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
Extensively modified F-15 airframe

- Thrust vectoring nozzles
- ARTS II computer for added computational capability (Neural Network algorithm)
- 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)

Rate limit drift, start persistence counter

Max persistence ctr, downmode

Window size

Floating limiter

Sigma pi cmd (pqr)

Lower range limit (down mode)

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

Black – sigma pi cmd
Green – floating limiter boundary
Orange – limited command (fl_drift_flag)
Red – down mode condition (fl_dmode_flag)
Gen I Indirect Adaptive Control Architecture

- Model Following
- LQR-Based Research Controller
  - Online Riccati Solver
  - Control Allocation
- Online Parameter Estimation
- Sensors

pilot inputs
Gen II Direct **Adaptive**

Control Architecture

- Pilot inputs
- Model Following
- Dynamic Inversion – Based Research Controller
  - Feedback Error
  - Direct Adaptive Neural Network
  - Sensors
  - Control Allocation
Simplified Sigma-Pi Neural Network
Pitch Axis

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”

Apparent Longitudinal Plant

Sym. Stab Command → A/C Plant → Canard Multiplier → Control System

Canard Multiplier

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
Stability Margin Trends
Symmetric Stab Loop, NN On

![Graph showing stability margin trends.](image-url)
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
Pilot Ratings with Adaptation
Formation Flight Task

CHR

Level II

Level I

No NN  Trim  -2  -4

Pilot A
Pilot B

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

Failure Insertion

Tracking Starts

PIO

Input to WP1 learning

After deadzone

WP1

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
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?