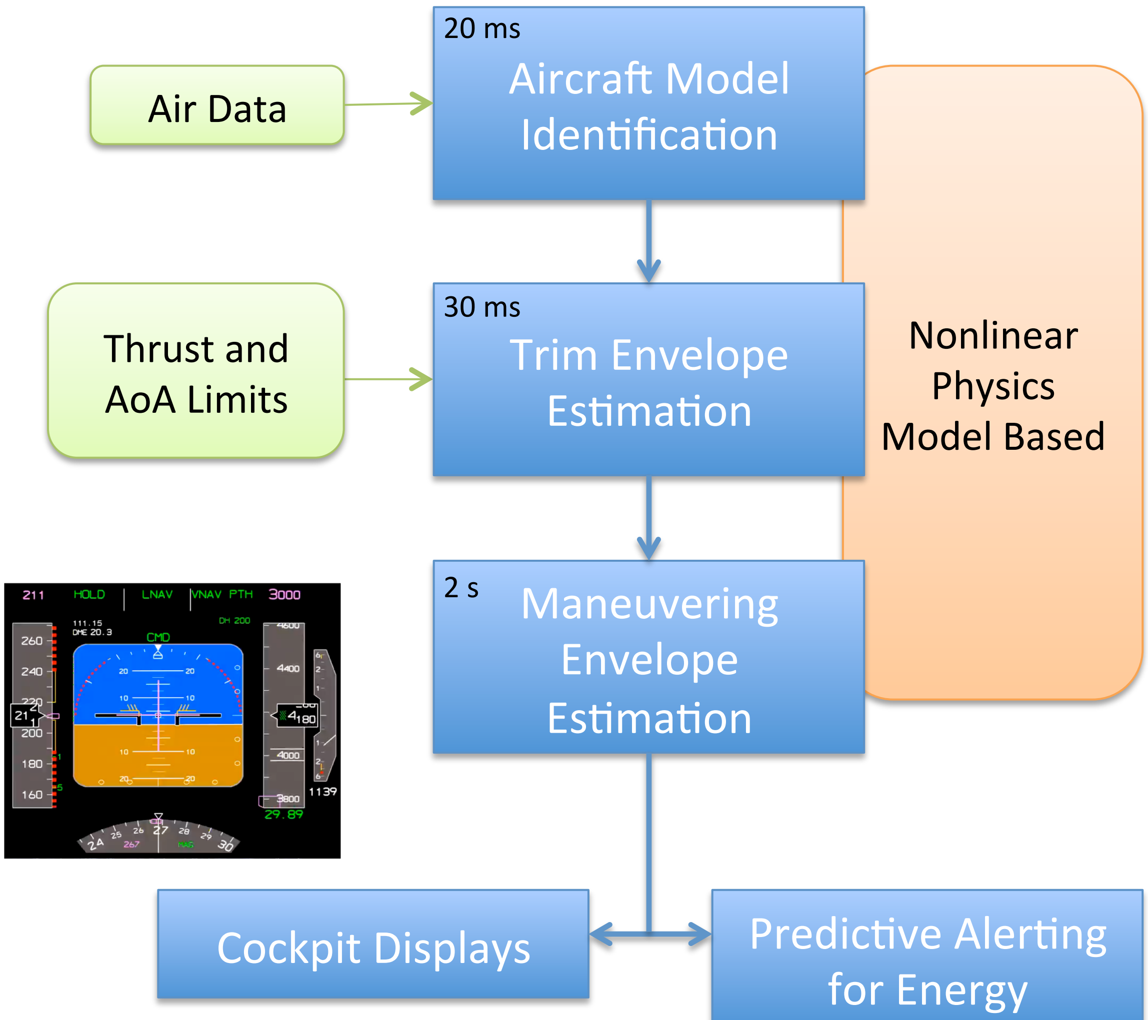
ACFS, B-747 (2014)

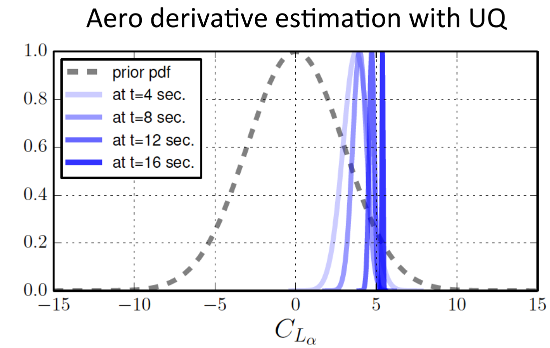


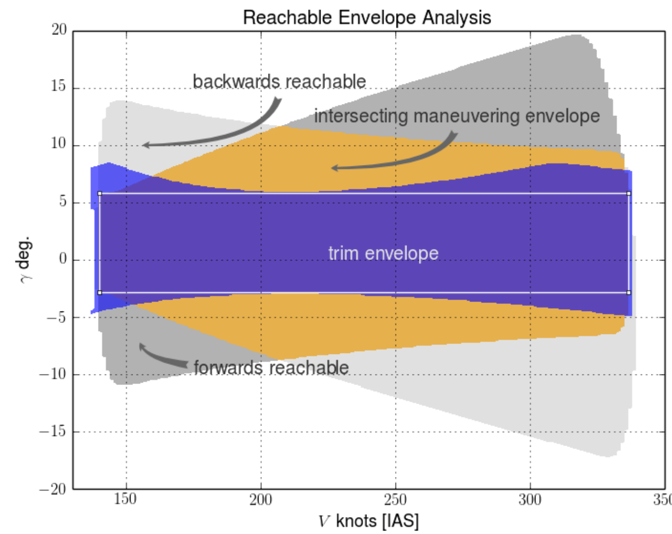
Trajectory prediction on the Navigation Display (ND) and Vertical Situation Display (VSD)

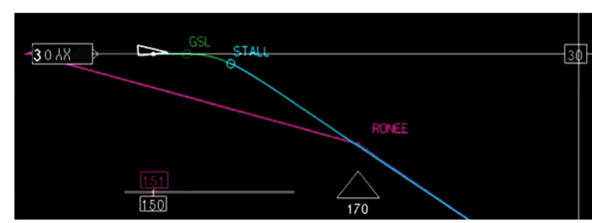
K. Shish, et. al., "Trajectory Prediction and Alerting for Aircraft Mode and Energy State Awareness," AIAA 2015-1113, Jan 2015 (Best Paper of Conference Award)

Safe Flight Envelope Estimation



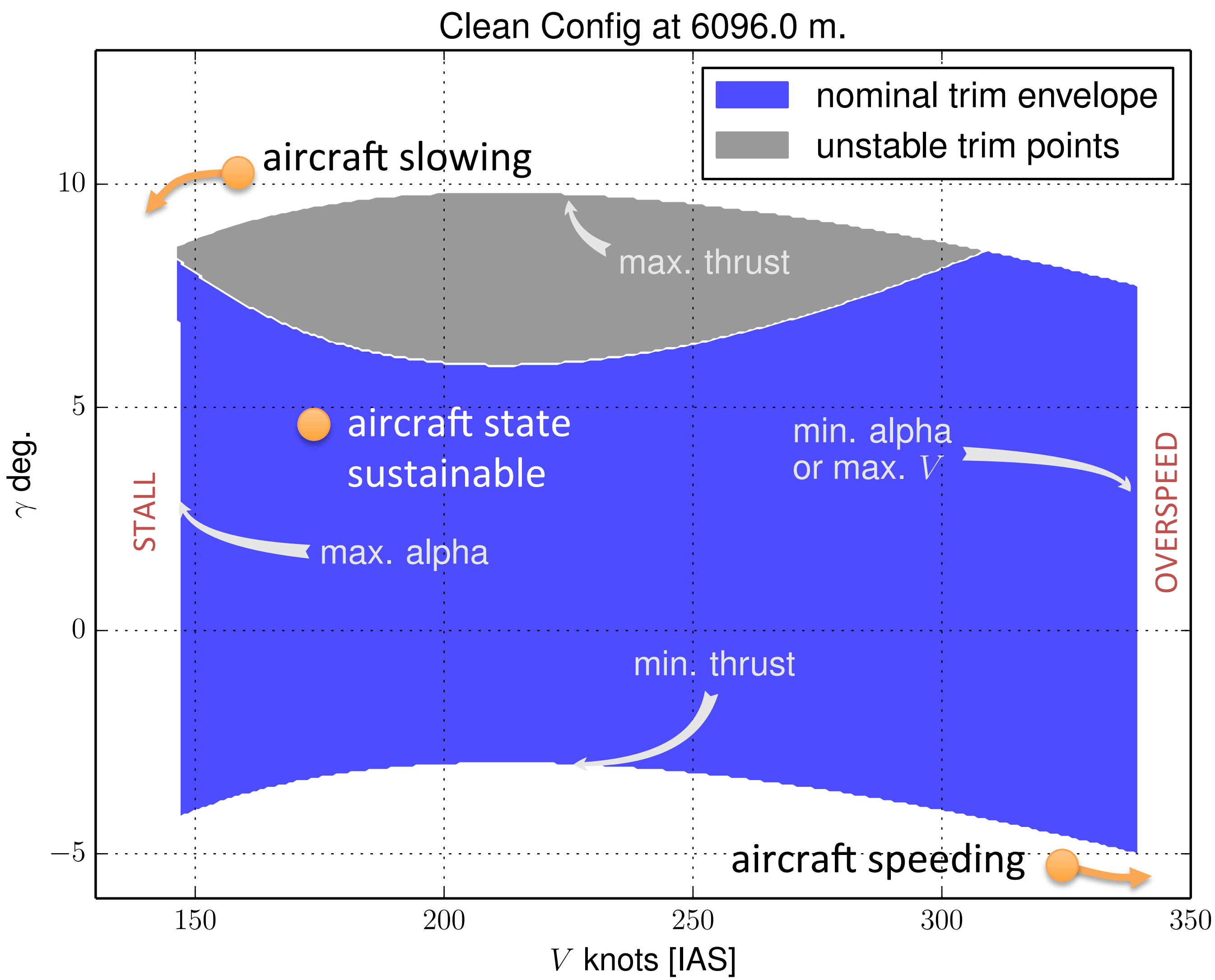




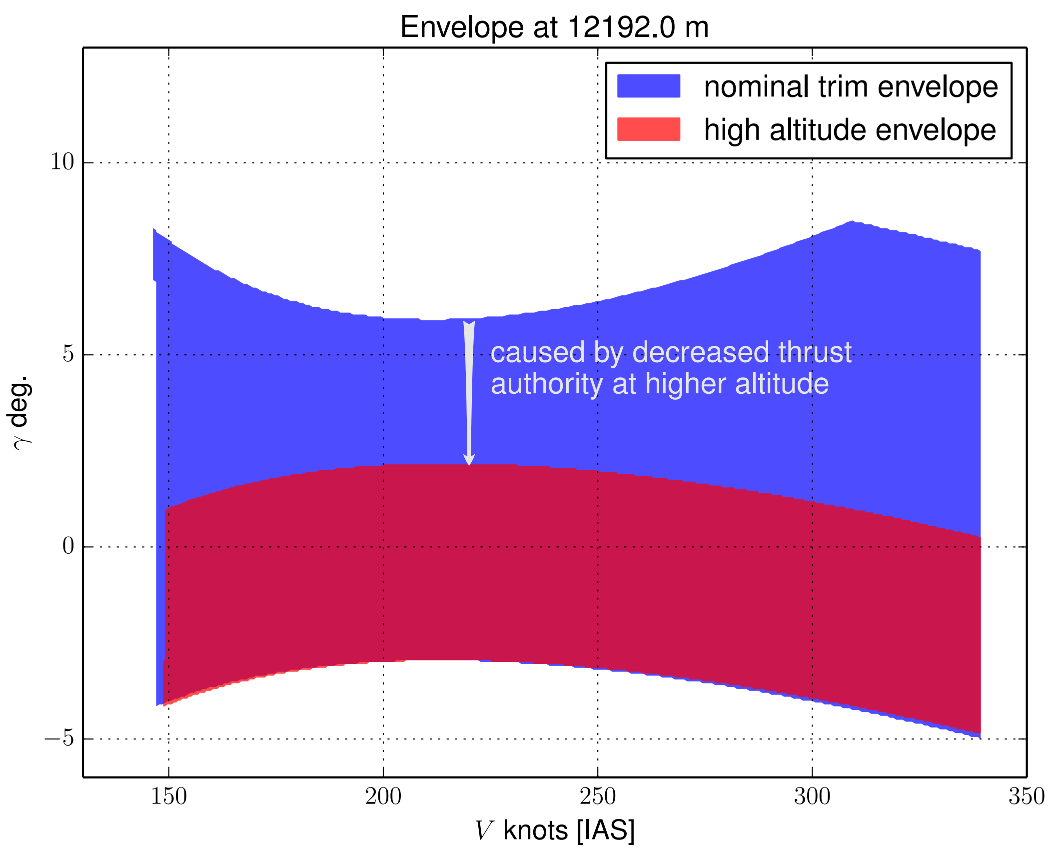


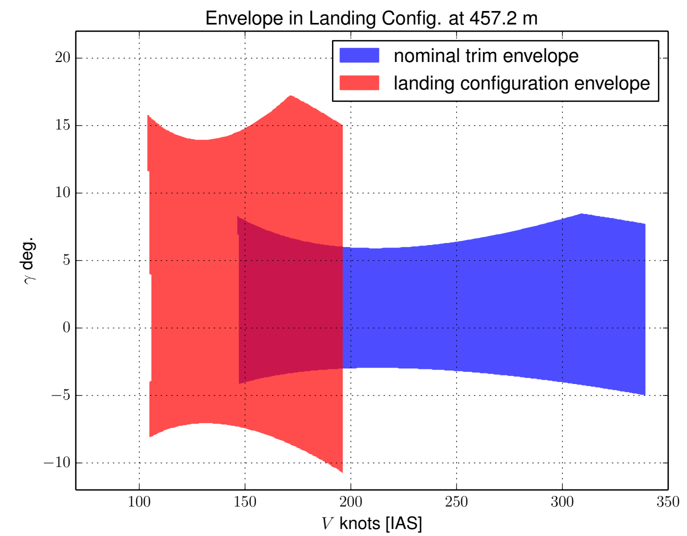
Stefan Schuet, et al., "Autonomous Flight Envelope Estimation for Loss-of-Control Prevention," Journal of Guidance, Control, and Dynamics, Online: September 15, 2016

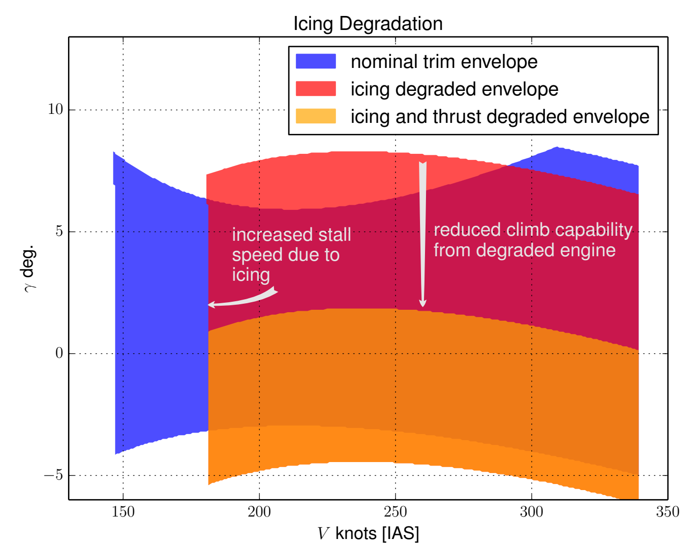
Trim Envelopes



Dynamic Effects

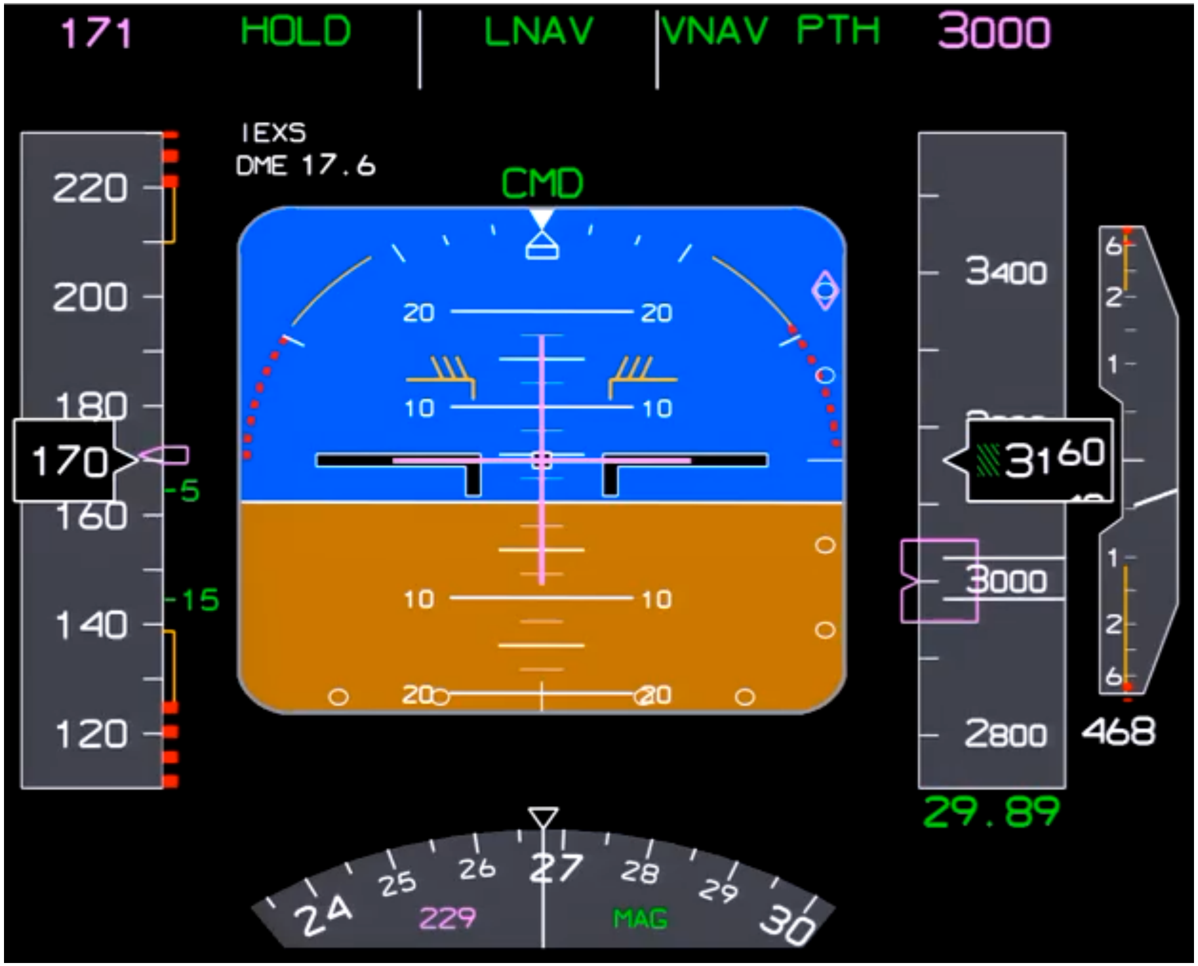






Flight Envelope Driven PFD

ACFS, B-747 (2014)



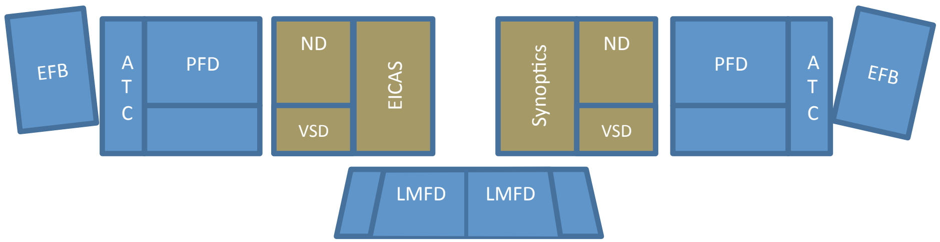
Thomas Lombaerts, et al., "Piloted Simulator Evaluation of Safe Flight Envelope Display Indicators for Loss of Control Avoidance," Journal of Guidance, Control, and Dynamics, Publication Date (online): May 24, 2016

Flight Envelope Driven PFD

CMF/RFD, B-787 (2015-16)

S. D. Young, et al., Evaluating technologies for improved airplane state awareness and prediction. In AIAA Infotech @ Aerospace, number AIAA 2016-2043. American Institute of Aeronautics and Astronautics, January 2016.

Predictive Notifications & MHP*



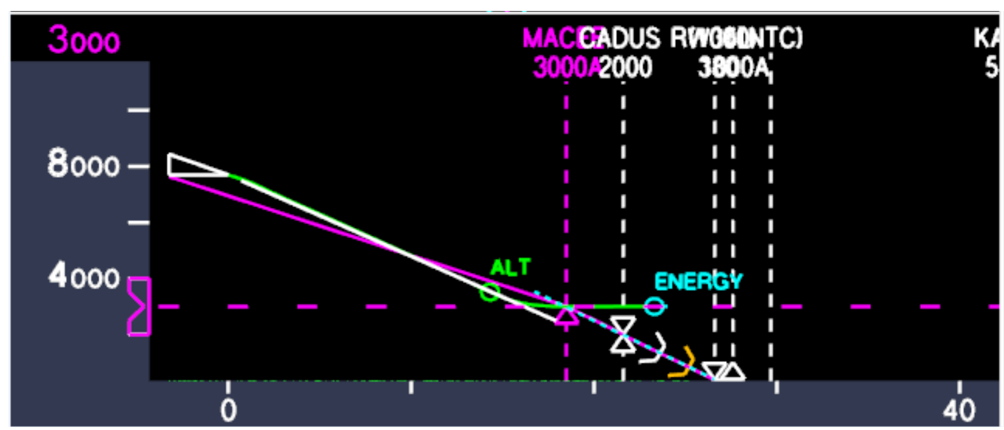
Multiple Hypothesis Prediction (MHP*) function

- New EICAS message types will come from the MHP software indicating a predicted unsafe energy-related state
- Type and location of ND/VSD TP symbol (circle, label) will also come from the MHP software indicating how far into the future the state will occur if no intervention

1 EICAS (Predictor Types and Messages

EICAS Message	ND/VSD TP Symbol Label
Δ OVERSPEED PRED Δ OVERSPEED PRED	OVSPD OVSPD
Δ STALL PRED Δ STALL PRED	STALL STALL
Δ VERT SPEED LIMIT PRED	V/S
Δ UNSTABLE LIMIT PRED	UNSTB
Δ HIGH FAST PRED	ENERGY
Δ LOW SLOW PRED	ENERGY

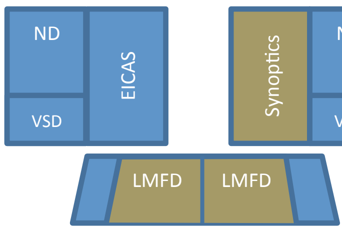
2 Vertical Situation Display



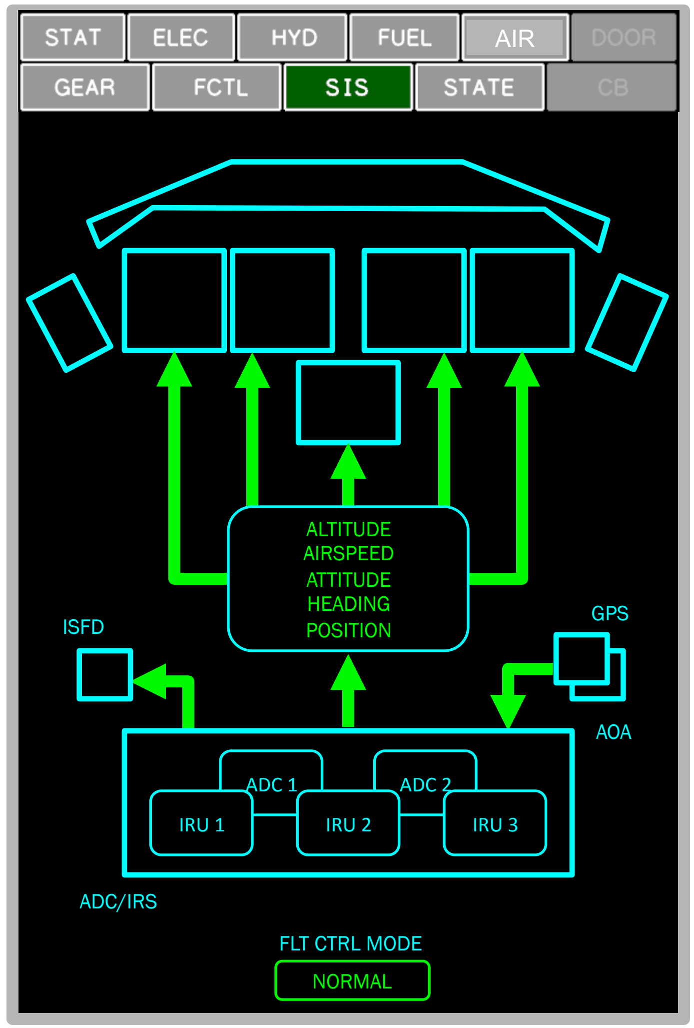
3 Corresponding ND image not shown

*M. Uijt de Haag, et al., "Energy State Prediction Methods for Airplane State Awareness," Proceedings of AIAA/IEEE Digital Avionics Systems Conference, Sep 25-29, Sacramento, CA

System Interaction Synoptic



Available on any of these display spaces



Normal

Mode control panel

Display panels

Flight-critical information

Flight-critical data systems

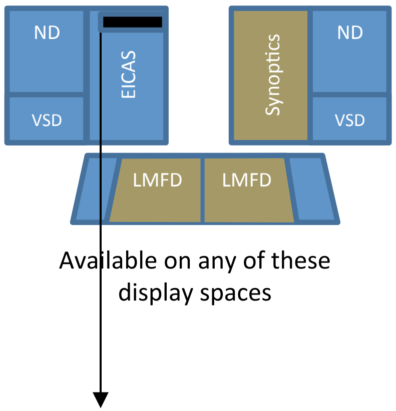
:ISFD – standby instrument :Flight control mode

S. D. Young, et al., "Flight simulation study of airplane state awareness and prediction technologies," 2016 IEEE/AIAA 35th Digital Avionics Systems Conference (DASC), Sacramento, CA, 2016, pp. 1-11.

System Interaction Synoptic

Non-normal

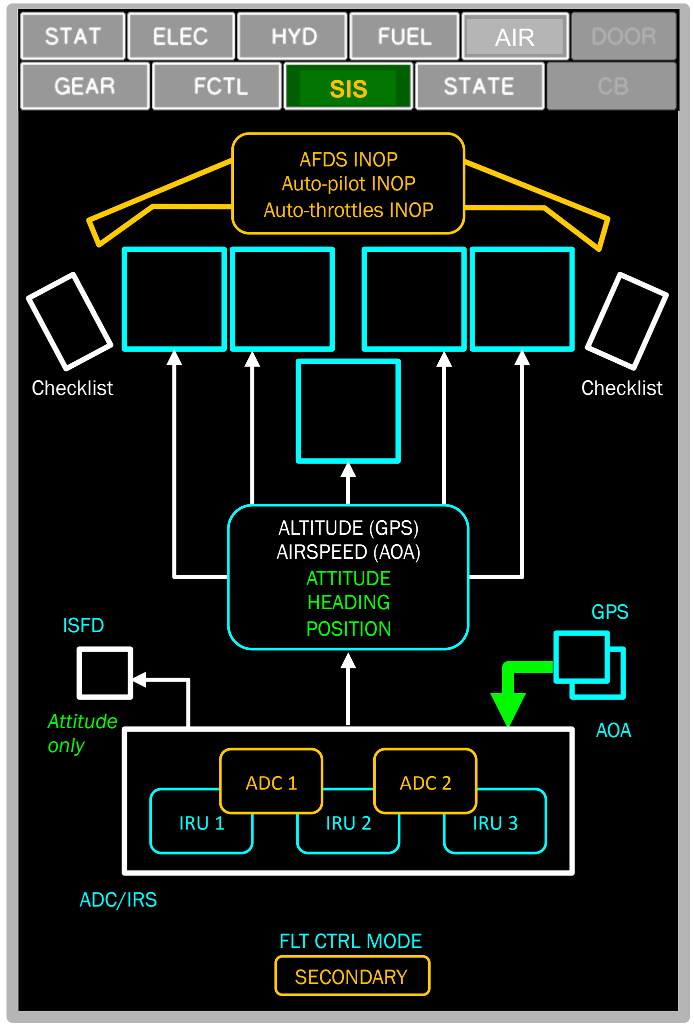
(example)



Available on any of these display spaces

EICAS Msg:

- ❑ NAV AIR DATA SYS

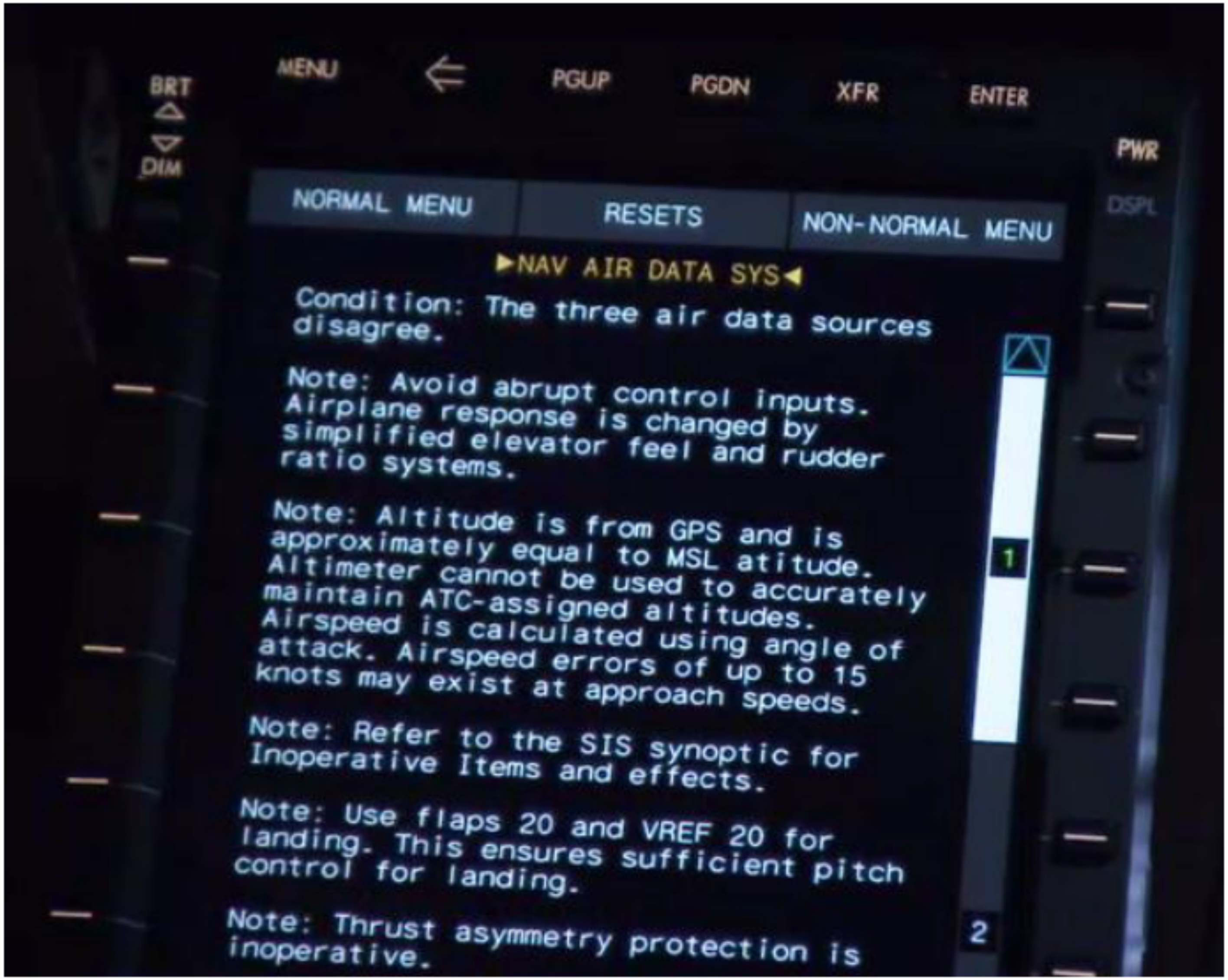


Associated checklist(s) available on both Electronic Flight Bags (EFBs)

Checklist(s) will be simplified:

1. Removes information now provided on this display
2. Context-relevant data provided rather than lists, or needs to look in reference documents

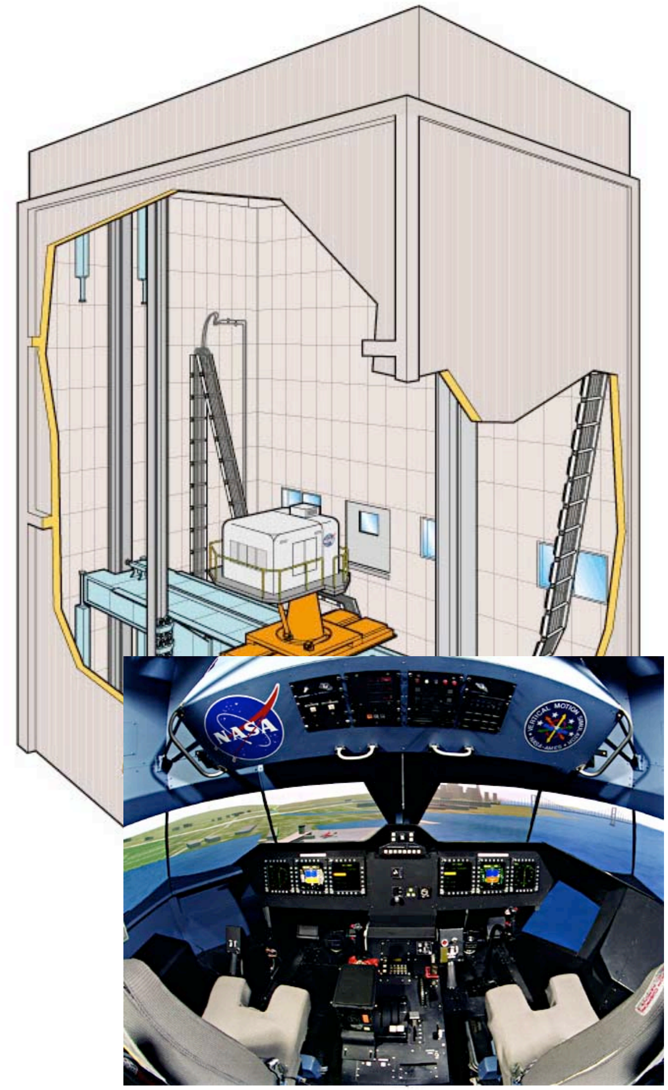
Revised Check List



Stall Recovery Guidance

Objective: To develop guidance technology that helps pilots efficiently recover from stall. (SE207/Output 2)

- Aircraft model with stall dynamics
  - B757 like Generic Transport Model (GTM)
- Vertical Motion Simulator
  - Provides high fidelity motion for stall dynamics
- Developed algorithms that use flight dynamics to determine scenario/aircraft specific recovery guidance
  - 2 recovery guidance algorithms
  - Same displays for all algorithms
- Study looks at four scenarios, simulating different stall entry conditions
  - High alt. low energy
  - Low alt. with bank
  - Low alt. with bank and excessive nose-up trim
  - Final approach, descending
- Experiment designed with AFRC and FAA pilot feedback
  - Study includes 30 commercial pilots, 6 AFRC test pilots, 3 FAA AEG pilots



Stall Recovery Procedure

FAA Stall Recovery Template AC120-109A*, 2015

1	**Disconnect autopilot and autothrottle/autothrust** Rationale: Leaving the autopilot or autothrottle/autothrust connected may result in inadvertent changes or adjustments that may not be easily recognized or appropriate, especially during high workload situations.
2	**(a) Nose down pitch control until impending stall indications are eliminated.** **(b) Nose down pitch trim as needed.** Rationale: Reducing the angle-of-attack is crucial for recovery. This will also address autopilot-induced excessive nose-up trim. If the control column does not provide sufficient response, pitch trim may be necessary.
3	**Bank wings level.** Rationale: This orients the lift vector for recovery.
4	**Apply thrust as needed.** Rationale: Amount of thrust depends on aircraft configuration and in some cases applying maximum thrust may create a strong nose-up pitching moment if airspeed is low.
5	**Retract speed brakes/spoilers.** Rationale: This will improve lift and stall margin.
6	**Return to the desired flightpath.** Rationale: Apply gentle action for recovery to avoid secondary stalls then return to desired flightpath.

* Abbreviated here for brevity

How to achieve a stall recovery?

- In a high-stress/workload environment, recalling the template is difficult
- FAA template does not specify:
  - – Pitch down target
  - – Airspeed to begin pitching up
  - – Pitch up rate, without causing secondary stall
- Issues can be solved by guidance algorithms
  - – Using flight dynamics (physics) to compute the missing, scenario dependent information

Stefan Schuet, et al., "Stall Recovery Guidance Using Fast Model Predictive Control",
AIAA Guidance, Navigation, and Control Conference, AIAA SciTech Forum.

Predictive Model ($\alpha < \alpha_{stall}$)

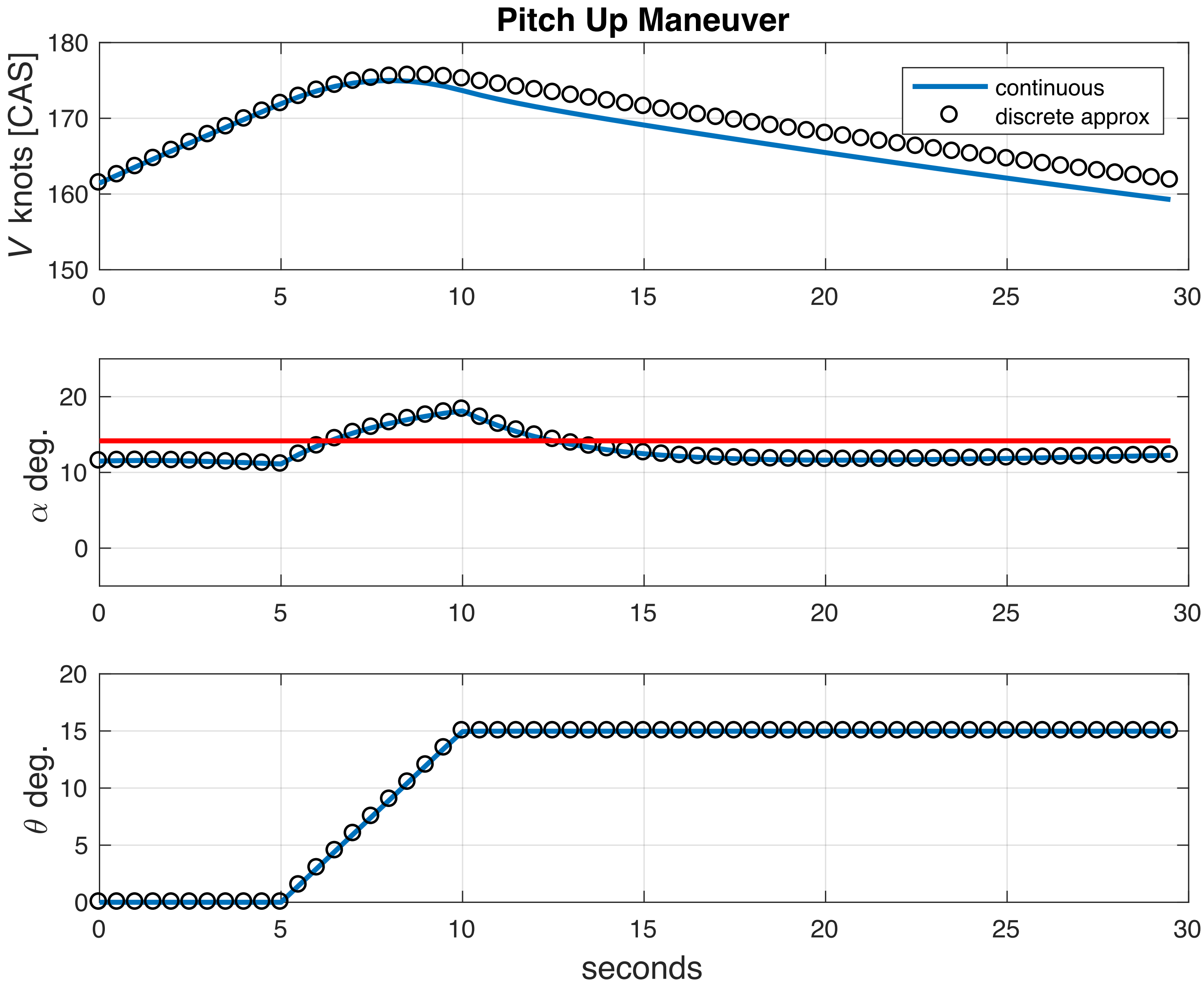
$$\dot{V} = -\frac{SV^2\rho}{2m}\left(C_{D0} + C_{D\alpha}\alpha + C_{D\alpha^2}\alpha^2\right) + \frac{T}{m}\cos(\alpha)\cos(\beta)$$
$$+ g\sin(\alpha)\cos(\beta)\cos(\phi)\cos(\theta)$$
$$+ g\sin(\beta)\sin(\phi)\cos(\theta) - g\sin(\theta)\cos(\alpha)\cos(\beta)$$

$$\dot{\alpha} = -\frac{SV\rho\left(C_{L0} + C_{L\alpha}\alpha\right)}{2m\cos(\beta)} - \frac{T\sin(\alpha)}{Vm\cos(\beta)}$$
$$+ \frac{1}{\cos(\phi)}\left[k_\theta u + r\sin(\phi)\right]$$
$$- \left[p\cos(\alpha) + r\sin(\alpha)\right]\tan(\beta)$$
$$+ \frac{g}{V\cos(\beta)}\left[\sin(\alpha)\sin(\theta) + \cos(\alpha)\cos(\phi)\cos(\theta)\right]$$

$$\dot{\theta} = k_\theta u$$

Guidance drives pitch rate

A Greedy Pitch-Up Maneuver



Optimal Control Formulation

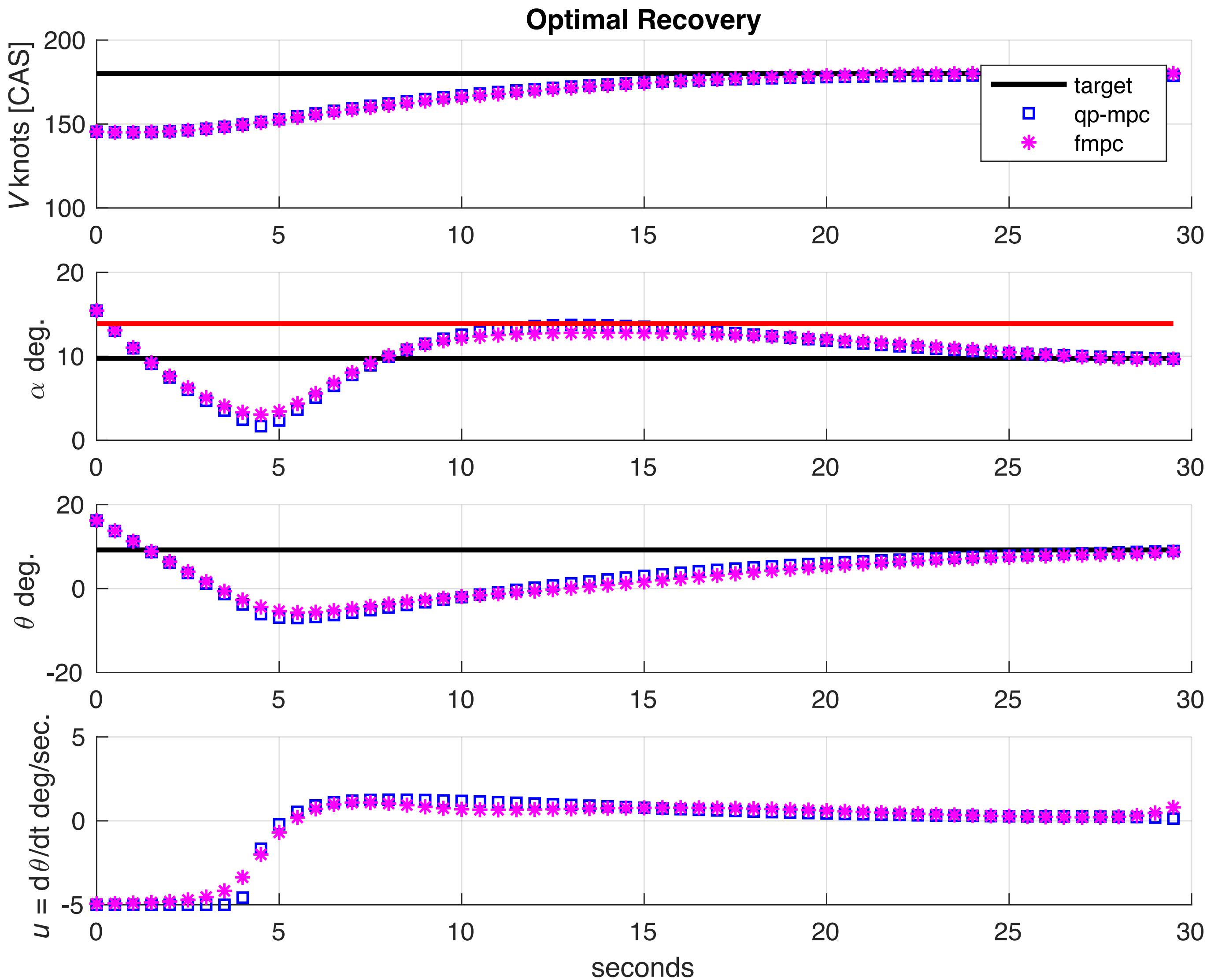
Given the recovery target ($V_{\mathrm{T}}, \alpha_{\mathrm{T}}, \theta_{\mathrm{T}} = \alpha_{\mathrm{T}} + \gamma_{\mathrm{T}}$), and weights $w_V, w_\alpha, w_\theta \geq 0$,

$$
\begin{aligned}
\text{minimize} \quad & \sum_{k=1}^{N} w_V (V_k - V_{\mathrm{T}})^2 + w_\alpha (\alpha_k - \alpha_{\mathrm{T}})^2 + w_\theta (\theta_k - \theta_{\mathrm{T}})^2 \\
& \quad + w_u \sum_{k=0}^{N-1} u(k)^2 \\
\text{subject to} \quad & V_{\min} \leq V_k \leq V_{\max}, \quad \alpha_{\min} \leq \alpha_k \leq \alpha_{\max} \\
& \theta_{\min} \leq \theta_k \leq \theta_{\max}, \quad u_{\min} \leq u(k) \leq u_{\max} \\
& \text{linear dynamics between } V, \alpha, \theta, \text{ and } u \text{ for all } k
\end{aligned}
$$

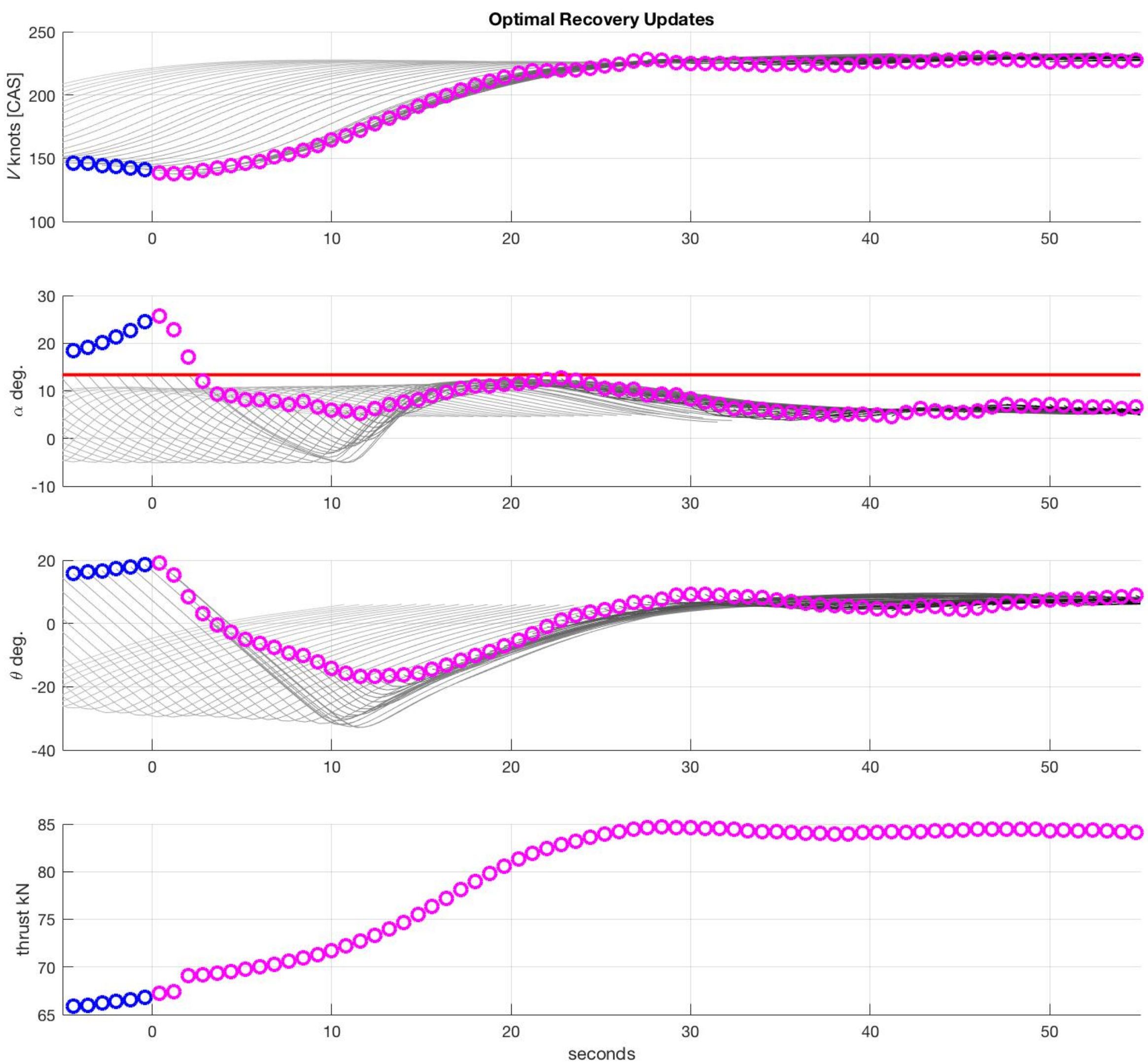
with respect to the **guidance** $u(k)$ for $k = 0, 1, 2, \ldots, N-1$.

Yang Wang and Stephen Boyd, "Fast model predictive control using online optimization," Control Systems Technology, IEEE Transactions on, vol. 18, pp. 267–278, March 2010.

Optimal Pitch Recovery



Recovery Updates with Pilot Flying



Each recovery trajectory is just a plan.

Pilot may not follow it exactly

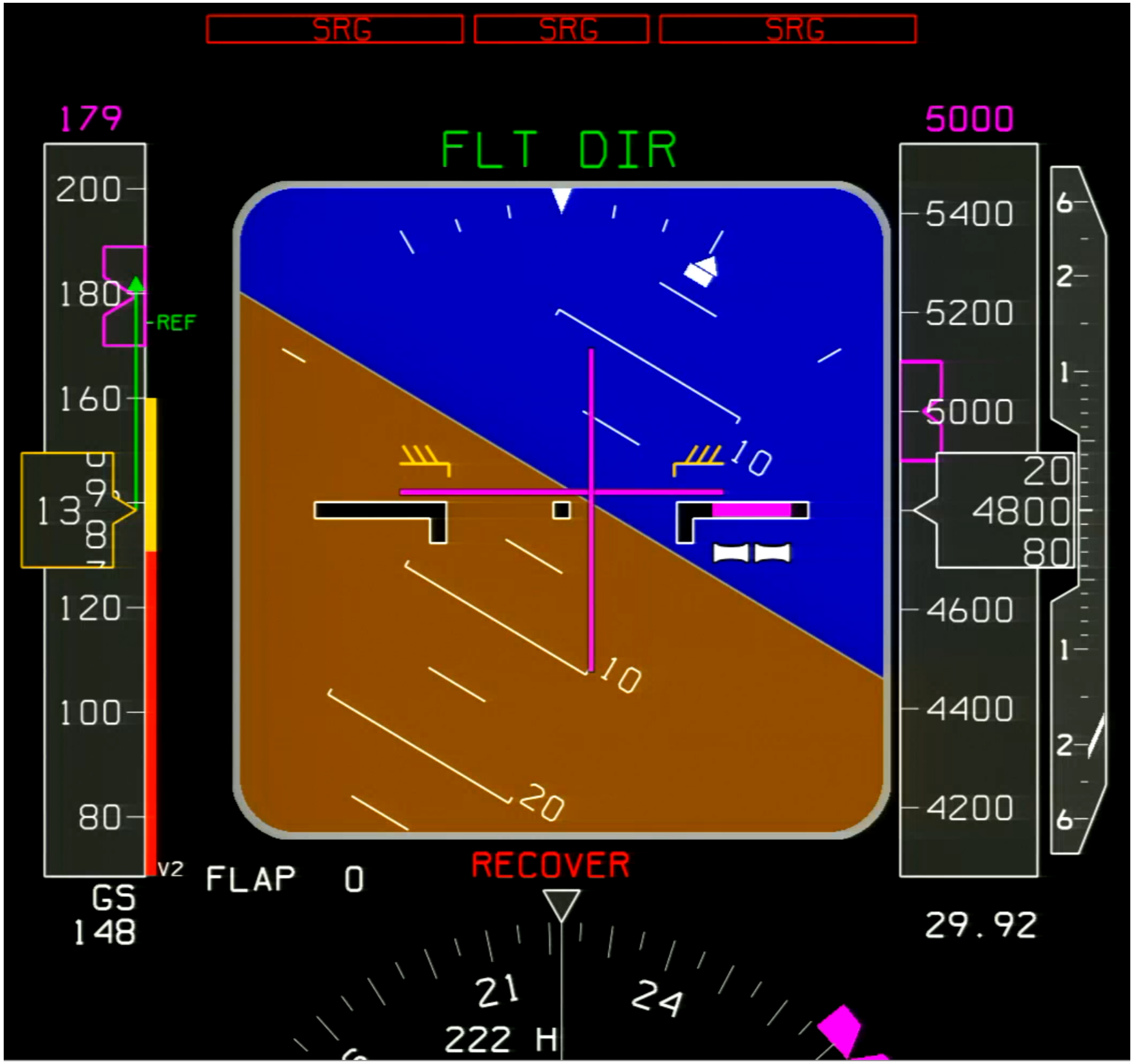
- Doesn't want to
- Not paying attention
- Just doesn't track it well

That's ok, optimal guidance is continuously updated at 50Hz from current aircraft info.

Thrust Guidance

- Recovery requires increasing kinetic energy (KE)
  - Can only get KE from altitude or fuel
  - So save altitude by applying max thrust ASAP
  - *Reducing AoA is always the priority*
- Pitfall: excess nose-up stabilizer trim can cause uncontrollable pitch up moment at full thrust
- Propose use of pitching moment coefficients to determine elevator limited max thrust
  - Requires engine thrust estimate (from look-up table)
  - Just a first stab at a tough problem

Guidance Display



Evaluation Roadmap

Sept. 2019 — Technology transition demo

Mar. 2018 — AIME 2

Apr. 2017 — SRG

Jan. 2016 — Automation and Information Management Experiment (AIME) – 11 crews, 220 flights
http://goo.gl/Jl7tJE, and analysis at DASC 2016, and SciTech 2016

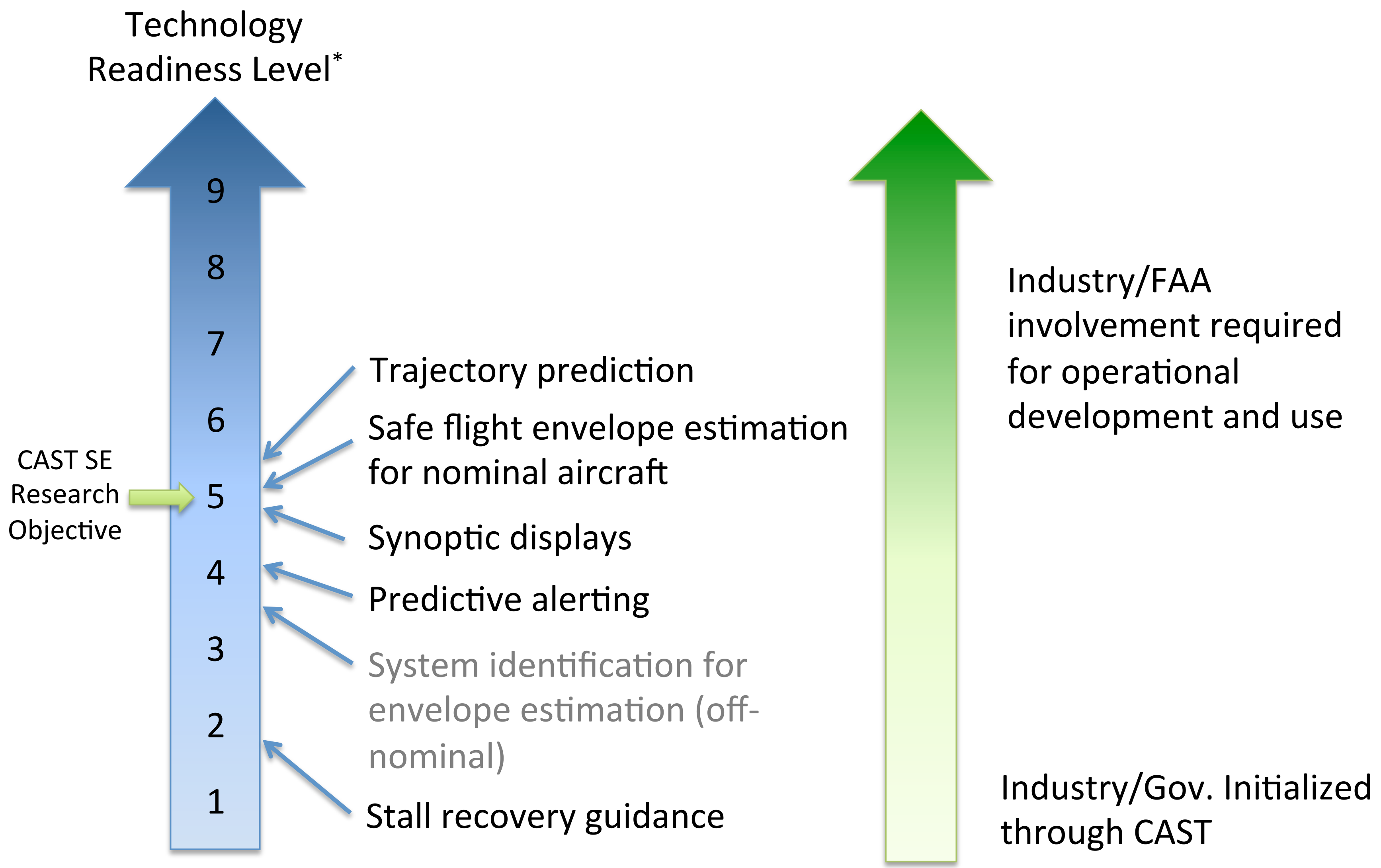
Aug. 2014 — Tactical Flight Management System with Maneuvering Envelope (TFMS-ME) Experiment – 10 crews, 80 flights
https://goo.gl/5FYhvv

Evaluation Objectives

- Development and Demonstration
  - Raise the TRL for new technology via testing and demo in a high-fidelity flight sim environment (e.g. confirm performance across span of targeted conditions)
  - **Study the effects of growing automation and information complexity**
- Evaluate the usability and acceptability of new technology concepts
  - Is project on correct path, or need a change of direction?
- Discovery ("learn by doing")
  - Design characteristics requiring refinement for future studies
  - Unknown unknowns related to state awareness and prediction
- Advance test infrastructure capability for future experiments
  - Evaluate the use of the eye-tracking system and physio measurement system for potential to validate design effectiveness, and to detect attention issues
  - Establish confidence in test platform performance given new modifications
  - Identify gaps and capabilities to be improved for subsequent studies

S. D. Young, et al., Evaluating technologies for improved airplane state awareness and prediction. In AIAA Infotech @ Aerospace, number AIAA 2016-2043. American Institute of Aeronautics and Astronautics, January 2016.

Current Tech. Readiness Levels



* not including operational readiness

Conclusion

- CAST motivated research objectives

- Looked at some technology interventions that may achieve these Safety Enhancement objectives
  - Now at various readiness levels
  - By-product: A set of scenarios that can induce/expose loss of state awareness
  - Core technology maturation for other applications

- Looking for increased feedback and interaction as technologies are matured
  - Email: stefan.r.schuet@nasa.gov; steven.d.young@nasa.gov
  - Software licensing
  - Space Act Agreements
  - NASA Research Announcements

- More info:
  - https://ti.arc.nasa.gov/tech/asr/aces/tfmsme/

Papers

S. D. Young, M. U. D. Haag, T. Daniels, E. Evans, K. H. Shish, S. Schuet, T. Etherington, and D. Kiggins. Evaluating technologies for improved airplane state awareness and prediction. In AIAA Infotech @ Aerospace, number AIAA 2016-2043. American Institute of Aeronautics and Astronautics, January 2016.

V. Stepanyan, K. S. Krishnakumar, J. Kaneshige, and D. M. Acosta. Stall Recovery Guidance Algorithms Based on Constrained Control Approaches. Number AIAA 2016-0878. American Institute of Aeronautics and Astronautics, January 2016.

T. Lombaerts, S. Schuet, D. Acosta, J. Kaneshige, Advances in Aerospace Guidance, Navigation, and Control chapter "On-Line Safe Flight Envelope Determination for Impaired Aircraft." Springer Verlag, April 2015.

T. Lombaerts, S. Schuet, D. M. Acosta, J. Kaneshige, K. H. Shish, L. Martin. Piloted simulator evaluation of maneuvering envelope information for flight crew awareness. In AIAA Guidance, Navigation, and Control Conference. American Institute of Aeronautics and Astronautics, January 2015.

K. H. Shish, J. Kaneshige, D. M. Acosta, S. Schuet, T. Lombaerts, L. Martin, and A. N. Madavan. Trajectory prediction and alerting for aircraft mode and energy state awareness. In AIAA Infotech @ Aerospace. American Institute of Aeronautics and Astronautics, January 2015.

S. Schuet, T. Lombaerts, D. Acosta, K. Wheeler, J. Kaneshige. An Adaptive Nonlinear Aircraft Maneuvering Envelope Estimation Approach for Online Applications (AIAA 2014-0268). In AIAA Guidance, Navigation, and Control Conference, January 2014.

J. Kaneshige, J. Benavides, S. Sharma, L. Martin, R. Panda , M. Steglinski. Implementation of a Trajectory Prediction Function for Trajectory Based Operations (AIAA 2014-2198). In AIAA Atmospheric Flight Mechanics Conference, August 2014.

T. Lombaerts, S. Schuet, K. Wheeler, D. Acosta, and J. Kaneshige. Robust maneuvering envelope estimation based on reachability analysis in an optimal control formulation. In 2nd International Conference on Control and Fault Tolerant Systems. IEEE, October 2013.

T. Lombaerts, S. Schuet, K. Wheeler, D. Acosta, and J. Kaneshige. Safe Maneuvering Envelope Estimation based on a Physical Approach (AIAA 2013-4618). In AIAA Guidance, Navagation, and Control Conference, August 2013.

Papers (cont')

Papers presented at AIAA/IEEE Digital Avionics Systems Conference, Sep 25-29, 2016, Sacramento, CA:

- Flight Simulation Study of Airplane State Awareness and Prediction Technologies, Steven Young, Taumi Daniels, Emory T Evans, Jr and Evan Dill (NASA Langley Research Center); Maarten Uijt de Haag (Ohio University); Tim Etherington (Rockwell Collins)
- Analysis of Pilot Feedback Regarding the Use of State Awareness Technologies During Complex Situations, Emory T Evans, Jr, Steven Young, Taumi Daniels, Yamira Santiago-Espada (NASA Langley Research Center; Tim Etherington (Rockwell Collins)
- Energy State Prediction Methods for Airplane State Awareness, Maarten Uijt de Haag and Pengfei Duan (Ohio University); Tim Etherington (Rockwell Collins)

Kimberlee Shish, et al., "Aircraft Mode and Energy-State Prediction, Assessment, and Alerting," Journal of Guidance, Control, and Dynamics, Publication Date (online): August 26, 2016

Stefan Schuet, et al., "Autonomous Flight Envelope Estimation for Loss-of-Control Prevention," Journal of Guidance, Control, and Dynamics, Publication Date (online): September 15, 2016

Thomas Lombaerts, et al., "Piloted Simulator Evaluation of Safe Flight Envelope Display Indicators for Loss of Control Avoidance," Journal of Guidance, Control, and Dynamics, Publication Date (online): May 24, 2016

Stefan Schuet, et al., "Stall Recovery Guidance Using Fast Model Predictive Control", AIAA Guidance, Navigation, and Control Conference, AIAA SciTech Forum.

Thomas Lombaerts, et al., "Stall Recovery Guidance Using an Energy Based Algorithm", AIAA Guidance, Navigation, and Control Conference, AIAA SciTech Forum,