Generalized Automatic and Augmented Manual Flight Control

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Overview

• Automatic Flight Controls - State of the Art
  • automation issues
    • incident and accidents
    • requirements
    • traditional design process
    • man-machine interfaces

• FAA Safety Role
  • Regulations & Certification; FAR updates - high lights

• Generalized MIMO Control
  • Total Energy Control System (TECS)
  • Total Heading Control System (THCS)
  • Condor Application

• Fly By Wire Augmented Manual Control
State of the Art
Flight Guidance & Control

- Autopilot
- Autothrottle
- FADEC
- Engine
- Airplane
- Sensors
- Display
- Throttle
- Stick
- Servo
- Clutch
- Delta T
- Delta e
Automation Safety
Accidents & Incidents

- China Airlines B747 spiral dive after engine failure
- China Airlines A300 crash at Nagoya, Japan
- Air Inter A320 crash near Strasbourg, France
- American Airlines B757 crash neat Cali, Columbia
- Tarom A310 crash near Bucharest, Rumania
- Air France A320 crash near Habsheim France
- Britannia Airways B757 speed loss during FLCH
- British Airways B747 speed loss during FLCH
- Airbus A330 crash near Toulouse, France
Accident and Incidents Scenarios

• Pilot fails to monitor autopilot operation (Mexicana DC10) Autopilot stalls airplane
• A/P roll control saturation, engine out (China Airlines B747)
• unexpected high altitude automatic disengage, out-of-trim, pilot over controls (MD11)
• imperceptible airplane slow roll response, due to A/P sensor failure without proper alert (Evergreen 747)
• A/P reaches roll authority limit in icing, disconnects without timely warning, stall (Embrair Comair, Detroit)
• Pilot tries to take manual control, A/P remains engaged, overrides pilot (China Airlines A300, Nagoya)
• Pilot overcontrols rudder, after mild Wake Vortex encounter. Vertical Stabilizer fails (AA A300, New York)
Typical Transport Airplane
Flight Guidance & Control System
as many as 8 LRUs

- highly complex designs
- historically evolved subsystems
- extensive functional overlap
- operational inconsistencies
- incomplete envelope protection
- SISO control
- little or no standardization
Automation Safety Issues

- role and expectations of pilot in automated aircraft
  - automation - should not induce false sense of security
  - pilot expects basic operational safety
- crew difficulty of keeping abreast of automatic operations
  - operational complexities: current designs not pilot-like
  - situation awareness:
    - mode annunciation /caution and warnings
    - recognizing / managing abnormal conditions
  - predictability: when, how, why things happen
    - mixing manual & automatic can defeat basic safety features
- design
  - SISO control modes: can result in loss of control
  - poor man-machine interfaces
  - correct level of automation: keeping pilot “in the loop”
- adequacy of initial and recurrent training
Operational Complexity

• Who is in control? The pilot, FMS, autopilot, autothrottle?
  • *too many overlapping systems, modes, sub modes*
• what is the system doing, what will it do next?
  • *crew confusion!*
• inconsistent operations and performance:
  • *different modes, different results: automation surprises!*
  • complex mode logic, e.g. Flight Level Change, VNAV
• unsuitable man-machine interfaces,
  • *e.g. attention/procedure intensive CDU keyboard*
• inadequate mode annunciation /caution and warnings
  • when should pilot intervene, or take over
  • pilots putting too much trust in low integrity single channel designs, not aware their limitations
Design Complexity

- historic systems evolution has led to
  - new functions added-ons with each generation
    - e.g. GLS on 737 NG: 11 LRUs involved!
  - old problems “solved” by new modes / submodes
    - e.g. Flight Level Change, VNAV, Thrust modes
  - automation fragmentation into subsystems
    - autopilot, autothrottle, FMS, SAS, FBW
    - each subsystem handled by different organization
    - design of each function approached as new problem
- SISO control : integration difficulties
  - modes / sub modes cobbled together by intractable mode logic
- mix of old and new technologies
  - digital hardware with analog architectures!
- no overall design & integration strategy!
Design Requirements “Creep” on a Recent AFCS Program

Successive Spec Revisions.....
Flight Guidance and Control
Design Process

• 100 year evolution of systems & subsystems
  • more capabilities with each generation
  • most functions “Non-Flight Critical”
    • only Autoland and manual control considered “Flight Critical”
  • new technologies/ old control strategies
    • analog to digital / mechanical to FBW
    • introduction of Augmented Manual Control
    • Single Input / Single Output retained
      • no certified Multi-Variable designs

• Major Issues:
  • outdated Requirements and Design Approaches
Single-Axis SISO Control

- Single axis SISO automatic control modes have been the standard since earliest days of automation
- It works…. most of the time, however….
  - stability and performance cannot be guaranteed:
    - loss of control possible, e.g. vert path modes
    - full time pilot monitoring required!
- SISO control is root-cause of most automation complaints
  - single controller input not only changes intended variable, but also causes unintended responses of other variables:
    - need other controller inputs to suppress unintended control coupling errors
    - poor damping, high control activity
  - mode proliferation & complexities, operational inconsistencies and pilot confusion
BASIC AIRPLANE CHARACTERISTICS:
THRUST AND DRAG AS FUNCTION OF SPEED

Graph showing the relationship between Thrust, Drag, Speed, and other airfoil characteristics.
FUTURE SYSTEMS REQUIREMENTS

• Generalized all-encompassing MIMO control strategy for all automatic and augmented manual modes

• up-front integration of functions
  • pitch/thrust control
  • roll/yaw control (including rudder) - inherent
    • yaw damping /turn coordination
    • thrust asymmetry compensation

• improved failure detection, identification and isolation

• envelope protection
  • airspeed, normal load factor, angle of attack, roll angle
FUTURE FG&C SYSTEMS DESIGN OBJECTIVES

- large cost reductions, achievable through
  - reduced system complexity, less maintenance
    - faster system development cycle
    - design reusability - lower risk
  - reduced customization
  - standard off-the-shelf hardware
  - less lab/flight testing
  - reduction in pilot training need
- automation safety improvements
Future FG&C System Architecture

FMC
- Flight planning
  - Navigation
  - Path Definition
  - Performance Predict.

FG&C
- Airspeed/Mach
- Altitude/Vertical Spd
- Heading/Track
- Loc/GS, V-Nav/L-Nav
- Envelope Protection
- FBW Manual Mode

• Rational Function Partitioning
• No Function Overlap
• Common Control Strategy
• Simplified Reusable Design

CDU

MCP

Strategic Airline Operations Oriented Functions

Tactical Automatic & FBW augmented manual Control Modes and Safety Functions
FAA Role

• Safety and oversight of Aviation Safety through
  • Federal Aviation Airworthiness Regulations (FARs)
    • high level generic design requirements
    • some specific detailed “Special Conditions”
    • Aircraft Design Certification & Production oversight
  • Aircraft Operations and Maintenance oversight
  • Pilot training/licensing

• cooperative safety initiatives with Industry and Research Establishments:
  • FAA/NASA Aviation Safety Program (ASP)
  • Commercial Aviation Safety Team (CAST)

all have raised awareness of need for better regulations & design:
• Updated FAR and AC 25.1329
Updated FAR and AC 25.1329

• Coverage: Autopilot, Autothrust and Flight Director (not FMS)
• Key new requirements:
  • Vertical Modes preferred operational characteristics
  • engage/disengage/ mode switching transients
  • warning/alert for autopilot and autothrottle disengage
  • manual override must not create unsafe condition
    • significant override force should disconnect autopilot
  • speed envelope protection (as a minimum crew alert)
  • logical man-machine interfaces to minimize crew error and confusion
  • automatic trimming in opposition to pilot input prohibited
    • prevent “jack knifing” elevator/stabilizer
    • trim on elevator position, not stick force
Generalized Functionally Integrated Multi-Axes Control

• Automatic FG&C has contributed in a major way to flight safety

• Future FG&C systems can further enhance flight safety, operational effectiveness and reduce system costs through
  • Generalized Multi-Input / Multi-Output (MIMO) control strategy
    • pilot-like control, used for all control modes
      • automatic
      • augmented manual
      • envelope protection
    • reduced mode complexity
      • fewer Up-Front integrated modes
  • simpler more intuitive man-machine interfaces
    • Mode Control Panel (MCP)
    • advanced displays (e.g. SVS Terrain, HITS, FPA symbology)
Generalized Control Concept

Airplane independent design  ➔  Airplane tailored design

Guidance Error Normalization (Any Mode) ➔  Control Commands Coordination ➔  Innerloop Force and Moment Control ➔  Airplane

Feedback Signal Synthesis

IRU ➔  Air Data ➔  Nav/Guid

Designed to provide:
• Decoupled Control
• Standard Trajectory Dynamics
TECS/THCS Research Project

- Need for safer/more effectively integrated FG&C system was recognized in late seventies during NASA TCV program
  - Identified Root Cause of most FG&C System Deficiencies
    - Peace meal mode-by-mode systems evolution
    - SIS0 design
  - NASA/Boeing Research Program, initiated in 1979, resulted in
    - Total Energy Control System (TECS)
      - Generalized energy based MIMO Flight Path & Speed Control
      - Detailed system development & extensive Pilot-In-The-Loop simulator evaluations (1980-1985)
      - Validated by Flight Test & In-flight demonstrations (1985)
  - Generalized integrated lateral directional control concept was developed under DARPA/Boeing Condor program (1985-1990), resulting in
    - Total Heading Control System (THCS)
Energy based Longitudinal Control

- Responses to elevator and throttle are coupled in speed and altitude
- Pilots have learned through training to decouple flight path and speed control
- Current automatic control modes fail to account for this control coupling: its operation is like giving
  - throttle to one pilot to control speed
  - elevator to other pilot to control flight path

- Elevator and thrust control are ~orthogonal

- Throttle controls Total Energy Rate: \( \gamma + \frac{\dot{V}}{g} \)
- Elevator controls Energy Distribution: \( \gamma - \frac{\dot{V}}{g} \)

This Energy Strategy used to achieve “pilot-like quality” in automatic control
Flight Dynamics - Energy Control Relationships

- \( \text{Thrust}_{\text{REQ}} = W \left( \frac{\dot{v}}{g} + \sin \gamma \right) + \text{Drag} \)

- current autothrottles neglect largest term: \( W \sin \gamma \)
- trim thrust in level flight is equal to \( \text{Drag} \)

- \( E_t = W \cdot h + \frac{1}{2} \cdot \frac{W}{g} \cdot V^2 \)

- thrust changes produce \( W \left( \frac{\dot{v}}{g} + \sin \gamma \right) = \frac{\dot{E}_t}{V} \)

- elevator produces energy redistribution \( W \left( \frac{\dot{v}}{g} - \sin \gamma \right) \)

- conclusion: energy is the right control integration strategy
Total Energy Control System (TECS)

- concept
  - thrust controls Total Energy requirement
  - elevator controls distribution of energy
  - result: generalized multi-input / multi-output control strategy
    - speed / flight path mode errors are normalized into energy quantity, fed forward to throttle and elevator:
      - provides decoupled command responses
      - consistent/energy efficient operation in all modes

- control priority when thrust limits:
  - generally speed control has priority
  - exception: glide slope / flare mode
  - Vmin/Vmax envelope always protected

- Vcmd limited to Vmin/Vmax

- control authority allocation: handles complex maneuvers
Generalized Integrated Automatic and Manual FBW Control

- Mode Control Panel
- INTEGRATED FLIGHT GUIDANCE & CONTROL COMPUTER
- PATH MODES FEEDBACK NORMALIZATION
- SPEED MODES FEEDBACK NORMALIZATION
- COMMANDS COORDINATION
- FEED FORWARD COMMANDS PROCESSING
- THRUST SCALING
- PITCH INNER LOOP
- ENGINE
- ELEVATOR ACTUATOR
- THROTTLE
- COLUMN

Components:
- CDU
- FMC
- IRU
- ADC

Symbols:
- $\gamma_C$
- $\frac{\dot{v}_C}{g}$
TECS Functional Architecture and Mode Hierarchy

energy control ↔ energy rate control

- **Altitude**
- **Glide Slope**
- **Vert. Path**
- **Vmax**
- **IAS**
- **Mach**
- **Time Nav**
- **Vmin**

**Generalized Thrust and Elevator Commands Coordination**

- **Manual FBW**
- **Go Around**
- **Flight path Angle**
- **Flare**
- **Rate Limit**
- **Rate Limit**
- **Vmax**
- **Vmin**
- **V**
- **Tc**
- **\( \dot{V}_c \)**
- **\( g \)**
- **\( \delta_{ec} \)**
TECS Core Algorithm
Energy Rate Control

Airplane independent design ← Airplane tailored design

\[ \gamma_c \rightarrow KTI_S \rightarrow \left( E_{T_e} \right)_{SN} \rightarrow KTP \rightarrow \text{Engine Control} \rightarrow \text{Engine} \rightarrow T \]

\[ \gamma \rightarrow -2-K \rightarrow \text{Weight} \]

\[ \dot{V}/g \rightarrow K \rightarrow \text{Specific Net Thrust Command} \]

\[ \dot{V}_c/g \rightarrow KEI_S \rightarrow \text{Pitch Innerloop Control} \rightarrow \text{Actuator} \rightarrow \delta_e \]

(TLIM). (PATH PRIORTY)
ALT/CAS Modes, Combined Descend/Acceleration

B-737 TECS

- **ALT/CMD**: 10,000 ft, 9,600 ft
- **CAS/CMD**: 270 kn, 260 kn, 250 kn
- **VERT ACCEL**: Limited to 0.1g
- **THROTTLE**: 55.0 deg, 30.0 deg, 5.0 deg

Note: Negligible Throttle Response!
Control Authority Allocation Example

- Maneuver Authority $= \left( \frac{\dot{V}}{g} + \gamma \right)$

- During climb at $T_{\text{max}}$, $\dot{V}_c /g$ limited to $0.5 \left( \frac{\dot{V}}{g} + \gamma \right)$, allowing speed cmd execution by reducing climb gradient temporarily by half

- During descent at $T_{\text{min}}$, $V/g$ is limited to $1.0 \left( \frac{\dot{V}}{g} + \gamma \right)$, allowing speed reduction by temporary level off
ALT/CAS Modes, Descent With Subsequent Deceleration

B-737 TECS

(100% Deceleration Priority)

Descent Rate Reduced to Decelerate

Throttles at Idle
Envelope Protection Functions

- **Airspeed**: keep between Vmin and Vmax, preferably at IAS_{cmd}
  - Solution can get very complex in traditional systems
    - requires mode switching & crew alerting
- **Normal Load Factor (n_z)**:
  - automatic modes: |n_z| < .1 for passenger comfort
  - FBW manual mode:
    - 0 < n_z < (n_z)_{structural limit}
    - low speed: n_z < (n_z)_{\alpha-limit} ; (n_z)_{\alpha-limit} = (V_e/V_{e_{stall-1g}})^2
- **Angle of Attack (\alpha) limit**: implicit if n_z and Airspeed protected
- **Bank Angle**: bank limit depends on mode & flight condition
- **Sideslip (\beta) limiting**: possible in some FBW manual designs
High-Speed Glide Slope Capture With Flap Extension and $V_{\text{MIN}}$ Control

737 TECS

GSE 0.70
deg -0.70

ALT 2000
ft

FLAP P 40
deg

THROTTLE 55.0
deg

0 GAMMA
-2
-4 deg
200 CAS
150
100 kn
Down
GEAR
Up
6 ELEV
2
-2 deg

Time, sec
TECS/THCS Mode Control Panel Concept with Integrated ATC data link Functions
Advanced Displays
TECS Digital FCC / Throttle / FADEC Interface Concept

**Diagram:***

- **Throttles**
- **FCC**
- **Engine failure logic**
- **Weight**
- **No of oper engines**
- **A to D**
- **Servo**
- **FADEC**
- **Engine**
- **IO**
Total Heading
Lateral-Directional Control Strategy

Design approach analogous to TECS:
• aileron control sum of heading and sideslip errors
• rudder controls difference between heading and sideslip errors

Resulting Total Heading Control System (THCS) algorithm provides
• full-time coordinated innerloop roll/yaw control (THCS Core)
  • yaw damping
  • turn coordination
  • engine-out thrust asymmetry compensation / $\delta r$ & $\delta a$ trim
  • envelope protection (bank angle & sideslip)
• all outerloop modes
  • automatic modes (Heading/Track angle, LOC, LNAV)
  • augmented manual mode
• decrab / flat turn capability
• consistent performance - all modes / all flight conditions
THCS Functional Architecture and Mode Hierarchy
THCS Core Algorithm

Airplane independent design ↔ Airplane tailored design

\[ \begin{align*}
\psi_c &\rightarrow K_\psi \rightarrow \frac{g}{V_{\text{True}}} \rightarrow \dot{\psi} \\
\dot{\psi} &\rightarrow \frac{V_{\text{True}}}{g} \rightarrow K_{\text{Ri}} \rightarrow \phi \\
\phi &\rightarrow \frac{1}{K_p} \rightarrow -1 \rightarrow \text{Actuator} \rightarrow \delta_a \\
\beta_c &\rightarrow K_\beta \rightarrow \frac{g}{V_{\text{True}}} \rightarrow \dot{\beta} \\
\dot{\beta} &\rightarrow \frac{V_{\text{True}}}{g} \rightarrow K_{\text{VY}} \rightarrow \psi \\
\psi &\rightarrow \frac{1}{K_p} \rightarrow -1 \rightarrow \text{Actuator} \rightarrow \delta_r
\end{align*} \]
TECS and THCS Application on Condor
PROGRAM OBJECTIVE:
DESIGN, DEVELOP AND DEMONSTRATE AIR VEHICLE CAPABLE OF:

- 50,000 - 70,000 FT ALTITUDE
- LONG ENDURANCE - MEASURED IN DAYS
- GLOBAL DEPLOYMENT
- PILOTLESS AUTONOMOUS OPERATION

APPLICATIONS:

- RECONNAISSANCE, SURVEILLANCE
- COMMUNICATIONS RELAY
- ATMOSPHERIC RESEARCH / WEATHER MONITORING
- RESOURCE MANAGEMENT / LAW ENFORCEMENT
LIFT / DRAG (L/D) COMPARISONS

Legend:
- Per Janes 1 1979-1980
- Flight test data
- Boeing estimate

Span = \sqrt{\frac{\text{Wetted area}}{\text{Aspect ratio (AR)}}}

\[ \frac{\text{Span}}{\sqrt{\text{Wetted area}}} = \sqrt{\frac{\text{Aspect ratio (AR)}}{A_{\text{WET}}/S_{\text{REF}}}} \]
FEATURES:

- TWO 6-CYLINDER LIQUID-COOLED HIGH-COMPRESSION RECIPROCATING INTERNAL-COMBUSTION ENGINES
- TWO-STAGE TURBOCHARGERS WITH INTERCOOLING AND AFTERCOOLING
- CONSTANT ENGINE POWER TO 65,000 FEET
- TWO-SPEED GEARBOX
- LARGE DIAMETER (16 FT), ALL-COMPOSITE CONTROLLABLE-PITCH PROPPELLERS
- ALL ELECTRONIC/DIGITAL ENGINE CONTROL
- ALL FLIGHT MANAGEMENT / CONTROL FUNCTIONS IMPLEMENTED IN DUAL REDUNDANT ACTIVE / STANDBY MISSION COMPUTERS

- GENERALIZED AUTOPILOT DESIGN WITH INTEGRATED CONTROL FUNCTIONS
  - VERTICAL FLIGHT PATH & SPEED: TOTAL ENERGY CONTROL CONCEPT
  - HORIZONTAL FLIGHT PATH & YAW: TOTAL HEADING CONTROL CONCEPT

- ANALYTICAL SENSOR REDUNDANCY MANAGEMENT

- MICROPROCESSOR CONTROLLED SELF-MONITORED ELECTROMAGNETIC ACTUATORS
CONTROL ARRANGEMENT

CONTROL:

PITCH:  HORIZONTAL STABILIZER
ROLL:   AILERONS + FLAPERONS / SPOILERONS
YAW:    RUDDER + FLAPERONS / SPOILERONS
THRUST: ENGINES / PROPELLERS
DRAG:   FLAPERONS / SPOILERONS
LIFT:   CONTROL SURFACE UPRIG (WING BENDING MOMENT RELIEF, PASSIVE)
ACTUATORS:

- ELECTROMAGNETIC - 135VDC SAMARIUM COBALT MOTOR
- DISTRIBUTED HYBRID ACTUATOR CONTROL ELECTRONICS
  - 1553 DATA BUS INTERFACE
  - MICROPROCESSOR LOOP CLOSURE AND FAILURE DETECTION BASED ON VARIETY OF PERFORMANCE TESTS

REDUNDANCY MANAGEMENT:

- FAULT STATUS REPORTED BY EACH ACTUATOR TO MISSION COMPUTERS
- 1553 COMMAND AND POSITION WRAP AROUND CHECKS IN MISSION COMPUTER
- REINITIALIZATION / RECONFIGURATION / POWER OFF DECISION BASED ON OVERALL FAULT STATUS AND THAT OF RELATED ACTUATORS
SENSORS

- INERTIAL SENSORS:
  - IRU:
    - THREE 2-DEGREE-OF-FREEDOM SKEWED-AXIS RATE GYROS
    - X, Y, Z + DIAGONAL AXIS ACCELEROMETERS
  - M. C.:
    - CONTINUOUS PARITY ERROR-BASED DESELECTION OF POOREST RATE GYRO
    - PERSISTENT LARGE PARITY ERROR FOR ONE RATE GYRO TRIGGERS KALMAN FILTER RECONFIGURATION
    - PERSISTENT ACCELEROMETER PARITY ERROR TRIGGERS
      - IRU BITE WILL ISOLATE FAILED UNIT FOR LARGE ERROR
      - ANALYTICAL FAULT ISOLATION USING OTHER IRU AND AIR DATA CORRELATION
    - BASIC FLIGHT CONTROL MODES USE AHRS ATTITUDES
    - ONLY WAYPOINT STEERING MODE REQUIRES NAV SOLUTION

- AIR DATA SENSORS: STANDARD DUAL REDUNDANT TRANSDUCERS:
  - $\Delta p$
  - $\Delta q$
  - $\Delta \alpha$
  - $\Delta \beta$
  - OAT

- ALL DERIVED AIR DATA QUANTITIES COMPUTED BY M. C.
- ANALYTICAL FAULT ISOLATION USING INERTIAL DATA CORRELATION
• DUAL MISSION COMPUTERS
  - SOFTWARE BIT
    o RAM PARITY CHECK
    o A/D MUX OF PRECISION REFERENCE VOLTAGES
  - HARDWARE BIT
    o WATCHDOG TIMER
    o NON-RESPONDING / ILLEGAL I/O
    o I/O OR A/D MUX FAILURE
    o CPU PARITY OR OTHER FATAL CPU FAULT
    o BOTH 1553 TERMINALS FAILED
    o OPERATIONAL SELF-TEST

• MASTER / MATE OPERATION (HOT SPARE)

• MASTER SELECTION PERFORMED BY EXTERNAL HARDWARE ("COMPUTER POWER CONTROLLER")
  - INTERNALLY REDUNDANT
  - PROGRAMMED LOGIC ARRAY IMPLEMENTATION
  - INPUTS FROM COMPUTERS:
    o HARDWARE "GO"
    o SOFTWARE "GO"
  - COMPLEMENTARY OUTPUTS

• MASTER AND MATE PERFORM SAME COMPUTATIONS, MATE DOES NOT OUTPUT

• NEW MASTER INITIALIZES FLIGHT CONTROL LAWS (OUTPUT INTEGRATORS) BASED ON SENSED
  STATE OF CONTROL SURFACE POSITIONS
FLEXIBLE AIRPLANE DYNAMICS

1. FLEXIBLE MODES ARE CALCULATED IN VACUO AND VERIFIED BY GROUND VIBRATION TEST (GVT). MODES ARE ORTHOGONAL.

2. UNSTEADY AERODYNAMICS PRODUCES COUPLING BETWEEN FLEXIBLE MODES AND BETWEEN RIGID AND FLEXIBLE MODES.

3. FLEXIBLE MODEL WITH INFINITE NUMBER OF FLEXIBLE MODES IS EQUIVALENT TO QUASI-STATIC MODEL.

4. AEROSEROELASTIC MODEL IS THE SAME AS FLUTTER MODEL BUT WITH ADDED DEGREES OF FREEDOM FOR CONTROLS.
OPEN LOOP FREQUENCY RESPONSE WITHOUT FILTERS

GAIN IN DB

FREQUENCY IN RAD/S

RUDDER
AILERON
OPEN LOOP FREQUENCY RESPONSE WITH FILTERS

Gain in dB vs Frequency in rad/s
Fly-By-Wire Design

- **Definition:** Airplane control concept whereby surfaces commanded through electrical wires
- **Sought benefits:**
  - Weight reduction – elimination of mechanical systems
  - Drag reduction - Optimized aerodynamic performance by Relaxed Static Stability
  - Standardized / improved handling qualities through SAS and CAS
  - Cost reductions
    - Improved fuel economy
    - Reduced pilot training (common type rating)
    - Design commonality/design cycle time reduction
    - Reduced maintenance
FBW Functional Architecture

FLIGHT CONTROL COMPUTER

Display

Throttle

Engine

ΔT

Airplane

Δe

δs

Actuator

Actuator

Interface

Stick

Feel system

Trim up

Trim down
FBW Design Opportunities

• simplify operations concept
• simplify hardware architecture and design
  • shedding historically accumulated “baggage”,
    e.g. design features typically belonging to
    previous generations of technologies:
    • complex feel systems
    • column, wheel back-drive systems
    • stick shaker, stick pusher
    • individual actuator loop closure - Force Fight

• Instead of designing Band-Aids to make it possible for the
  pilot to live with the vagaries in the system, the FBW system
  should eliminate these vagaries (and Band-Aids)
Major FBW Design Issues

- Controllers - Column & Wheel versus Sidestick
- Feel system - Passive (e.g. spring) or Active (*expensive !*)
- Control augmentation - Algorithm response type
  - simple or none - little or no HQ advantages
  - stability/command – substantial benefits possible
    - more complex/costly – many issues
  - Handling Qualities: what HQ, how best achieved
- envelope protection - major safety benefit !
  - Good design enhances pilot control authority
- mode changes *takeoff/landing*
- Actuators: loop closure, e.g. central or remote loop closure
- Redundancy architecture & component reliability
Definition: The conglomerate of characteristics and features that facilitate the execution of a specific flight control task; includes display and feel characteristics

- good HQ requires design attributes appropriate to control task (e.g. pitch attitude, FPA, or altitude control)
- each task has a finite time allotment or expectation for its completion (bandwidth requirement)
- direct control of “slow variables” requires special design attributes (e.g. FPA response augmentation & display)
- control harmony is achieved when the pilot can execute the task without undue stress and conscious effort
FBW Control
Response Attributes for Good HQ

Desired Attributes:
• “K/S”- like response
• low response lag $\tau$
• correct sensitivity $K$
• good damping
• no overshoot
• control harmony with other variables ($\theta$, $\gamma$, $n_z$)
• consistency between flight conditions

NOTE: signal $\frac{K}{S} \delta_{\text{col}}$ can serve as the cmd reference
FBW Control Algorithm Types

- **Pitch:**
  - pitch attitude rate command (+ pitch attitude hold)
  - $n_z$-command
    - proportional angle of attack (AOA) command
    - $C^* = n_z$ command / Vertical Speed hold
    - FPA rate command / FPA hold

- **Roll:** roll rate command / roll attitude hold
  + heading or track hold for bank angle < $X^o$

- **Yaw:** sideslip command proportional to pedal

Given sufficient know-how, all of these concepts can be made to perform well: *the devil is in the details!*
Basic FBW System Example
Embraer RJ-170 / DO-728 concept

- Stick
- Passive Feel
- Autopilot servo clutch
- Air Data
- IRU
- Mod Avionics Units
- Default Gains
- Actuator Electronics
- Actuator
- δe

Airspeed Gain Sched
AOA limiting
Autopilot cmds
Raytheon Low Cost GA FBW Concept
Bonanza Flight Demo System

- Stick commands proportional FPA; Throttle commands speed
Rationale For Low End GA FBW

• Eliminate most low pilot skill related accidents
  • stall, spin
  • Loss of Control due to spatial disorientation
  • Lack of IMC flight skills (inadvertent weather)

• Accept new FBW system related accidents, but lower overall rate

Approach:
• embedded envelope protection functions
• low cost FBW design strategy:
  • simple control algorithm
  • simple high reliability components
    • dual sensor set, computer and data bus
  • basic redundancy and FDIR strategies, e.g.
    • single servo on split surfaces
C* Design Concept

stick

throttle

K_S

C*_cmd

FCC

FF shaping

comp

K_1

S

ACE

act.

C*

V_c

V_c_0

g

ΔT

Airplane

δ_e

q

n_z, pilot
C* Morphed into FPA rate cmd/hold

- responses identical to original C*, if gains are equivalent
- fewer, simpler sensors
- no pilot-out-of-the-loop control reference drift
- still need extensive flight condition tuning
- **missing**: integral control of γ-error
Augmented Manual Control Algorithm

**Design Objectives**

- produce a generalized reusable design with
  - generic innerloop, shared with automatic modes
  - integral feedback control, to prevent response droop
  - final dynamics = classical airplane with ideal constant speed HQ:

$$\frac{\theta}{\delta_{\text{stick}}} = \frac{K_{\text{stick}}(\tau_nS + 1)}{S((1/\omega_{SP}^2)S^2 + (2\zeta_{SP}/\omega_{SP})S + 1)} = \frac{K_{\text{stick}}(\tau_nS + 1)(\tau_nS + 1)}{S((1/\omega_{SP}^2)S^2 + (2\zeta_{SP}/\omega_{SP})S + 1)}(\tau_nS + 1)
$$

$$\frac{\gamma}{\delta_{\text{stick}}} = \frac{K_{\text{stick}}(K_{\text{FFP}}S^2 + K_{\text{FFP}}S + 1)}{S((1/K_qK_0K_1)S^3 + (1/K_qK_1)S^2 + (1/K_1)S + 1)(\tau_0S + 1)}
$$

- no undesirable response variability with flight condition
- responses decoupled from airspeed - by autothrust
- tracking of Control Reference when pilot out of the loop, e.g.
  - pitch/roll attitude
  - flight path angle (preferred – minimizes workload)
Proposed Design Methodology for FBW Control Algorithms

Desired:
- systematic/reliable process, producing desired results:
- generalized/reusable design – minimal application & Flt Condition adaptation

Approach:

Step 1: Stability Augmentation using Static Inversion
- eliminates flight condition dependencies, gain schedules
- defines basic SP innerloop characteristics: \( \omega, \zeta \)

Step 2: Add Integral Feedback loop
- “retrims” airplane - eliminates SS command response droop

Step 3: Add Command Augmentation Feed Forward Paths
- shapes response to pilot control inputs, as desired
- provides “Hold” function for pilot established command
TECS FPA Control Algorithm Implementation

stick

$K_{\text{Stick}}$ 

$\frac{1}{S}$

$\gamma_c$

Feed Forward Control Augmentation

FPA Feedback Control Augment.

Invariant Short Period design

Static Inversion

Short Period Dyn.

Airplane

$\frac{1}{\tau_{\theta_2} S + 1}$

Pitch rate

Pitch attitude

$\gamma$

$\delta_e$

$\gamma_c$
Pilot Induced Oscillation

Avoidance

• pilot in the loop control requirements
  • bandwidth - appropriate to the task
  • response predictability
    • linearity highly desirable
  • suitable controller forces & displacements
  • display(s) – appropriate to pilot task
• overall system design harmony - need
  • adequate control algorithm bandwidth
  • adequate actuator bandwidth and rate limits
  • correct controller sensitivity & authority
    • matching of front-end and back-end design
  • display dynamics appropriate for pilot loop closure
Questions??