FLIGHT CONTROL SYSTEM WITH REMOTE ELECTRONICS

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Abstract

A primary flight control system is presented which resulted from Boeing's Large Airplane research from the mid-to-late 1990's. The system is a derivative of the 777 flight control system and is simplified to remove expensive interfaces and to minimize wiring for a large aircraft. The new architecture is shown and contrasted with the existing 777 flight controls. Estimated costs show when remote electronics on the actuators will reduce cost. A novel two-wire power and data bus is shown for communication to the actuators.

777 Flight Control System

The baseline for new large airplanes[1] at the time was the 777 flight control system [1]. The 777 flight control system is generally triple redundant with three channels, left, center, and right. The sensors and actuators in the cockpit and on the flight control surfaces interface to four Actuator Control Electronics (ACE), two for left channel, one for center and right channel. These ACE's communicate over ARINC 629 to the three Primary Flight Computers (PFC), one for each channel. This is shown in Figure 1.

Each PFC has three redundant lanes with dissimilar processors [2][3][4][5]. The lanes determine which lane will be the master lane, and then that lane becomes the lane to transmit on the channel's ARINC 629 bus. Each lane has the capability to shut down ARINC 629 transmission from the master lane. Each lane has it's own power supply, all are connected to the channel's flight control power bus. The flight control power buses have separate generators on the engine and each has a separate backup battery. Each lane has control over a relay at the power input to each lane, and can disable a lane by disconnecting its input power.

Problems with 777 Flight Control System

One of the problems of adapting the 777 flight control system was the long wire runs in the new large airplane compared to the 777. About 15-19 wires are required from each actuator to the ACEs. For long wire runs, this adds up to a large amount of airplane weight associated with the flight control wiring.

Another difficulty is the large surfaces which need to be controlled with the actuators. The structure, actuator, and actuator control loop must be designed to provide high bandwidths in the face of extremely high control surface inertias without destabilizing lightly-damped control surface structural modes. It was possible this would require a more complex actuator control loop than the 777 control loop.

Flight Control System With Remote Electronics

Replace ACE with RAEs at Actuators

To mitigate these problems, a new architecture is proposed where the 777 ACEs are replaced by Remote Actuator Electronics (RAE) located at the actuators. The RAE's provide the interfaces needed to the actuator while communicating directly to the PFC via a bus. This reduces the number of wires to the actuator from 15-19 to a maximum of six. This is shown in Figure 2.

[1] Approximately the same size as the Airbus A380

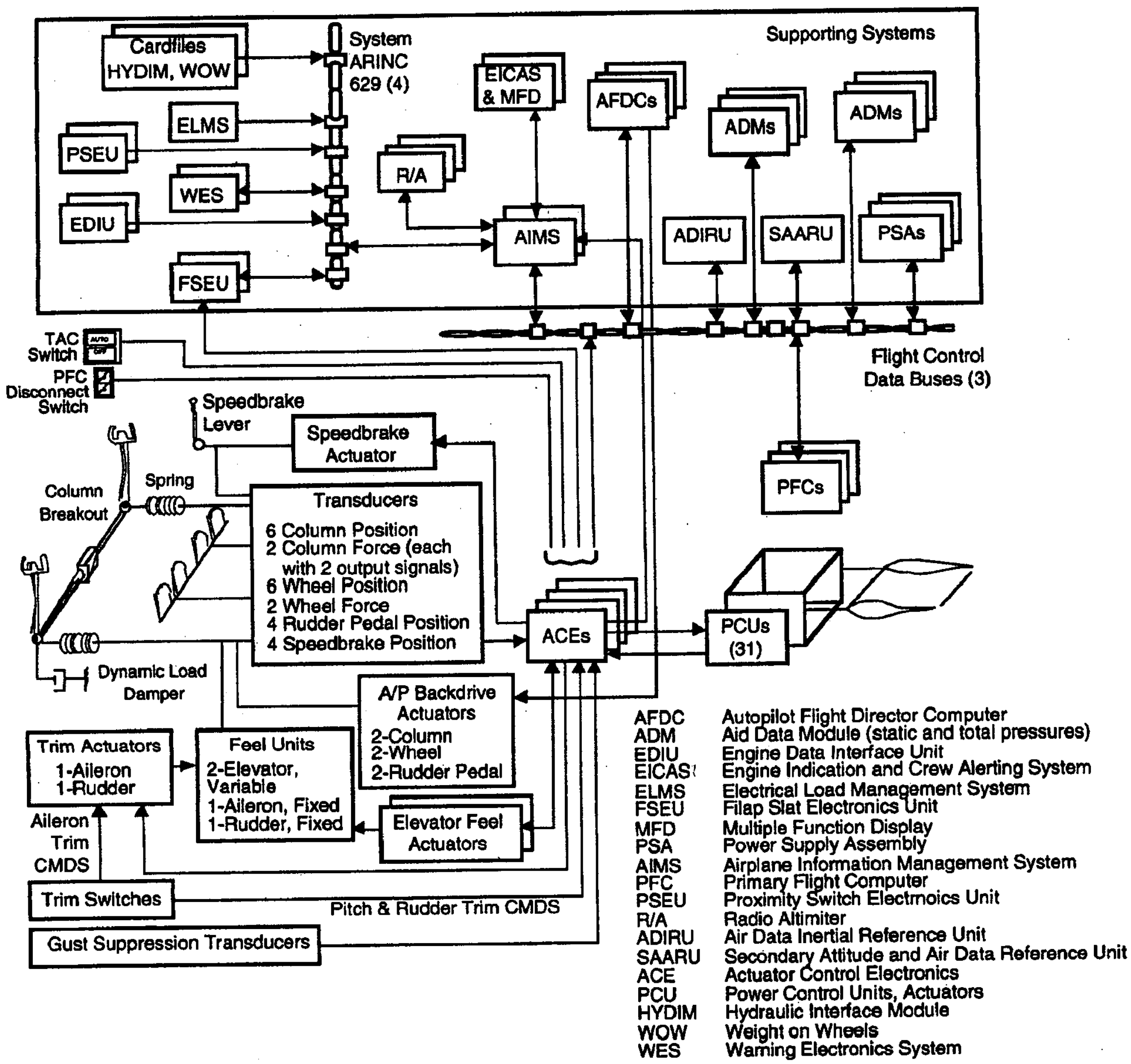

Figure 1. 777 Flight Controls Architecture

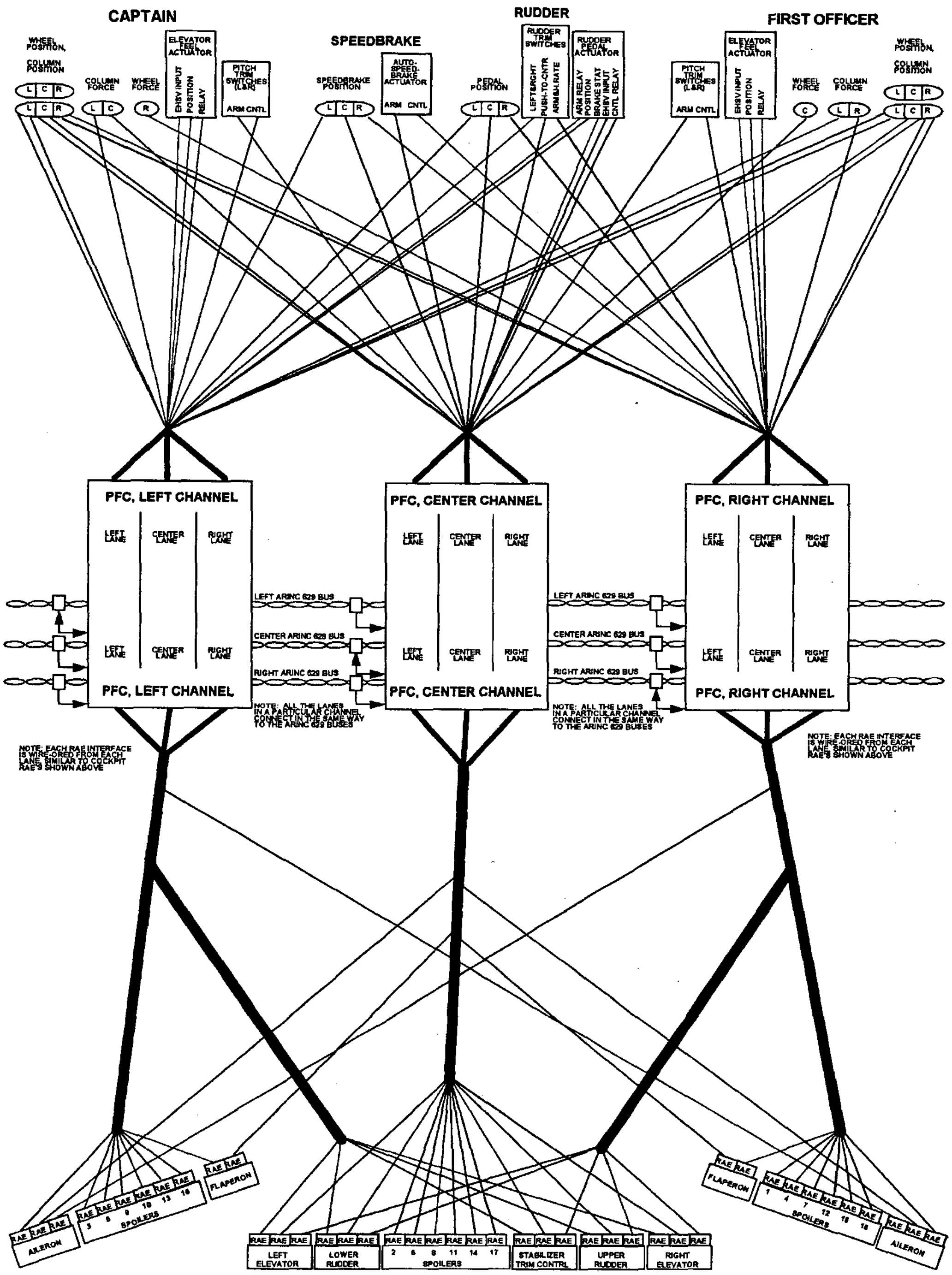

Figure 2. Remote Electronics Flight Controls Architecture

Each individual lane of the PFC is connected to each RAE, as shown in Figure 3.

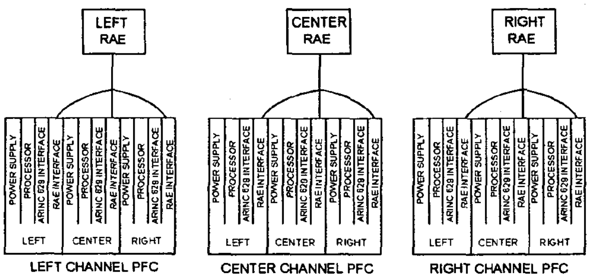

Figure 3. Remote Actuator Electronics Connection

Only one lane is in command of the RAE, but the other two lanes listen and can take control, similar to the triplex ARINC 629 interfaces between the PFC channels.

The RAEs are bolted to the actuators so all sensor wires are within the metal of the actuator and shielded. Since the RAE is bolted to the actuator, and all wiring is internal to the actuator for all the sensors, there will be very little EMI problems with the interfaces between the RAE and the actuator from external sources. For this reason lower voltages can be used for LVDT excitation and sensing to reduce the power consumption and dissipation by the RAE. Note that the RAE case and actuator housing is one cohesive shield if the RAE connector has low resistance to the actuator housing when engaged.

Internal sources inside this shield may be a problem if neglected. The highest load in the actuator is the bypass solenoid. Large currents can flow from the solenoid when it is turned off. If these lines are not separated from the other sensor lines, it is possible that this current could be coupled into other sensitive lines.

The wiring to the RAE from the PFC is routed into a connector on the actuator and inside the actuator to the RAE connector. These wires are very long in the airplane and are likely to have large amounts of induced EMI on them even though the cable is shielded. For this reason they should be separated by a metal barrier from all other wires inside the actuator, and within the RAE connector if possible. The RAE may have to be designed physically internally such that these lines are shielded from all other sensitive traces and circuitry until they are filtered.

Three Actuators On Each Surface

In the 777 flight control system, there are three redundant channels. One channel can fail, and the airplane can be controlled with two channels which can check each other. Each channel has to be independent, so each channel needs actuators on the flight control surfaces. In most cases, there are three actuators per surface, one for each channel. For the spoilers, there is only one actuator per surface because there are many redundant surfaces.

In some cases on the 777, there are only two actuators per surface. This creates problems because one channel's electronics or actuator can fail, and the other functioning channel cannot keep control of the surface. In the 777, a lot of monitoring was added in the electronics to keep the time very short between when a critical failure occurs, is detected, and corrective action taken. There are still some faults, like oscillatory faults, which are difficult to detect and may be present without being detected.

To remove the possibility of single channel failures causing loss of control of a surface, all surfaces have three actuators, one for each channel. One actuator can fail, and the other two actuators will keep control of the surface. Three actuators per surface is also needed for a large aircraft because of the larger surface inertias.

Three actuators per surface gives benefits in the actuator design because the system is more fault tolerant. Blocking valves were added in several 777 actuators to enable the actuators to lock up or have a resistance to movement in addition to the normal bypass mode. These are no longer needed if three actuators per surface are used.

6-2 Wire Power And Communication Bus

Communication is handled by a serial bus between the PFC and the RAE. Power is provided to the RAE by two wires, +28V and Ground. With a normal ARINC 429 implementation, this is six wires total, 2 for data transmission, 2 for data reception, and 2 for power and ground.

By making the ARINC 429 bi-directional and having a command/response protocol from the PFC, this can be reduced to 4 wires: 2 for data transmission, 2 for power. Another option would be to replace the ARINC 429 physical layer with RS-485 running at the same speed. RS-485 has off-the-shelf drivers and receivers and is a bi-directional bus.

By magnetically coupling the data onto the power wires, only 2 wires can be used to transmit power and data. This is the preferred method because it has the least overall system weight for a large airplane. An example of this is shown in Figure 4.

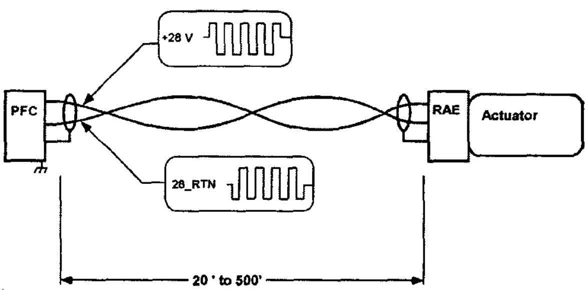

Figure 4. 2-Wire Power-And-Data Bus

Because a magnetically coupled signal is needed for this 2-wire power-and-data bus, MIL-STD-1553 is the bus interface of choice on and off the power lines.

For a smaller airplane the 4-wire bi-directional ARINC 429 (RS-485) is the best approach because the added complexity of the 2-wire power-and-data bus interface is not worth the two wires saved.

Note that the expensive ARINC 629 interfaces between the ACE and PFC are removed. Each channel controls only one actuator so there is a low-speed direct link from the PFC channel to each RAE. This link contains the position command to the RAE and feedback from the RAE. A diagram showing the direct link, bus information, and RAE interfaces is shown in Figure 5.

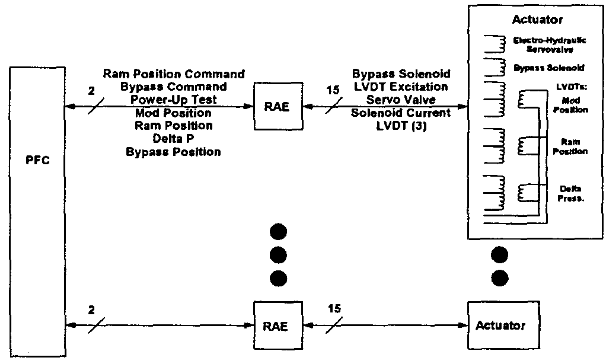

Figure 5. Bus Information and RAE Interfaces

The 15 wires used for actuator sensing and control are reduced to 2 wires. In Table 1 below is shown the detailed breakdown of the Bus data.

Table 1. Power and Communication Bus Data

Data Item	Bits
Position Command	12
Bypass Solenoid Command	1
RAE Personality Command	8
Built-In-Test Command	4
Position Command Echo	12
Bypass Solenoid Command Echo	1
RAE Personality Command Echo	8
Built-In-Test Command Echo	4
Actuator Ram Position	12
Actuator Mod Piston Position	12
Actuator Delta Pressure	12
Actuator Bypass Solenoid Position	1
RAE And Sensor Faults	1
Total Number Of Bits	88

The first four items are sent from the PFC to the RAE, the rest are what the RAE sends back to the PFC. The RAE repeats back every command received from the PFC. Note that this data would have to be placed into the protocol that was used, and parity added, etc.

Originally the 2-wire power-and-data bus was envisioned to be a Manchester-encoded ARINC 429 signal. Eventually it was decided to change to a MIL-STD-1553 interface for this function. A prototype of this bus was constructed and tested to external EMI, HIRF, and lightning levels. The maximum upset was a single bit for the lightning events with the standard 1Mbit/sec MIL-STD-1553 speed. This error should be caught with the parity bit used in MIL-STD-1553.

PFC Is Central Controller

In this architecture, the PFC takes over much of the fault monitoring of the actuators. An effort was made to keep the RAEs as simple as possible, and move all the complex decision-making back into the PFC. This is because there are 43-55 RAEs in this architecture for a large airplane, and only three PFCs. Overall it is cheaper to make the PFCs the complex part of the system, and the three PFCs are already complex. The RAEs communicate what the sensor readings are and simple faults in themselves and the actuator sensors (like sensor short) back to the PFC, but make no control decisions. A block diagram of the RAE is shown in Figure 6 below.

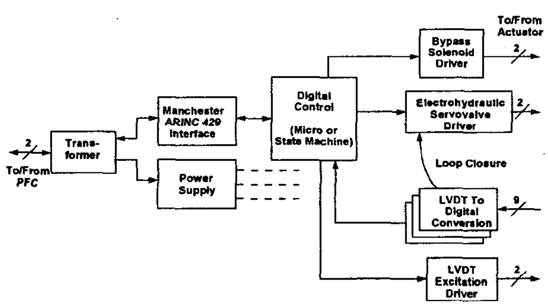

Figure 6. RAE Block Diagram

The 2-wire power-and-data bus implementation is shown above. The RAE was envisioned to not have software. As is shown it is a simple single-thread device. Because there are three actuators per control surface, less monitoring is needed in the actuator-controlling electronics. Simple non-independent in-line monitoring is used. The loop closure can be analog or digital.

Force fight is when from mis-rigging, mechanical tolerances, etc., the two actuators on a surface need to have different ram positions for the same surface position. When the two actuators are commanded to the same ram position, the two actuators will try to "fight" each other. The PFCs read all the delta-pressure sensors from the RAE's, and determine how much force fight is occurring and correct for it. The RAEs do not do this computation. This could be stored in a table so that the next time the actuator is commanded to the same position, force fight would be minimized.

Cockpit Interfaces

In the cockpit are RVDT and LVDT sensors used to sense the control wheel, column, and rudder pedal positions for the pilot and first officer. There are also switches used for pitch trim and rudder trim. In the 777 architecture these sensors and switches are input to the ACEs and then communicated to the PFCs over ARINC 629 as shown in Figure 1. In the new architecture, these interfaces are input directly to the PFC, shown in Figure 2. To communicate with the RAEs, a card is added to each lane of the PFCs, shown in Figure 3. This card also contains direct analog interfaces to the cockpit sensors. A block diagram of the card is shown below in Figure 7 where the RAE interface is implemented as a 2-wire power-and-data bus.

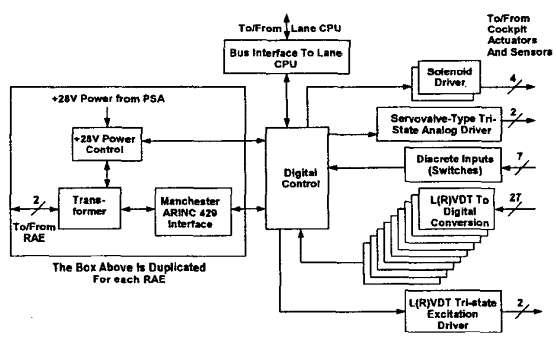

Figure 7. PFC Card Block Diagram

Other Interfaces (Stab Trim)

There are two Stabilizer Control Modules in the 777 for stabilizer trimming. Each module has control and arm relays for each direction, a rate relay, a brake status switch, an RVDT, and two limit switches for motion. This application for the

RAE is very different than the normal actuator application, needing far more relay outputs from the RAE. A separate RAE version will be used for the Stabilizer Control Module application, with more relay outputs and less LVDT/RVDT interfaces.

Power to RAE controlled by PFC

The 28V DC power to the RAE is fed through the PFC, as shown in Figure 8 below.

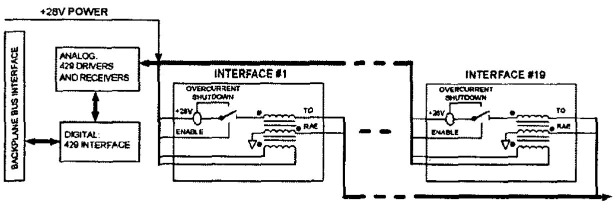

Figure 8. 28V Power Feed Through PFC

Again the 2-wire power-and-data bus is depicted. Keeping the power control of the RAE within the PFC allows the PFC to force a faulty RAE into bypass by removing its input power.

Cost and Weight Comparison

The addition of the RAEs was balanced by the reduction in cost of the wiring. In most cases the length and complexity reduction of the wire was not reduced that much because to really reduce wiring cost you need to remove a bundle, and in this case by adding the RAEs we are only reducing the number of wires in the buindle. Changing the spoilers to RAEs did not change the cost. Larger wire lengths and a larger number of wires do give a small net reduction (elevators and ailerons for example) for a large airplane.

By integrating the ACE and removing most of it's parts (power supply, ARINC 629 interface, analog inputs and outputs), this is where the major cost reduction occurs. Even though we add three cards to the PFC, the net cost reduction we found was about the same as if the ACEs were removed.

Probably the biggest improvement was in weight. By moving to the RAE approach for a large airplane the reduction in wiring weight was approximately 900 pounds.

Conclusion

A flight controls architecture is shown which provides considerable weight savings and cost savings over the present 777 flight controls architecture for a large airplane. Remote electronics are used at the actuators to reduce the amount of wiring to the actuator. Expensive ARINC 629 interfaces are replaced with low-cost point-to-point links to the actuator electronics. A 900 pound weight savings results from reduced wiring weight for a large airplane (>400 passengers).

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