Lessons Learned
and
Flight Results
from the
F-15 Intelligent Flight Control System Project

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Project Participants

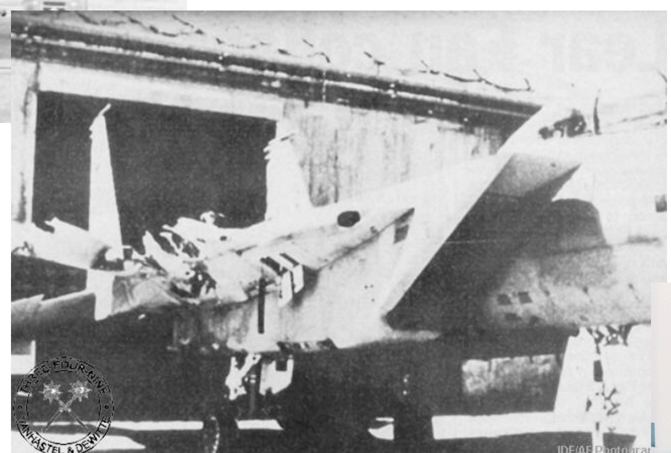
- **Nasa Dryden Flight Research Center**
  - Responsible test organization for the flight experiment
    - Flight, range and ground safety
    - Mission success
- **Nasa Ames Research Center**
  - Development of the concepts
- **Boeing STL Phantom Works**
  - Primary flight control system software (Conventional mode)
  - Research flight control system software (Enhanced mode)
- **Institute for Scientific Research**
  - Neural Network adaptive software
- **Academia**
  - West Virginia University
  - Georgia Tech
  - Texas A&M

F-15 IFCS Project Goals

- **Demonstrate Revolutionary Control Approaches that can Efficiently Optimize Aircraft Performance in both Normal and Failure Conditions**

- **Advance Neural Network-Based Flight Control Technology for New Aerospace Systems Designs**

Motivation



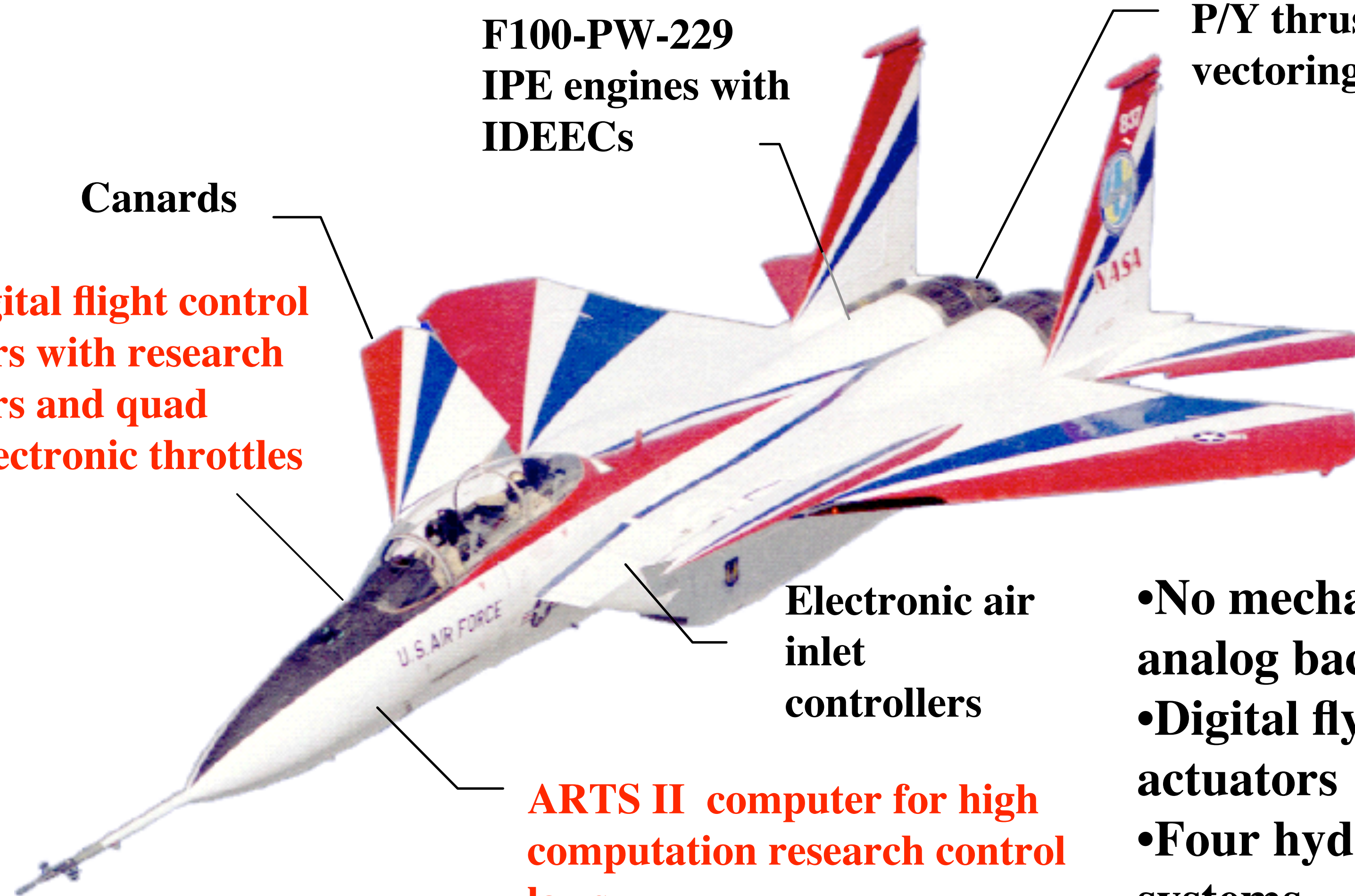
These are survivable accidents

IFCS has potential to reduce the amount of skill and luck required for survival

IFCS Approach

- Implemented on NASA F-15 #837 (SMTD and ACTIVE projects)
- Use Existing Reversionary Research System
- Limited Flight Envelope
- Failures Simulated by Frozen Surface Command (Stab) or Gain Modification on the Angle of Attack to Canard Feedback

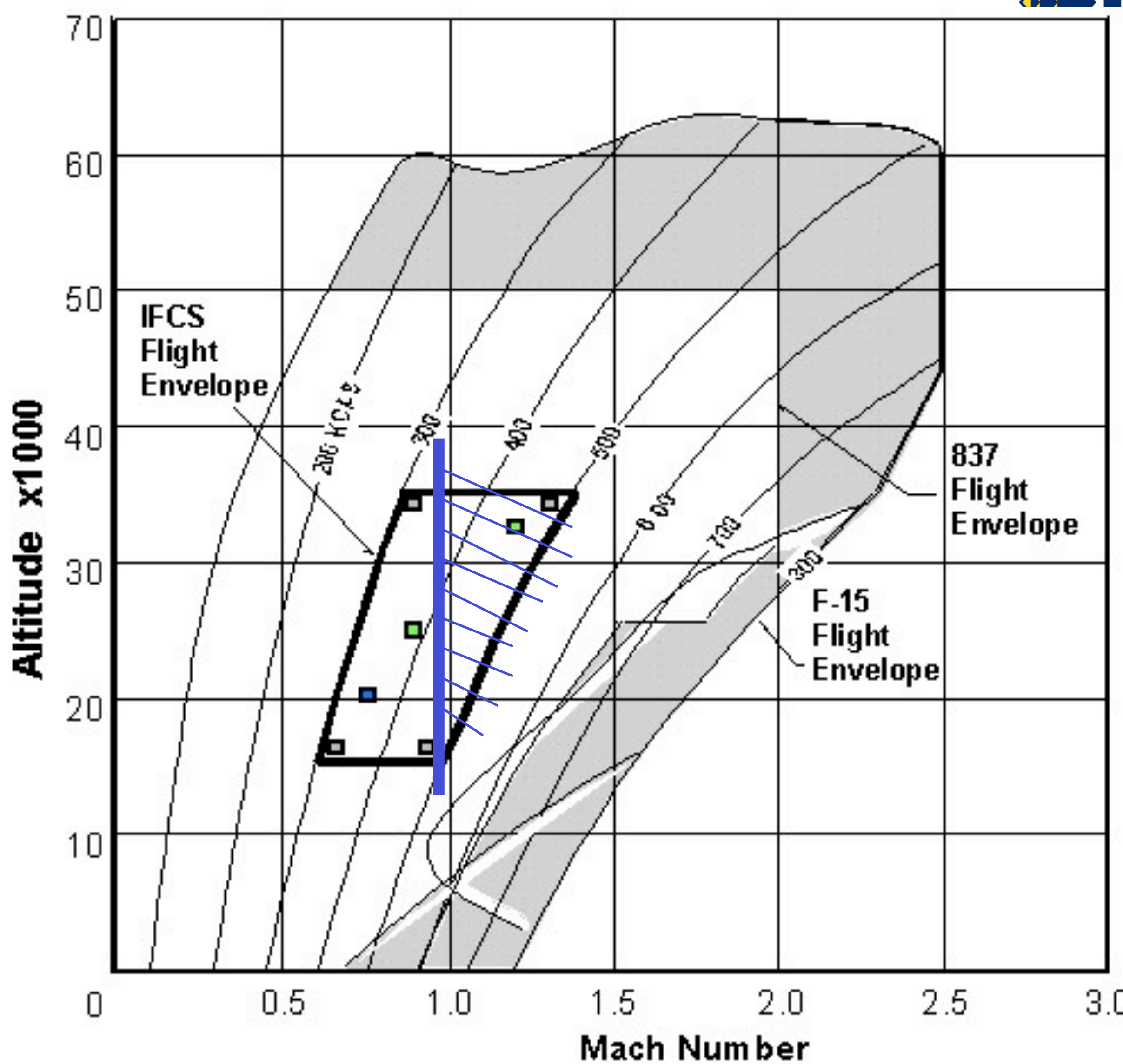
NASA F-15 #837 Aircraft Description



- No mechanical or analog backup
- Digital fly-by-wire actuators
- Four hydraulic systems

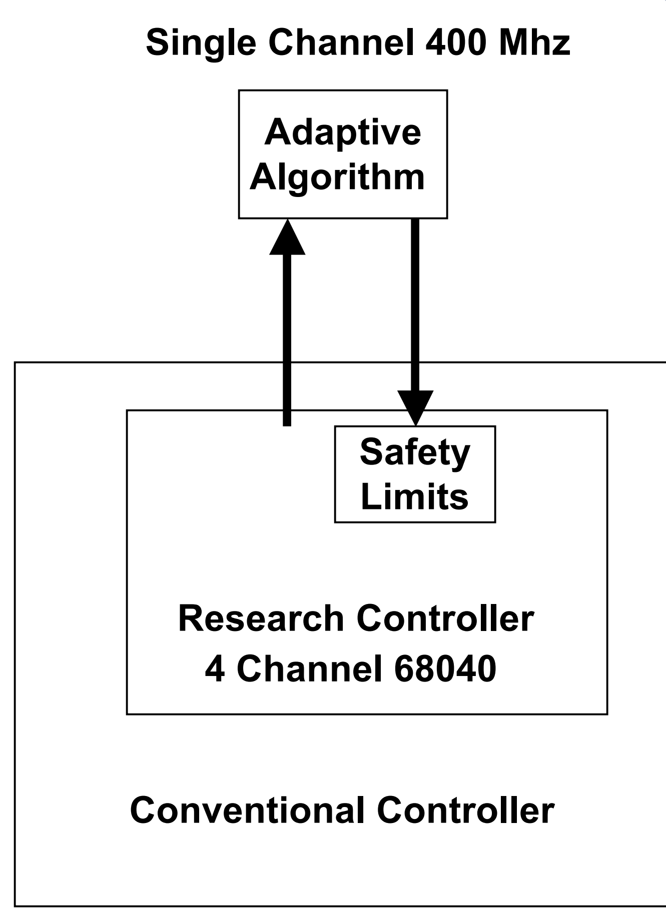
Flight Envelope

For Gen 2
Mach < 0.95

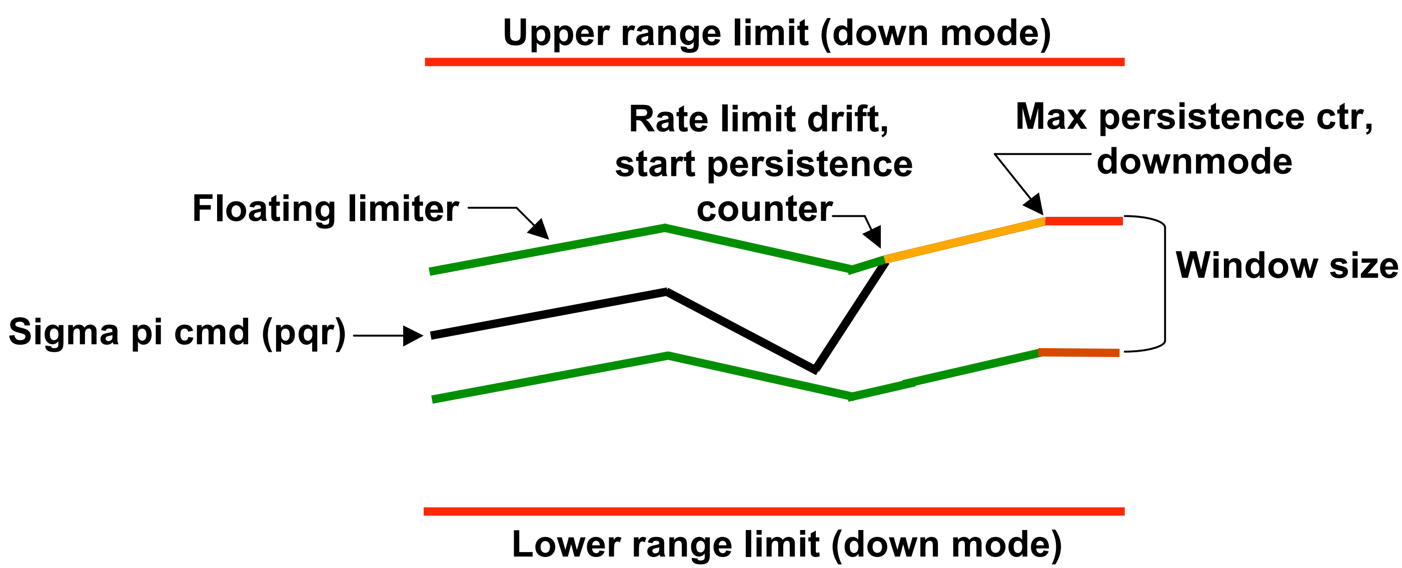


Limited Authority System

- Adaptation algorithm implemented in separate processor
  - Class B software
  - Autocoded directly from Simulink block diagram
  - Many configurable settings
    - Learning rates
    - Weight limits
    - Thresholds, etc.
- Control laws programmed in Class A, quad-redundant system
- Protection provided by floating limiter on adaptation signals



NN Floating Limiter



Black – sigma pi cmd
Green – floating limiter boundary
Orange – limited command (fl_drift_flag)
Red – down mode condition (fl_dmode_flag

Tunable metrics
- Window delta
- Drift rate
- Persistence limiter
- Range limits

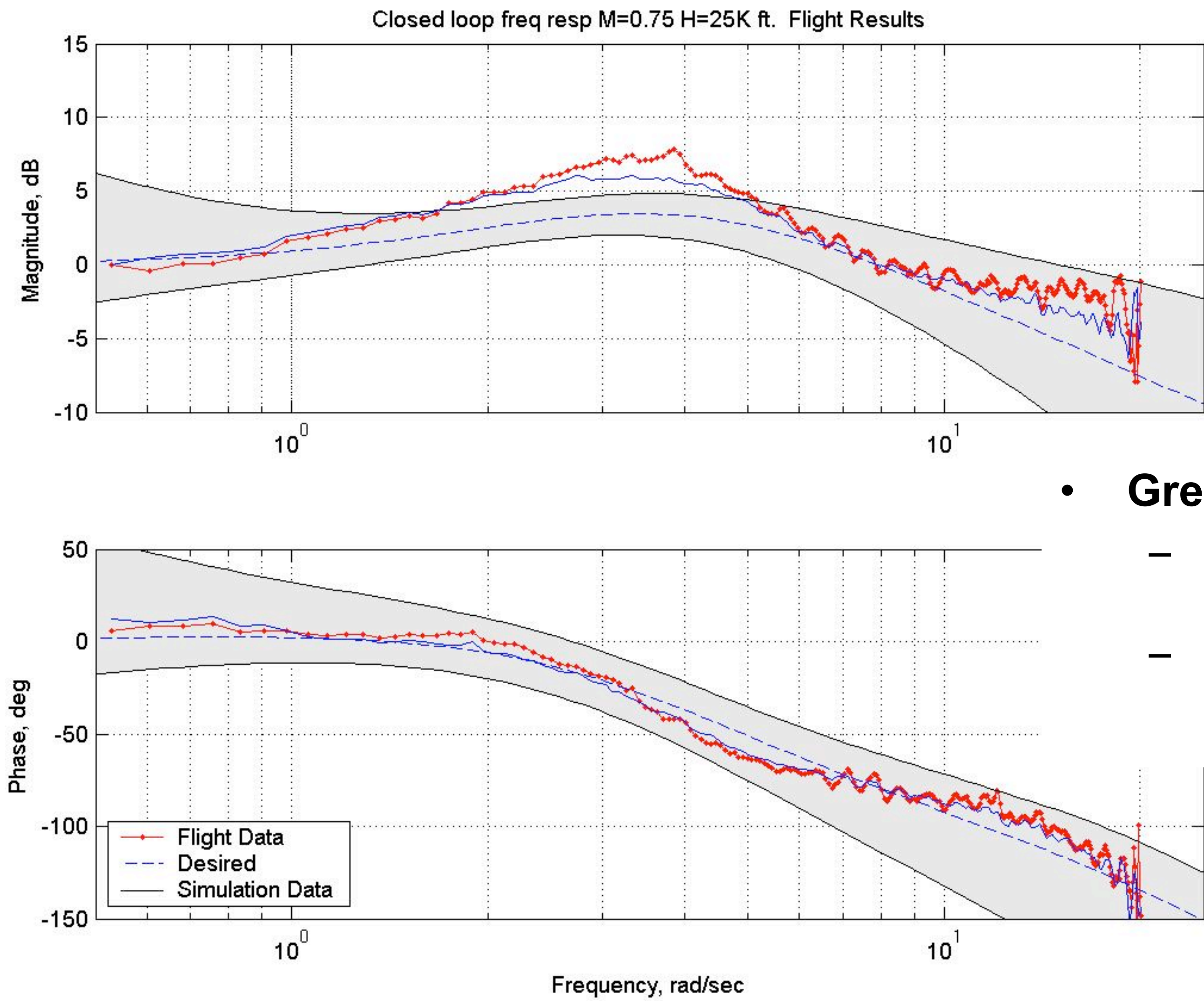
Flight Experiment

- Assess handling qualities of Gen II controller without adaptation
- Activate adaptation and assess changes in handling qualities
- Introduce simulated failures
  – Control surface locked (“B matrix failure”)
  – Angle of attack to canard feedback gain change (“A matrix failure”)
- Re-assess handling qualities with simulated failures and adaptation.
- Report on “Real World” experience with a neural network based flight control system

Adaptation Goals

- Ability to suppress initial transient due to failure
  - Trade-off between high learning rate and stability of system
- Ability to re-establish model following performance
- Ability to suppress cross coupling between axes
  - No existing criteria

Handling Qualities Performance Metric



- **Grey Region:**
  - **Based on model-to-be-followed**
  - **Maximum noticeable dynamics (LOES)**

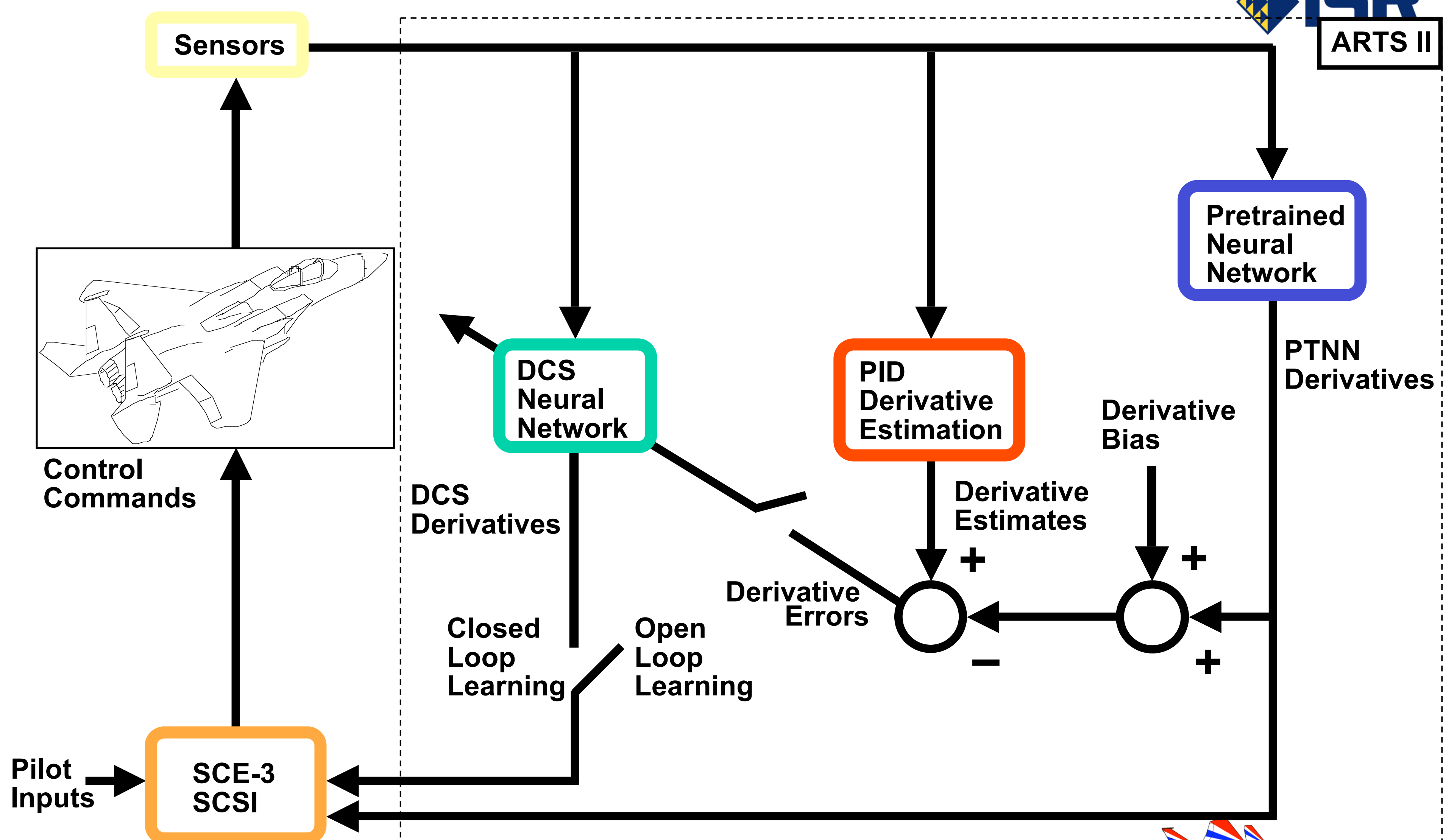
Project Phases

- Funded
  - Gen 1 Indirect adaptive system
    - Identify changes to “plant”
    - Adapt controls based on changes
    - LQR model based controller (online Ricatti solver)
  - Gen 2 Direct adaptive
    - Feedback error drives adaptation changes
    - Dynamic inversion based controller with explicit model following
- Future Potential
  - Gen 2+ Different Neural Network approaches
    - Single hidden layer, radial basis, etc
  - Gen 3 adaptive mixer and adaptive critic

Generation 1

Indirect Adaptive System

Indirect Adaptive Control Architecture



Indirect Adaptive
Experience and Lessons Learned

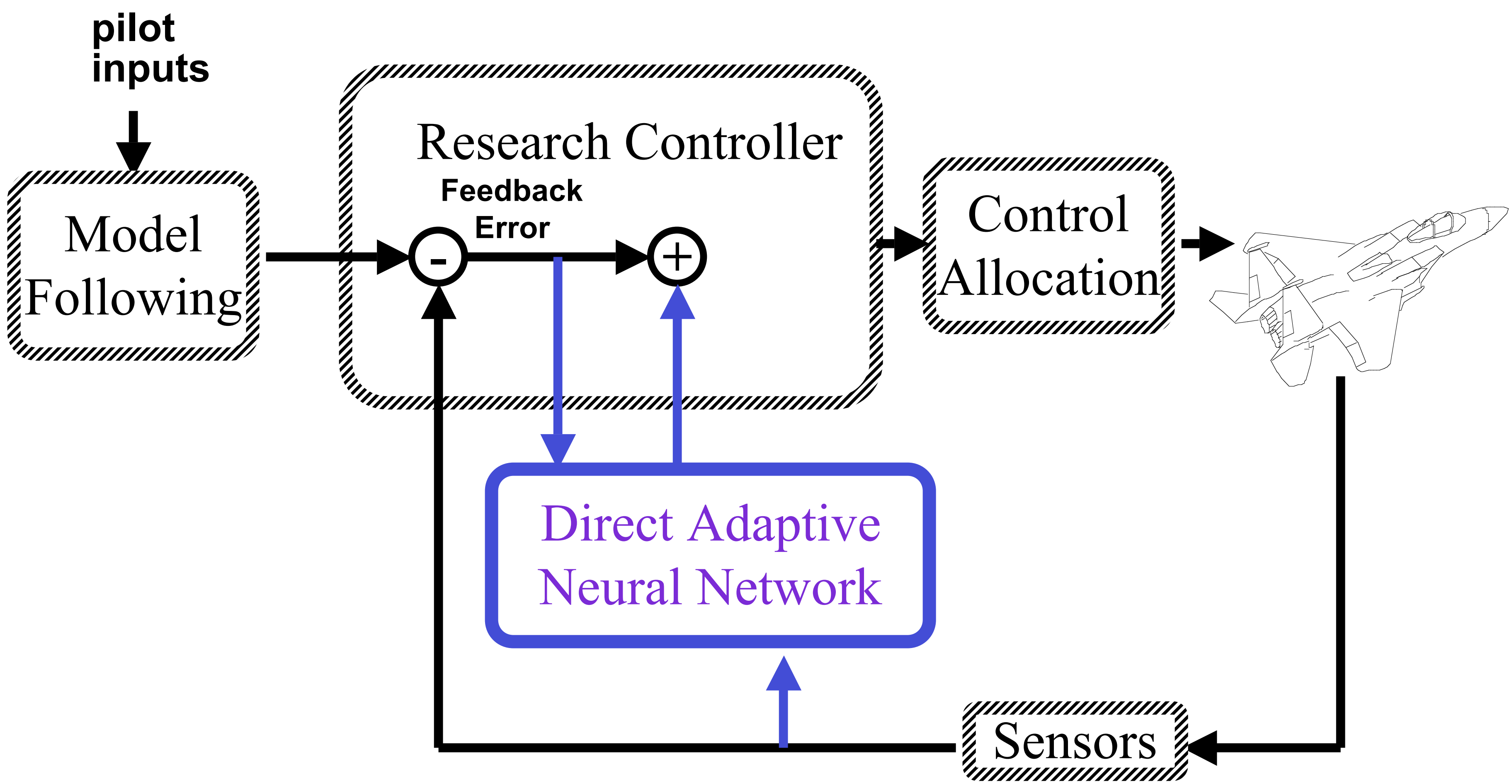
- System flown in 2003 – Open loop only

- Gain calculation sensitive to identified derivatives
  - Uncertainty in estimated derivative too high
- Difficult to estimate derivatives from pilot excitation
  - Normally correlated surfaces
  - Better estimation available with forced excitation
- Many derivatives required for full plant estimation However more are required when LatDir couples with Long
- No immediate adaptation with failure
  - Requires period of time before new plant can be identified
- Indirect adaptive might be more suited for clearance of new vehicles rather than failure adaptation

Generation 2

Direct Adaptive System

Gen II Direct Adaptive Control Architecture
(Adaptive)

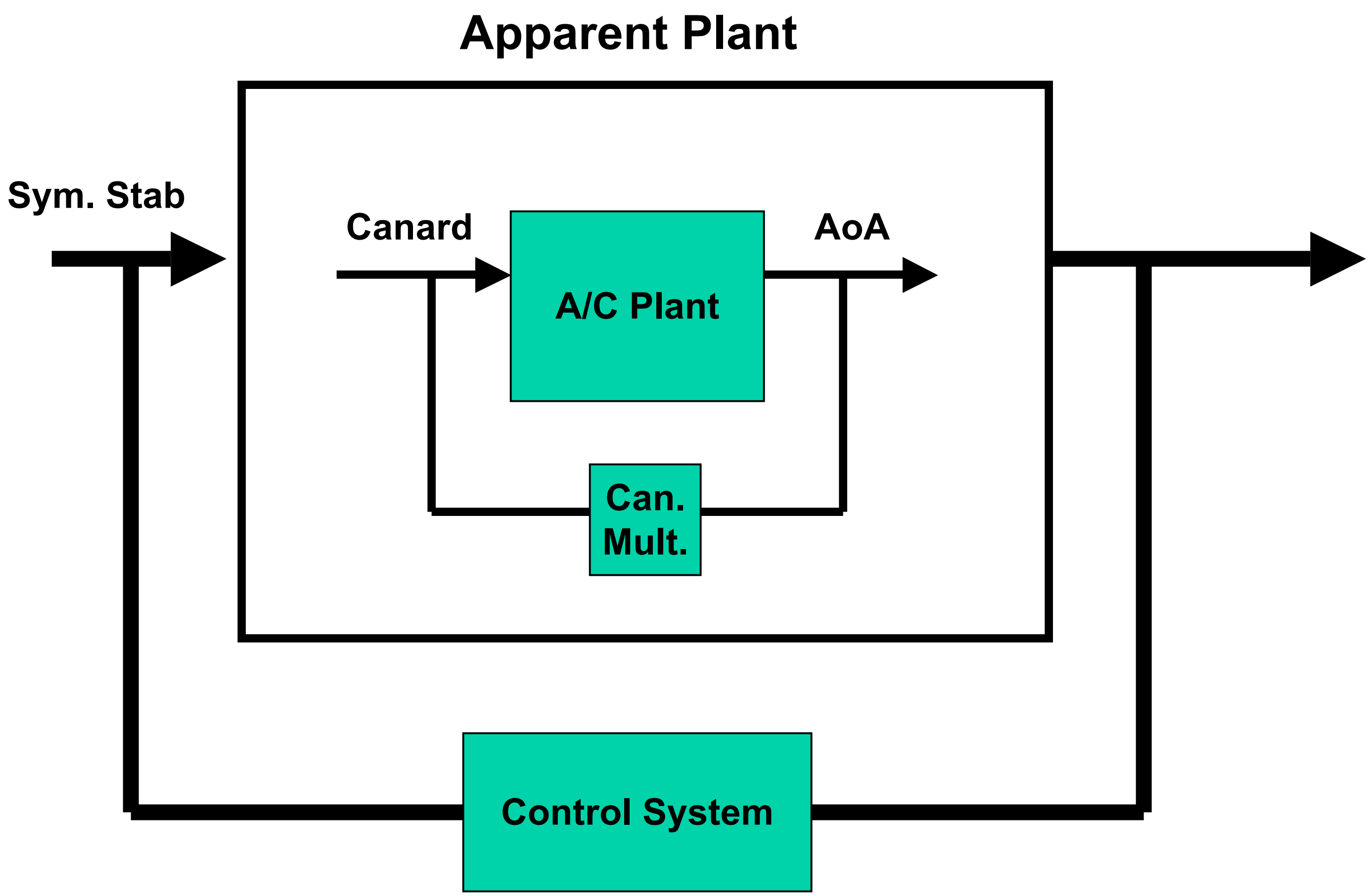


Current Status

- **Gen 2**
  - Currently in flight test phase
  - Simplified Sigma-Pi neural network
    - No higher order terms
    - Limits on Weights

Qdot_c = Q_err*Kpq*[1 – W1 – W2]
+ Q_err_int*Kiq*[1 - W1 – W3]
+ Q_err_dot*Kqd*[1 – W1]

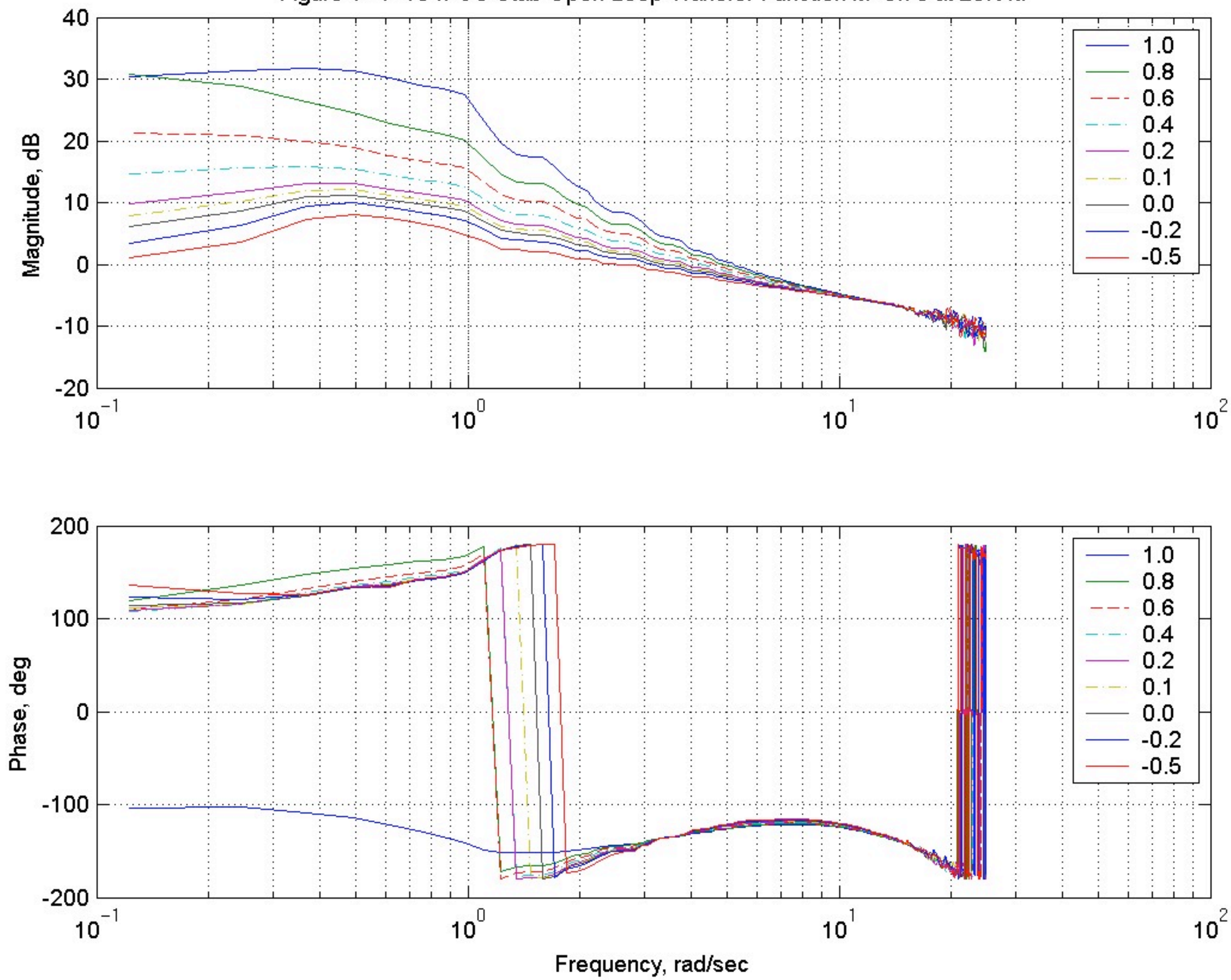
Effect of Canard Multiplier



Simulated Canard Failure

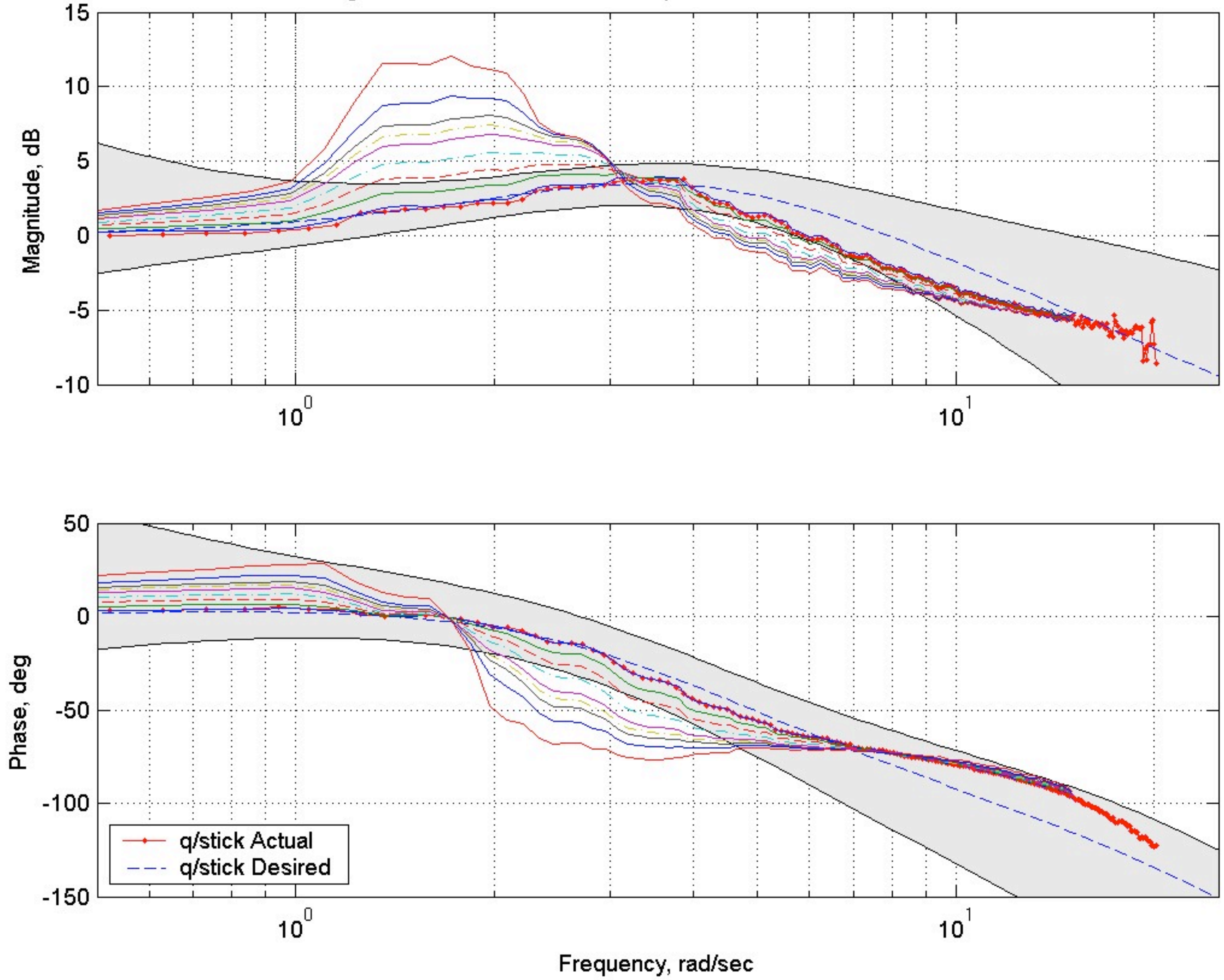
Stab Open Loop

Figure 1 - F-15 IFCS Stab Open Loop Transfer Function M=0.75 at 20K ft.

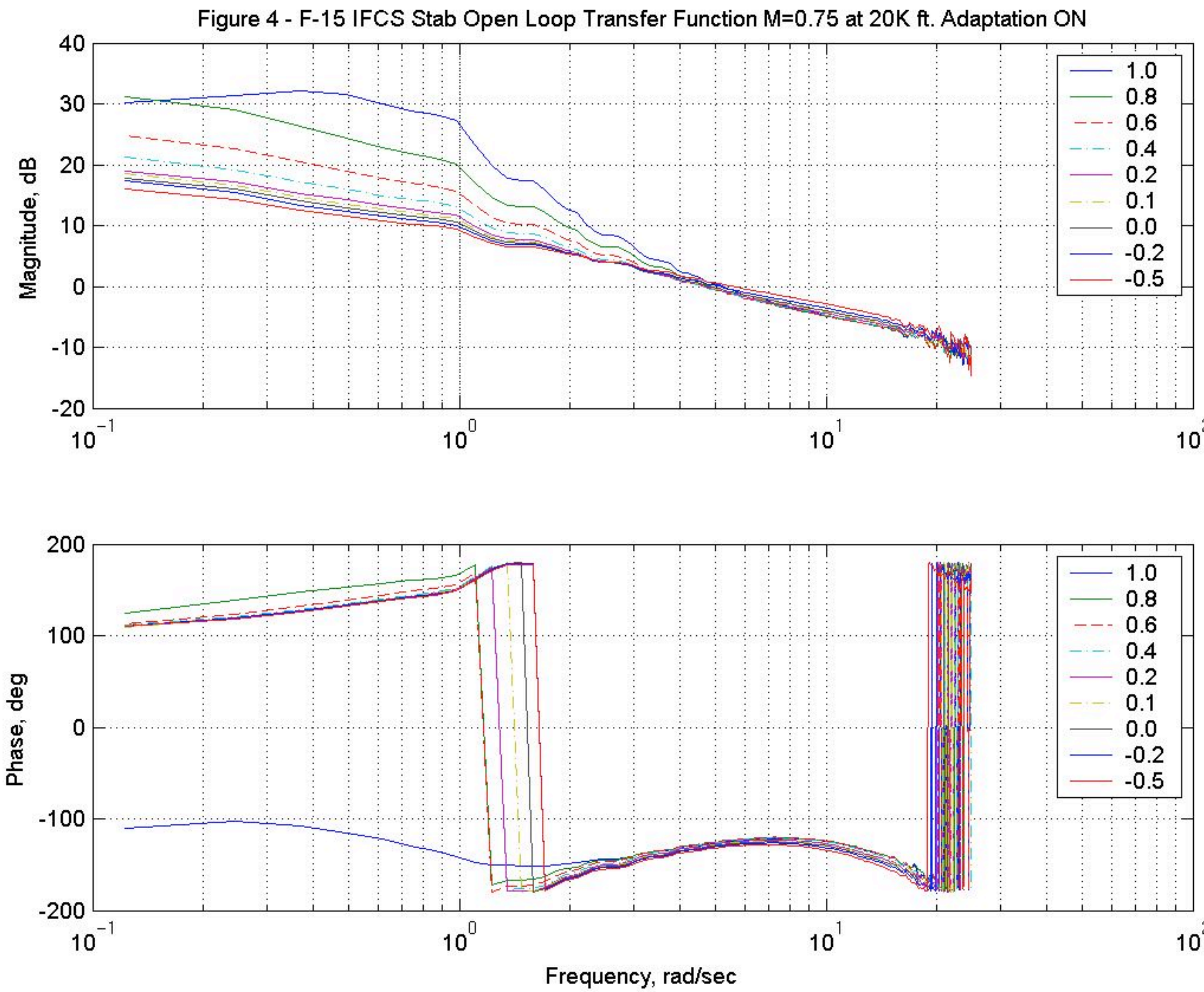


Canard Multiplier Effect
Closed Loop Freq. Resp.

Figure 3 - F-15 IFCS Closed Loop Technical Performance Metric

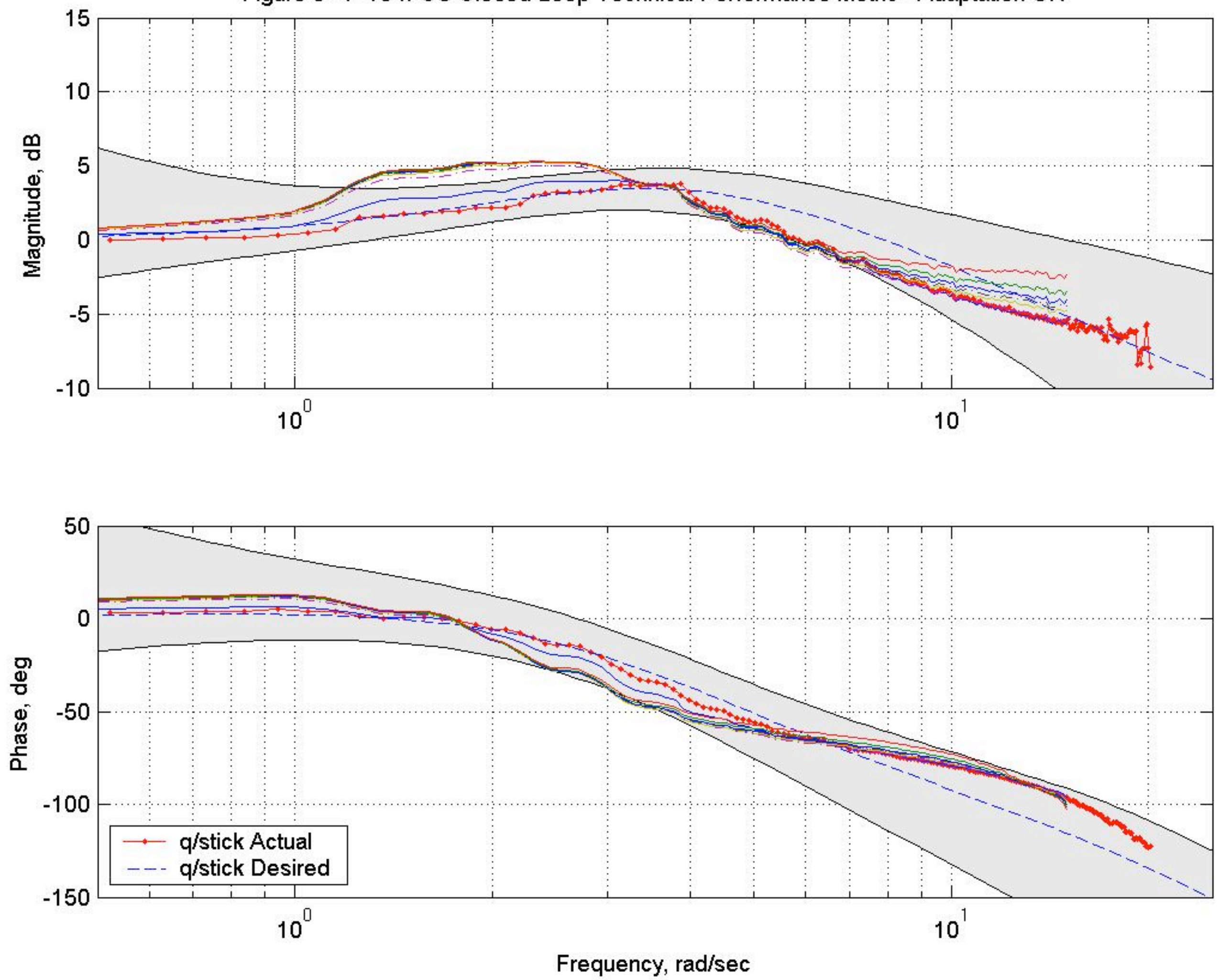


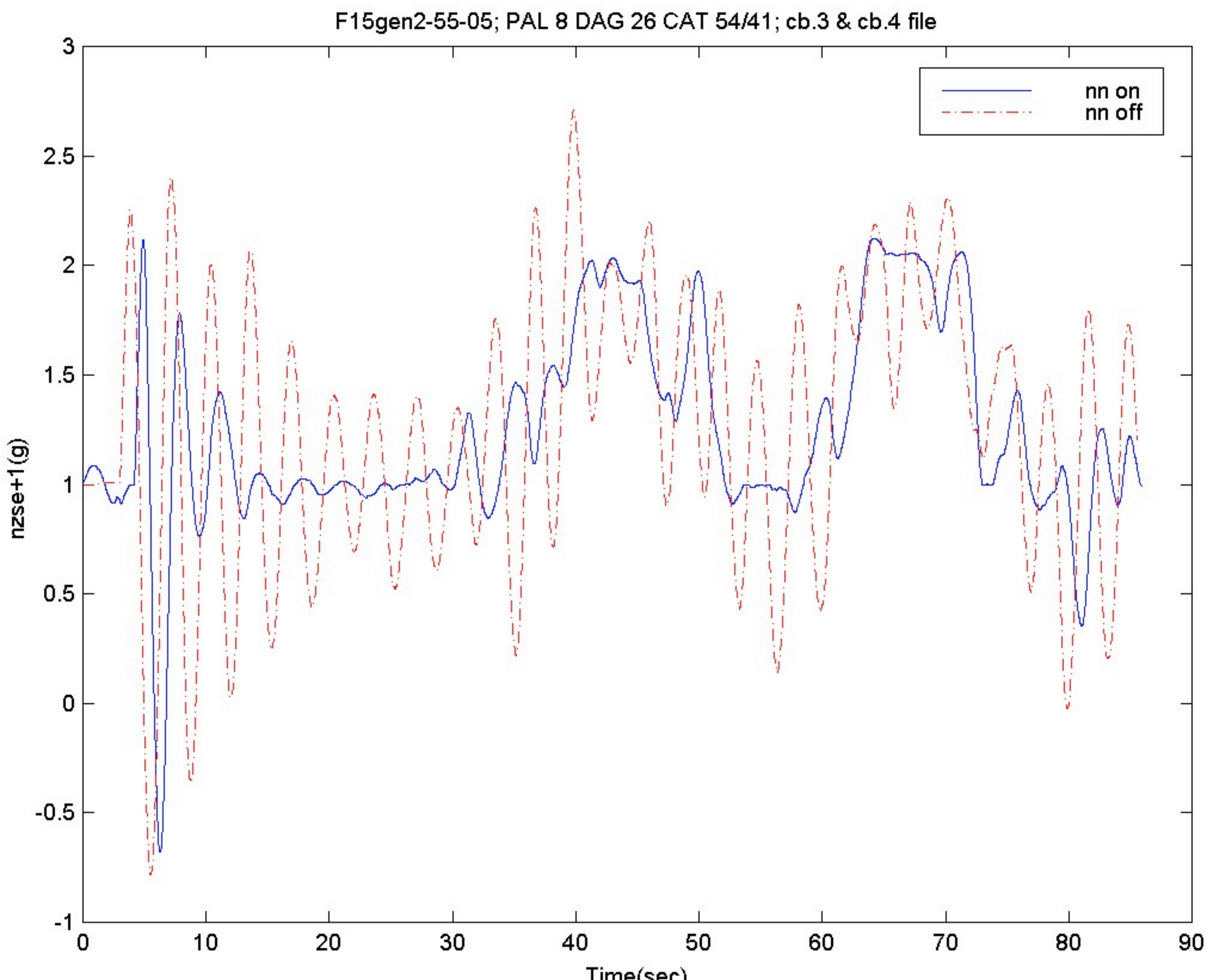
Simulated Canard Failure
Stab Open Loop with Adaptation



Canard Multiplier Effect
Closed Loop with Adaptation

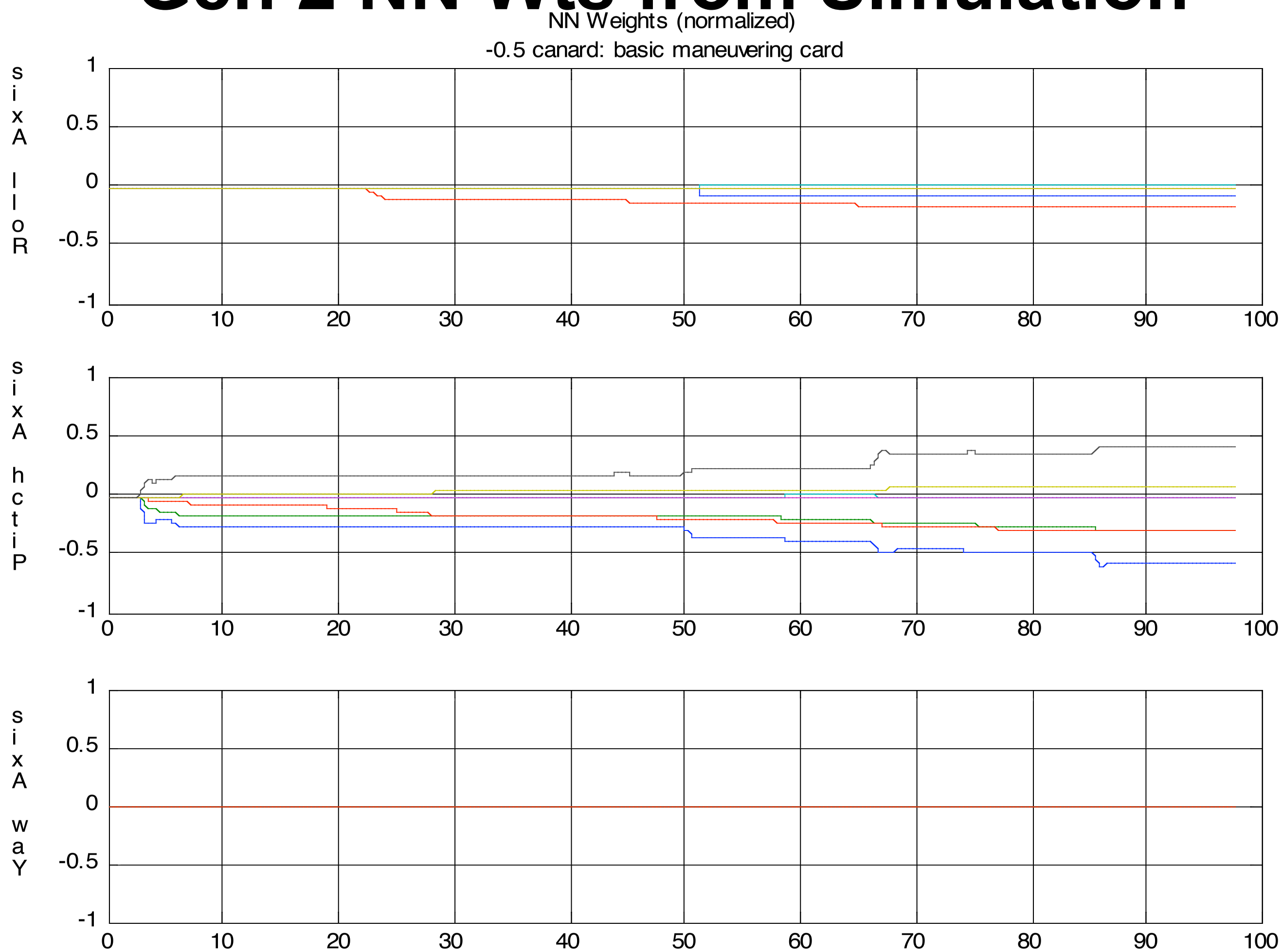
Figure 5 - F-15 IFCS Closed Loop Technical Performance Metric - Adaptation ON





-0.5 canard multiplier at flight condition 1; with & without neural networks

Gen 2 NN Wts from Simulation



Direct Adaptive
Experience and Lessons Learned

- **Initial simulation model had high bandwidth**
  - **Majority of system performance achieved by the dynamic inversion controller**
  - **Direct adaptive NN played minor role**
- **Dynamic Inversion gains reduced to meet ASE attenuation requirements**
  - **Much harder to achieve desired performance**
  - **NN contribution increased**
- **Initial performance objective emphasized transient reduction and achieving model following after failure**
  - **Piloted simulation results showed that reducing cross coupling was more important objective**
- **Explicit cross terms in NN required for failure cases**
  - **Relying on disturbance rejection alone doesn't work (also finding of Gen 1)**

Direct Adaptive
Experience and Lessons Learned

- Liapunov proof of bounded stability
  - Necessary but not sufficient proof of stability
  - Many cases of limit cycle behavior observed
  - Other analytic methods required for ensuring global stability
- Dynamic Inversion controller contributes significantly to cross coupled response in presence of surface failure (locked)
  - Redesigned yaw loop using classical techniques
- NN's require careful selection of inputs
  - Presence of transient errors "normal" for abrupt inputs in non-adaptive systems
  - Existence of transient errors tend to drive NN's to "high gain" trying to achieve impossible
- Significant amount of "tuning" required for to achieve robust full envelope performance
  - Contradicts claim of robustness to unforeseen failures
  - Piloted nonlinear simulation required

Conclusions

- Adaptive controls status
  - Currently collecting “real world” flight experience
  - Interactions with structure biggest challenge
  - Fruitful area for future research
- F-15 IFCS project is providing valuable research to promote adaptive control technology to a higher readiness level