Peak Seeking Control for Reduced Fuel Consumption with Preliminary Flight Test Results

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Abstract

The Environmentally Responsible Aviation project seeks to accomplish the simultaneous reduction of fuel burn, noise, and emissions. A project at NASA Dryden Flight Research Center is contributing to ERAs goals by exploring the practical application of real-time trim configuration optimization for enhanced performance and reduced fuel consumption. This peak-seeking control approach is based on Newton-Raphson algorithm using a time-varying Kalman filter to estimate the gradient of the performance function. In real-time operation, deflection of symmetric ailerons, trailing-edge flaps, and leading-edge flaps of a modified F-18 are directly optimized, and the horizontal stabilators and angle of attack are indirectly optimized. Preliminary results from three research flights are presented herein. The optimization system found a trim configuration that required approximately 3.5% less fuel flow than the baseline trim at the given flight condition. The algorithm consistently rediscovered the solution from several initial conditions. These preliminary results show the algorithm has good performance and is expected to show similar results at other flight conditions and aircraft configurations.

Agenda

- Background
  - Motivation
  - Previous Approaches
  - New Approach

- Precursor Open-Loop Experiment Flight Results (1 Flight)

- Closed-Loop Algorithm Preliminary Flight Results (2 Flights)

- Next Steps
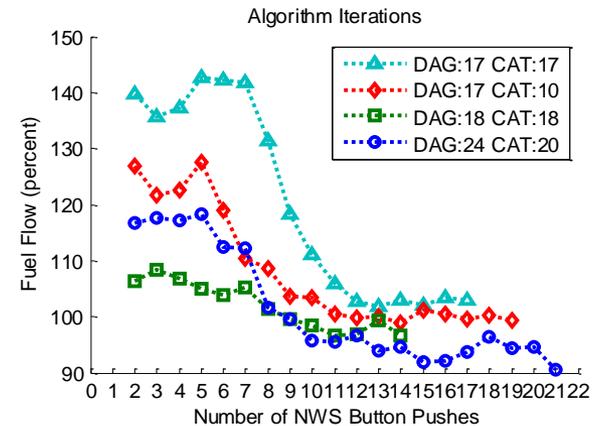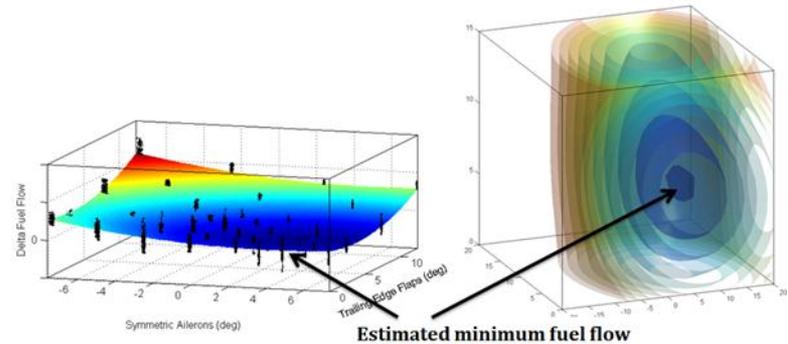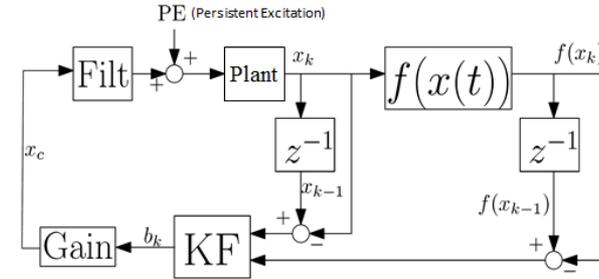
NASA Goals

- This work directly supports the Environmentally Responsible Aircraft (ERA) Project's goal of **reducing fuel burn**.

- Aeronautics Research Mission Directorate
  - Integrated System Research Program
    - **Environmentally Responsible Aviation**
      - Airframe Technologies
        - 2.2 Flight Dynamics and Controls
          - 2.2.4 Intelligent Controls

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?
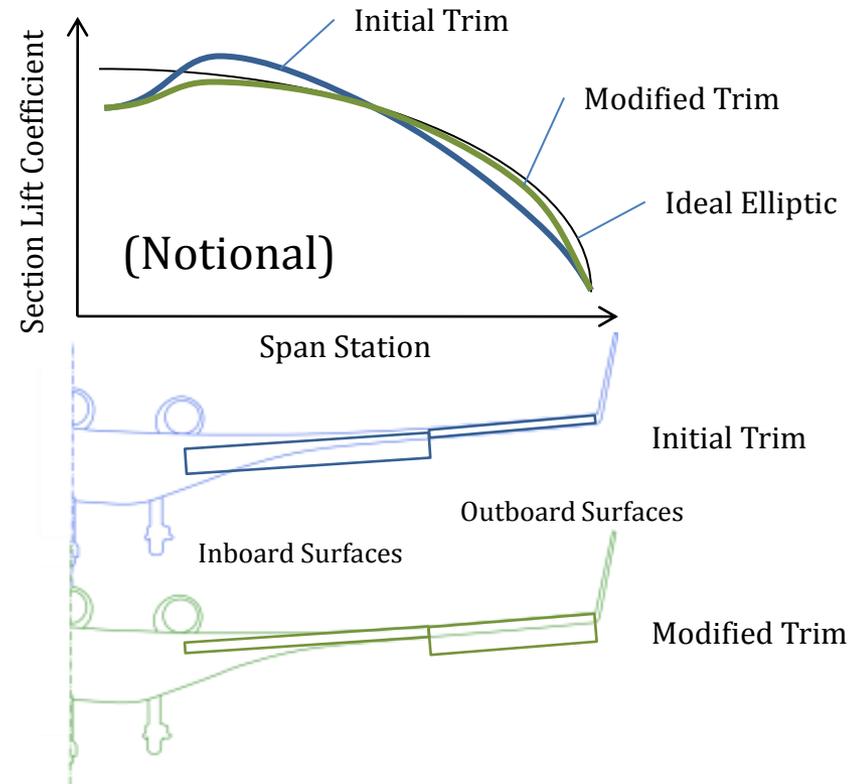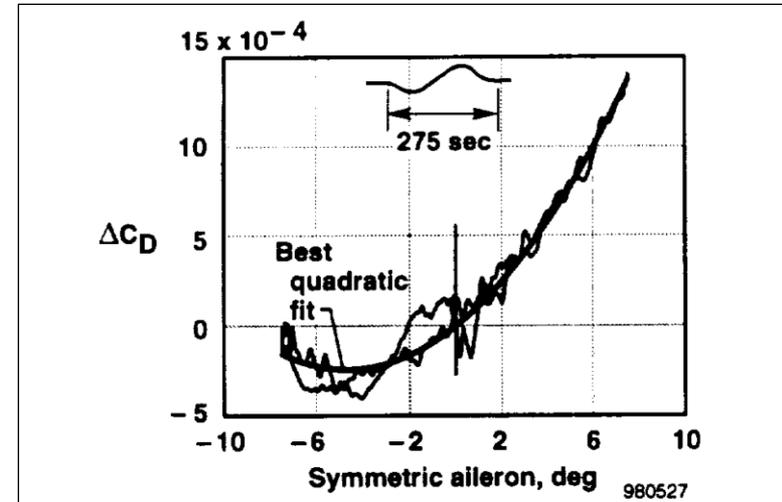
Previous Research Results

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

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)."

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.
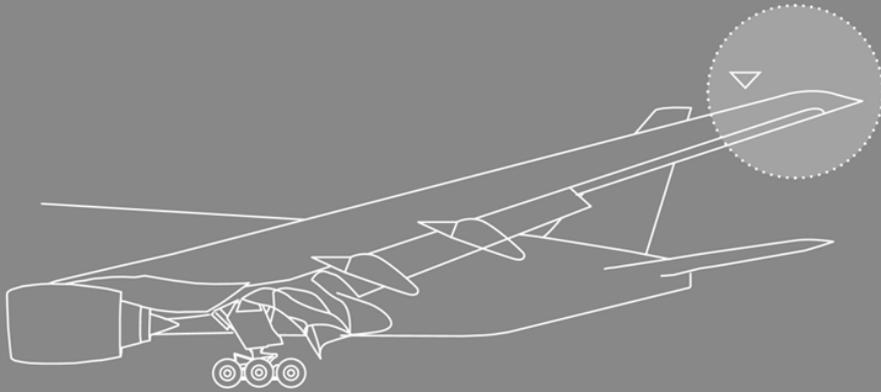Dryden Flight Research Center, 1999.
http://hdl.handle.net/2060/19990019435

Figure 2: Drooped aileron
Boeing engineers determined that a 2-degree aileron droop was optimal for flight performance.

Detail of aileron cross section

2°

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.
http://au.ibtimes.com/articles/125677/20110323/boeing-united-airlines-fleet-airline-airplane-fuel-777.htm

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

However, the new 747-8 does **not** have it:

> "Boeing also acknowledged that the Trailing Edge Variable Camber (TEVC), one of the unique features on the 787 Dreamliner, does not feature on the 747-8 family.
>
> 'The 747-8 does not have TEVC. The 747-8 Program did study adding TEVC but found the performance benefit was not as great as on the 787. The 747-8 does not have active gust suppression control laws. The 747-8 has better response to wind gust due to its physical size. However, the 747-8 will have active control laws designed to improve the ride quality of the airplane.'"
>
> Daniel Tsang, Aspire Aviation in 2010.
>
> http://www.aspireaviation.com/2010/06/21/747-8f-flight-test-progressing/
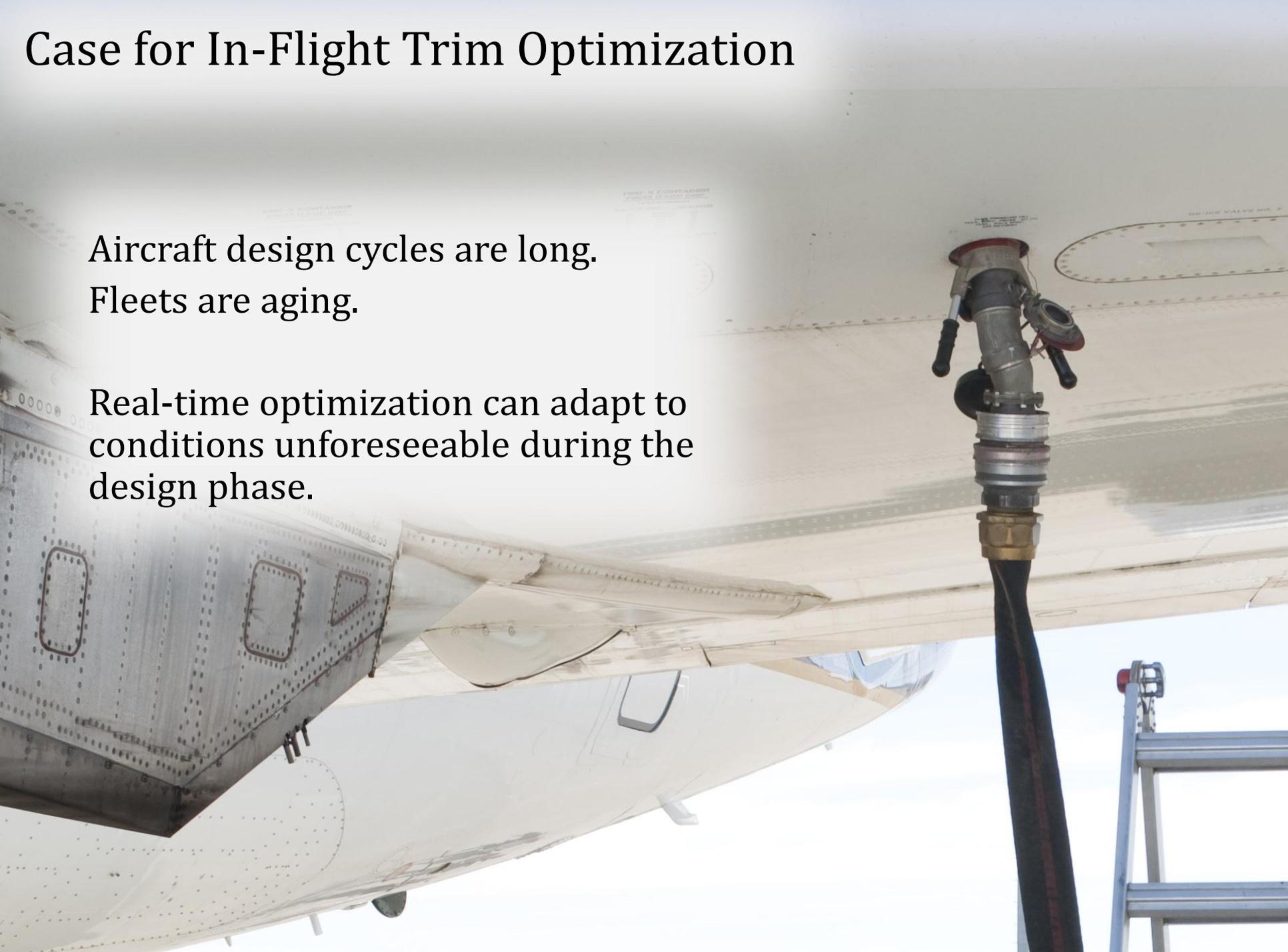
Case for In-Flight Trim Optimization

Aircraft design cycles are long.
Fleets are aging.

Real-time optimization can adapt to conditions unforeseeable during the design phase.

New Approach

Goal:

Reduce fuel burn in cruise flight.

Technical Challenge:

– Implement an algorithm to change trim allocation in flight for minimum fuel consumption.
– Evaluate if the algorithm is well-behaved in realistic conditions.

General Approach:

– Move effectors to minimize drag to reduce fuel flow.
– Maintain trim cruise speed and altitude.
– Peak-seeking control, steepest descent algorithm.
– Estimate performance function gradient with time-varying Kalman filter.
– Simultaneously optimize the position of multiple effectors.
– Kalman filter addresses noise issues directly.
– New method not reliant on models.
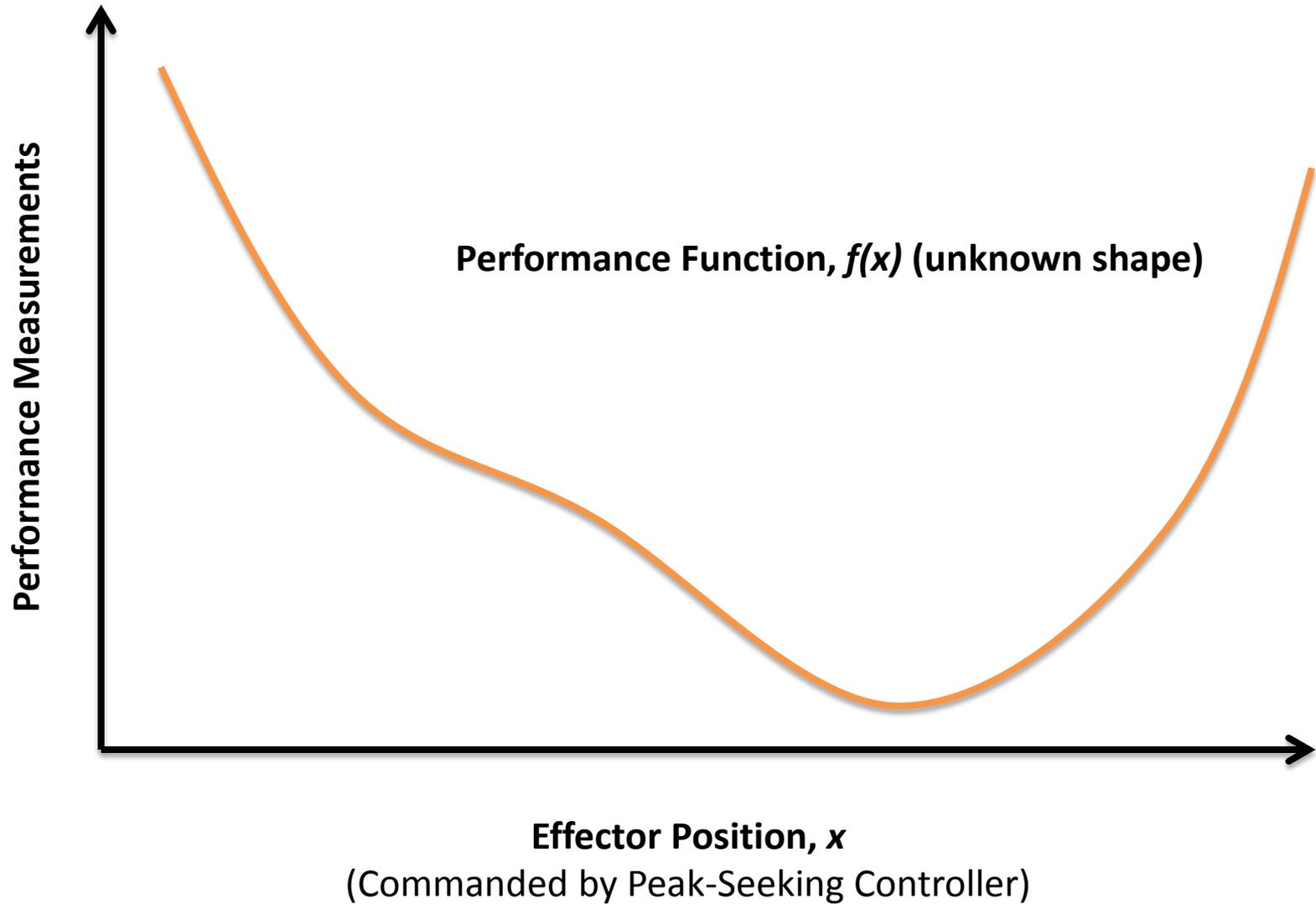– Controller seeks the minimum fuel flow solution.

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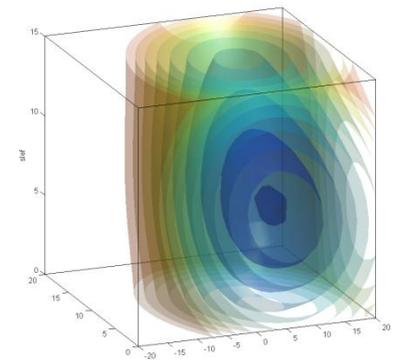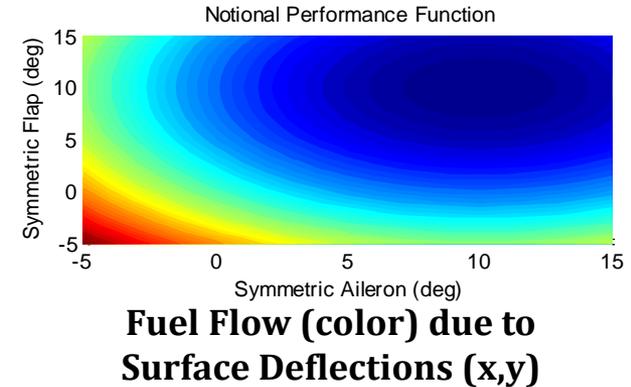
Fuel Flow (color) due to Surface Deflections (x,y,z)

Simplified Introduction to Approach: Single Effector

Performance Function, *f(x)* (unknown shape)

Performance Measurements

Effector Position, *x*
(Commanded by Peak-Seeking Controller)

Simplified Introduction to Approach: Single Effector

Simplified Introduction to Approach: Single Effector

Command (K*gradient)
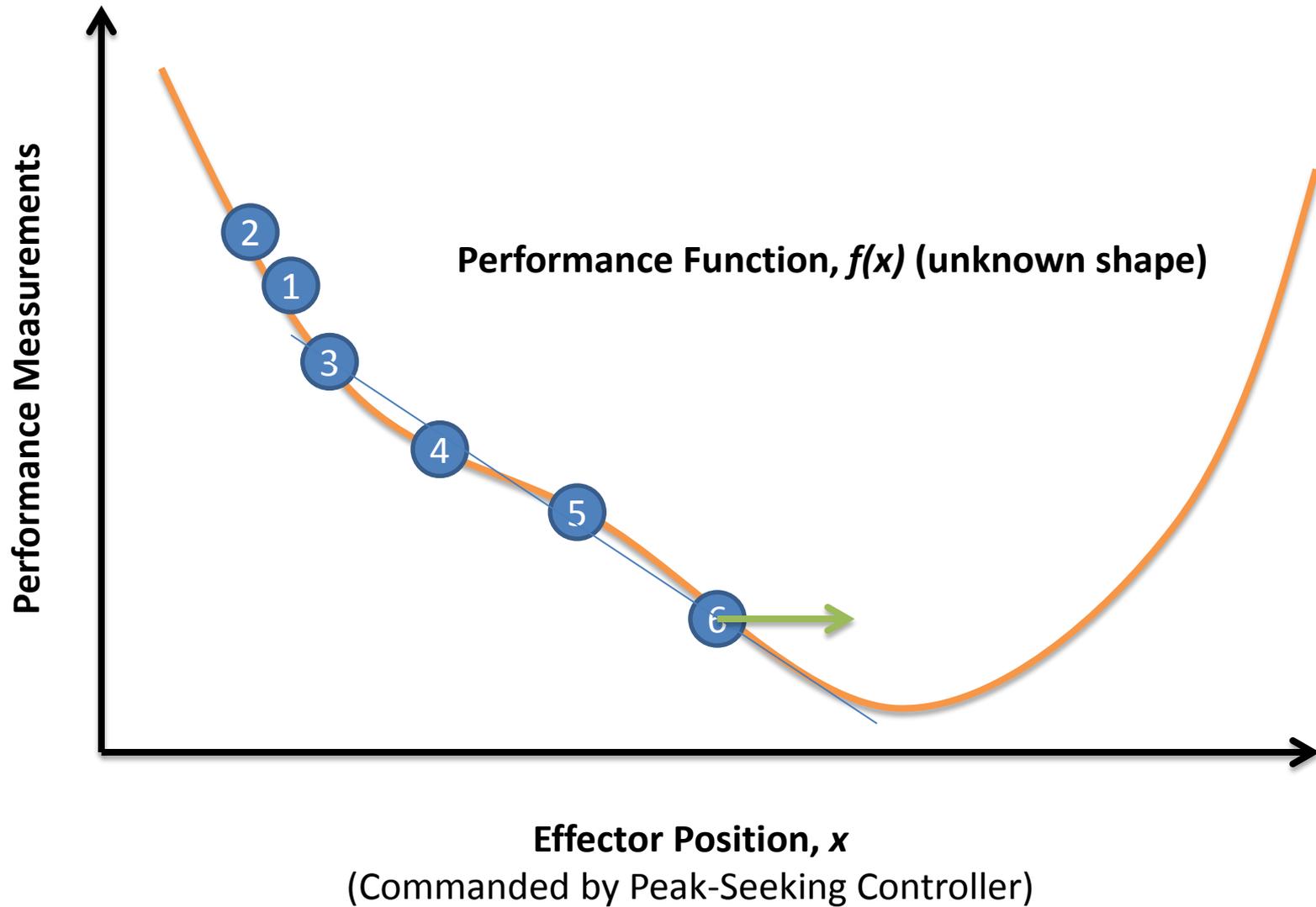
Performance Measurements

Effector Position, *x*
(Commanded by Peak-Seeking Controller)

Simplified Introduction to Approach: Single Effector

Updated Estimated Gradient

Command (K*gradient)

Performance Measurements (vertical axis)

Effector Position, *x*
(Commanded by Peak-Seeking Controller)

Simplified Introduction to Approach: Single Effector

Simplified Introduction to Approach: Single Effector

Simplified Introduction to Approach: Single Effector

Performance Function, *f(x)* (unknown shape)

Performance Measurements
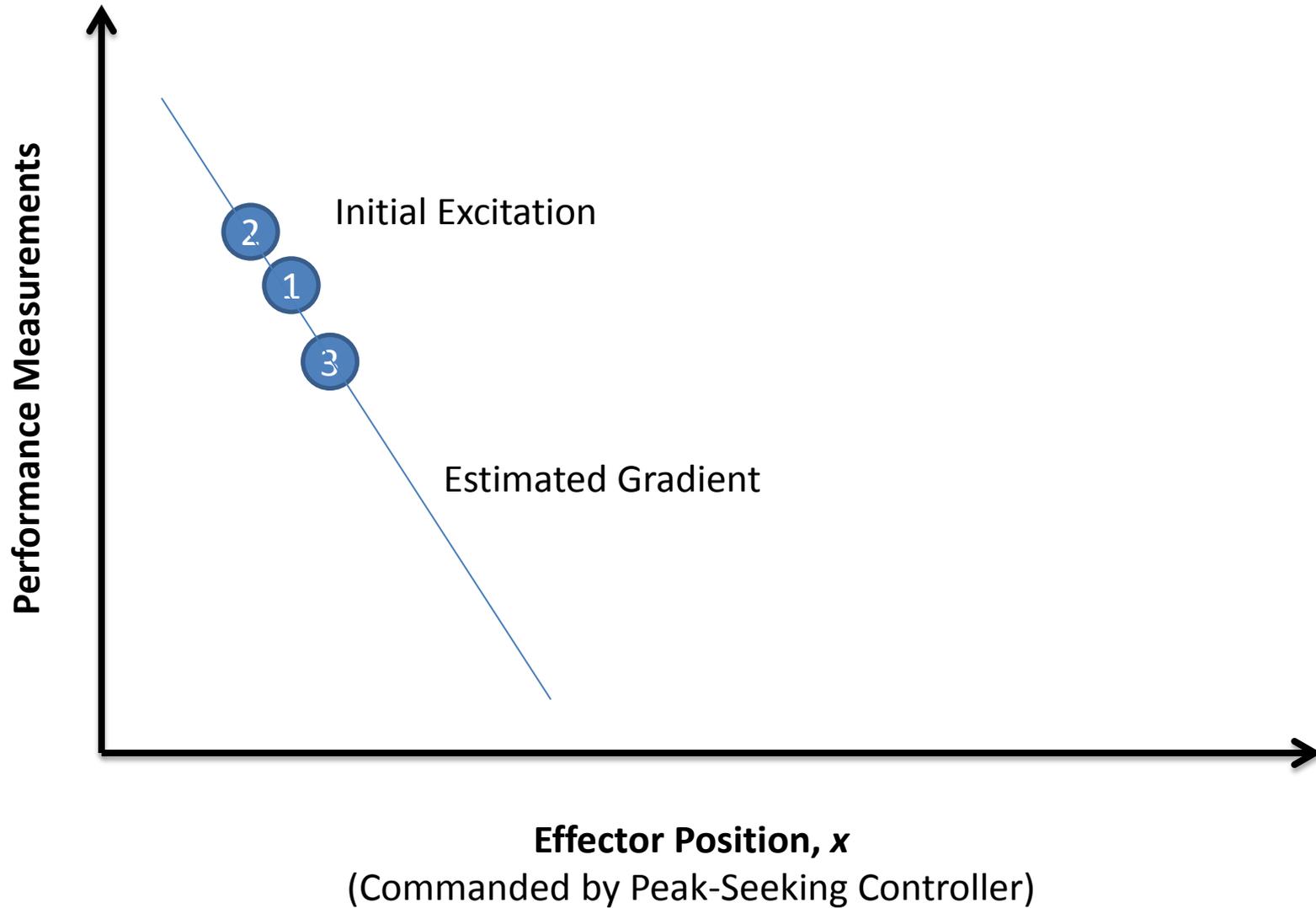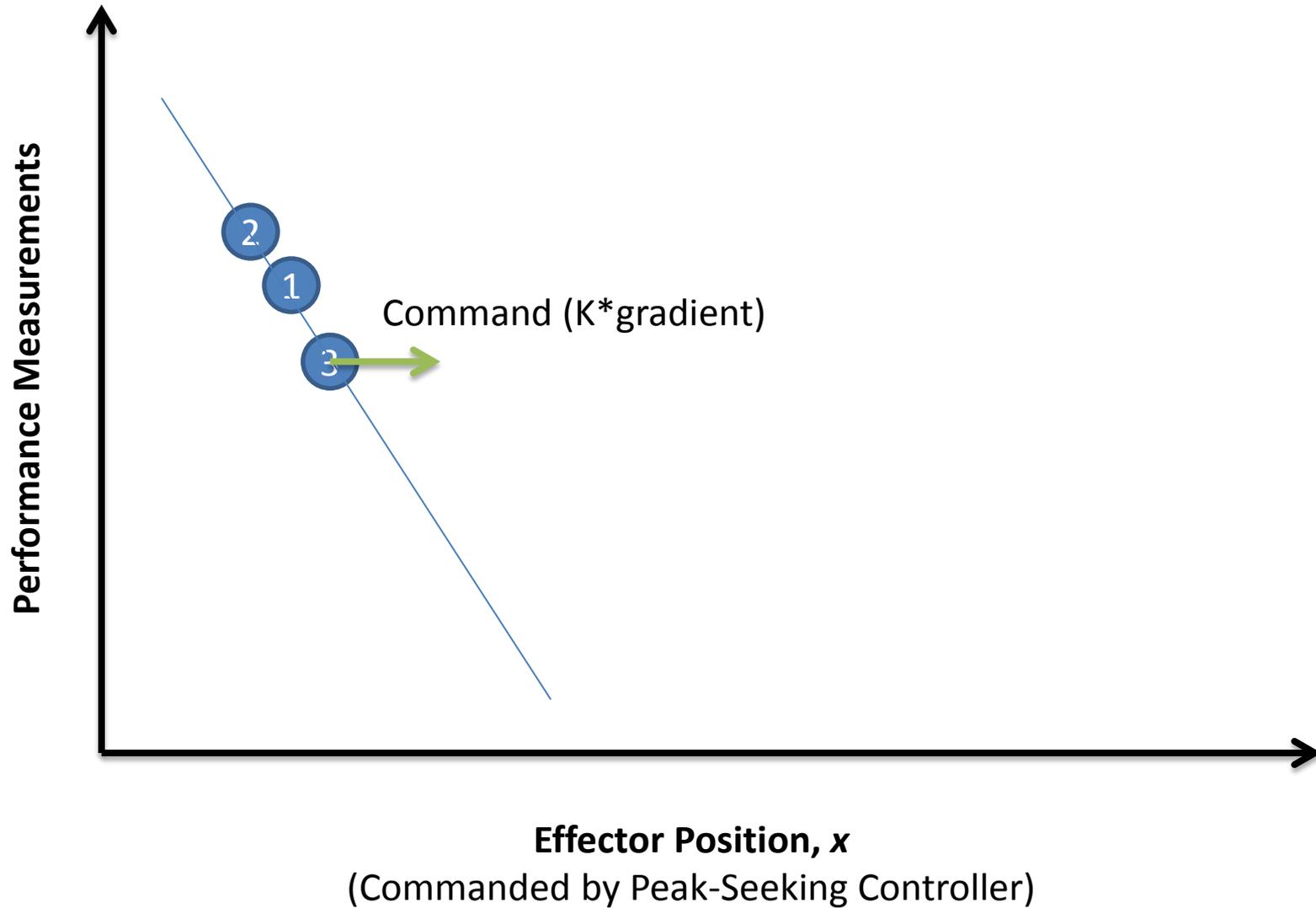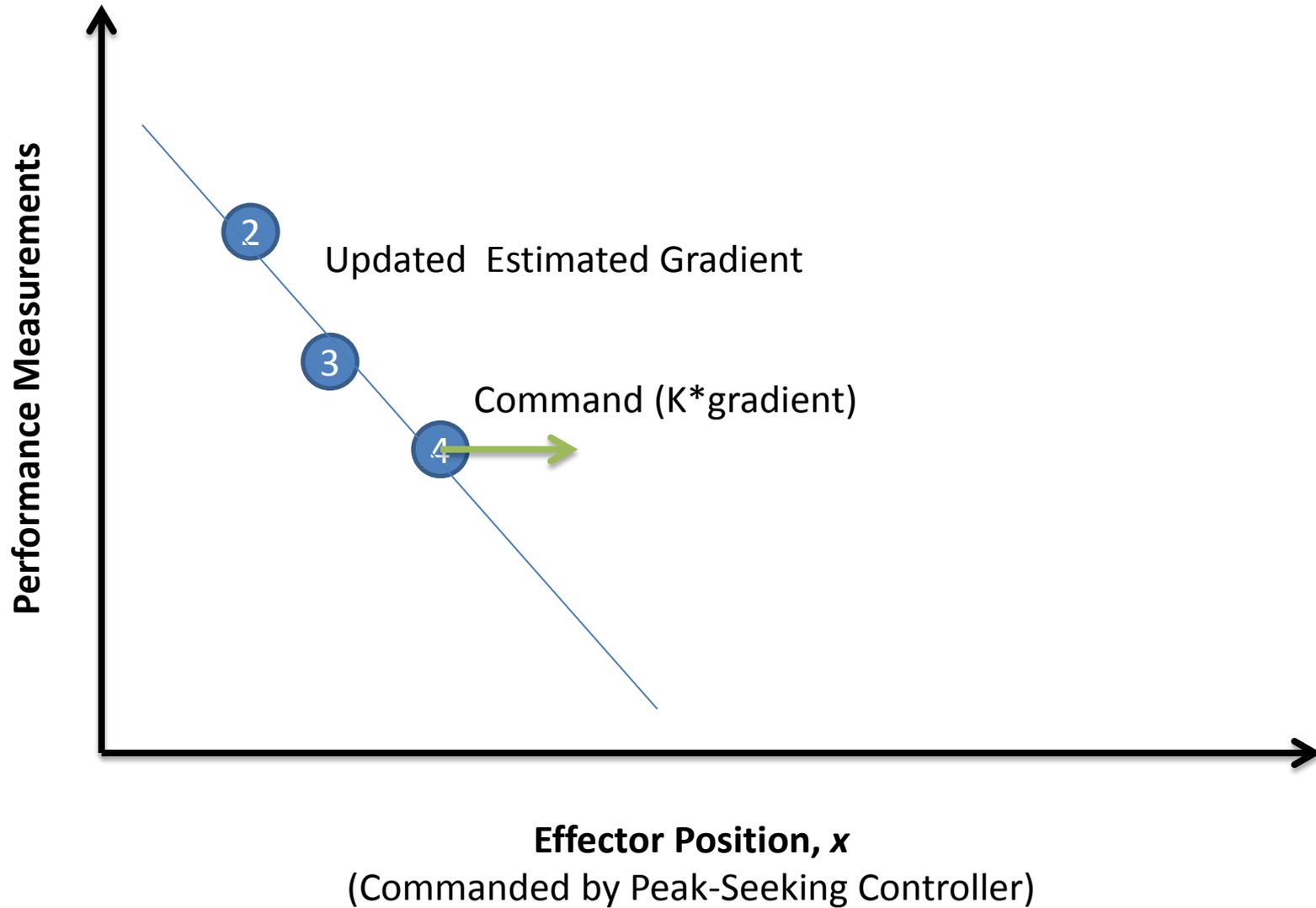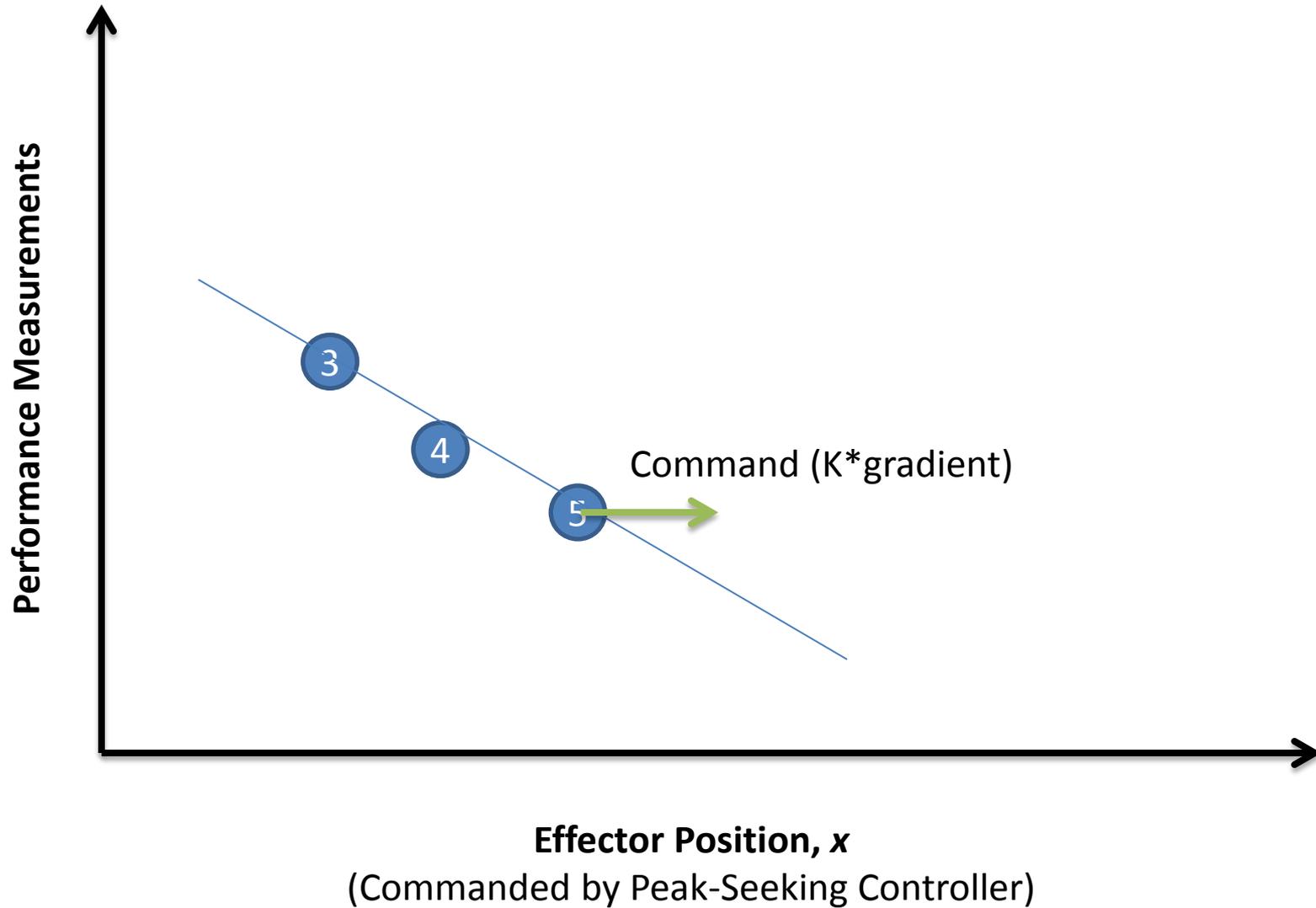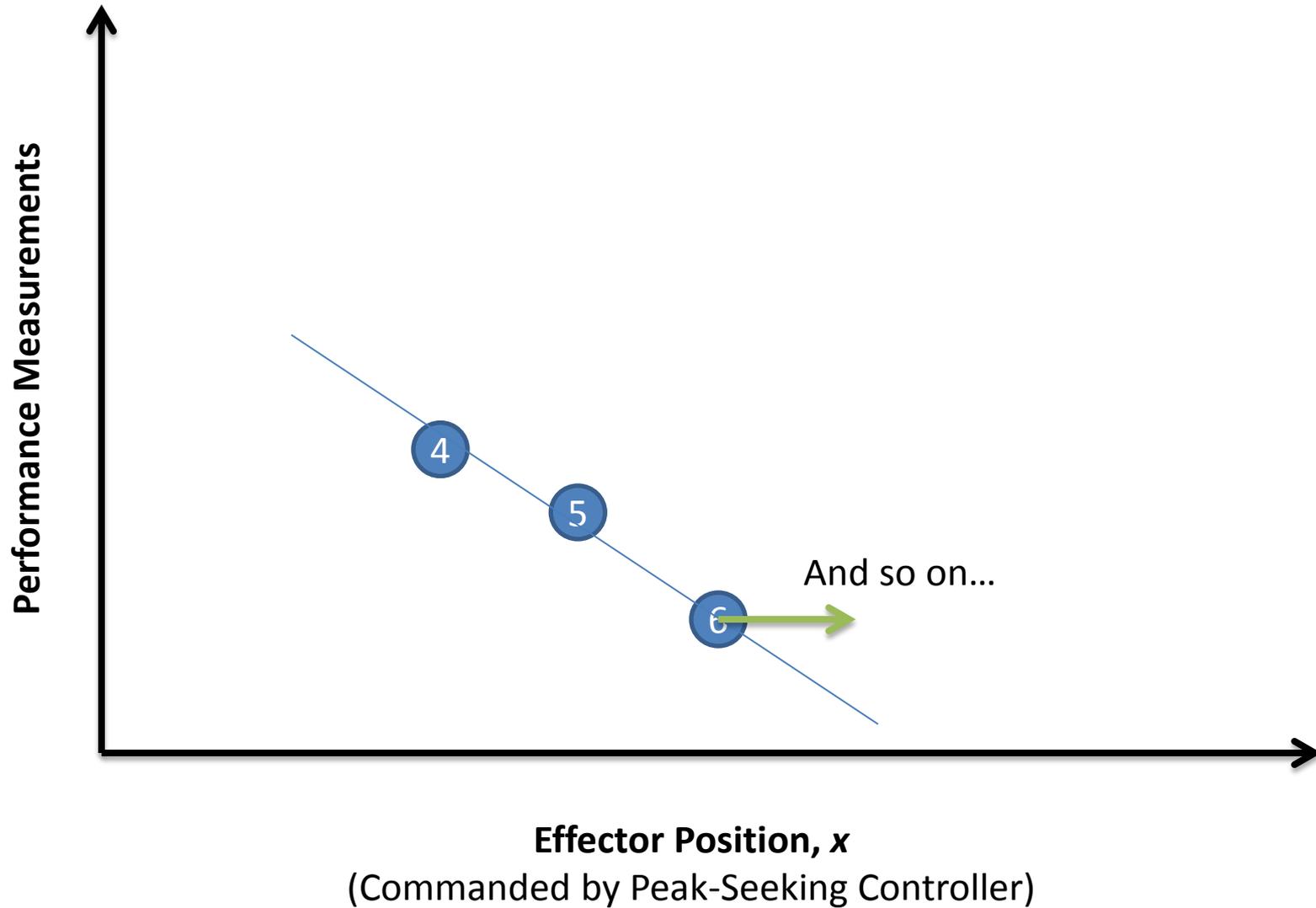
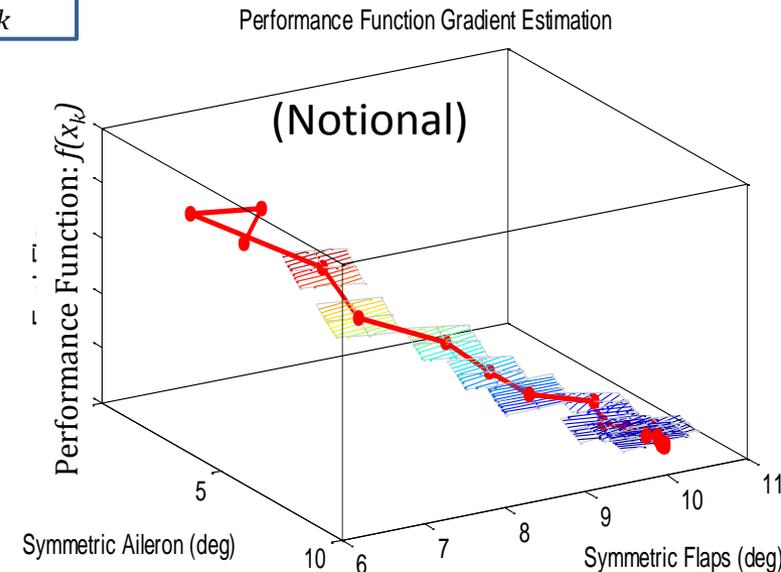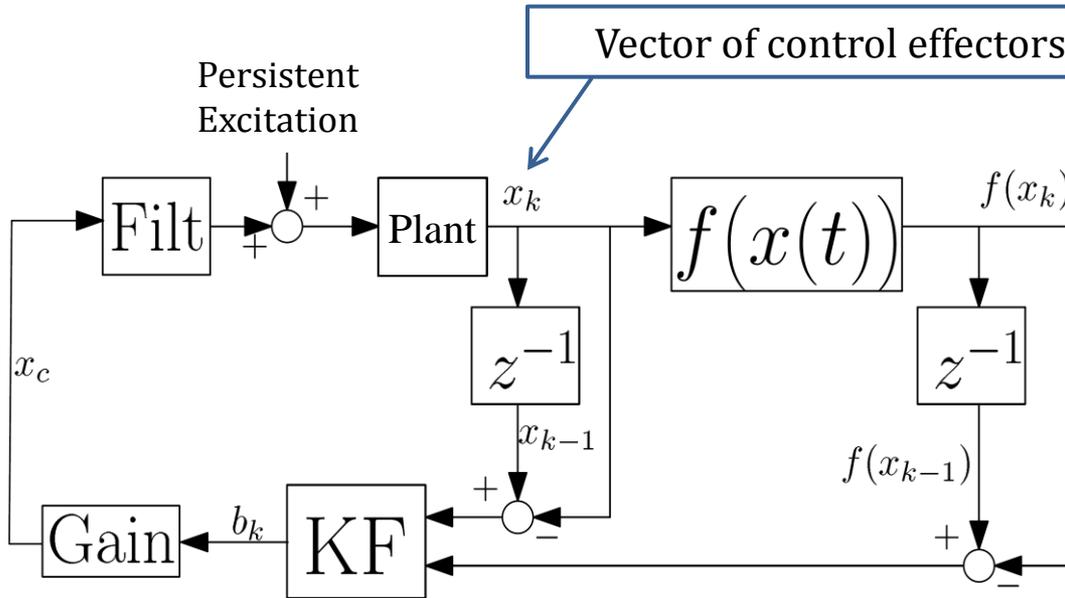**Effector Position, *x***
(Commanded by Peak-Seeking Controller)

Technical Approach: Architecture

Peak seeking control 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

Vector of control effectors: x_k

Persistent Excitation

Performance Function Gradient Estimation

(Notional)

Taylor series expansion of the performance function:

$$f(x) \approx f(x_k) + b_k^T(x - x_k) + O(x - x_k)$$

Gradient Estimate (transpose)

Higher order terms

Technical Approach: Performance Function

Change in PF:

$$\Delta f_k = f(x_{k-1}) - f(x_k)$$

Change in surface positions:

$$\Delta x_k = x_{k-1} - x_k$$

Assuming PF can be treated as linear at any control surface position:

$$\Delta f_k = b_k^T \Delta x_k$$

Rewritten:

$$\Delta f_k = \begin{bmatrix} \Delta x_{1_k} \\ \Delta x_{2_k} \end{bmatrix}^T \begin{bmatrix} b_{1_k} \\ b_{2_k} \end{bmatrix}$$

In this 2D example, we have two groups of effectors, symmetric ailerons and TEF:

$$\Delta x_{1_k} = x_{1_{k-1}} - x_{1_k}$$
$$\Delta x_{2_k} = x_{2_{k-1}} - x_{2_k}$$

(Ryan 2010)

This has been extended to 3D, and can be extended to more effectors.

Technical Approach: Kalman Filter States

Since the gradient may change with surface positions and measurements will be noisy, a Kalman filter is an appropriate choice of estimator.

Kalman filter states chosen to be:

$$\zeta_k = \begin{bmatrix} b_{1_k} \\ b_{2_k} \end{bmatrix}$$

The measurement equation of the linear time-varying Kalman filter takes the form:

$$\Delta f_k = H_k \zeta_k + v_k$$

$$H_k = \begin{bmatrix} \Delta x_{1_k} \\ \Delta x_{2_k} \end{bmatrix}$$

Represent zero-mean Gaussian white-noise processes,
with noise variances V and W (capital letters)

Given the unknown true dependence of the performance function on surface positions, the state is modeled as a Brownian noise process and the linear time-varying Kalman filter process equation is then given by:

$$\zeta_{k+1} = I\zeta_k + w_k$$

(Ryan 2010)

Linear Time-Varying Kalman Filter

Current Kalman gain:

$$K = \hat{P}_k H_k^T \left(H_k \hat{P}_k H_k^T + V_k \right)^{-1}$$

Current KF state estimate (gradient of PF):

$$\zeta_k = \hat{\zeta}_k + K \left(\Delta f_k - H_k \hat{\zeta}_k \right)$$

Current state covariance matrix:

$$P_k = (I - KH_k)\hat{P}_k$$

Predicted KF state estimate (gradient of PF):

$$\hat{\zeta}_{k+1} = \zeta_k$$

Predicted state covariance matrix:

$$\hat{P}_{k+1} = P_k + W_k$$

The noise variances Vk and Wk are used as tuning parameters influencing the filters performance.

(Ryan 2010)

Flight Research Implementation of Algorithm

Modified F-18 Aircraft - Full-Scale Advanced Systems Testbed (FAST). See Pavlock 2011.

http://hdl.handle.net/2060/20110015358

    Research quality fuel flow sensors installed.

Airborne Research Test System, 4th Generation (ARTS IV)

Nonlinear Dynamic Inversion Control Laws. See Miller 2011. http://hdl.handle.net/2060/20110015950
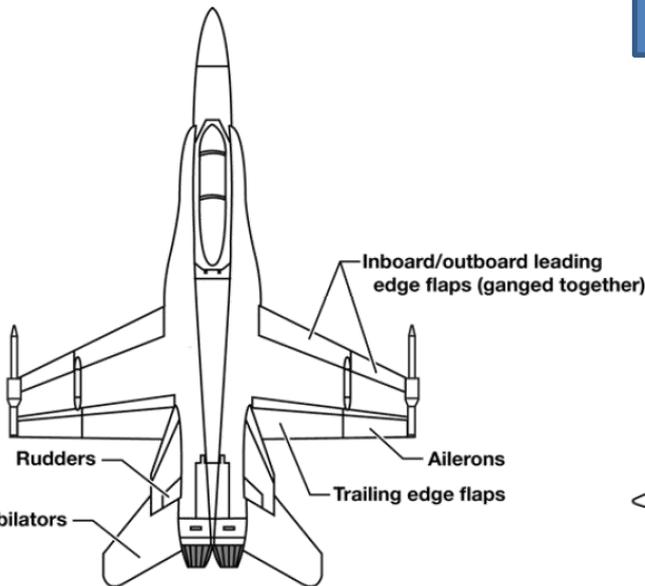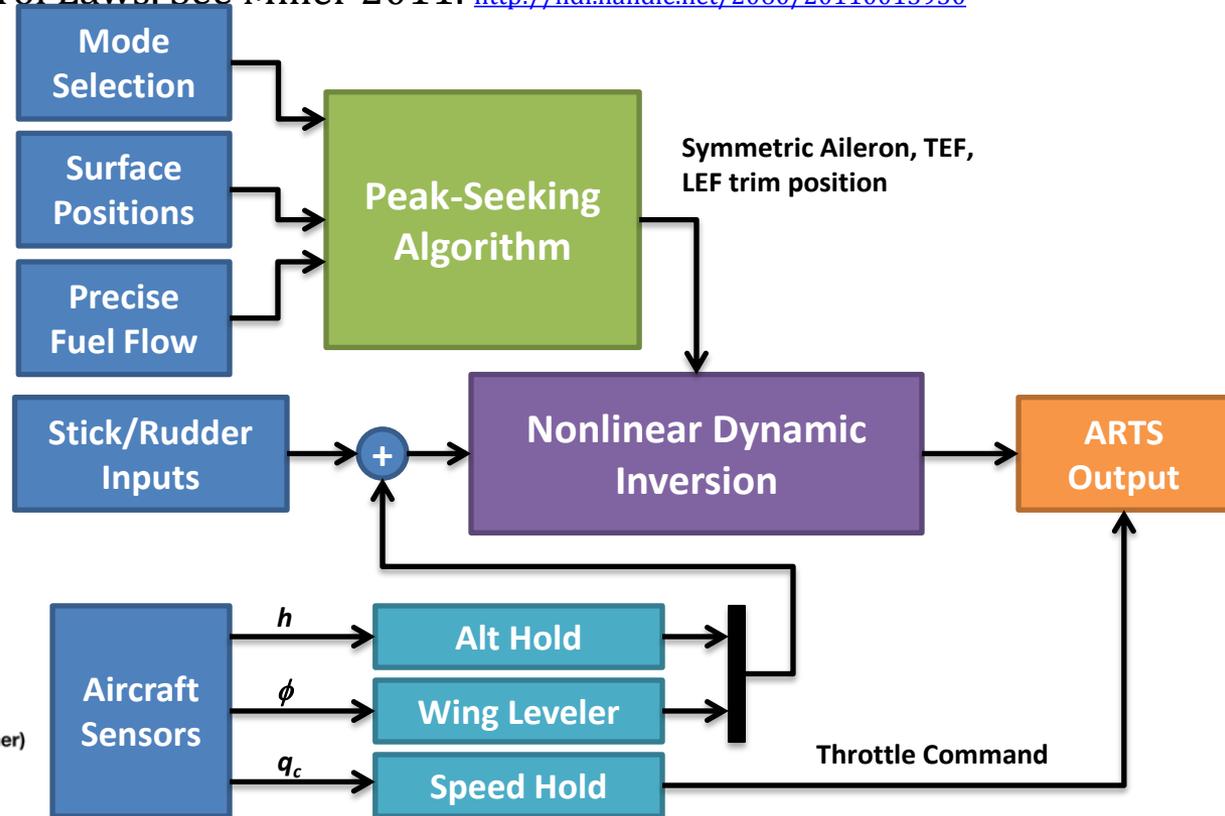
Autopilots:

    Altitude Hold

    Airspeed Hold

    Wing Leveler

Algorithm adds biases to:

    symmetric aileron

    trailing-edge flaps (TEF)

    leading-edge flaps (LEF)

Mode Selection

Surface Positions

Precise Fuel Flow

Peak-Seeking Algorithm

Symmetric Aileron, TEF, LEF trim position

Stick/Rudder Inputs

Nonlinear Dynamic Inversion

ARTS Output

Aircraft Sensors

h — Alt Hold

ϕ — Wing Leveler

q_c — Speed Hold

Throttle Command

Inboard/outboard leading edge flaps (ganged together)

Rudders

Stabilators

Ailerons

Trailing edge flaps

Research Fuel Flow Meters

Technology Transition Map

Transition Opportunities

n-D Performance Function

Eco Demonstrator?

Upgrade Existing
Aircraft

1D Performance Function

Fuel Flow

Outboard Elevon (deg)
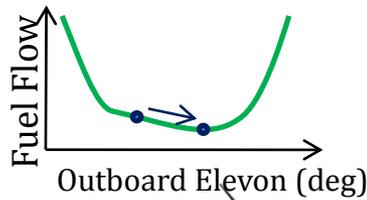
X-48B

FAST (F-18 853)
Multi-Effector Flight Research
(Prototype in Relevant Environment)

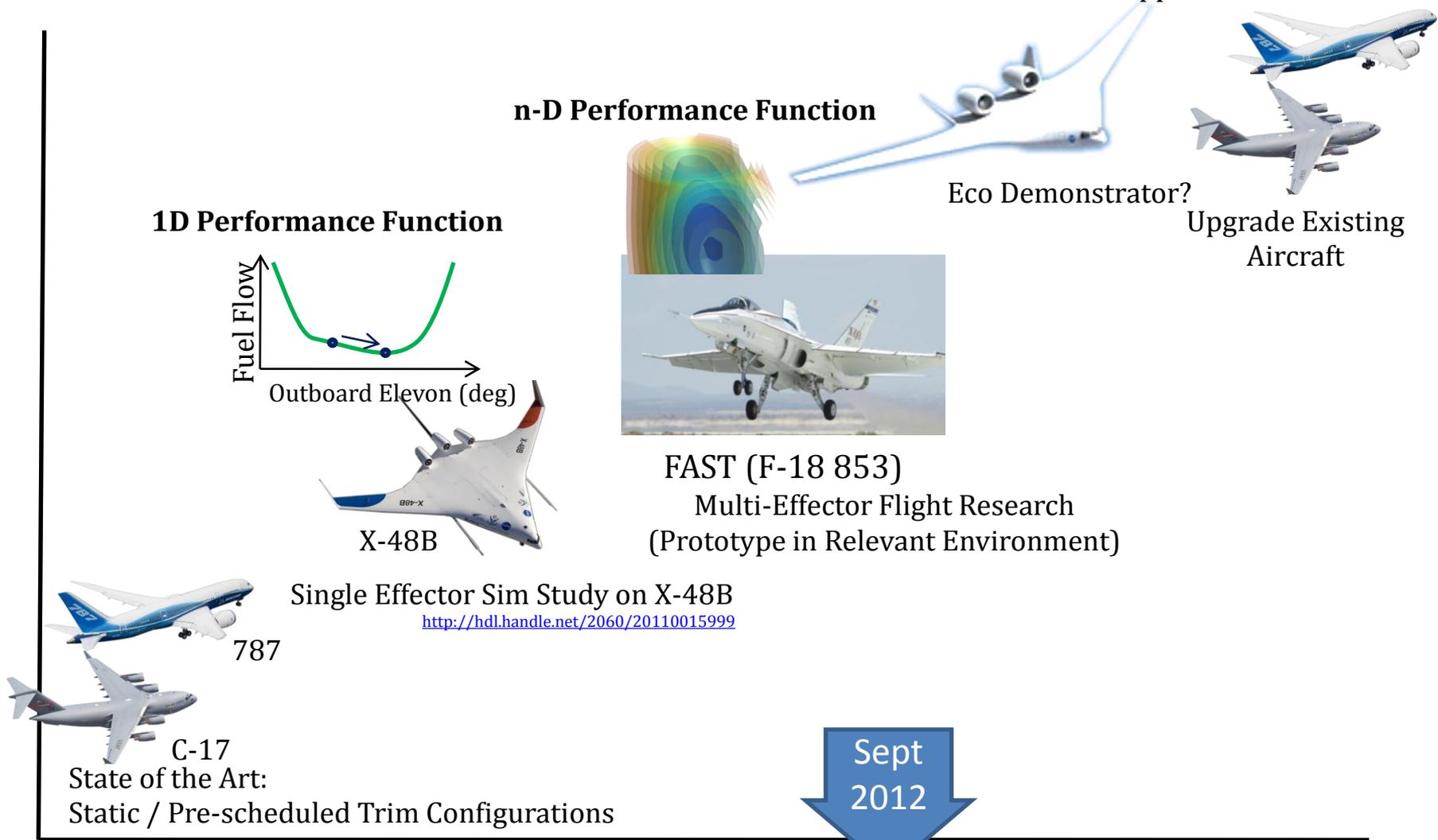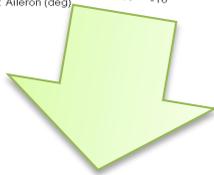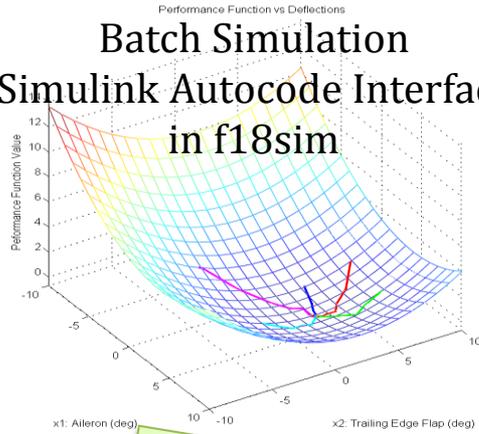Single Effector Sim Study on X-48B
http://hdl.handle.net/2060/20110015999

787

C-17
State of the Art:
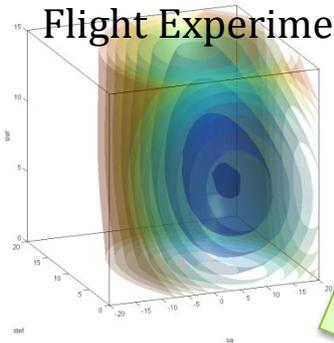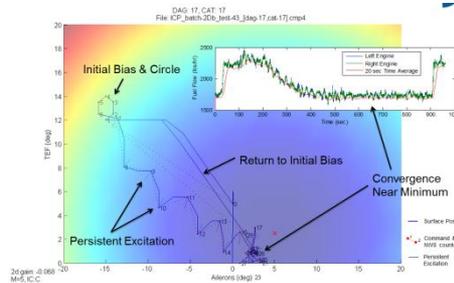Static / Pre-scheduled Trim Configurations

Sept
2012

Technology Maturation (TRL)

Time

Flight Research Approach

Batch Simulation
using Simulink Autocode Interface (SAI)
in f18sim

Notional Flight Test Point

- Baseline aircraft
- Initial surface biases
- Algorithm engaged

Fuel Flow

Fuel Savings

Time (approx. 10 minute duration)

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

Flight Research Approach

t Test Point

- ○ Baseline aircraft
- ○ Initial surface biases
- ○ Algorithm engaged

Fuel Savings
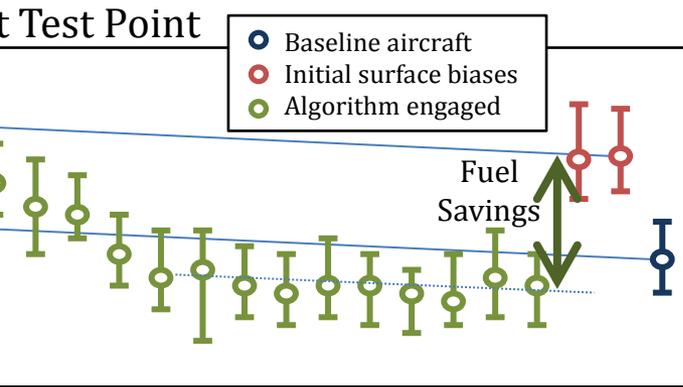
me (approx. 10 minute duration)

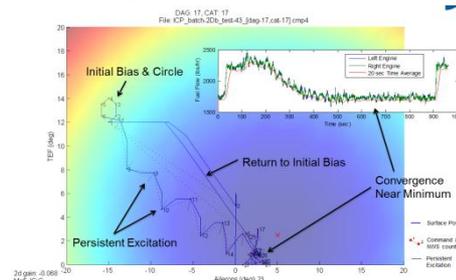Piloted HIL Simulation using ARTS
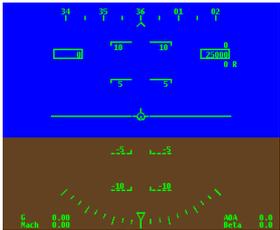
Algorithm-Engaged Initial Flight Experiment
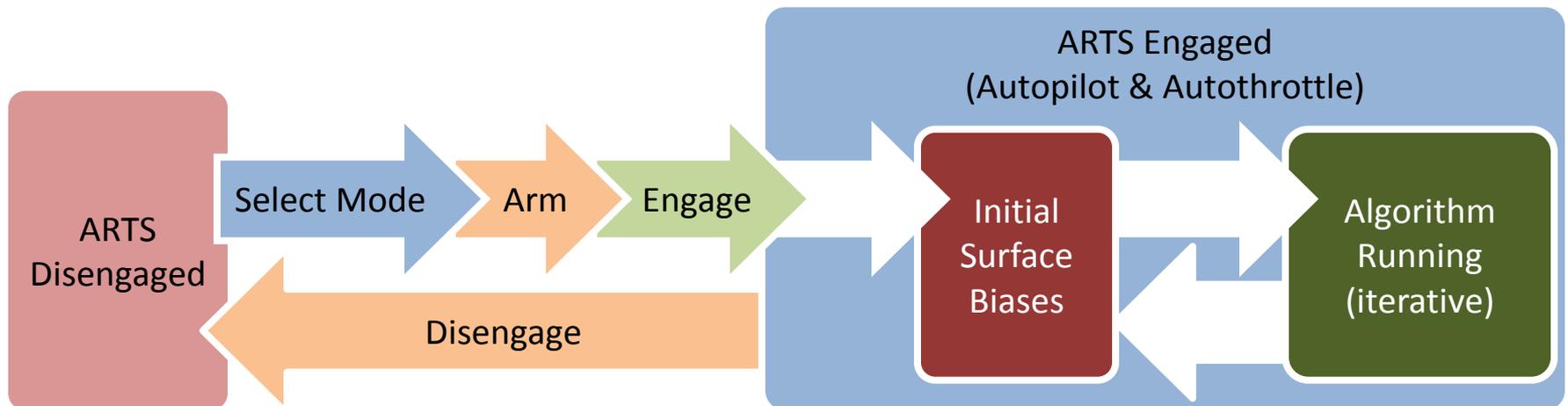
Fix, Modify, Tune, Regression Test

Algorithm-Engaged Flight Experiment

Concept of Operations

Test Flow:
- Get on condition (25k ft, 240 kcas)
- Pilot selects mode (configures experiment)
- Arm ARTS
- Engage ARTS (autopilots activated)
- Inserts initial trim biases
- Turn algorithm on
- Iterate algorithm repeatedly
- Turn off algorithm and re-insert initial trim
- Disengage

Completed Flights as of October 1, 2012

- Open Loop: Performance Function Identification (PFI)
  - Flight 132, Aug. 7, 2012
    - Autopilot evaluation
    - Matrices of surface deflection combinations (6 completed)

- Algorithm Engaged:
  - Flight 133, Sept. 19, 2012
    - Ailerons/TEF mode (2D), started from high-drag initial combinations.
      - 3 runs completed
    - Ailerons/TEF/LEF mode (3D), started from high-drag initial combination.
      - 1 run completed
  - Flight 134, Sept. 25, 2012
    - Ailerons/TEF/LEF mode (3D), started from production trim combination.
      - 3 runs completed
    - Ailerons/TEF/LEF mode (3D), started from high-drag initial combination
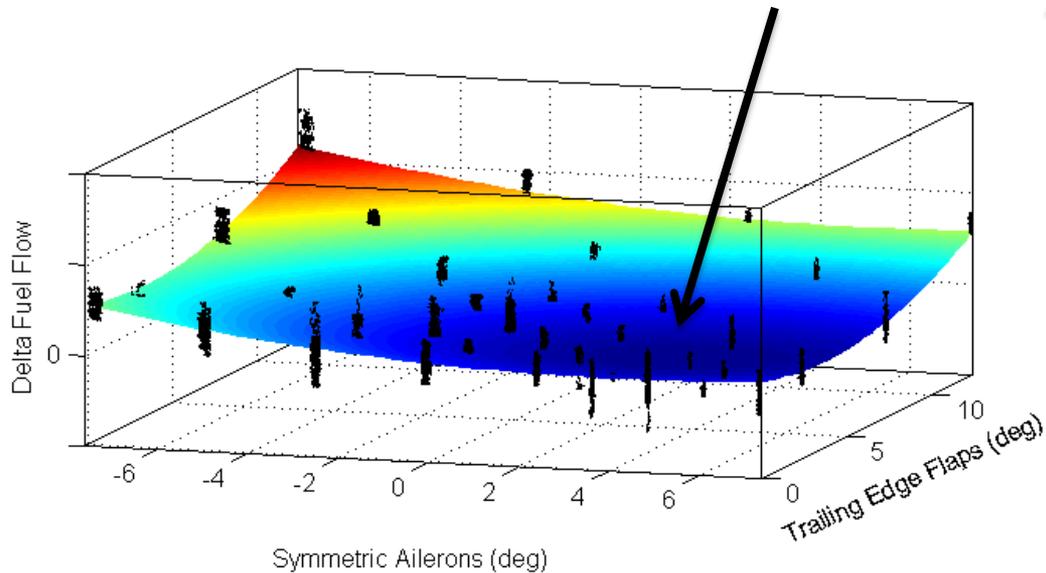   - 1 run completed

Flight 132: PFI Flight Data Examples
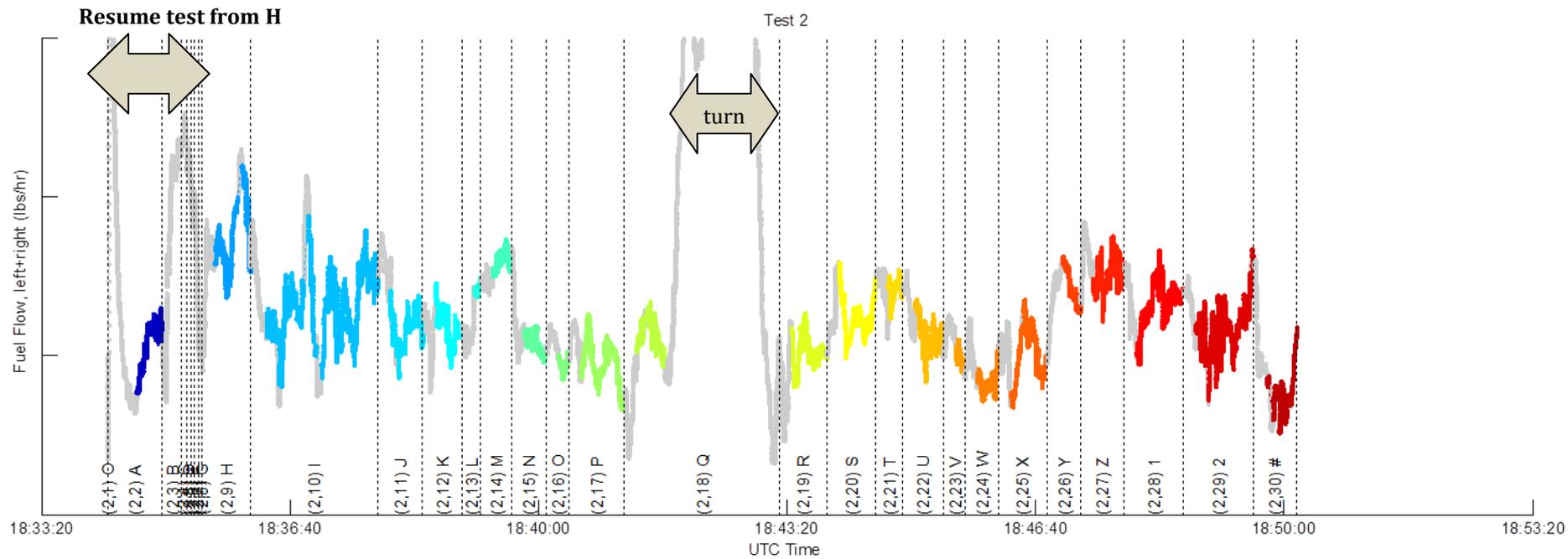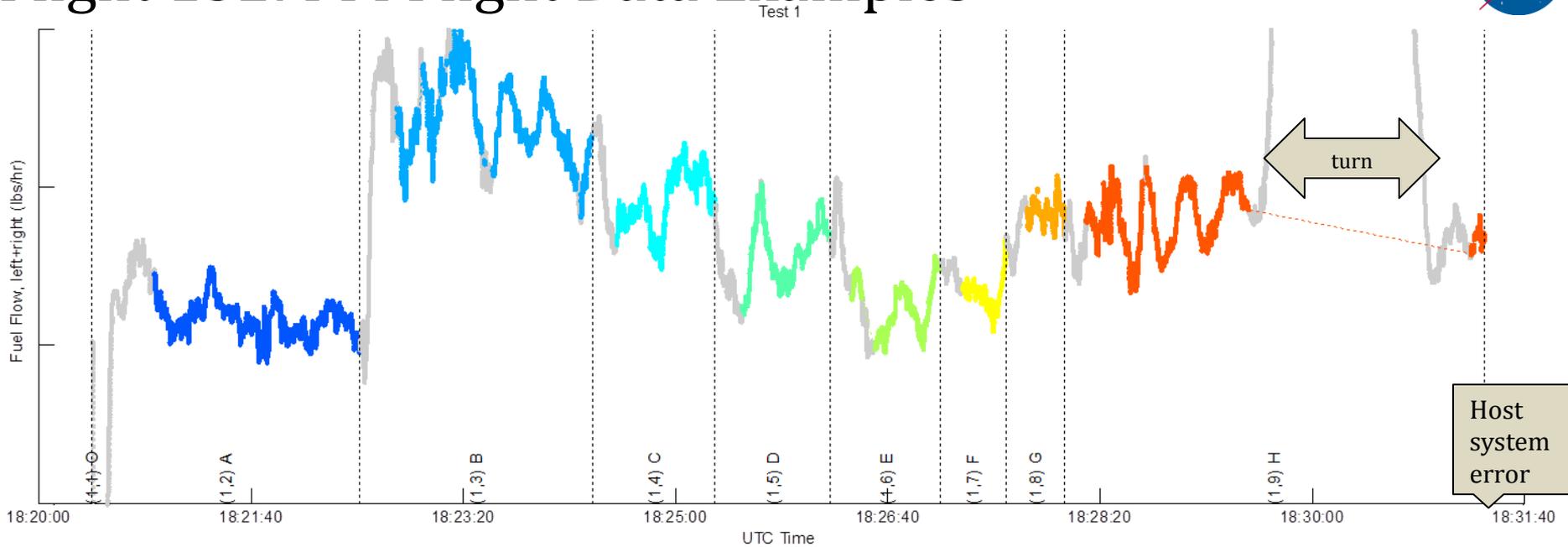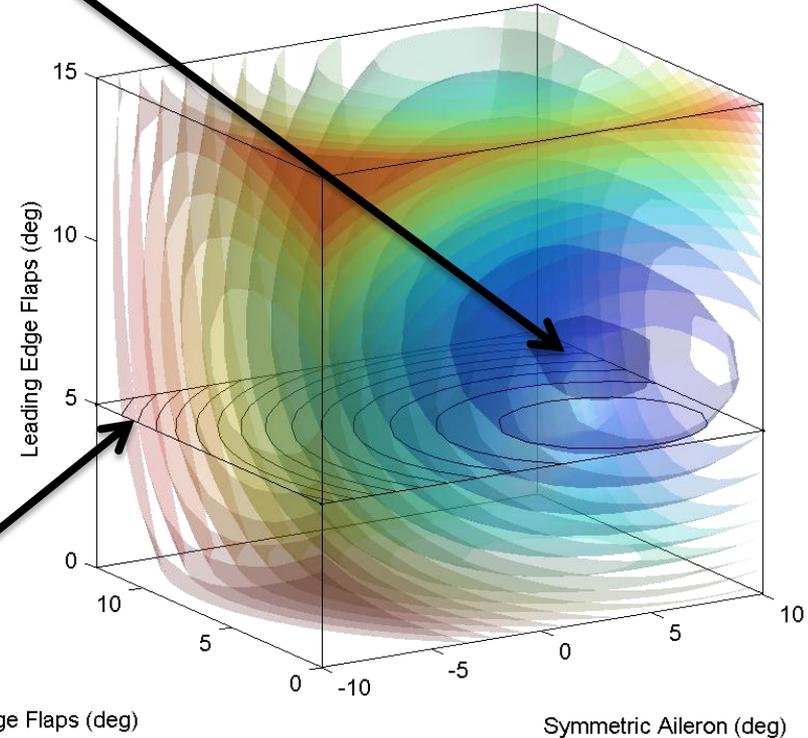
Flight 132: Estimated Performance Function

- 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.

Pilot-Selectable Algorithm Parameters
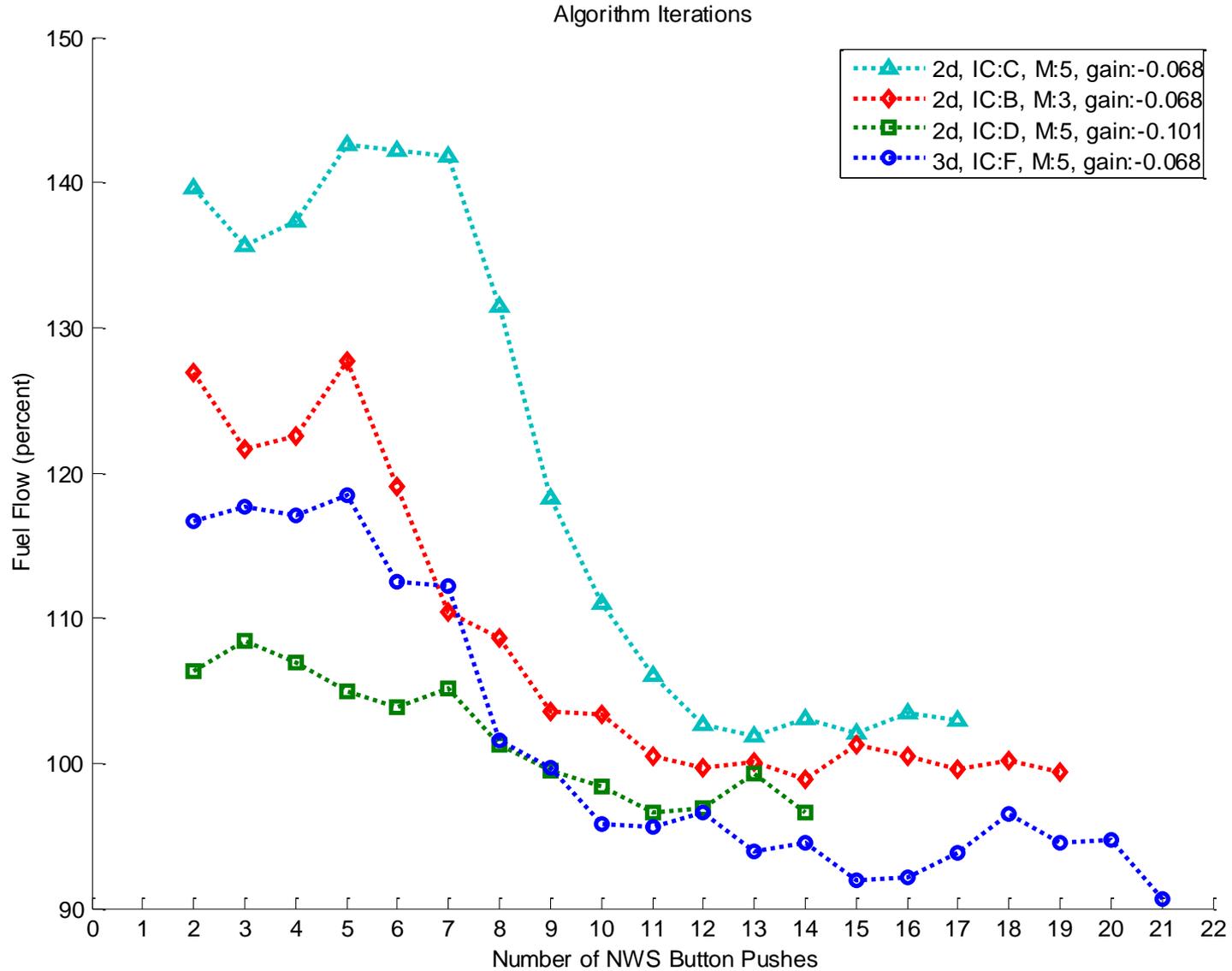
- Number of effectors (2D/3D mode)
- Initial trim bias, A through F
- Number of measurements fed to Kalman filter, M=3, 5, or 7
- Gain, 7 options from low to high

Flight 133 – First Algorithm-Engaged Flight
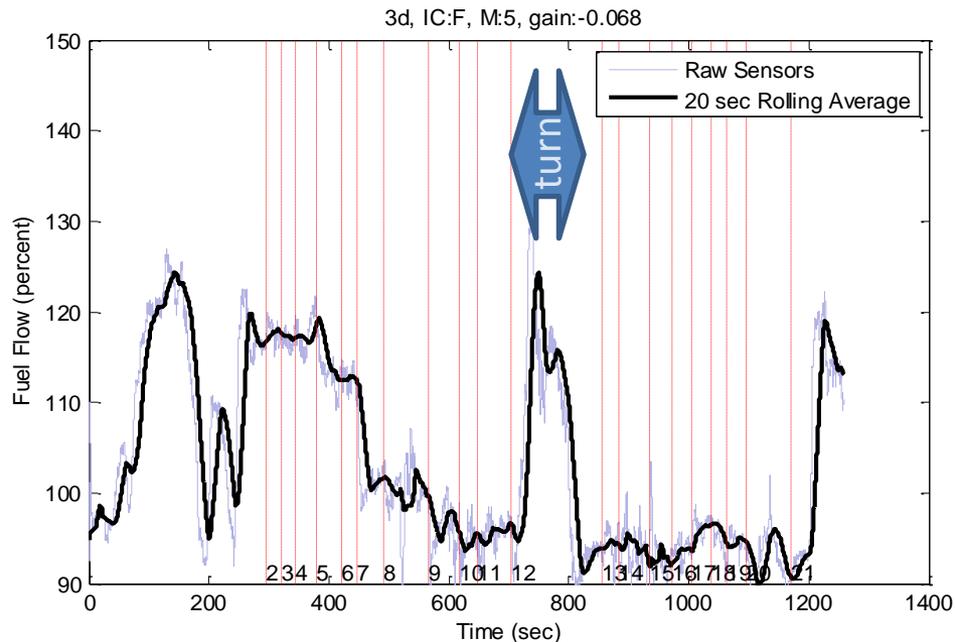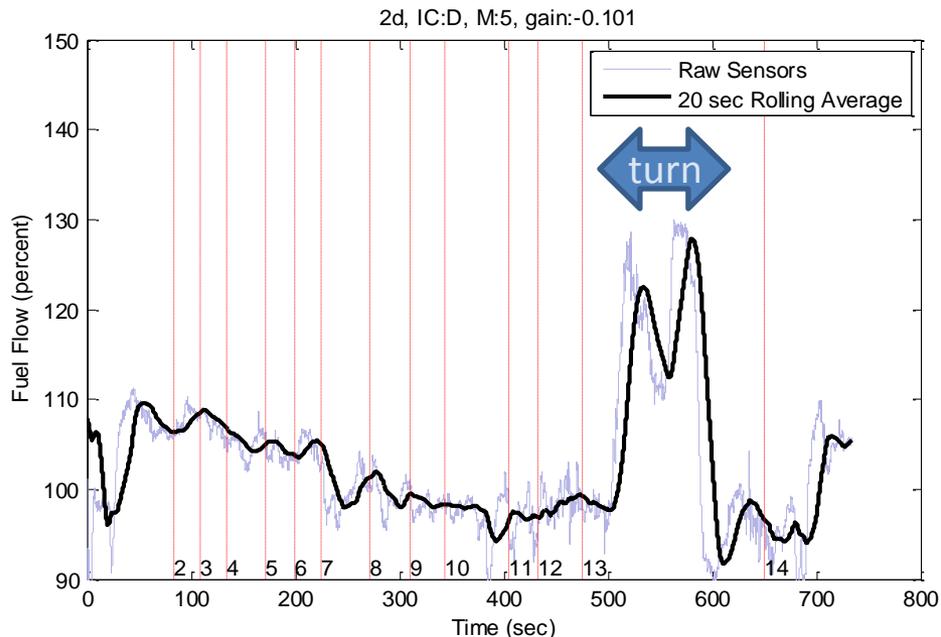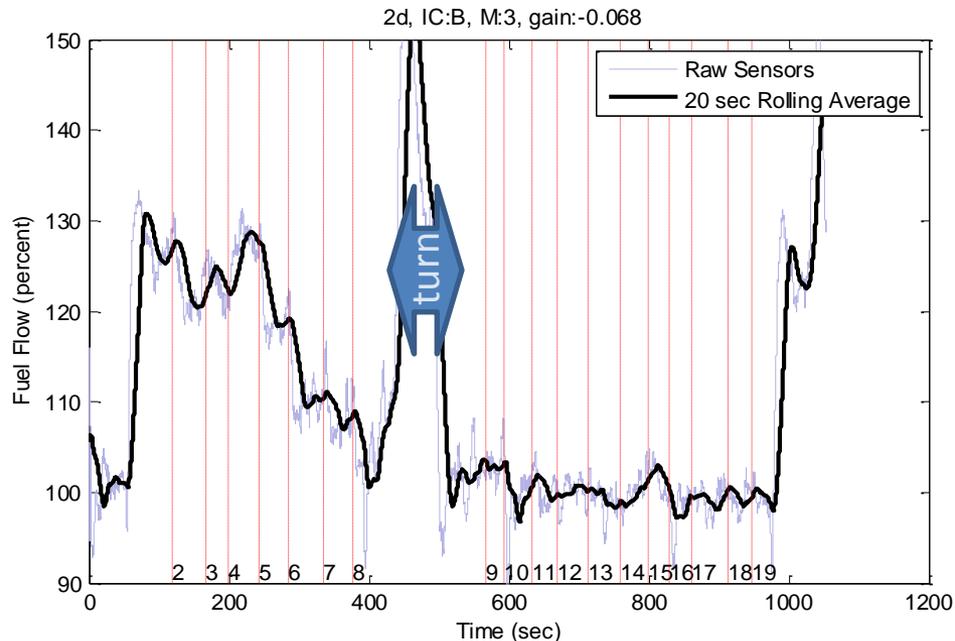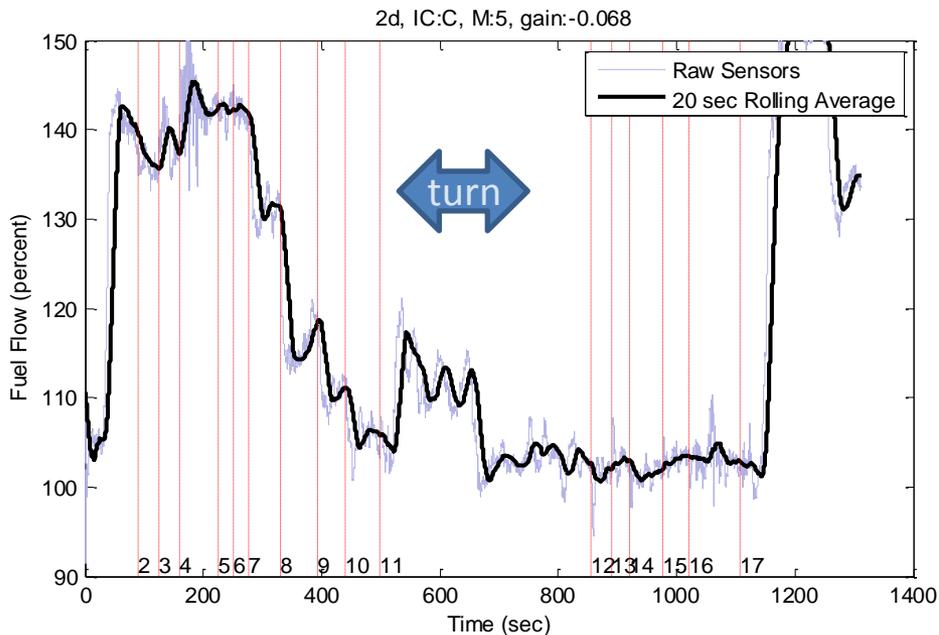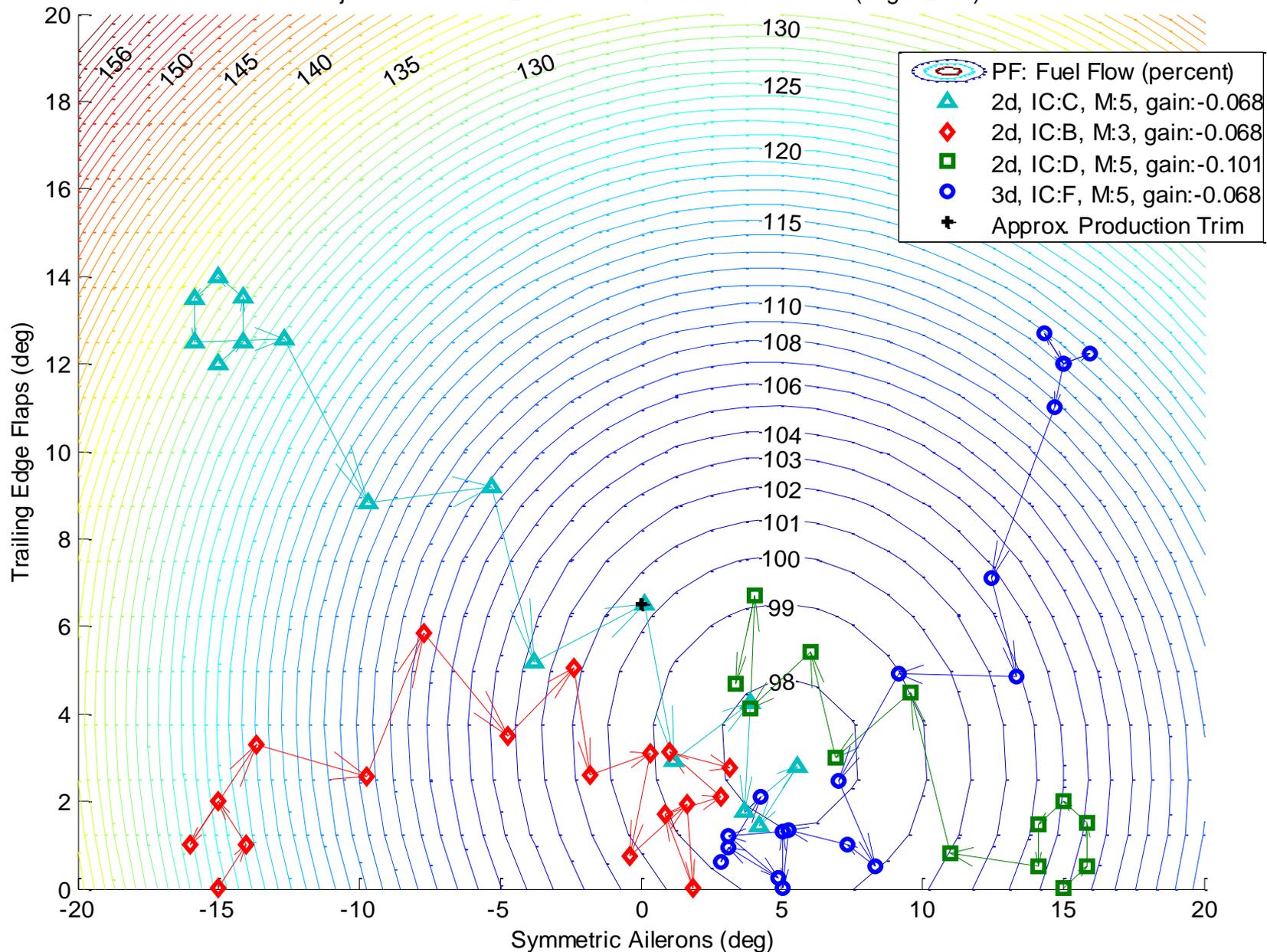
Flight 133: Algorithm Iterations

Note: Fuel flow should be de-trended to account for the airplane getting lighter due to fuel-burn.
This plot shows the raw results without de-trending.

Flight 133: Comparison to Estimated PF

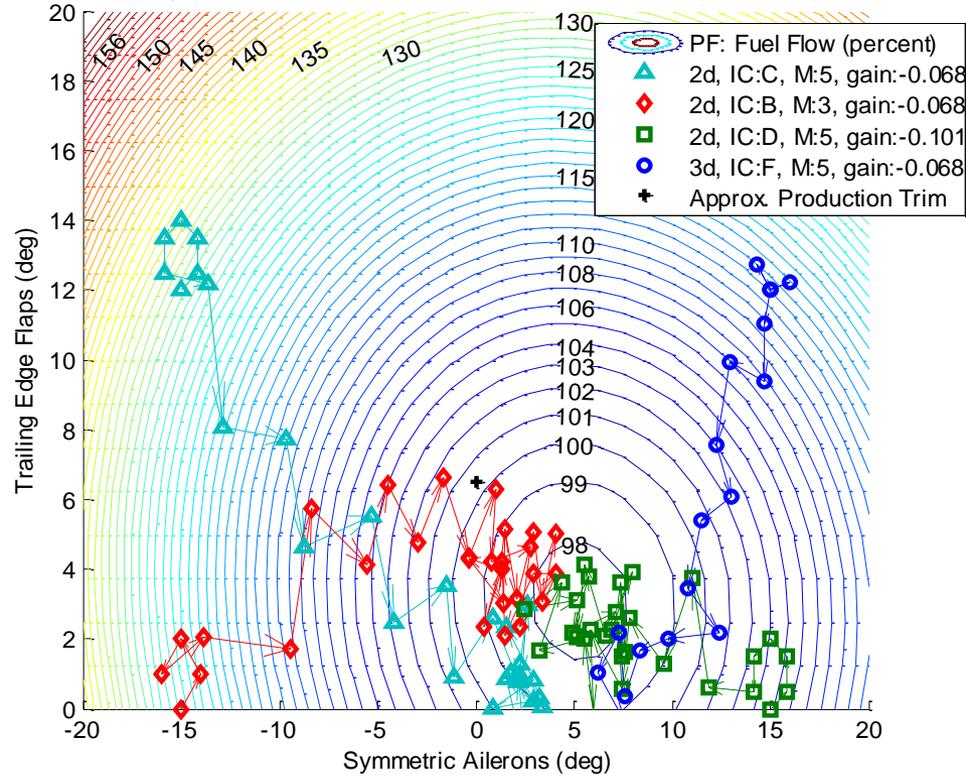Trajectories versus Estimated Performance Function (Flight Data)
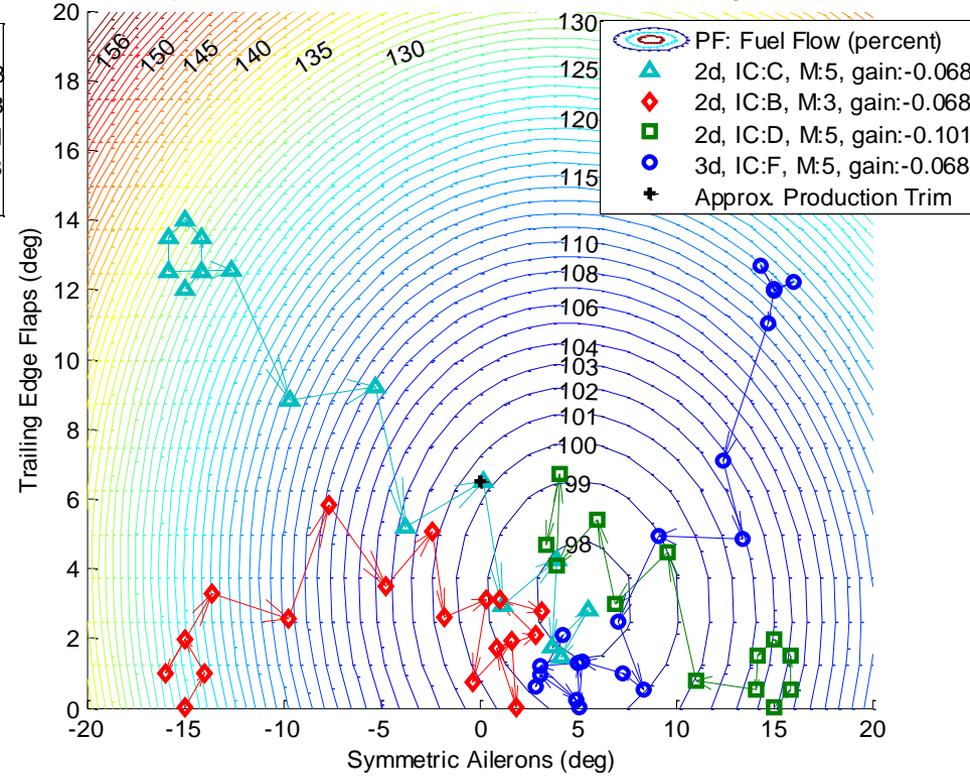
Predictions & Results

Simulation

Trajectories versus Estimated Performance Function (Simulation)
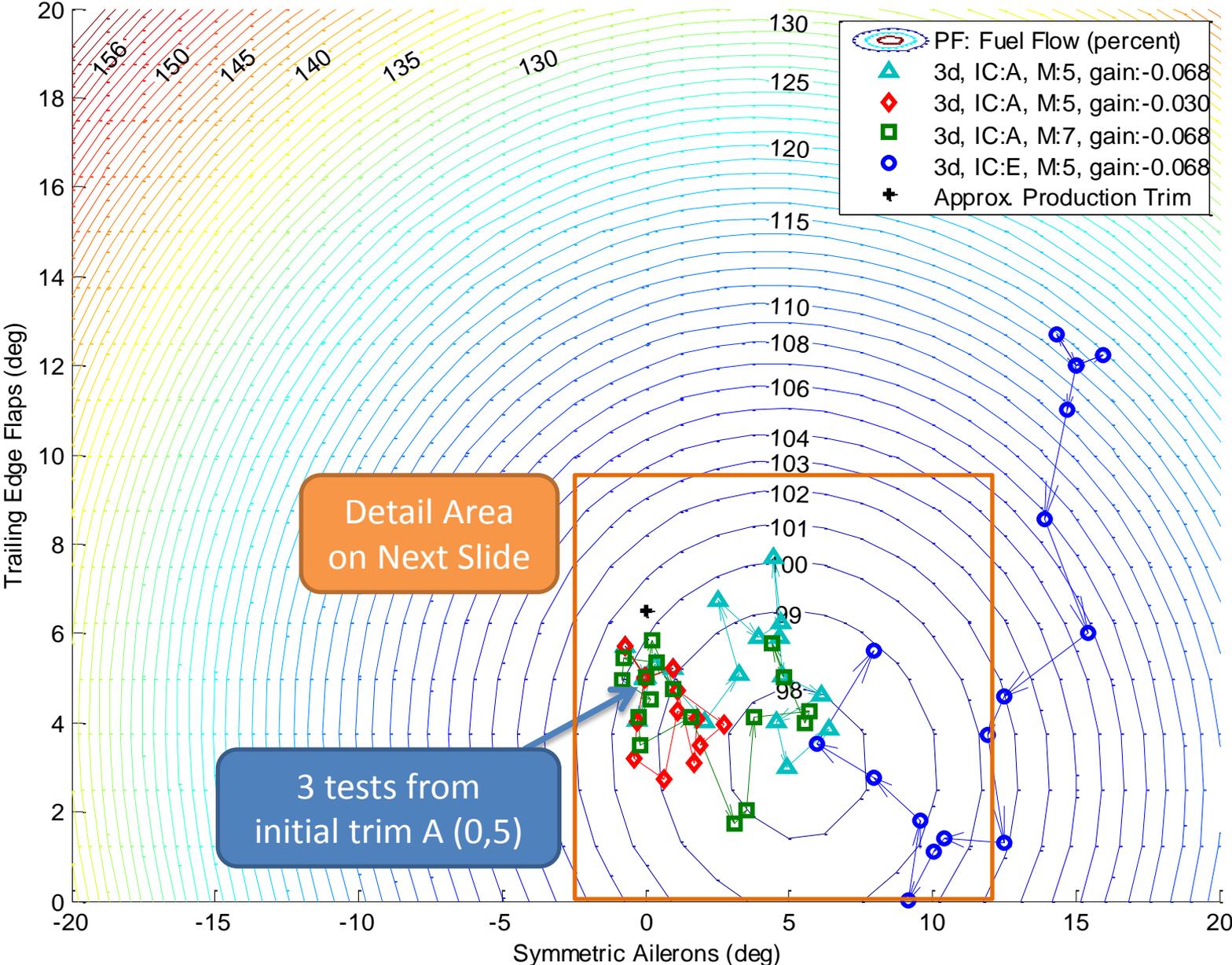
Flight

Trajectories versus Estimated Performance Function (Flight Data)

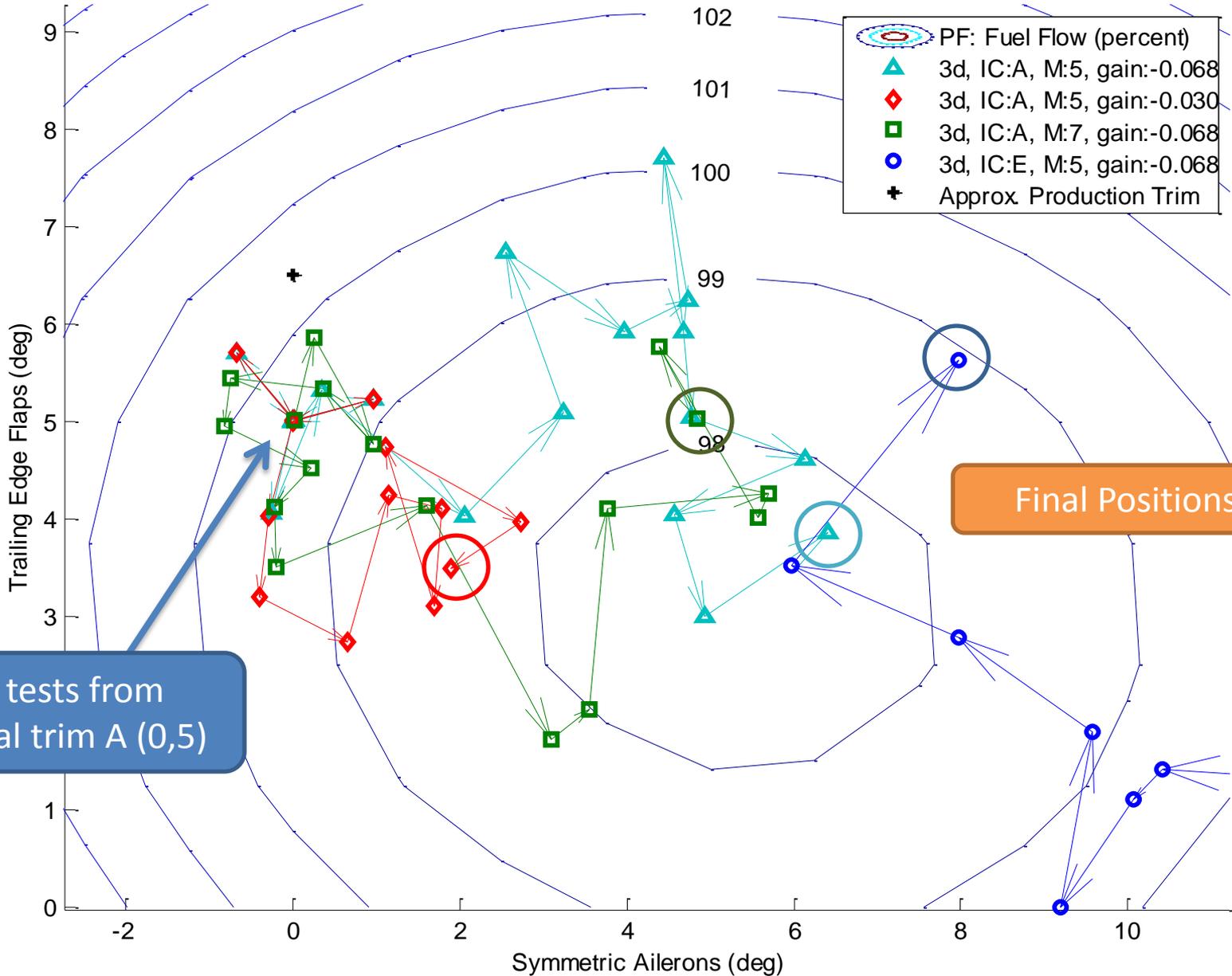# Flight 134 – Second Algorithm-Engaged Flight

Trajectories versus Estimated Performance Function (Flight Data)
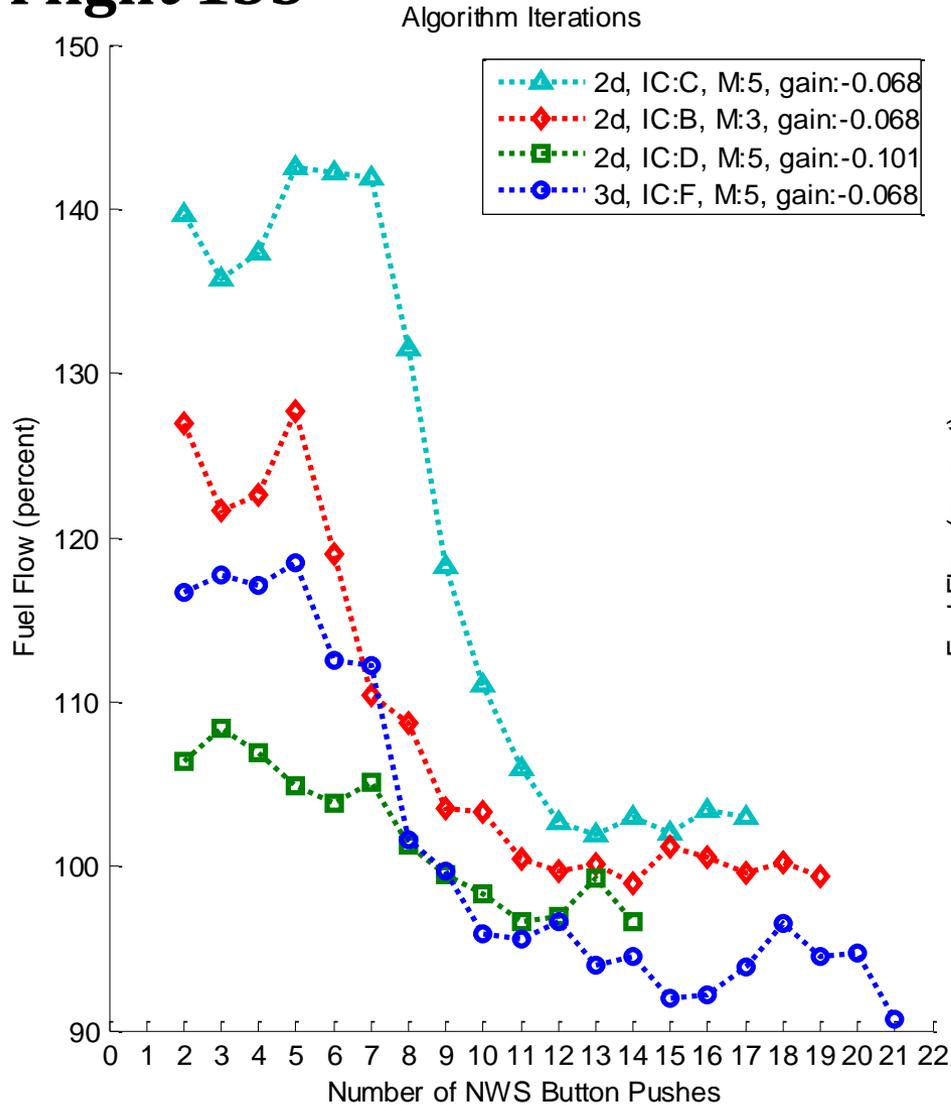
Flight 134: Detail

Comparison of Completed Flights

Flight 133

Algorithm Iterations

Legend:
- 2d, IC:C, M:5, gain:-0.068
- 2d, IC:B, M:3, gain:-0.068
- 2d, IC:D, M:5, gain:-0.101
- 3d, IC:F, M:5, gain:-0.068

Y-axis: Fuel Flow (percent)
X-axis: Number of NWS Button Pushes

Flight 134

Algorithm Iterations

Legend:
- 3d, IC:A, M:5, gain:-0.068
- 3d, IC:A, M:5, gain:-0.030
- 3d, IC:A, M:7, gain:-0.068
- 3d, IC:E, M:5, gain:-0.068

Y-axis: Fuel Flow (percent)
X-axis: Number of NWS Button Pushes
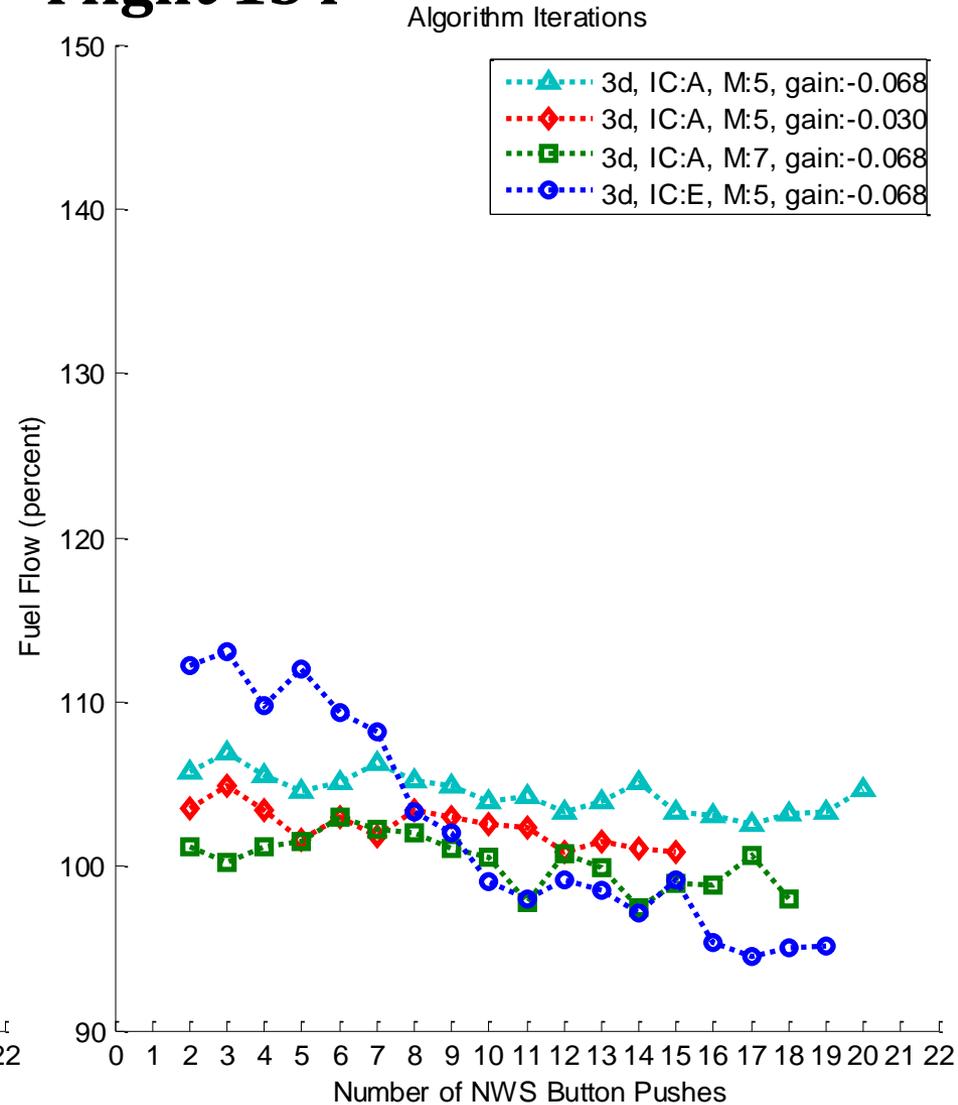
Near Term: Next Steps (now)

- Improve fine-tuning performance
  - Tune V and W covariance matrices in KF
  - Longer dwell times, more pre-filtering
  - More measurements (M) fed to Kalman filter
  - Reduce minimum Persistent Excitation (PE)

- Not a point-design
  - Fly slower, e.g. 200 knots (within the envelope approved for experiment)
  - Fly higher and lower

- Vary the configuration
  - Empty centerline tank, smokewinders
  - Speedbrake
  - Rudder toe-in

- Does it work with production sensors? (not research-quality)
  - Throttle position, stock fuel flow meters

Ideas for Future Work

- Expanded testing with current platform aircraft (FAST F-18):
  - Stores
  - High speed
  - Coordinate with other upcoming experiments (dual experiment flights)

- Transition to Transport-Class Airplane

- UAVs (Ikhana, etc.) – requires more automation.
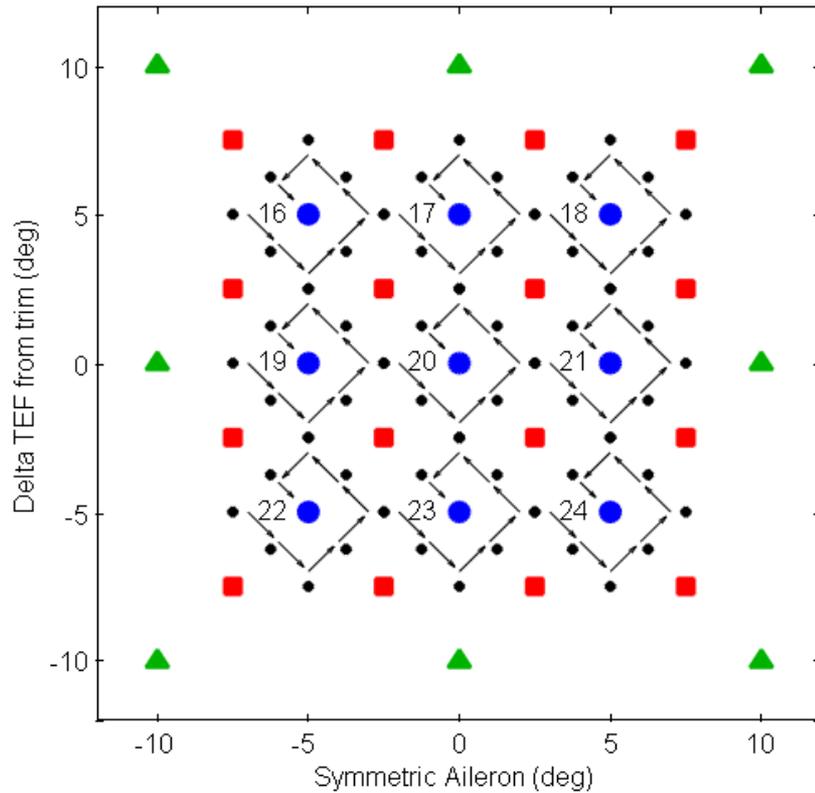
Questions and Discussion

BACKUP SLIDES

Performance Function Identification (PFI)

## Autopilot, Autothrottle Evaluation
Matrix of Trim Allocations

DAG: "Dial-A-Gain" mode selected by pilot to select experiment configuration.

Algorithm Flight Test Approach

- All test points at:
  - 25,000 ft (+/-2000ft)
  - 240 kts

- Initial ICP Evaluation at:
  - DAG 17: 2D Nominal Gain
  - CAT 17: IC-C, 5 Measurements

- Plan:
  - If DAG 17, CAT 17 is well behaved
    - Continue to evaluate the other 2D IC's
    - (DAG 17, CAT's 15-18)
  - If DAG 17, CAT 17 is not well behaved
    - Determine if behavior is related to gain or number of measurements(M)
   - Select DAG, CAT to attempt to improve behavior (different gain and number of measurements(M))
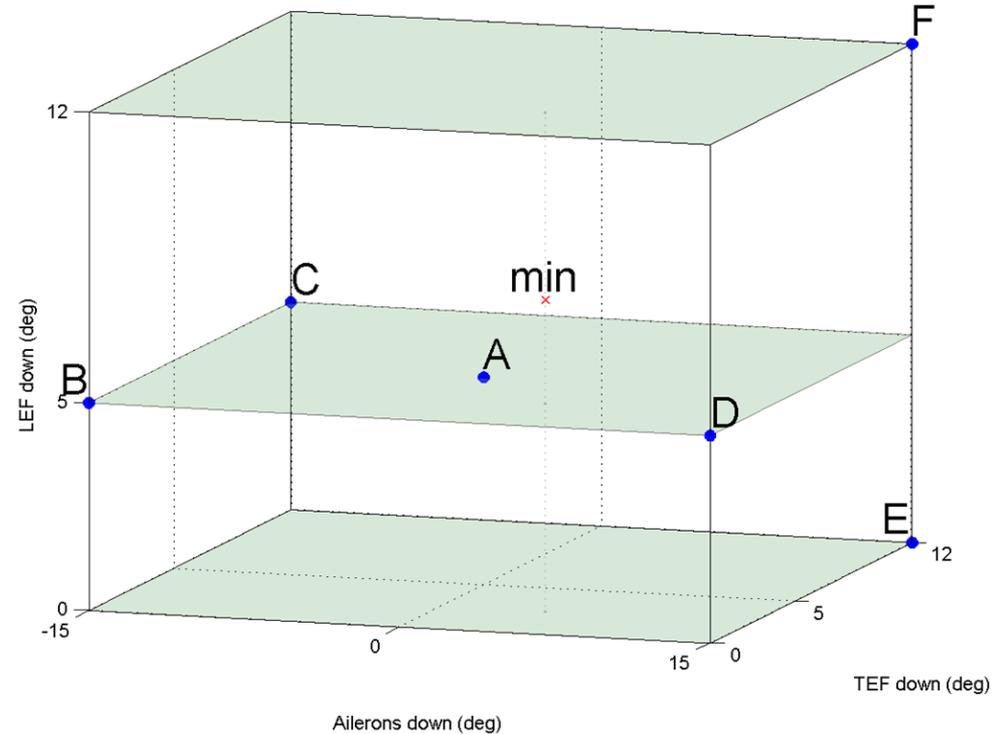
- Further ICP Evaluations (as time allows)
  - 3D Evaluations with same gain and number of measurements(M) as successful 2D
  - Evaluations with different gain sets and measurements(M) for both 2D and 3D

DAG		
Gain	2D	3D
-0.020	14	21
-0.030	15	22
-0.045	16	23
-0.068	17	24
-0.101	18	
-0.152	19	25
-0.228	20	

IC	Aileron	TEF	LEF	CAT		
				M=3	M=5	M=7
A	0	5	5	0	15	21
B	-15	0	5	10	16	22
C	-15	12	5	11	17	23
D	15	0	5	12	18	24
E	15	12	0	13	19	25
F	15	12	12	14	20	26

Flight Plan
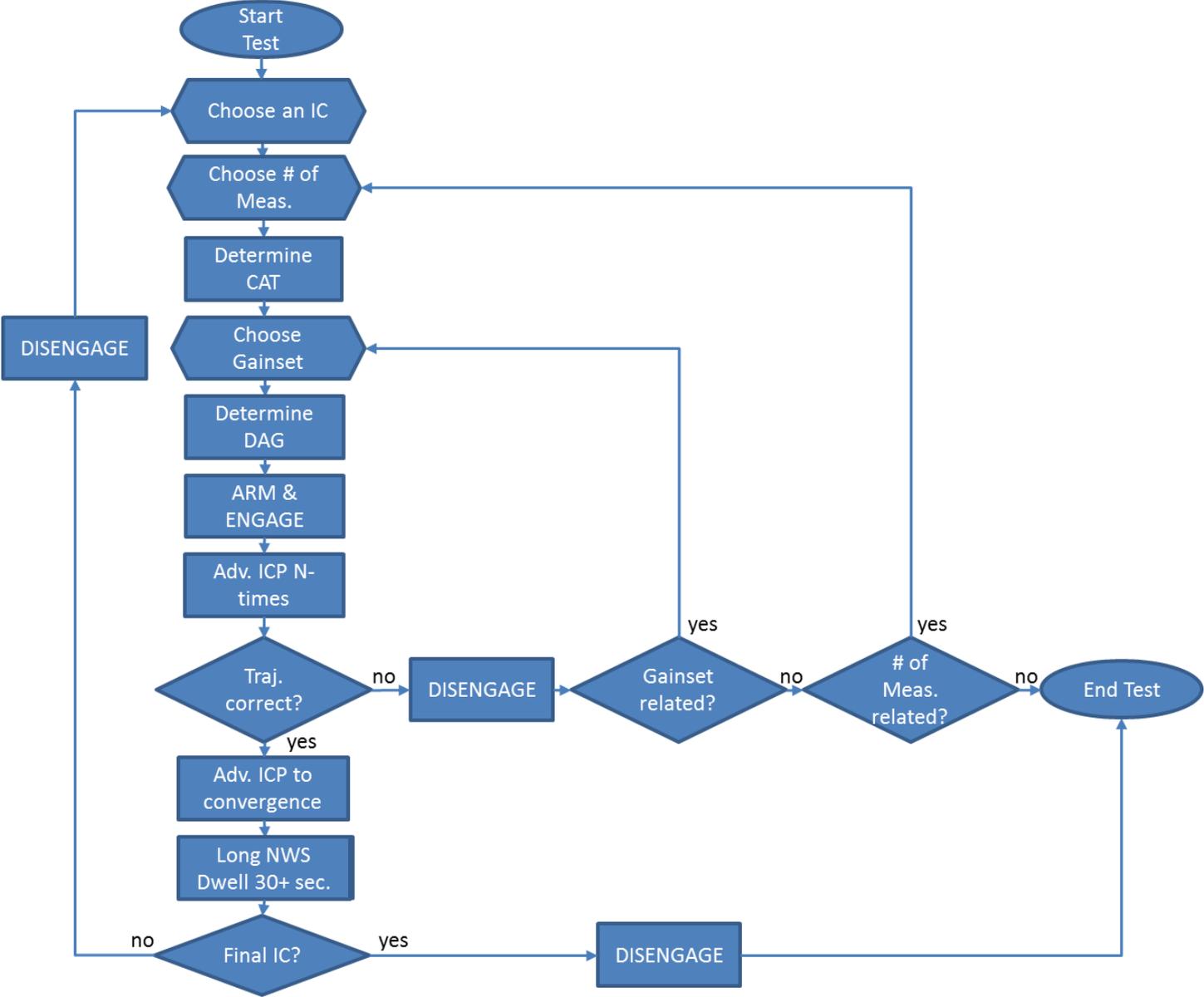
Pilots' Comments

- I did notice some low freq movement on the first ICP flight. It wasn't bad and eventually only noticed when I "looked for it". And when I "looked for it" I didn't always find it.