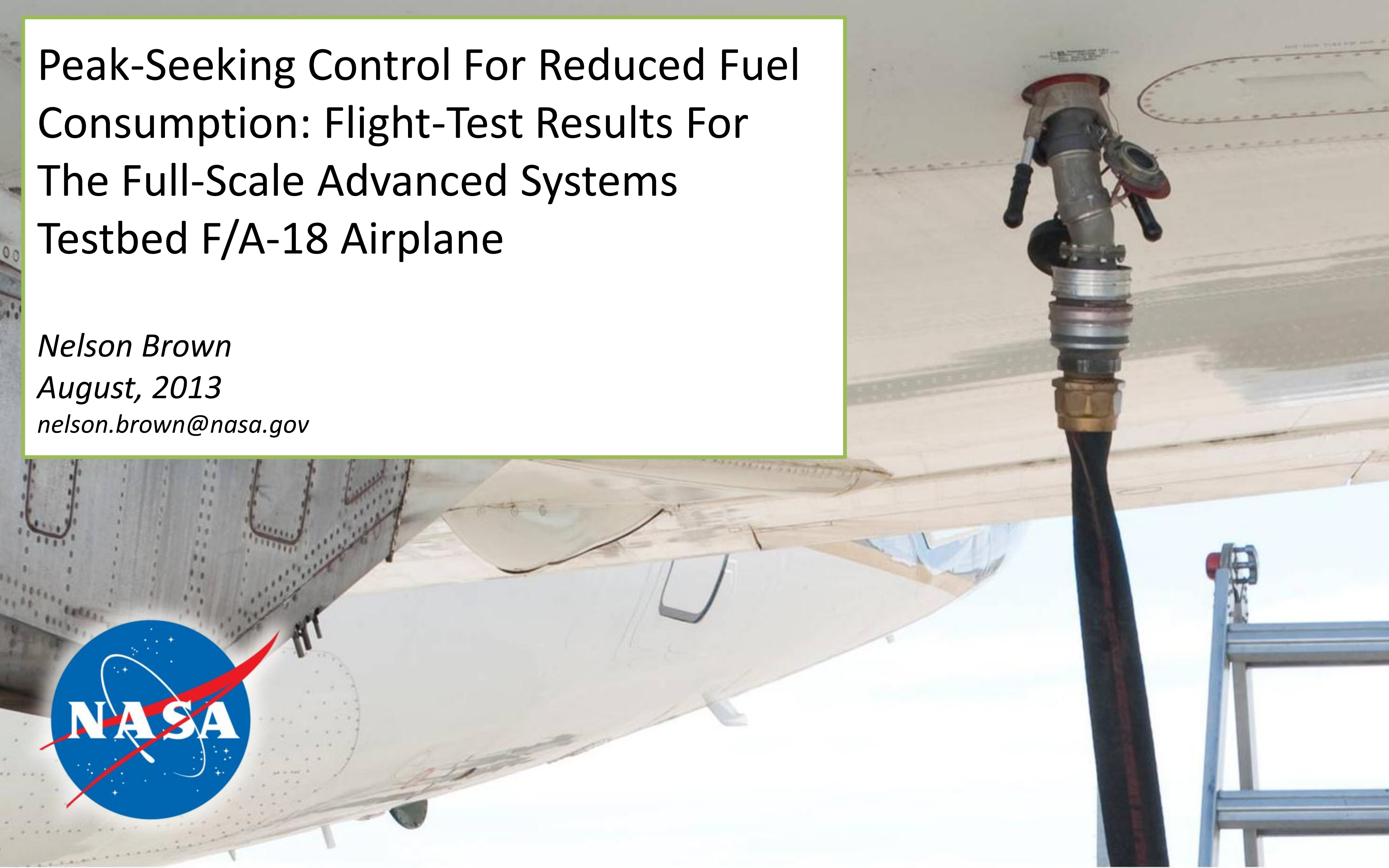
Peak-Seeking Control For Reduced Fuel Consumption: Flight-Test Results For The Full-Scale Advanced Systems Testbed F/A-18 Airplane

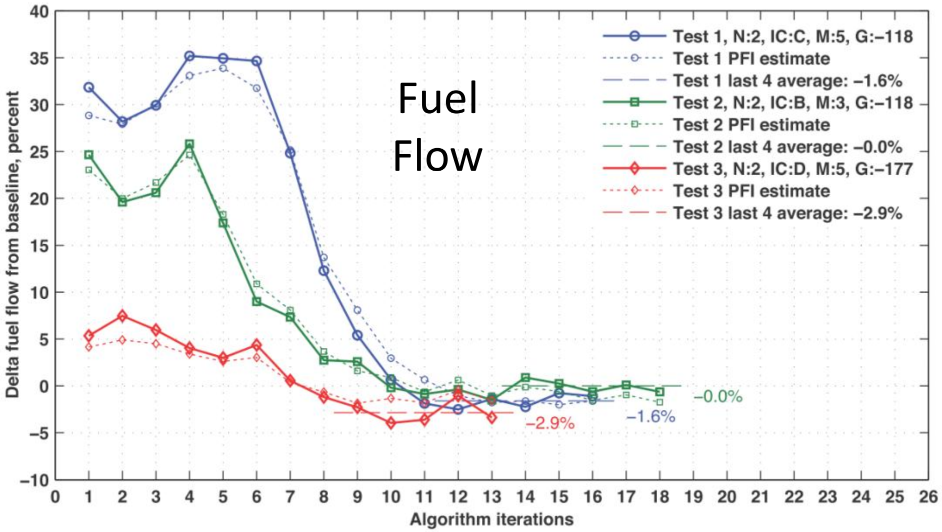
Nelson Brown
August, 2013
nelson.brown@nasa.gov

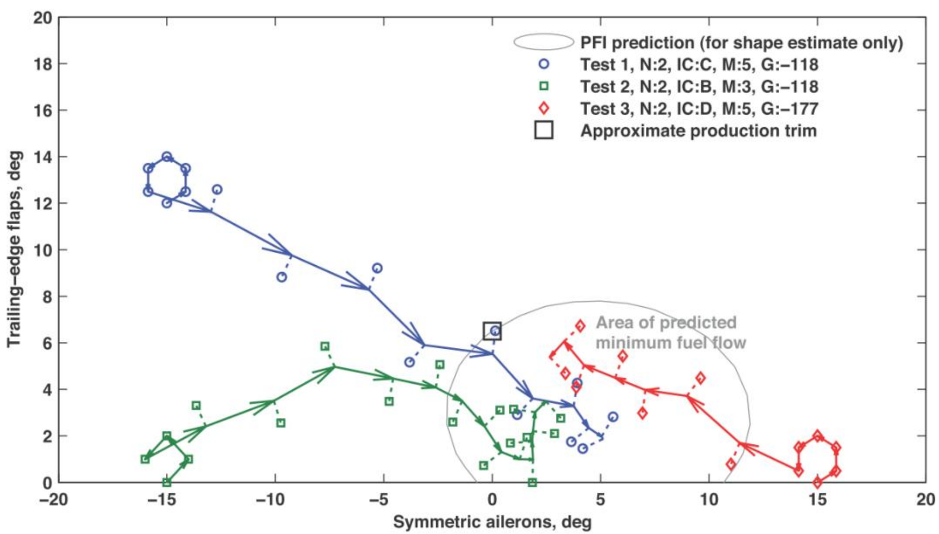


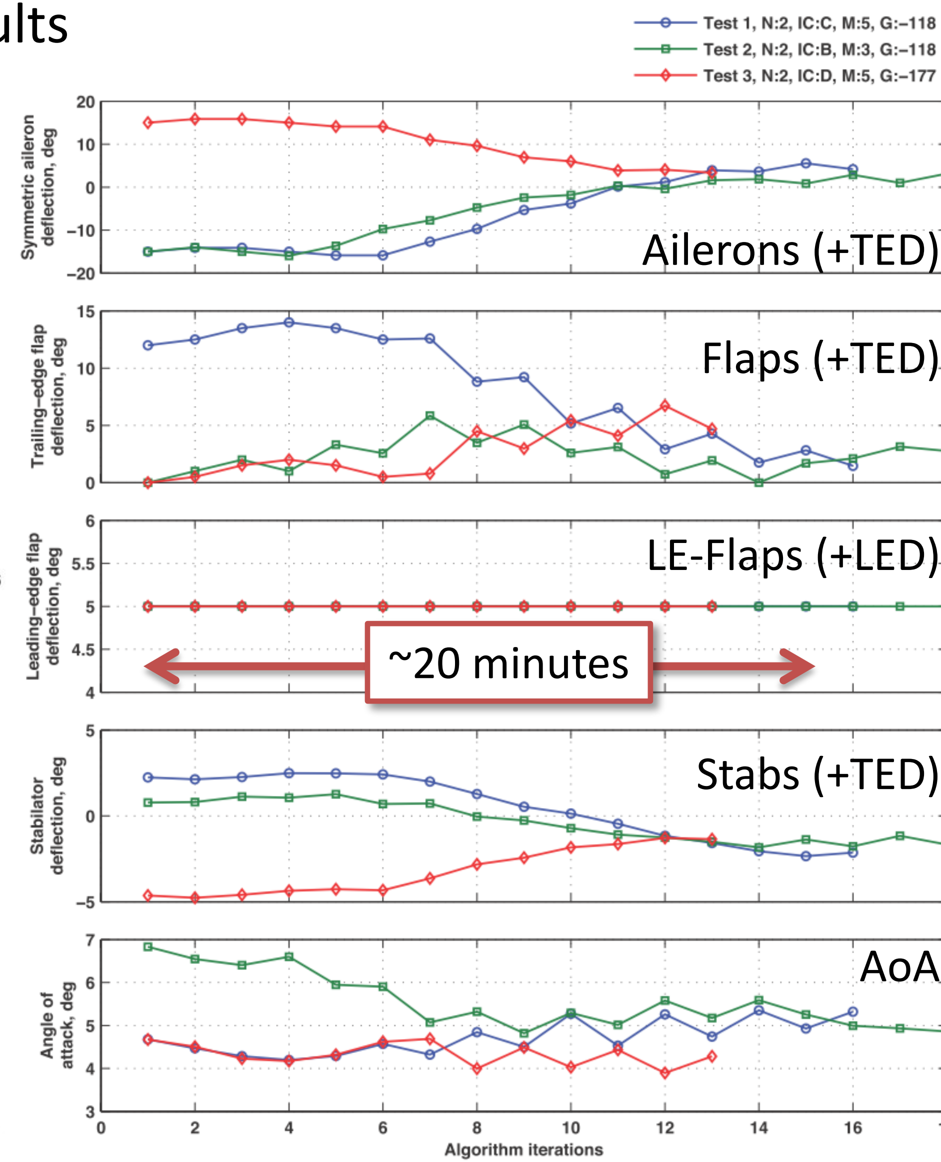
Abstract

A peak-seeking control algorithm for real-time trim optimization for reduced fuel consumption has been developed by researchers at the National Aeronautics and Space Administration (NASA) Dryden Flight Research Center to address the goals of the NASA Environmentally Responsible Aviation project to reduce fuel burn and emissions. The peak-seeking control algorithm is based on a steepest-descent algorithm using a time-varying Kalman filter to estimate the gradient of a performance function of fuel flow versus control surface positions. In real-time operation, deflections of symmetric ailerons, trailing-edge flaps, and leading-edge flaps of an F/A-18 airplane are used for optimization of fuel flow. Results from six research flights are presented herein. The optimization algorithm found a trim configuration that required approximately 3 percent less fuel flow than the baseline trim at the same flight condition. This presentation also focuses on the design of the flight experiment and the practical challenges of conducting the experiment.

Peak-seeking control: Typical flight results







Previous Research

Adaptive Performance Optimization
Patent 5,908,176

Gilyard's L-1011 flight test results in 1999:

"Optimizing the symmetric outboard aileron position realizes a drag reduction of 2-3 drag counts (approximately 1 percent)."

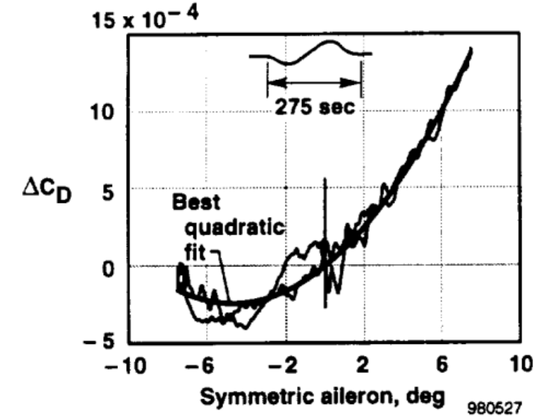
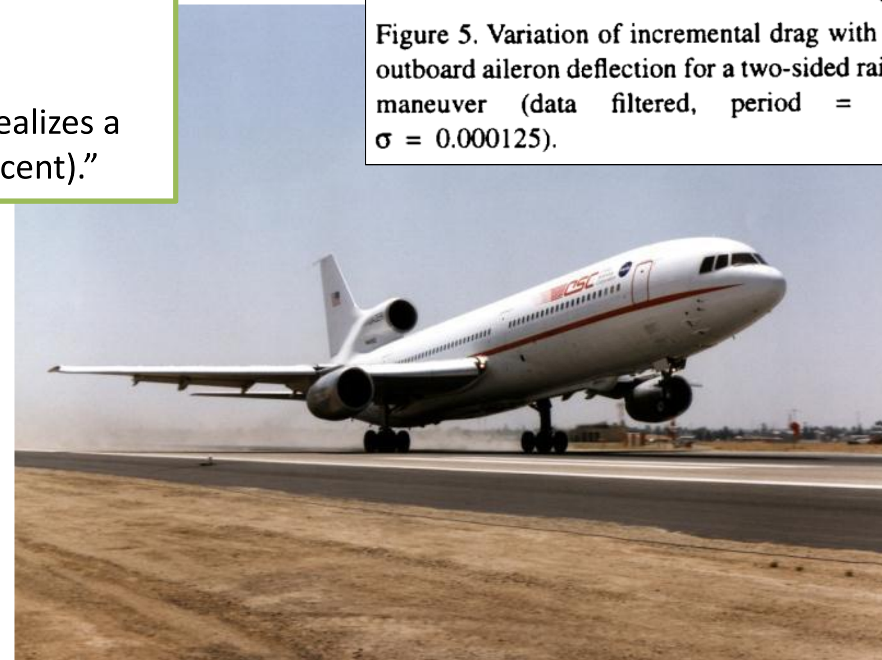


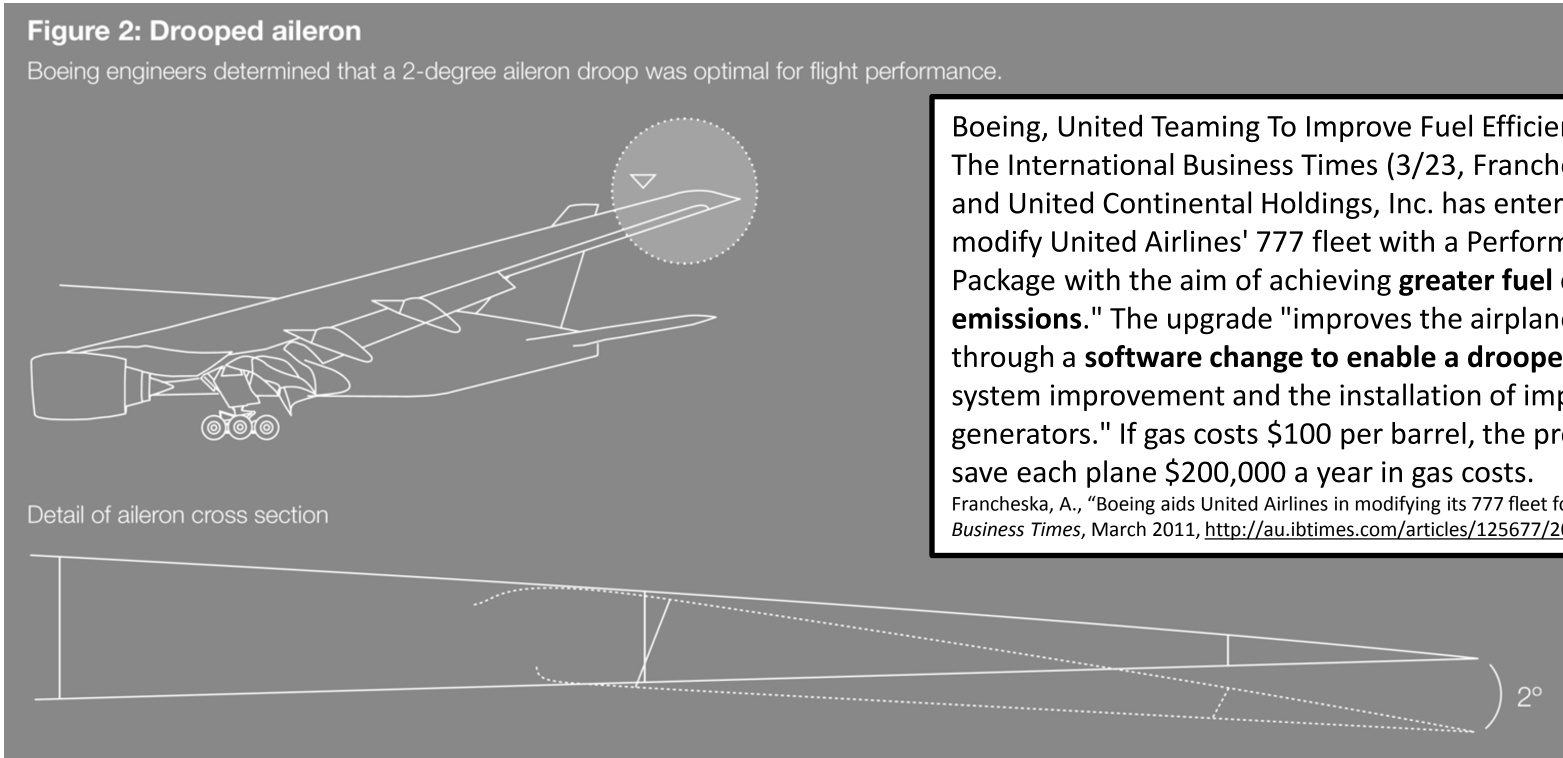
Figure 5. Variation of incremental drag with symmetric outboard aileron deflection for a two-sided raised-cosine maneuver (data filtered, period = 150 sec, σ = 0.000125).



Dryden Flight Research Center EC97-44077-3 Photographed May1997
This modified Lockheed L-1011 TriStar operated by Orbital Sciences Corp. lifts off on its first flight in NASA's Adaptive Performance Optimization study. (NASA/Tony Landis)

Flight Test of an Adaptive Configuration Optimization System for Transport Aircraft
Gilyard, Glenn B.; Georgie, Jennifer; Barnicki, Joseph S.
Dryden Flight Research Center, 1999.
http://hdl.handle.net/2060/19990019435

Performance Improvement Package (PIP) for 777



Boeing, United Teaming To Improve Fuel Efficiency.
The International Business Times (3/23, Francheska) reports, "Boeing and United Continental Holdings, Inc. has entered into an agreement to modify United Airlines' 777 fleet with a Performance Improvement Package with the aim of achieving **greater fuel efficiency and reduced emissions**." The upgrade "improves the airplane's aerodynamics through a **software change to enable a drooped aileron**, a ram air system improvement and the installation of improved wing vortex generators." If gas costs $100 per barrel, the program is expected to save each plane $200,000 a year in gas costs.

Francheska, A., "Boeing aids United Airlines in modifying its 777 fleet for fuel efficiency," *International Business Times*, March 2011, http://au.ibtimes.com/articles/125677/20110323, accessed July 15, 2013.

Delivering Fuel and Emissions Savings for the 777
By Ken Thomson, and E. Terry Schulze
http://www.boeing.com/commercial/aeromagazine/articles/qtr_03_09/pdfs/AERO_Q309_article02.pdf

Boeing Trailing Edge Variable Camber (TEVC) System

TEVC System on 787:

> "The TEVC cleverly articulates the trailing edge of the flaps in various cruise conditions to help reduce drag."

Guy Norris, Aviation Week in 2010

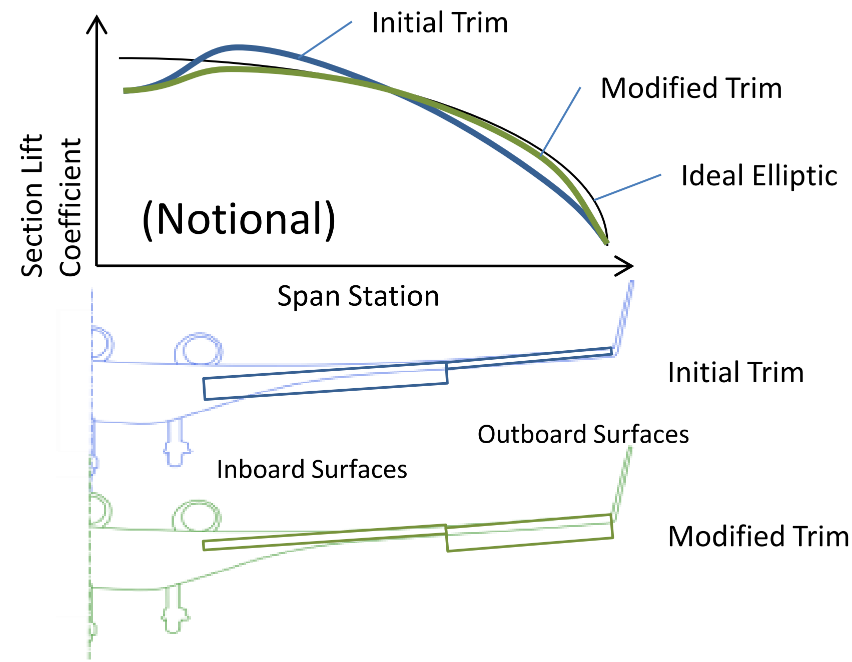
http://www.aviationweek.com/aw/blogs/commercial_aviation/ThingsWithWings/index.jsp?plckController=Blog&plckScript=blogScript&plckElementId=blogDest&plckBlogPage=BlogViewPost&plckPostId=Blog%3A7a78f54e-b3dd-4fa6-ae6e-dff2ffd7bdbbPost%3A57b52637-d9a6-4589-b174-7aece76b0c46

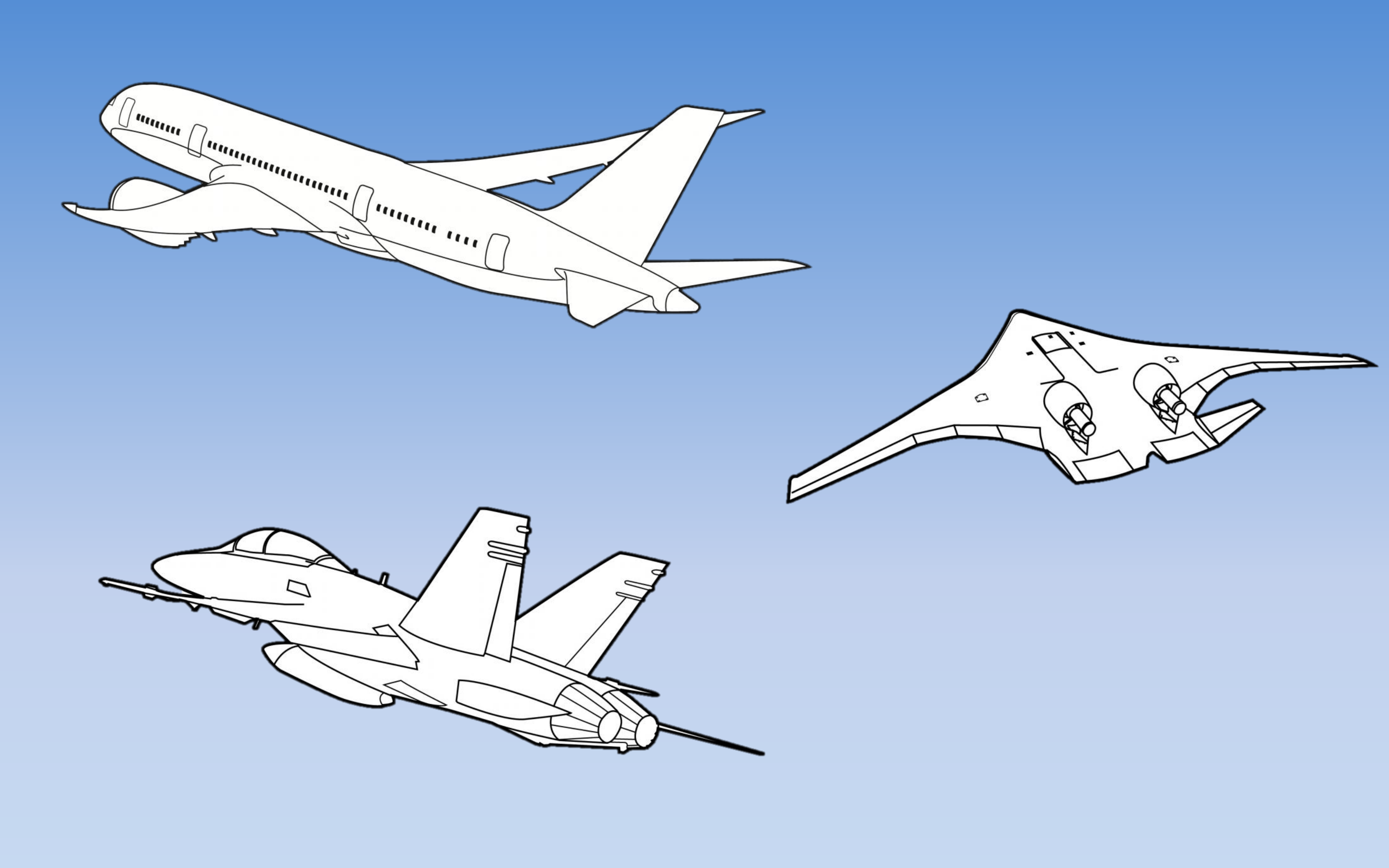
> "…the flight tests also included simulation of the 787's drooped ailerons as well as a drag-reducing feature called the trailing edge variable camber (TEVC) function. Boeing expected that the TEVC could cut cruise drag and save the equivalent of 750 to 1,000 pounds in weight, and took advantage of the all-new wing and flight control surface design. The fully automatic system, which was the first practical commercial application of in-flight variable camber, operated by deflecting the trailing edge flaps in 0.5-degree increments while in cruise. The system could be moved through a 3-degree arc, with the trailing edge being set up and down by as much as 1.5 degrees on either side of a neutral position."

Wagner, M., and Norris, G., *Boeing 787 Dreamliner*, MBI Publishing Company, 2009.

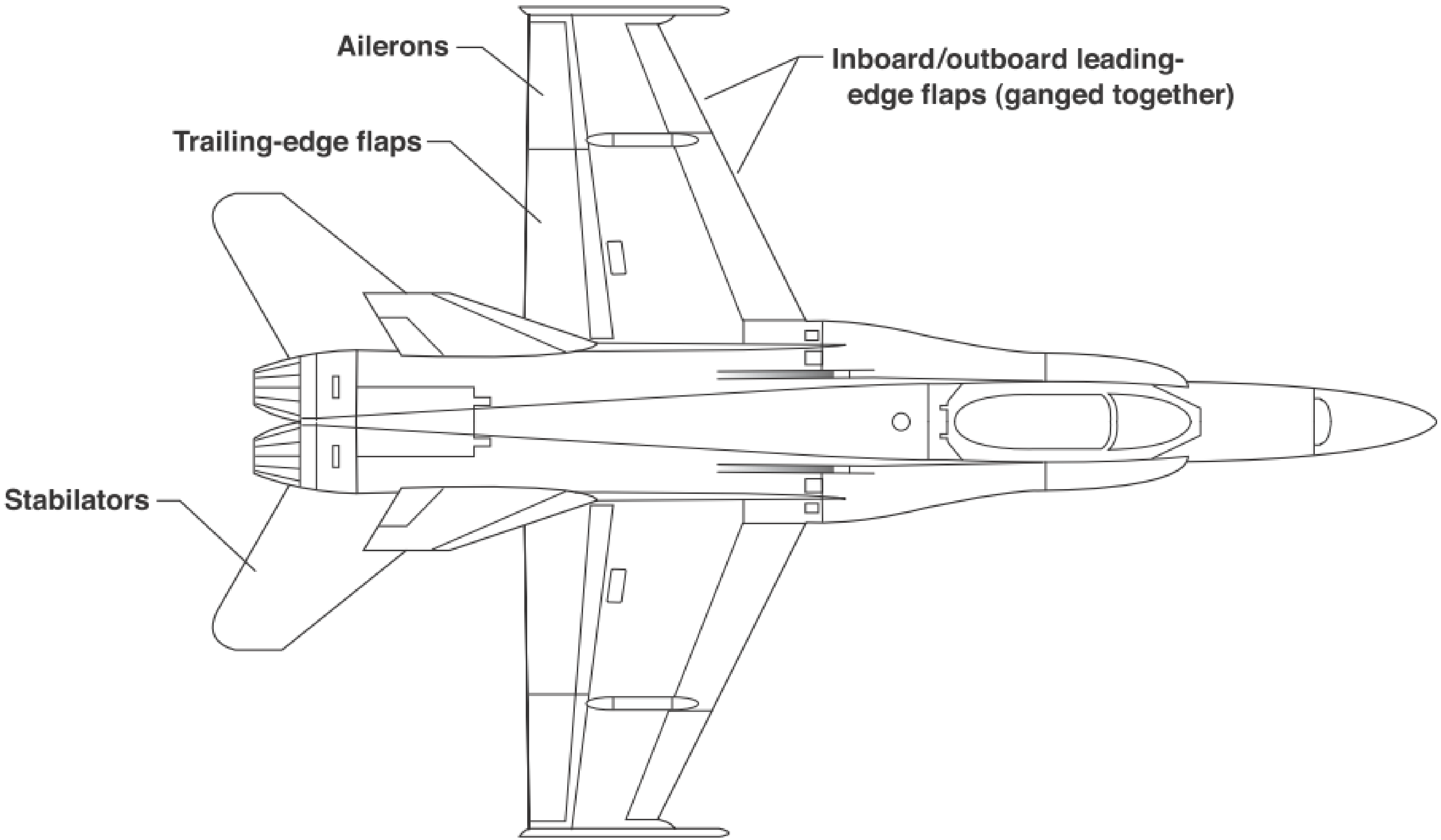
Motivation

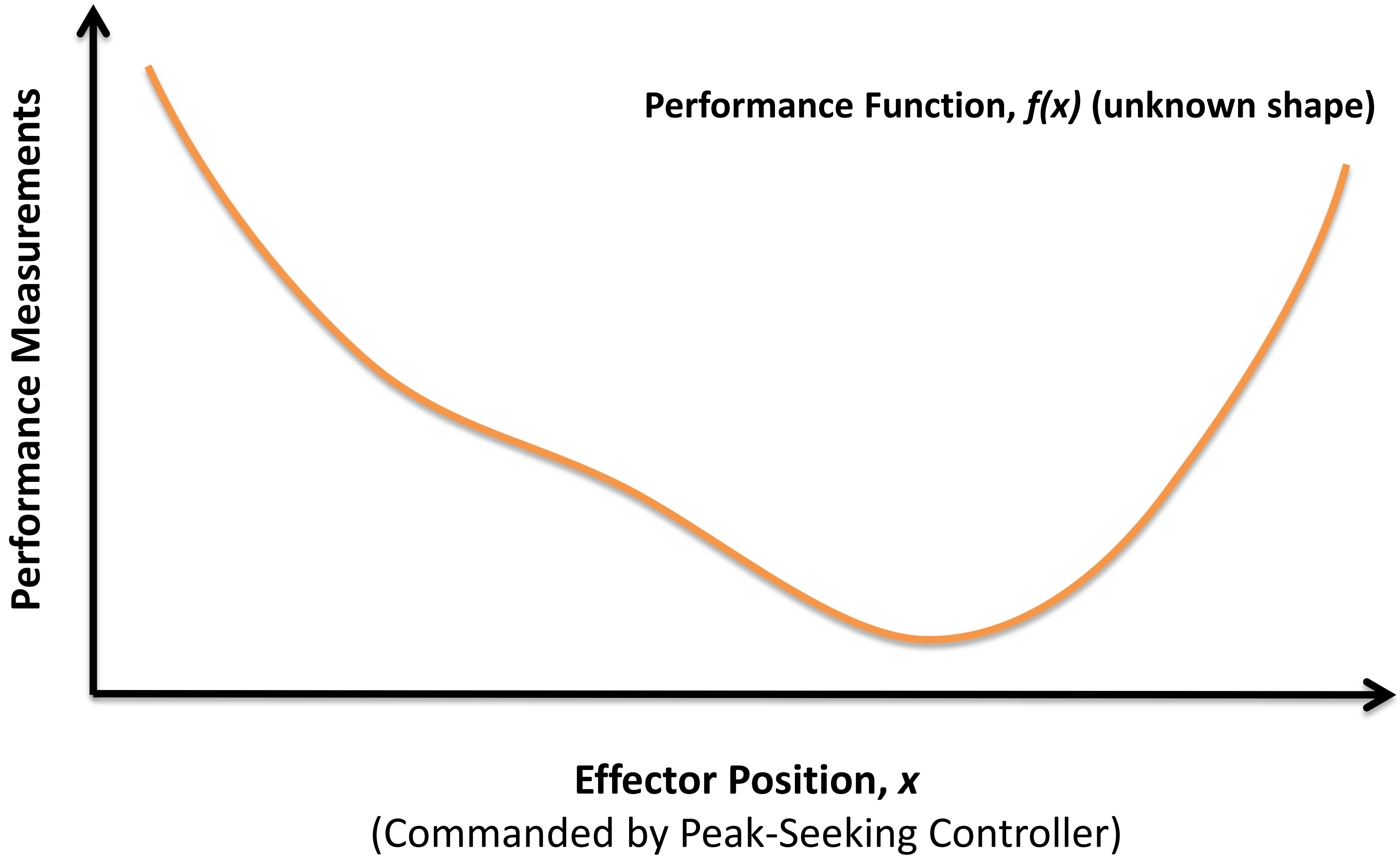
- Multiple longitudinal effectors for trim
  - Traditionally horizontal tail incidence angle or elevator.
  - But also: Symmetric ailerons, flaps, leading-edge devices, thrust vectoring, pump fuel fore/aft for c.g. control, etc.
- Is there an alternative, lower-drag trim solution?
- Can we adjust to variations between:
  - Aircraft?
  - Configurations?
  - Flight conditions?

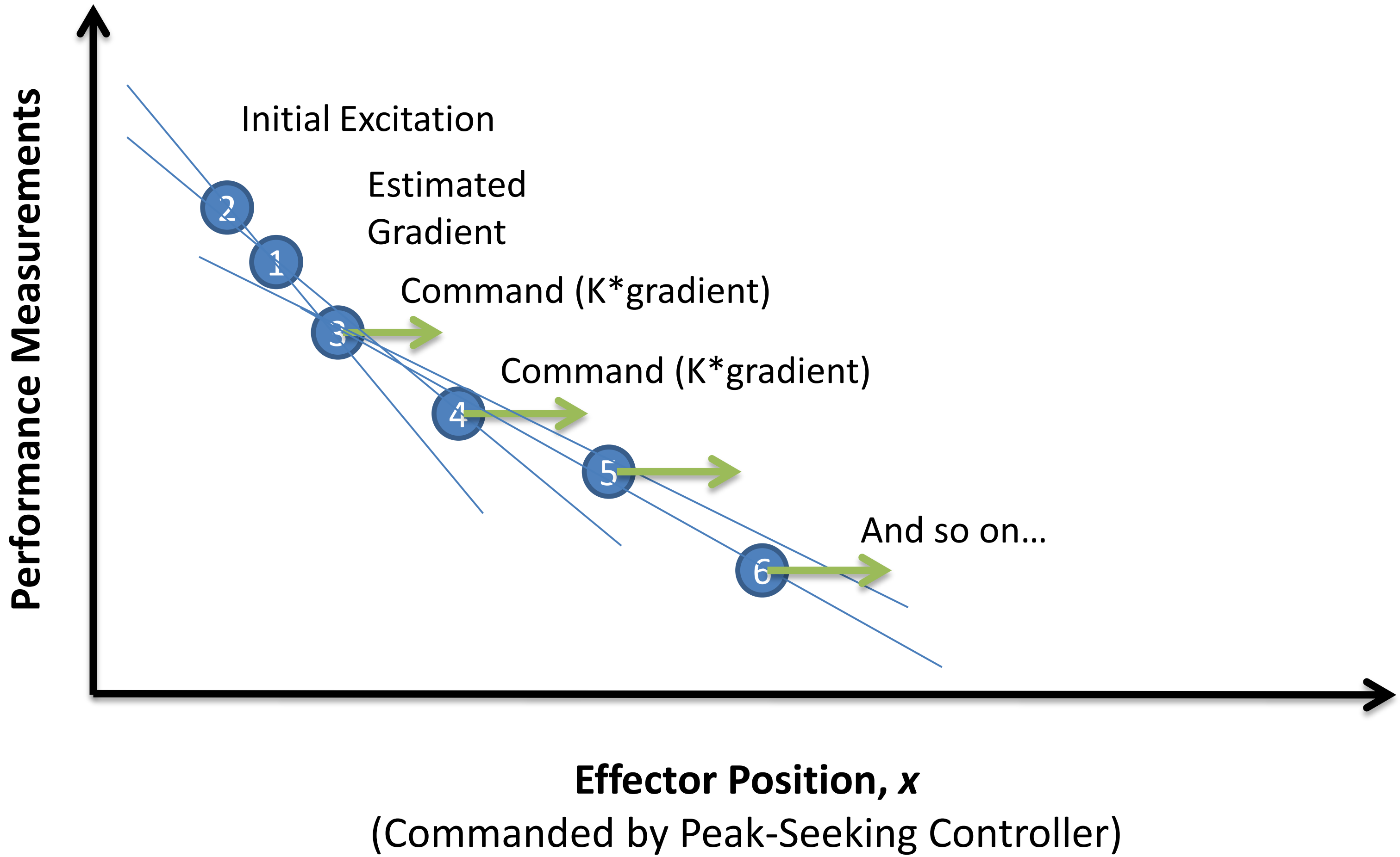




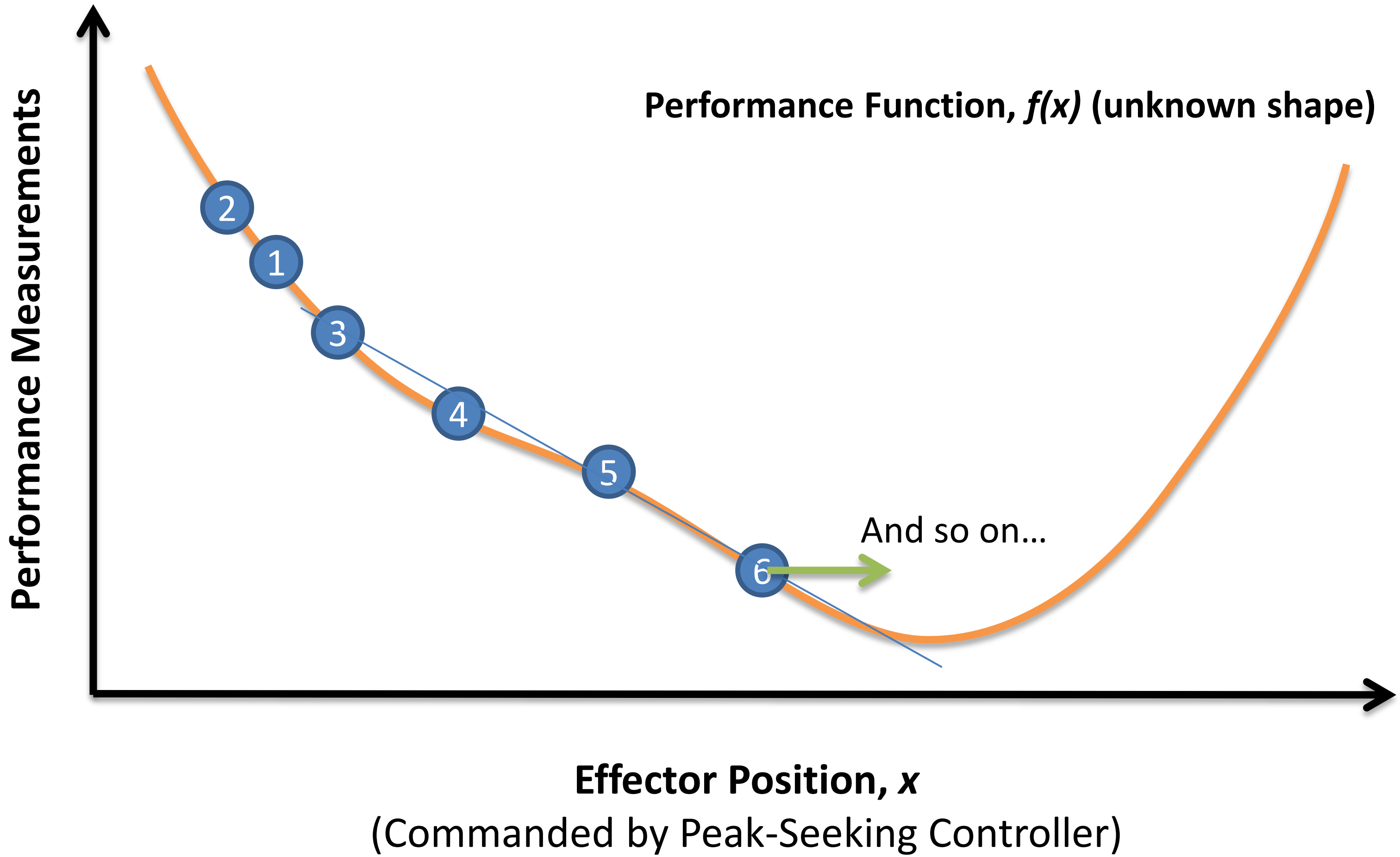
F/A-18 Effectors




Performance Measurements
Performance Function, *f(x)* (unknown shape)
Effector Position, *x*
(Commanded by Peak-Seeking Controller)

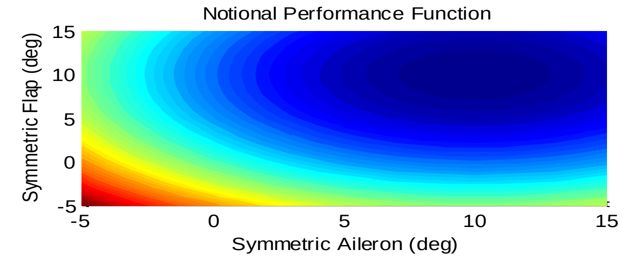


Performance Measurements
Initial Excitation
Estimated
Gradient
Command (K*gradient)
Command (K*gradient)
And so on…
2
1
3
4
5
6
Effector Position, x
(Commanded by Peak-Seeking Controller)

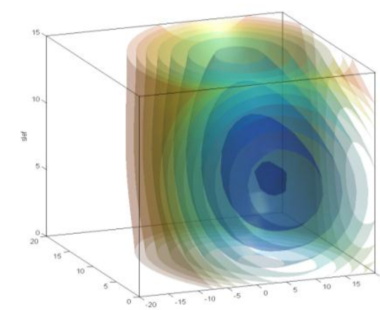

Performance Function, *f(x)* (unknown shape)
Performance Measurements
2
1
3
4
5
6
And so on…
Effector Position, *x*
(Commanded by Peak-Seeking Controller)

Peak-Seeking Control

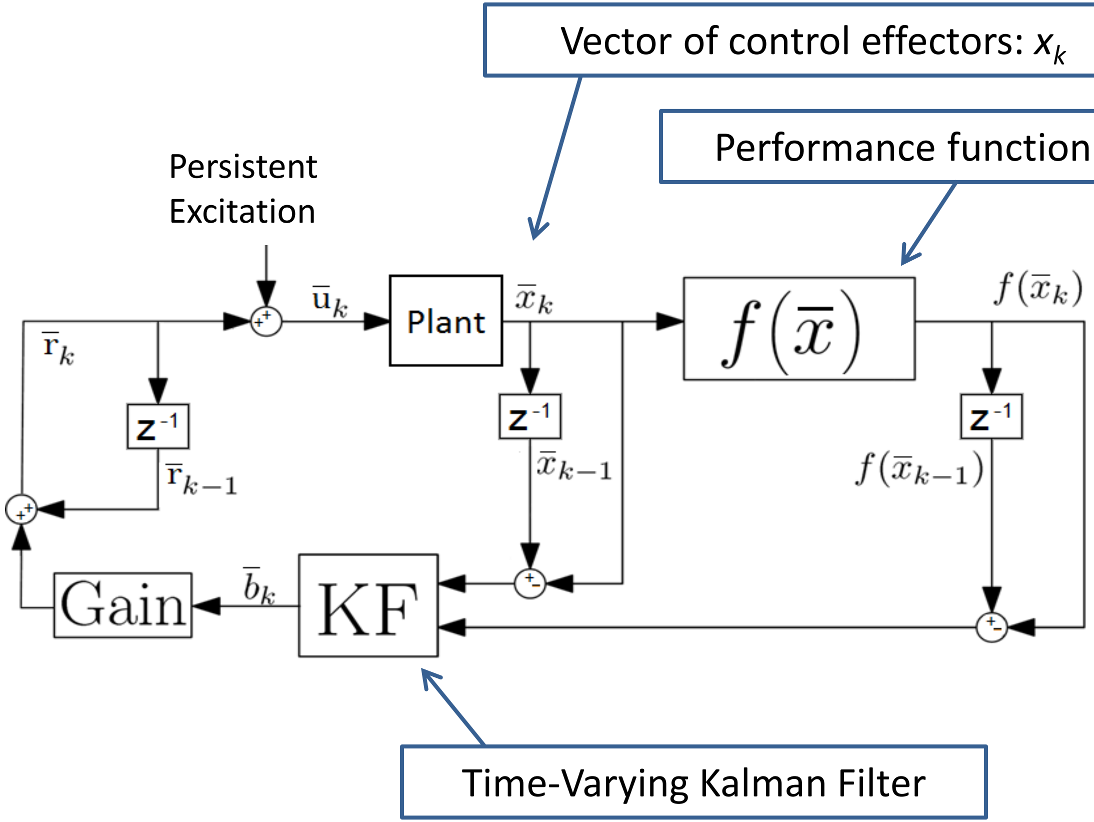
- Given:
  - A performance measurement, fuel flow, that is a function of surface positions
    - The minimum-cost (blue) combination of surface positions (x,y,z) is **unknown**
    - This is called the **Performance Function**
  - Measurements of surface positions and fuel flow are **noisy**.
- Find:
  - Minimum of the performance function, in flight
- Assumptions:
  - Performance function has a single minimum
  - Measureable surface positions and fuel flow
  - Gaussian distributed noise
  - Plant is stable and controllable (inner loop control design treated as separate problem)

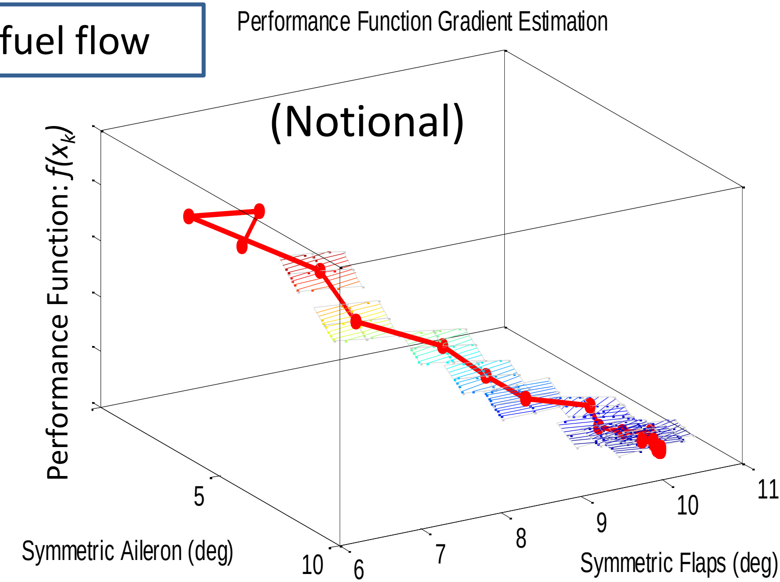


Fuel Flow (color) due to Surface Deflections (x,y)



Fuel Flow (color) due to Surface Deflections (x,y,z)





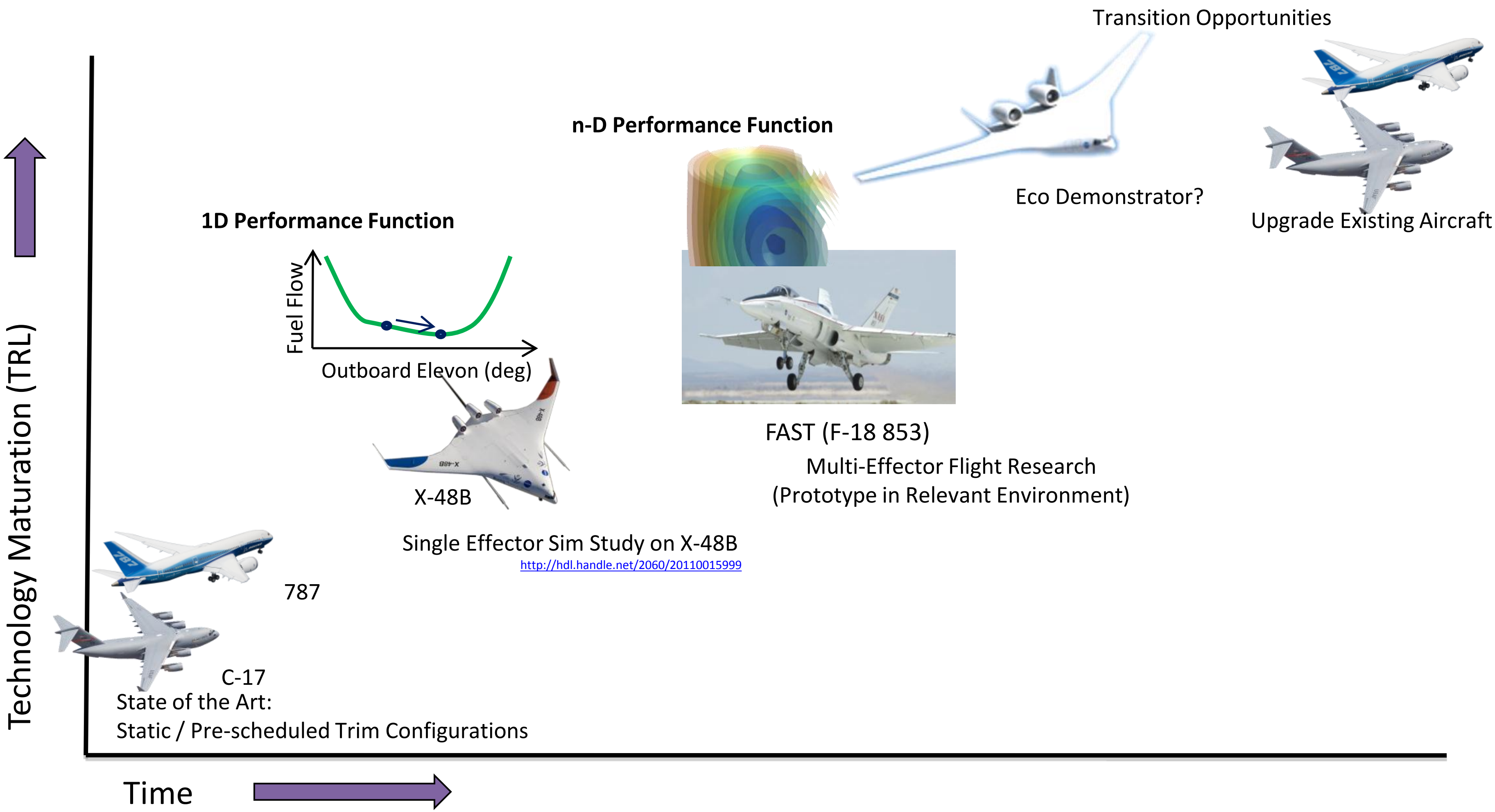
Approach based on work by Ryan and Speyer:

Ryan, J.J. and Speyer, J.L., "Peak-Seeking Control Using Gradient and Hessian Estimates" Proceedings of the 2010 American Control Conference, June 30-July 2, 2010, pp. 611-616.

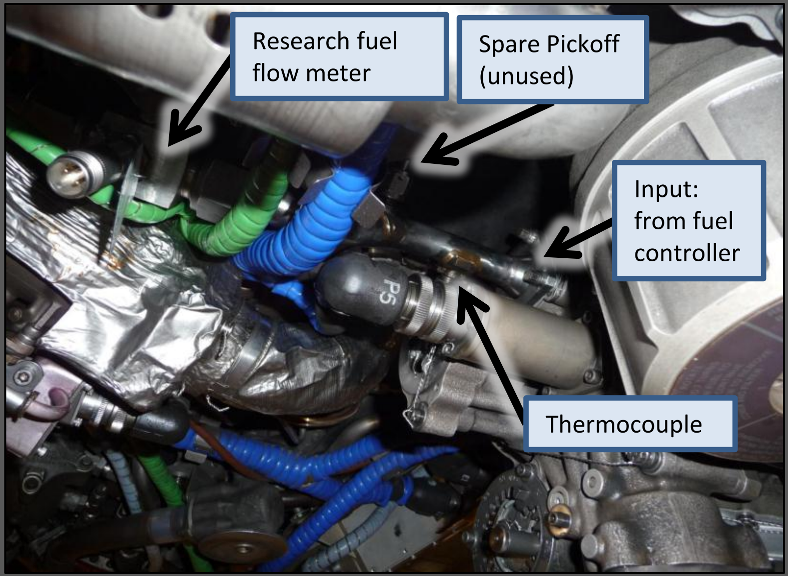
http://hdl.handle.net/2060/20100024511

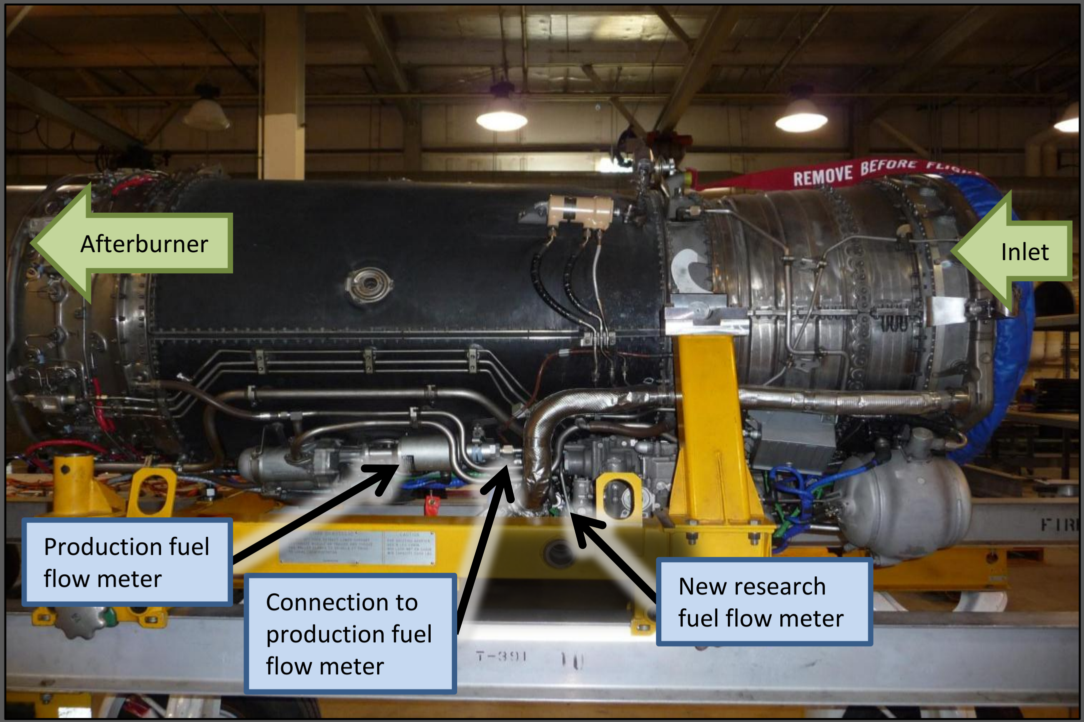
Ryan, J. J., and Speyer, J. L., "Systems and Methods for Peak-Seeking Control," US Patent No. 8,447,443, May 21, 2013.

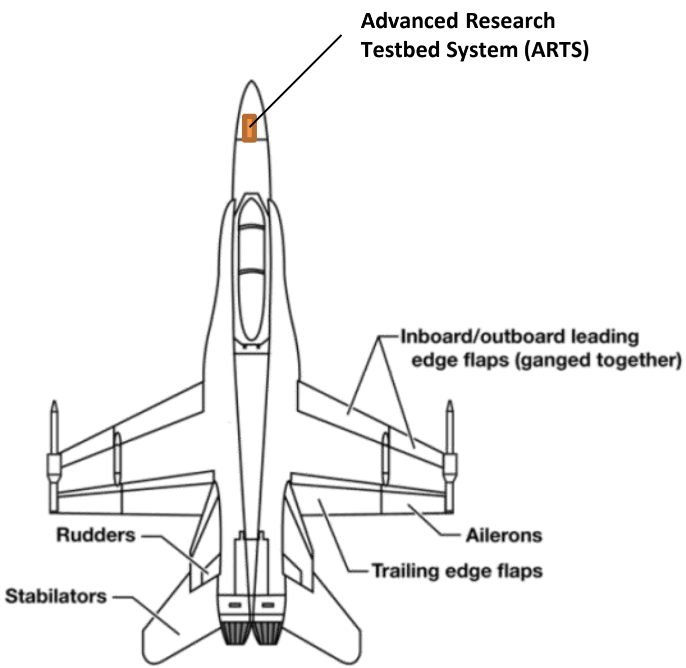
Technology Transition Map

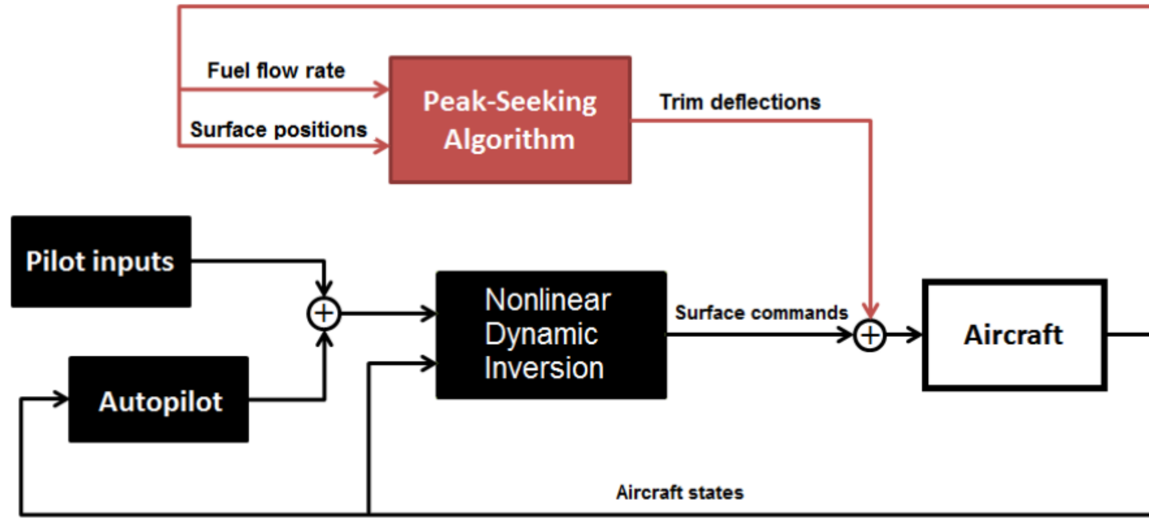


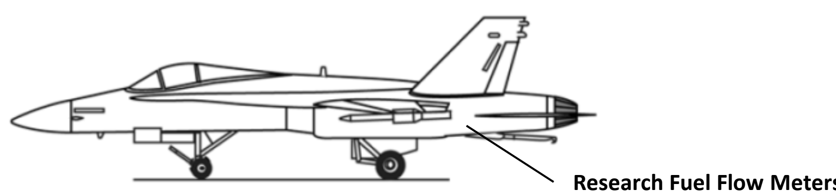

Dryden Flight Research Center
NASA
NASA
853
BOEING


Research fuel flow meter
Spare Pickoff (unused)
Input: from fuel controller
Thermocouple

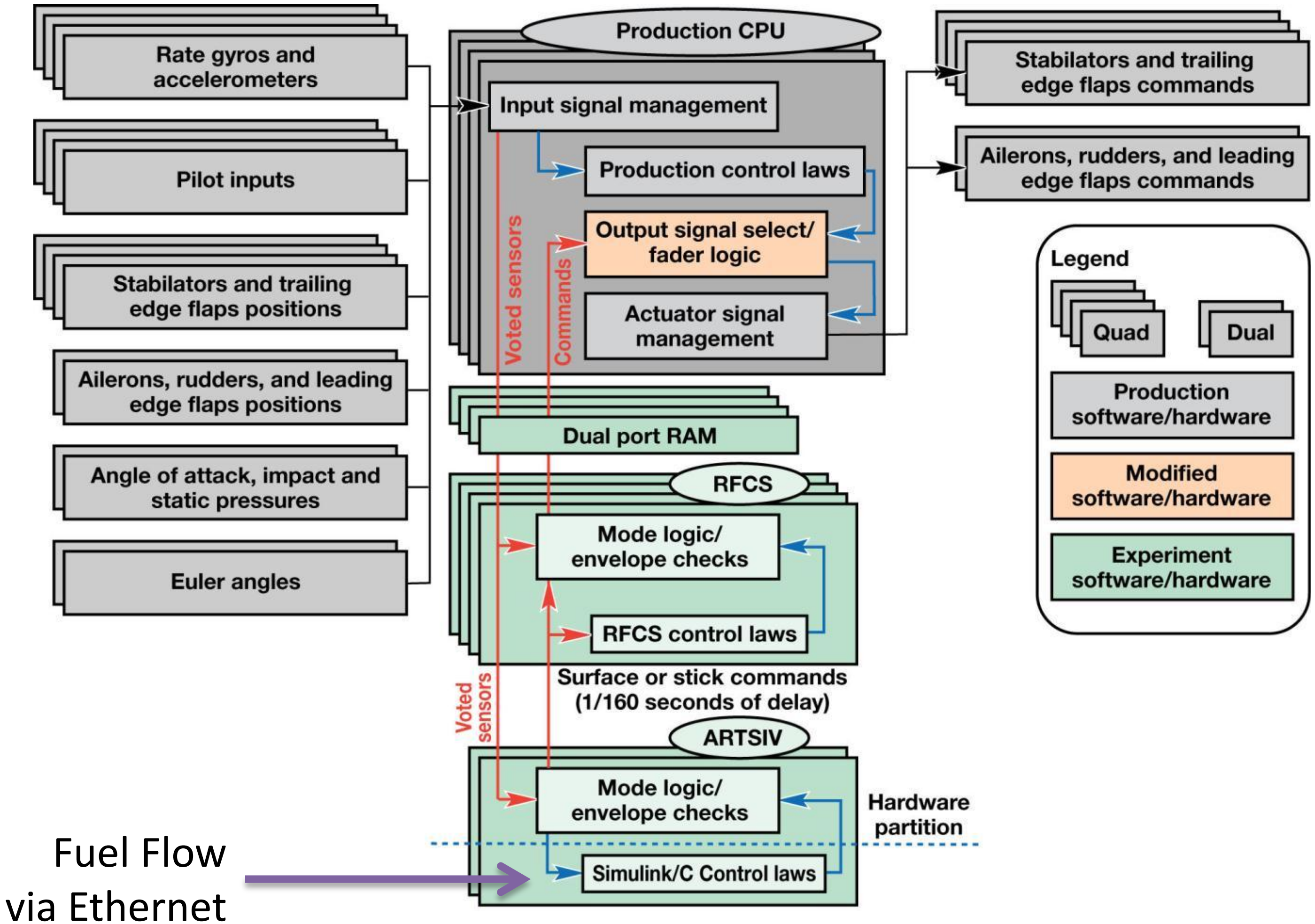

Afterburner
Inlet
Production fuel flow meter
Connection to production fuel flow meter
New research fuel flow meter


Advanced Research
Testbed System (ARTS)
Inboard/outboard leading
edge flaps (ganged together)
Rudders
Ailerons
Trailing edge flaps
Stabilators


Fuel flow rate
Surface positions
Peak-Seeking
Algorithm
Trim deflections
Pilot inputs
Autopilot
Nonlinear
Dynamic
Inversion
Surface commands
Aircraft
Aircraft states

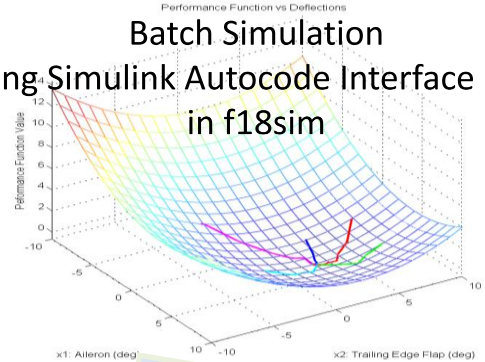

Research Fuel Flow Meters

Full-scale Advanced Systems Testbed (FAST)

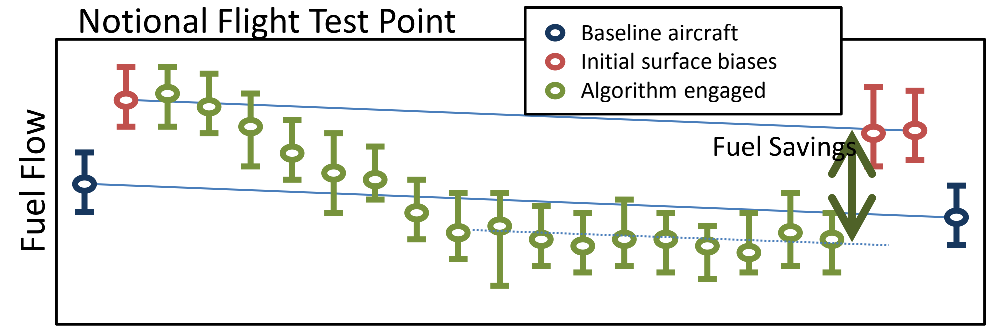


Flight Research Approach

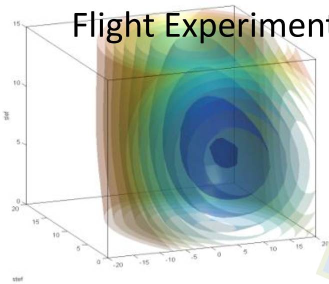
Batch Simulation
using Simulink Autocode Interface (SAI)
in f18sim



Notional Flight Test Point

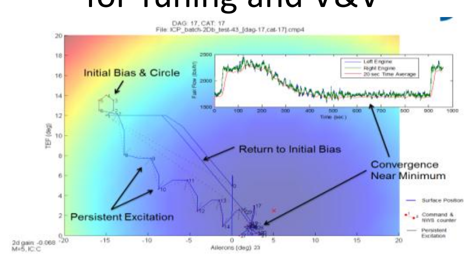


Performance Function Identification
Flight Experiment



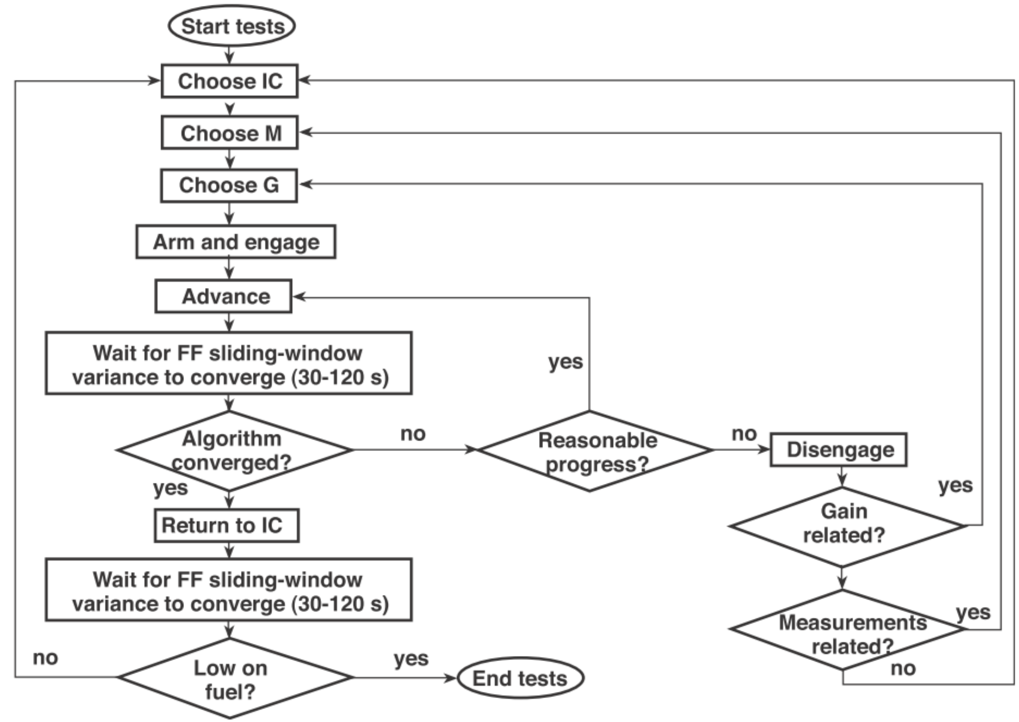
Piloted HIL Simulation
using ARTS

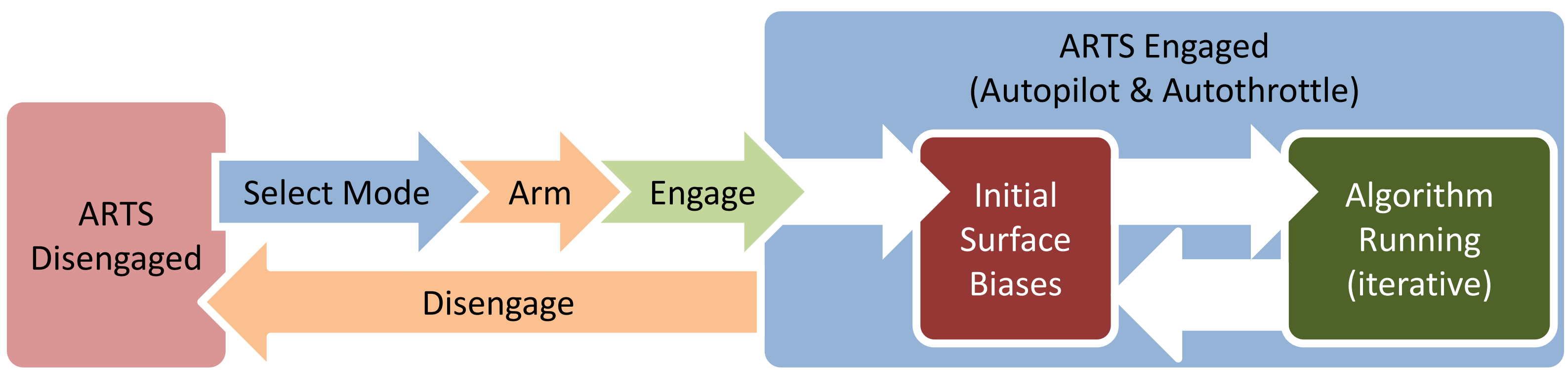
Batch Simulation (SAI)
Using PFI Surface Fit & Noise
for Tuning and V&V



Algorithm-Engaged Initial Flight
Experiment

Test Plan

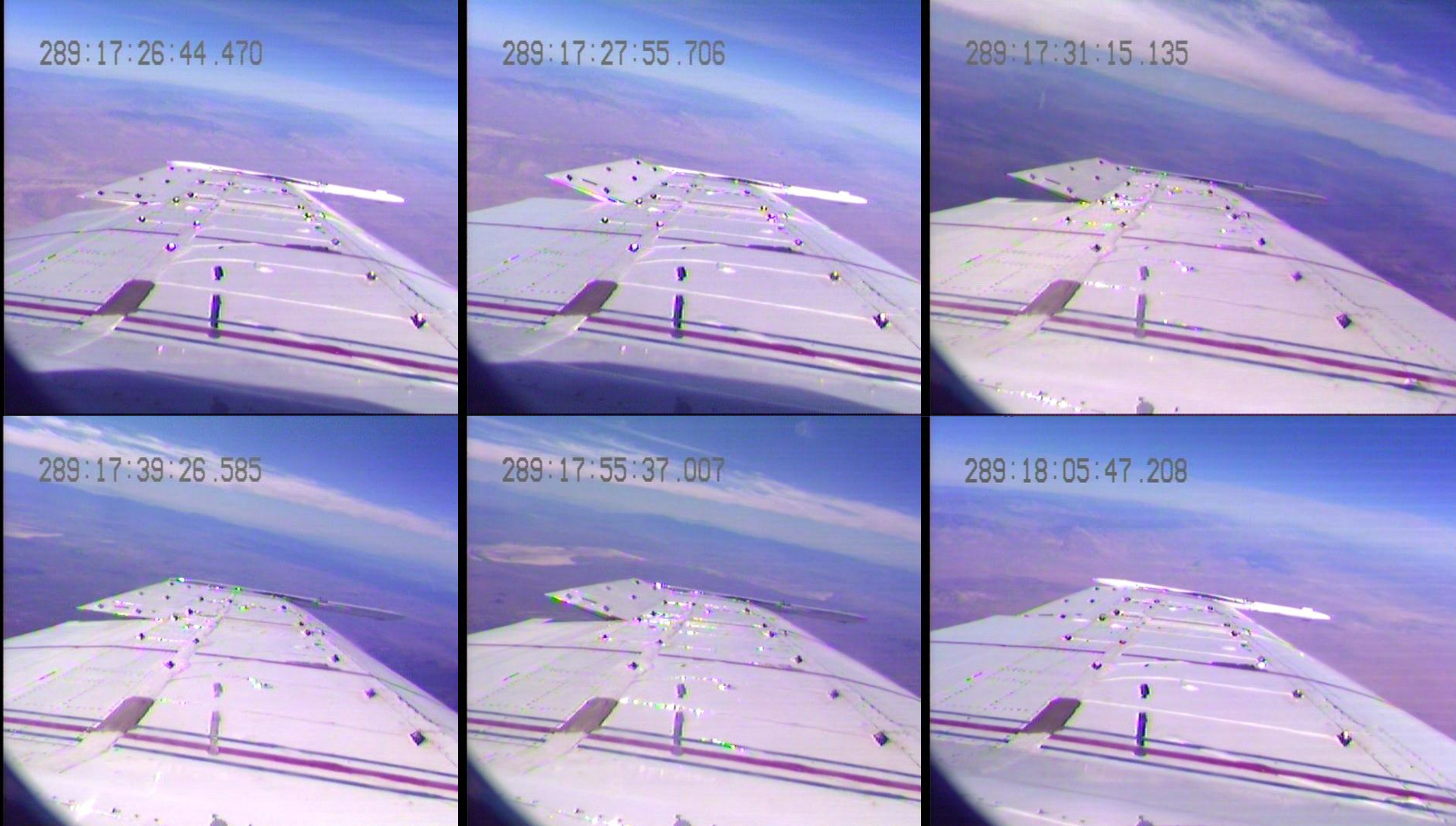

Start tests
Choose IC
Choose M
Choose G
Arm and engage
Advance
Wait for FF sliding-window variance to converge (30-120 s)
Algorithm converged?
no
yes
Reasonable progress?
yes
no
Disengage
Gain related?
yes
Measurements related?
yes
no
Return to IC
Wait for FF sliding-window variance to converge (30-120 s)
Low on fuel?
no
yes
End tests


ARTS Disengaged
Select Mode
Arm
Engage
ARTS Engaged
(Autopilot & Autothrottle)
Initial Surface Biases
Algorithm Running (iterative)
Disengage

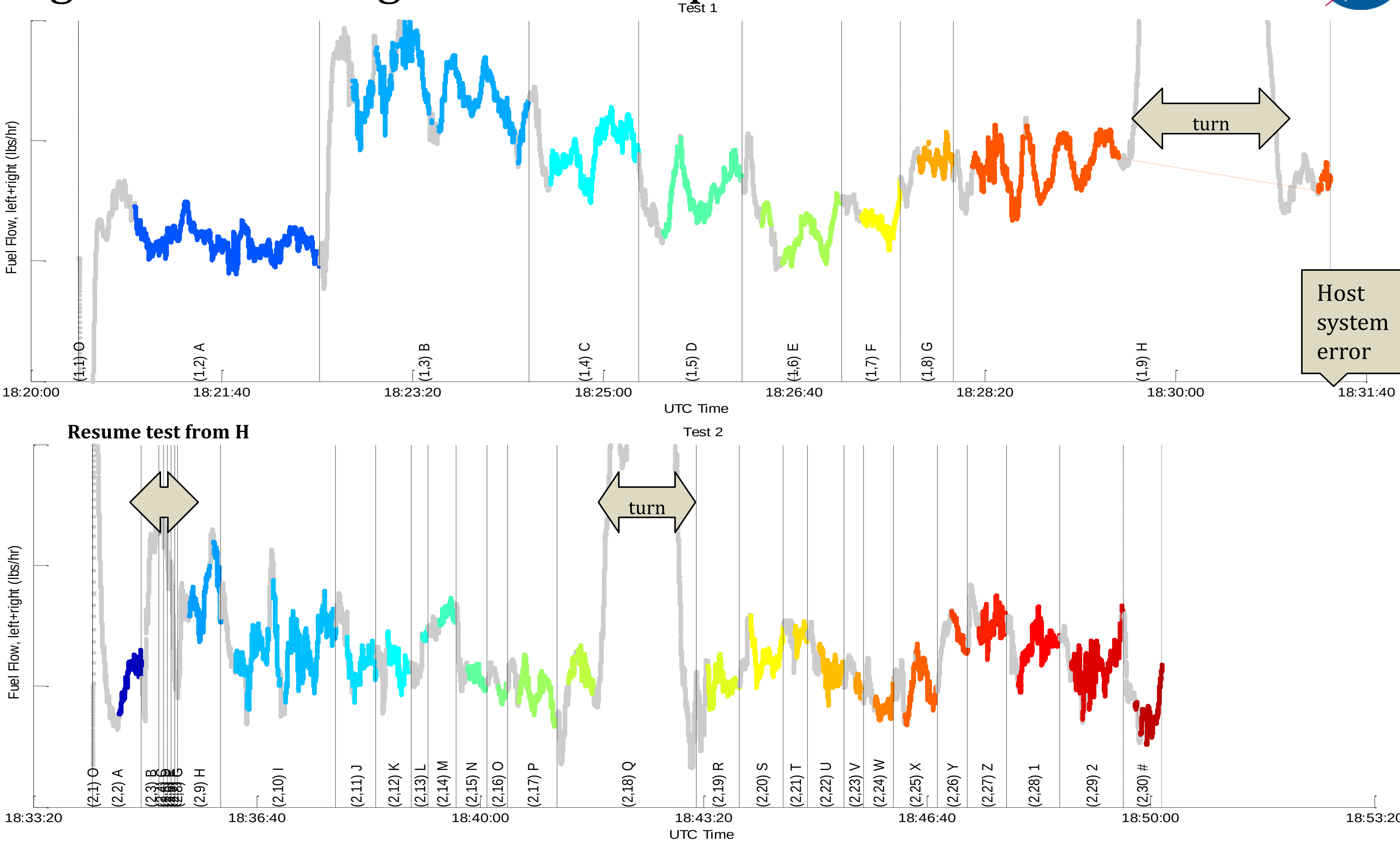

DANGER DO NOT PULL HANDLE
Center
JIM "CLUE" LESS
NILS LARSON
DANGER
EJECTION
SEAT
DANGER
DANGER


NASA
853


NASA
IADS


289:17:26:44.470
289:17:27:55.706
289:17:31:15.135
289:17:39:26.585
289:17:55:37.007
289:18:05:47.208

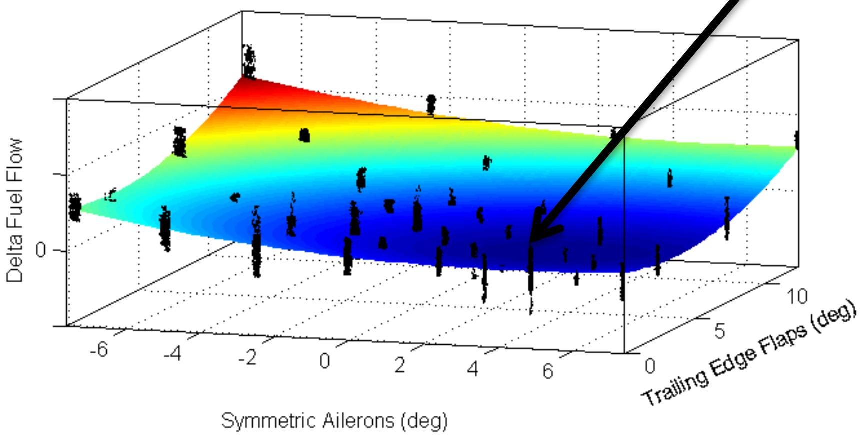
Flight 132: PFI Flight Data Examples



Flight 132: Estimated Performance Function

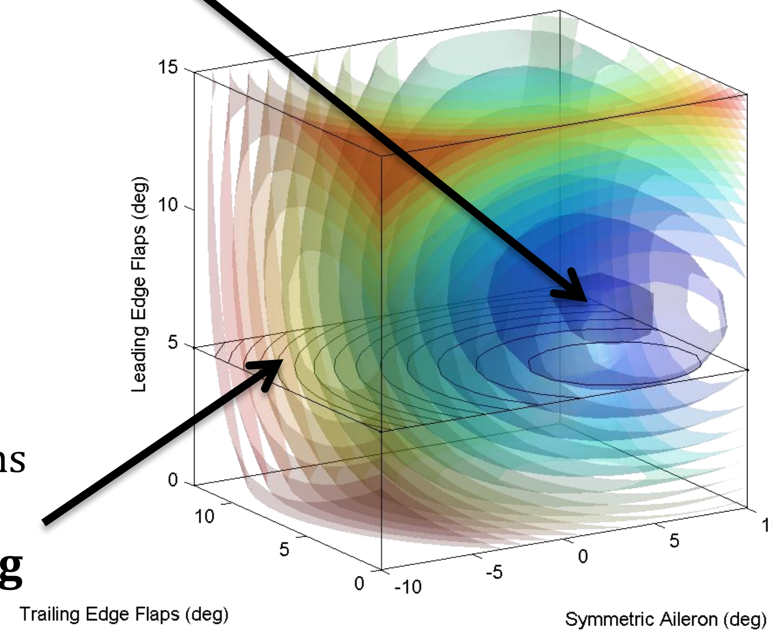
- Recognizable shape
- Substantial gradient relative to noise

Estimated minimum fuel flow



Delta Fuel Flow due to Aileron and TEF Deflections (LEF at 5 deg)

Slice at LEF 5 deg



Delta Fuel Flow due to Aileron, TEF, and LEF Deflections (for simulation)

Flight 132: Summary of PFI Flight Results

Questions Before PFI Flight

Is the approach feasible?

- The algorithm detects small changes in fuel flow. Noise and disturbances may be too large.
- PFI experiment will quantify the signal/noise ratio.

Minimum duration dwell-time interval?

- Short intervals are desired for faster convergence, better use of flight time.
- Short intervals increase the impact of disturbances.
- PFI experiment will inform the designers' choice of dwell time for the algorithm.

Can autopilot transients be reduced?

- Short settling times & minimal overshoots are desired for faster convergence, better use of flight time.
- Autopilot evaluation will include 3 autopilot gain sets.

What is the shape of the performance function?

- PFI data will be used to choose initial conditions
- Surface fit to PFI data will be used in control room to verify algorithm is 'on course'.
- PFI data will be used in post-flight analysis & technical reports.

Answers from Post-PFI Analysis

The approach is feasible.

- Substantial gradients were seen between trim configurations despite standard deviations of around 50 lbs/hr.

Dwell time intervals should not be fixed.

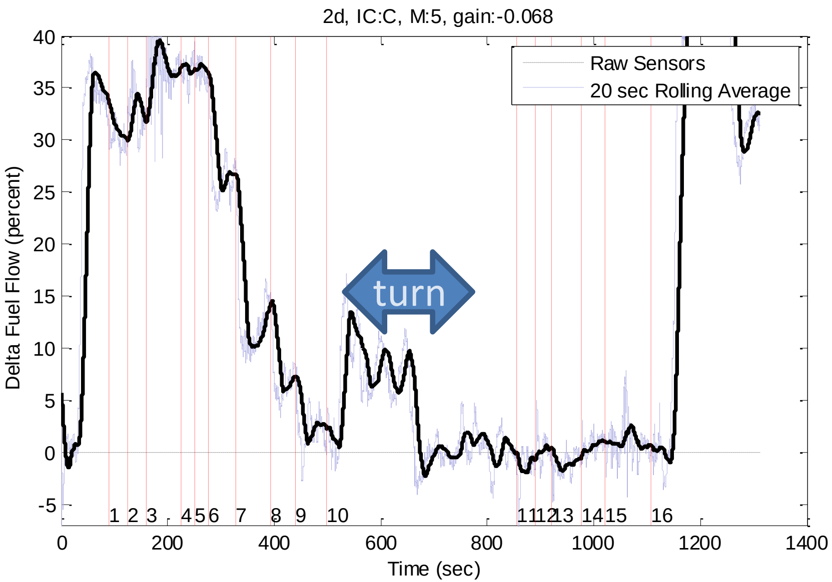
- Lesson learned: Manual advance allows flexibility for maneuvering. (Pilot's suggestion.)
- 30 sec is a good minimum dwell time.

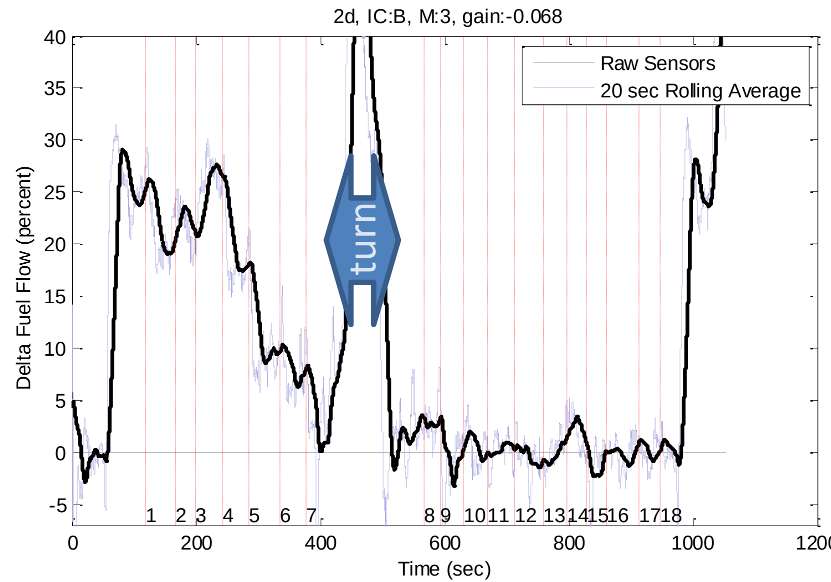
Autopilot performance is good.

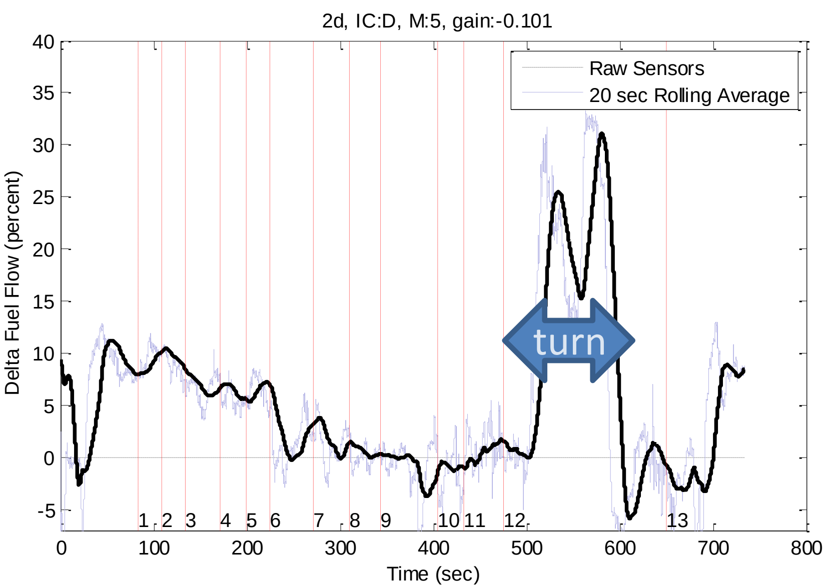
- Nominal gainset was selected.
- Good sim prediction of autopilot dynamics.
- Pilot A: "These autopilots are rock-solid on condition."

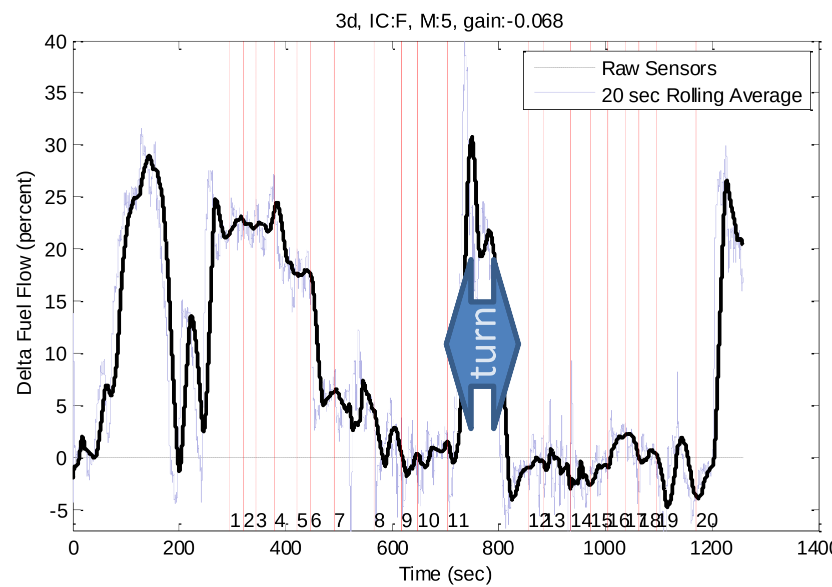
Second-order polynomial (paraboloid) fits the PFI data well.

- Six initial conditions selected.
- Performance function added to sim for algorithm tuning.


2d, IC:C, M:5, gain:-0.068
Raw Sensors
20 sec Rolling Average
turn
Delta Fuel Flow (percent)
Time (sec)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16


2d, IC:B, M:3, gain:-0.068
Raw Sensors
20 sec Rolling Average
turn
Delta Fuel Flow (percent)
Time (sec)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18


2d, IC:D, M:5, gain:-0.101
Raw Sensors
20 sec Rolling Average
turn
Delta Fuel Flow (percent)
Time (sec)
1 2 3 4 5 6 7 8 9 10 11 12 13


3d, IC:F, M:5, gain:-0.068
Raw Sensors
20 sec Rolling Average
turn
Delta Fuel Flow (percent)
Time (sec)
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20

Flight results at 200 KCAS flight condition