F-15 IFCS
Intelligent Flight Control System

John Bosworth
Project Chief Engineer
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
NASA NF-15B Tail Number 837

Extensively modified F-15 airframe

- ARTS II computer for added computational capability (Neural Network algorithm)
- Canards
- Thrust vectoring nozzles
- Quadraplex digital flight control system
- No mechanical or analog backup
- Research control law processor (Enhanced Mode)
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

Upper range limit (down mode)

Floating limiter
Rate limit drift, start persistence counter
Max persistence ctr, downmode
Window size

Lower range limit (down mode)

Sigma pi cmd (pqr)

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
Gen I Indirect **Adaptive**
Control Architecture

- Model Following
- Online Parameter Estimation
- Online Riccati Solver
- Control Allocation

Pilot inputs

Sensors

LQR-Based Research Controller
Gen II Direct Adaptive Control Architecture

- Model Following

\[ \text{pilot inputs} \rightarrow \text{Model Following} \rightarrow \text{Dynamic Inversion – Based Research Controller} \]

- Feedback Error

\[ \text{Direct Adaptive Neural Network} \]

\[ \text{Sensors} \rightarrow \text{Control Allocation} \]

- Dynamic Inversion – Based Research Controller

\[ \text{Feedback Error} \]

\[ \text{Control Allocation} \]

- Gen II Direct Adaptive Control Architecture
Simplified Sigma-Pi Neural Network
Pitch Axis

Pitch Forward Path Com. → WQ1
Pitch Proportional Error → WQ2
Pitch Integral Error → WQ3
Roll Forward Path Com. → WQ4
Yaw Forward Path Com. → (0.0) WQ5
Bias Term → 1.0 WQ6
Angle of Attack → WQ7

Pitch Adaptation

Weight Update Law:
\[
\dot{W} = -G(U_{err}B_a + LU_{err}W)dt
\]

- Deadzones on weight update inputs
- Weight limits
Simulated Destabilization
A-Matrix Failure
Canard Multiplier – “An A-Matrix Failure”

Changing this multiplier changes the stability of the apparent plant.
Flight Results – Failure with No Adaptation
Stability Margin Trends
Symmetric Stab Loop, NN Off

Gain Margin (dB)

Phase Margin (deg)

Canard Multiplier

simulation

flight data

flight trend

Canard Multiplier
Stability Margin Trends
Symmetric Stab Loop, NN On
Frozen Stabilator
B-Matrix Failure
Simulated Stabilator Failure

Left Stab frozen at 0, -2, & -4 deg from trim
Flight Results
Simulated Frozen Stabilator
Response Due To Pitch Stick Sweep

Magnitude, dB

Frequency, rad/sec
Pilot Ratings with Adaptation
Formation Flight Flight Task

CHR
Level II
Level I

Pilot A
Pilot B

No NN
Trim
-2
-4

No NN
Trim with NN
-2 with NN
-4 with NN

John T. Bosworth – IRAC V&V Testbeds Co-API
Simulated Frozen Stabilator

- Pilot unconsciously compensates for asymmetry
- Correlated pilot input presents greater challenge for adaptive system

+ Adaptive system reduced the amount of cross coupling

- Adaptive system also introduced tendency for pilot induced oscillations (PIO)
Deadzone Effect

Input to WP1 learning

After deadzone

WP1

Failure Insertion

Tracking Starts

PIO

Time, sec
F-15 837 Summary

• Adaptive system generally behaved as predicted
  – Weights adjusted in correct direction
  – Real world turbulence and measurement noise did not adversely affect learning
  – Only safety disengagements observed were due to very aggressive pilot inputs

• Simulated destabilization less than predicted
  – Flight vehicle more stable than aero model predicts
  – Software change in work to increase destabilizing gain

• Adaptation to frozen stabilator introduced PIO tendency
  – Interesting interaction between pilot adaptation and system adaptation
  – Working on an improved neural network
Future adaptive research areas:
- Implementing adaptive control algorithms in a multi-processor redundant system
- Adaptively augmenting control by integrating propulsion control
- Assessing integrated adaptive flight management and planning
- Automatically sensing and suppressing aeroservoelastic (ASE) interactions
- Integration of static structural load measurements with adaptive controller

Quad 68040 Research Flight Control System with production control system as backup
- Extensively instrumented for flight loads
- Wing deflection measurement system
- Faster, more capable RFCS in work
Potential Future Work

• How to sense and incorporate structural limitations into the adaptive algorithm
• Develop better metrics – What is most important to ensure that a damaged vehicle can be safely landed?
• Investigate adaptive notch filters to avoid adverse aero-servo-elastic (ASE) interactions
• Develop and validate requirements for the use of propulsive control for failure / damage conditions
• Maintain long-term effort to advance adaptive control technology
Questions?