Large Transport Aircraft:

Solving control challenges of the future

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Introduction

• Industry / Academia collaboration
  – Plenary, Special panel sessions & Invited session
  – Success story (mutual)

• Accessibility
  – Assuming a diverse audience
  – Diverse technical topics

• Large Transport Aircraft
  – Focus areas with specific example projects in Automation & Control

• Research approach
  – Focus on practical & realisable solutions to complex industry challenges
Content

• Who we are
  – Stellenbosch University
  – ESL within the Dept. of E&E Engineering

• What we do in the ESL

• Focus on Control/Automation of Large Transport Aircraft
  – General functional automation
  – Improving safety
  – Improving efficiency

• Conclusion
Who we are: SU

• Stellenbosch University
  – Founded in 1886, 60km from Cape Town
  – Comprehensive with 4 campuses & 10 Faculties
  – 28 000 students
  – Most effective research University in Africa (NRF)
  – In Top 200 of most international university ratings

• Faculty of Engineering
  – 4 000 students
  – Disciplines:
    • E&E, Mechanical, Mechatronic, Civil, Chemical, Industrial
Who we are: ESL

- Dept. of Electrical and Electronic Engineering: Electronic Systems Laboratory
  - Founded in 1992 as a space systems lab
  - 50 graduate students
  - 12 academic/research/technical staff
  - Strong international industrial and academic ties

- Research focus
  - Automation & Control
    - General
    - Space vehicles
    - Terrestrial and underwater robotics
    - Aeronautics
What we do: Aeronautics

• Focus on Aeronautical Automation & Control
  – Unmanned Aircraft (RW, FW, etc.)
    • The other half... for another day
  – Large Transport Aircraft (LTA)
    • Airbus / dti NAC (50/50) program since 2008
    • First expanded to 4 universities
    • Then successes lead to open project applications for all SA universities on project merit basis
    • Initial “Airbus Central Entity” funding for work with CoCs, then weaned off to CoCs
    • ESL goal: Solving future automation & control challenges for the LTA sector, our niche
    • ESL Projects with Airbus CoCs in 3 countries
LTA Control and Automation

• Primary LTA development drivers
  – Cost
  – Passenger safety & comfort
  – Environmental impact

• Industrial environment
  – Huge multinational organisations
  – Highly competitive
  – Highly regulated (certification)

• Focus on LTA Automation & Control
  – General functional automation
  – Improving safety
  – Improving efficiency
LTA: General Automation

- General functional automation
  - Adding useful operational automation features
  - Strong links to safety & efficiency
- Example: Automated Airborne Refuelling
  - Airborne refuelling of large transport aircraft
    - Range extension without landing
    - Larger cargo component to take-off mass
  - Difficult and strenuous piloting exercise!
Autonomous Refuelling

• Refuelling Process

- Solid boom: 20min & 83 tons of fuel
- Receptacle is above and behind cockpit
- Receptacle is far in front of the CG
Autonomous Refuelling
Autonomous Refuelling

- Refueling Envelope
  - Small disconnect envelope
  - Even smaller connect envelope
  - Relatively slow aircraft dynamics / response
Autonomous Refuelling

• Goals
  – Autonomous receptacle regulation
  – Conditions: Light & Medium turbulence
  – Standard configuration & operational envelope / maneuvers
  – Prefer to operate via FBW
  – High fidelity model

• Approach
  – Improving modelling  ⇐ Trust
  – Insightful conventional design  ⇐ Benchmark
  – Optimal robust design  ⇐ Explore Limits
Autonomous Refuelling

- Improving modelling
  - Remodel from CG to Receptacle
  - Thrust response is critical (longitudinal control)
  - Proximity: Tanker to receiver
    - Trim and AoA effects
  - Proximity: Receiver to tanker
    - Clear reported bow-wave effects
    - Enforce time-scale separation
    - Break tanker-receiver control system coupling (fixed throttle)
Autonomous Refuelling

- Conventional Design (longitudinal)
  - CG to RR: Added zeros
    - Apply imperfect pole-zero cancellation
    - Negligible residual verified
  - Actuators
    - Throttle (low BW)
    - Elevator (high BW)
    - Spoilers (medium BW) deflected trim
  - Basic control architectures attempted
    - Feedback loops
    - LQR
Autonomous Refuelling

- Conventional Design Results

- RR regulation results in increased CG load factors
- RHP zeros not limiting response
- Control BW sufficient via FBW
- Simple tanker control = best performance
Autonomous Refuelling

• Optimal Robust Design
  – Much literature
    • Mainly for smaller receivers
    • Actuation limits not included
    • Control accuracy requirements not in optimisations
  – Maintain the model complexity
    • Inside optimisation, not only for testing
    • Include limits and accuracy requirements
  – Our approach: apply LMI optimisation
Autonomous Refuelling

• LMI Optimisation
  – Formulate closed loop stability & performance as LMIs
  – Absorb control variables into LMI structures
  – Remove resulting non-linearities with substitutions/transformations/shaping
  – Define objective function i.t.o. LMI variables
  – Solve for controller by optimising objective

• Model
  – 60th order norm-bounded SS
  – Includes improved Dryden turbulence model
Autonomous Refuelling

- Controller synthesis
  - Output feedback = simple solution
  - 9 different controller variants
  - No FBW usage = find limits
  - Linear formulation for separation
  - Optimised with SDPT3 in Matlab
LTA: Improving safety

- LMI Optimised Controller Results
Autonomous Refuelling

AAR
Light Turbulence
Straight and Level
LTA: Improving safety

- Improving safety
  - A primary driver \( \Rightarrow \) lucky for us!
  - Huge improvements made over 100 years
- Example: Automatic Return to Envelope
  - Protect aircraft from exiting envelope
  - Bring aircraft back into envelope \( \Leftarrow \) Focus
LTA: Improving safety

- **Goals**
  - Automatic return to envelope function for an LTA
  - Robust, common-sense strategies
  - Maintain safe structural load factors
  - Careful: Don’t trust air data!
  - Test / Validate for LTA
  - Post-stall spin recovery as example

- **Approach**
  - Model
  - Create strategy
  - Test / Validate strategy
LTA: Improving safety

• Model
  – High AoA and Side-slip and Attitude rates
  – Very few good models available
  – Decided on the NASA GTM
    • Twin-turbine LTA
    • Wind tunnel & CFD & Scaled flight testing
    • Extensive flow angles, attitude rates & control deflections
    • Highly non-linear
LTA: Improving safety

• AREF Solution approach
  – Intuitive & Robust to various aircraft
  – Based on recommended piloting practice
  – Recover linear behaviour first (reduce uncertainty)
  – Quickly exploit FBW protection systems

• AREF strategy
  – Step 1: Recover angular rates and aerodynamic envelope
  – Step 2: Recover attitude
  – Step 3: Recover over-speed and altitude
Enter Upset Recovery

Recover Aerodynamic Envelope
- alpha, beta exit envelope
- P, Q, R reduced
- alpha, beta recovered

Recover Attitude Envelope
- bank angle, flight path angle recovered

Obey normal load factor constraints

Recover Overspeed and Altitude
- overspeed, altitude recovered

Normal Flight Control

Recovery Aerodynamic Envelope

Damp Angular Rates
- P, Q, R reduced
- alpha, beta close?

Capture Alpha, Beta
- P, Q, R, alpha, beta recovered?

Recover Attitude
LTA: Improving safety

• Step 1: Aerodynamic recovery
  – Highly non-linear
  – Multiple stable & unstable equilibria outside flight envelope
  – Actuator inputs and initial conditions govern transitions between equilibria
  – We need more understanding!
LTA: Improving safety

• Bifurcation Analysis
  – Solve & track equilibria of non-linear system for various static control deflections
  – Matlab Dynamical Systems Toolbox (Coetzee et al. 2010)
  – Condition GTM to be compatible with toolbox
  – No FBW for analysis
  – Vary static elevator input for analysis
  – Zero throttle and trim other surfaces for straight and level flight
  – View the equilibria (no transients) for each state as a function of the elevator position
  – Augment with time domain analysis (transients)
LTA: Improving safety

two stable branches corresponding to LH and RH spin modes

zero elevator corresponds to equilibrium around alpha=5 deg
LTA: Improving safety
LTA: Improving safety

• Step 1: Aero & Rate Recovery Result
  – High-fidelity non-linear model
  – State-of-the-art bifurcation analysis
  – Confirm a simple solution: Zero elevator!
  – Simple is good!
• Step 2: Attitude Recovery
  – Use protected FBW control to level pitch and roll
• Step 3: Recover Over-speed and Altitude
  – Use protected FBW to climb to altitude
LTA: Improving safety

- Test / Validate

Aircraft is recovered within 600ft of altitude after AREF activation
LTA: Improving safety

- Normal flight
- Elevator-Induced Stall and Spin
- Overspeed Recovery
- Post Recovery

Graph showing time [sec] vs. alpha [deg] and beta [deg].

Aerodynamic Recovery
Attitude Recovery
LTA: Improving safety

- Test / Validate
  - Post-stall spin is induced at 8 000ft using elevator
  - Aircraft is recovered within 600ft altitude of AREF activation
  - Structural load limits are not exceeded in any part of the simulation
  - The solution is simple and relies on existing FBW flight protection systems for final stages of recovery
  - Result: Post-stall recovery validation on GTM, but this is just the tip of the iceberg
LTA: Improving safety
LTA: Improving efficiency

- Improving efficiency
  - Using less fuel
  - Using that fuel wisely (Greener)
- Example: Automated Formation Flight
  - 66% Increase in airliner traffic up to 2033
  - Formation flight (more lift/less drag)
  - Up to 40% reduction in fuel consumption
  - Exploit persistent cruise wakes
  - At least 10x wingspan separation behind
  - Same vertical level
  - Primarily control lateral separation
LTA: Improving efficiency

• Goals
  – Autonomous Formation Flight
  – Probably 2 to 3 aircraft
  – Focus on dynamics and control
  – Calculate real fuel savings
  – Practical: Affordable, Safe & Comfortable

• Approach
  – Model & Understand ➙ Quite mature
  – Create algorithms / strategy ➙ Initial results
  – Test / Validate ➙ Initial results
LTA: Improving efficiency

- Model
  - Literature primarily for smaller trailing aircraft
  - UCT Study
  - Use Boeing 747 because of available data
  - Trailing vortex model behind leader
  - Convert flow field to complete $C_{\text{new}} = C_{\text{old}} + C_{\Delta \text{t}}$ lookup / polynomials
LTA: Improving efficiency

- Relative placement

- Dominant effects of lateral separation
  - Reduced drag
  - Roll moment
- Watch trim / actuation limits!
LTA: Improving efficiency

- Relative placement (Trim perspective)
LTA: Improving efficiency

- Relative placement (Dynamics perspective)

(a) Lateral sandwich region locus

(b) Lateral outer region locus

(c) Vertical sandwich region locus

(d) Vertical outer region locus
LTA: Improving efficiency

- Relative placement
  - Sandwich region
    - Best drag reduction (15%)
    - Smaller space
    - More variation in dynamics
    - Stuck between trim limits
    - More turbulent / reduced comfort
    - Model accuracy may be questioned
  - Outer region
    - Significant drag reduction (10% to 15%)
    - Larger space
    - More forgiving dynamics changes
    - Easy approach / exit
    - Less turbulence
LTA: Improving efficiency

- Control and Simulation

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Conventional Controller

Aircraft State Communication

Formation Flight State Machine Control
  Conventional Controller
  Extremum Seeking Controller
  Formation-Hold Controller

Leader Aircraft
  Aerodynamic Model
  Gravitational Model
  Higher Order Thrust Model

Follower Aircraft
  Aerodynamic Model
  Wake Aerodynamic Model
  Gravitational Model
  Higher Order Thrust Model

6 Degrees of Freedom Model
```
LTA: Improving efficiency

- Extremum seeking control
LTA: Improving efficiency
Conclusions

• Industry
  – Complicated problems
  – Much insight into practical issues
  – Many unique constraints to consider

• Academia
  – Access to powerful tools & support networks
  – Time and a need to solve difficult problems

• Mutually beneficial collaboration is possible
  – Champions and support (Airbus & dti / NAC)
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