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- Boeing 777 Primary Flight Computer
  - Paper: *Triple-Triple Redundant 777 Primary Flight Computer*
    - Y.C. Yeh
    - 1996 IEEE Aerospace Applications Conference
    - pg 293-307
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- Primary Flight Control Surfaces
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Overview

- Flight control system is a Fly-by-Wire (FBW) system.
- Delayed Maintenance for major electronic Line Replacement Units (LRU)
- Triple redundancy for all hardware
  » computing system
  » airplane electrical power
  » hydraulic power
  » communication paths
- Primary Flight Computer (PFC) are the central computational elements of the FBW system.
- PFC architecture is based on TMR
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- N-version dissimilarity integrated into TMR
  » 3 similar channels
  » each channel has 3 dissimilar computation lanes
  » software written in ADA (dissimilar compilers)
- DATAC bus, also known as ARINC 629 bus, is used for all communication between all computing systems for flight control functions.
  » DATEC = Digital Autonomous Terminal Access Communication
  » designed by Boeing
  » busses are isolated (physically and electrically)
  » DATACs are not synchronized
  » http://www.arinc.com
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777 FBW design philosophy
– Considerations
  » common mode/common area fault
  » separation of FBW components
  » FBW functional separation
  » dissimilarity
  » FBW effect on the structure
– Triple-dissimilarity for PFC processors and interface hardware
– By nature of TMR no Byzantine faults allowed.
– Avoidance of asymmetry by:
  » ARINC629 requirements
  » Deal with root causes of functions/communication asymmetry
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Flight Control Functions

- Control electric and electro-hydraulic actuators
- Provide manual and automatic control in pitch, roll and yaw axes
- Control pilot input: column, wheel, rudder pedals, speed brakes
- Pitch Control: 2 elevators and horizontal stabilizer
- Roll Control: 2 ailerons, 2 aperons, 14 spoilers
- Jaw Control: tabbed rudder
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- **Three operation modes:**

<table>
<thead>
<tr>
<th>CONTROL MODE</th>
<th>PITCH</th>
<th>ROLL</th>
<th>YAW</th>
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<tr>
<td><strong>NORMAL CONTROL</strong></td>
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<td>C* Maneuver Cmd with Speed</td>
<td>Surface Cmds</td>
<td>Surface Cmd Ratio Changer</td>
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<td>Feedback</td>
<td>Manual Trim</td>
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<td><strong>CONTROL</strong></td>
<td><strong>CONTROL</strong></td>
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<td>Surface Cmd (Augmented)</td>
<td>Surface Cmd</td>
<td>Surface Cmds, Flaps Up/Down</td>
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<td>Flaps Up/Down Gain</td>
<td>Manual Trim</td>
<td>Gain</td>
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<td>Direct Stabilizer Trim</td>
<td>Fixed Feel</td>
<td>PCU Pressure Reducer</td>
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<td>Flaps Up/Down Feel</td>
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<td>Manual Trim</td>
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<td>Fixed Feel</td>
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<td><strong>DIRECT</strong></td>
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Yeh96 fig.2
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Sequence of events:

1) Actuator Control Electronics unit (ACE)
   - Position transducers (mounted on each pilot controller) sense pilot commands for the ACE
     » two actuator controlled feel units provide variable feel for control column
     » mechanical feel units provide fixed feel for wheel and paddles.
   - ACE performs A/D conversion
   - Transmits signals to PFCs via redundant ARINC 629 buses
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2) Primary Flight Computer
   - Receive inertial data from
     » Air Data Inertial Reference System (ADIRS)
     » Secondary Attitude and Air Data Reference Unit (SAARU)
     » ACE
   - Compute Control-Surface position commands
   - Transmit position commands back to ACE via ARINC 629 buses
3) Actuator Control Electronics unit

- Receives digital command from PFC
- D/A conversion
- Control electro-hydraulic actuators of control surfaces
- In *Direct Mode*, the ACEs use the analog pilot controller transducer signals to generate surface commands

- Line Replacement Unit (LRU)
  - PFC and ACE are the major LRU, connected via ARINC 629 buses
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- **Actuator Control Electronics (ACE)**
  - 4MR configuration
  - Interface between analog domain, e.g. crew controllers, electric/electro-hydraulic actuators, and digital domains, e.g. ARINC 629, PFCs
  - Controls all control surfaces
  - Controls variable feel actuators
  - 3 ARINC 629 interfaces
  - In *Direct Mode* commands on the digital bus are ignored => Provide direct surface control
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![Boeing 777 Diagram]

**Figure 3**  Actuator Control Electronics Overview

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Figure 4  777 Primary Flight Controls Hydraulic / ACE Distribution

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- Primary Flight Computer (PFC)
  - TMR configuration
  - Receive data on all 3 ARINC 629 buses
  - Transmit on only one ARINC 629 bus
  - Each PFC contains 3 internal computation lanes
  - Each lane accesses all 3 buses
  - Each lane has dissimilar processors
  - Different Ada compilers
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Three identical channels: Left, Center, Right

Three dissimilar lanes in each channel: One in command, two functioning as monitors

Two PFCs in the E/E bay, one PFC forward of the forward cargo door

**Figure 5** Primary Flight Computer Channel Architecture
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- ARINC 629 Digital Data Bus
  - time division multiplex system, up to 120 users
  - terminal access is autonomous, terminal listens, waits for quite period and transmits

3 protocol timers
insure fair access
in round robin fashion

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- receiver listens to all traffic and determines which wordstrings are needed

Figure 7  ARINC 629 Functional Block Diagram
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– ARINC 629 bus requirements:
  » data bus availability requirements
  » tolerance to error occurrences of 1 in $10^8$ bits
  » tolerance of aperiodic bus operation
  » transmission requirements to provide indication of output data freshness and to not output split-frame data
  » common CRC algorithm
Figure 8  FBW Forward Path Signal Monitor
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- **Common Mode & Common Area Fault**
  - Component and functional separation. Resistant to
    - maintenance crew error or miss-handling,
    - impact of objects, electric faults, electric power failure, electro-magnetic environment, lightning, hydraulic failure, structural damage
  - Separation of components
    - multiple equipment bays
    - physical separation, (including wiring)
    - separation of electrical and hydraulic line routing
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- Functional Separation
  » Left, Center, Right flight control electrical buses
  » Unit transmits on only 1 ARINC 629,
    ■ each unit transmits on its dedicated bus, but monitors the others
    ■ unit failure can effect only single bus
  » Distribution of actuator control,
    ■ i.e. L/C/R units control actuators using L/C/R respective buses.

- Dissimilarity
  » dissimilar microprocessors
  » dissimilar compilers
  » dissimilar control & monitor functions
  » dissimilar inertial data systems
  » ACE direct mode allowing bypassing of buses
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Safety Requirements

- PFC: probability of $10^{-10}/h$ for
  - functional integrity (active failures affecting plane structure)
  - functional availability (passive failures)
- $10^{-10}/h$ for
  - all PFC operational
  - any single lane fault
- $10^{-10}$/h per auto-land operation for:
  - full operational system
  - single lane fault in any/all PFC
  - single PFC fault
  - single PFC fault & multiple single lane faults
- No single fault should cause error without failure indication
- No single fault should cause loss of $> 1$ PFC
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- Redundancy Management
  - PFC inter-lane communication within each PFC channel
  - Frame synchronization
  - (Input) Data synchronous operation
  - Median value selection
  - Cross-Channel Consolidation and Equalization
  - PFC external resource monitoring
  - In addition to ARINC bus: private cross-lane data bus for
    » frame synchronization within a PFC channel
    » data synchronization within a PFC channel
    » cross-lane data transfer
Redundancy Management: typical control path

Figure 9  PFC Redundancy Management Overview (Typical Control Path)
Figure 10  PFC Lane Redundancy Management (Output Signal Monitoring)
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- Synchronization
  - Frame Synchronization
    » to allow tight cross-lane monitoring
    » convergent (mid-point selection) frame synchronization
    » tight synchr. within a few microseconds (what about worse case?)
  - Data Synchronization
    » 2 MHz ARINC 629 => transmit duration > 20us
    » 20us >> frame synchronization time, thus giving sufficient time for data synchronization
    » all PFC lanes are synchronized to the same data set.
      ■ this data is then used at the beginning of each computation frame
      ■ allows tighter tracking between lanes
    » occasional PFC lane differences are tolerated
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Monitoring

Dual role of PFC lanes
- Command role:
  » only one lane
  » will send proposed surface command to ARINC 629
  » output is result of median select
  » other ARINC 629 receive command from other PFCs
- Monitor role:
  » “selected output" monitoring
  » cross-line inhibit hardware logic
- Cross-Line and Cross-Channel monitoring
- Critical discretes and variables are equalized between PFC channels