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

Production design
P/Y thrust vectoring nozzles

F100-PW-229 engines with IDEECs

Canards
Quad digital flight control computers with research processors and quad digital electronic throttles

Electronic air inlet
• No mechanical or analog backup
• Digital fly-by-wire actuators

ARTS II computer for high computation research control laws
• 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

Single Channel 400 Mhz

Adaptive Algorithm

Safety Limits

Research Controller
4 Channel 68040

Conventional Controller
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
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

- Sensors
- Control Commands
- SCE-3 SCSI
- Pilot Inputs

DCS Neural Network
- DCS Derivatives
- Closed Loop Learning
- Open Loop Learning

PID Derivative Estimation
- Derivative Estimates
- Derivative Errors
- Derivative Bias

Pretrained Neural Network
- PTNN Derivatives

ARTS II

John T. Bosworth – Project Chief Engineer
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)

Pilot inputs

Model Following

Feedback Error

Direct Adaptive Neural Network

Control Allocation

Sensors
Current Status

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

\[
Q_{\text{dot}_c} = Q_{\text{err}} \cdot K_{pq} \cdot [1 - W1 - W2] \\
  + Q_{\text{err\_int}} \cdot K_{iq} \cdot [1 - W1 - W3] \\
  + Q_{\text{err\_dot}} \cdot K_{qd} \cdot [1 - W1]
\]
Effect of Canard Multiplier

Apparent Plant

A/C Plant

Can. Mult.

Control System

Sym. Stab

AoA

Canard
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

- Magnitude, dB
- Phase, deg
- Frequency, rad/sec

Legend:
- q/stick Actual
- q/stick Desired
Simulated Canard Failure
Stab Open Loop with Adaptation

Figure 4 - F-15 IFCS Stab Open Loop Transfer Function M=0.75 at 20K ft. Adaptation ON

Magnitude, dB

Frequency, rad/sec

Phase, deg
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

NN Weights (normalized)

-0.5 canard: basic maneuvering card

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