FEATURE ARTICLE
CONTROL OF THE SKIES
COMMERCIAL AVIATION’S DIGITAL REVOLUTION
The cockpit of an Airbus A320, one of the first fly-by-wire commercial aircraft to reach mass production. What does its computerized control system mean for pilots, passengers, and the future of aviation?
Modern passenger aircraft are showing a common trait: sophisticated computer systems that link the pilot’s commands to the aircraft’s motions. Does this digital addition make flying safer, or does it rob pilots of control when they need it most?

An hour after departing from Denver, the pilots of United Airlines Flight 232 felt a jolt go through their aircraft. One of the three engines on the DC-10 passenger jet had malfunctioned, and the pilots soon realized they had lost control of many of the aircraft’s vital systems. Thinking on their feet, the flight crew managed to descend and set a course for Sioux City by manipulating the left and right engines independently to steer the aircraft. As ingenious as their plan was, they were unable to prevent a crash landing, and 111 of 296 passengers died when the jet broke apart on the runway.

Over 20 years later, United 232 is still a prime example of the role that control systems play in keeping an aircraft in the air. When debris flew from the malfunctioning tail-mounted engine of the DC-10, it struck the rear of the aircraft and broke through three hydraulic lines, quickly draining their fluid. These lines were integral to the control system, which allows the pilot to interact with the aircraft from her seat in the cockpit. With no hydraulic fluid, the crew couldn’t control the ailerons, elevators, rudder, or even the landing gear.

Though we as passengers rarely give a moment’s thought to the control systems of the aircraft we board, they are incredibly important and equally complex, and they are quietly evolving. Increased demands on the performance and safety of commercial aircraft have led to the growing popularity of fly-by-wire (FBW) flight control systems. These are electronic systems which aim to replace traditional mechanical control systems with computers and electrical signals.

A number of questions have arisen: what advantages does a FBW system offer? Do traditional systems really need to be replaced? Which system do pilots prefer to interact with?

What Is a Control System?

First, a little background: a fixed-wing aircraft, such as a passenger jet, has three main sets of control surfaces, called the ailerons, elevators, and rudder. The ailerons are mounted on the rear edge of each wing, and rotating them in opposite directions causes the aircraft to roll to the left or right. For example, rotating the left-hand aileron upwards and the right-hand aileron downwards would cause the plane to roll to the right. The elevators are mounted in a similar way to the horizontal stabilizers, which are the small “wings” at the base of the tail. Rotating these up or down causes the aircraft to pitch – that is, to point its nose either up or down. The rudder is at the rear edge of the tail, and allows the aircraft to yaw, causing the nose to point right or left while the entire aircraft remains horizontal.

Unless the pilot can control these surfaces from the cockpit, the aircraft can’t fly. That’s where control systems come in. Through various means, they connect the pilot’s controls (a control column for pitch and roll, and rudder pedals for yaw) to the control surfaces.

Traditional Systems: Rods, Pulleys, and Pipes

One of the simplest flight control systems, and one still in use today, connects the pilot to the control surfaces by rods and cables [1]. Depending on the aircraft, these may be inside or they may be visible from the outside. Putting them inside is more complex, because each linkage has to fit inside the already crowded body of the aircraft. This means using an intricate system of levers or pulleys to transmit the pilot’s exerted force to the control surfaces.

Modern passenger jets don’t use pure linkage systems [2]. Compared to the alternatives, such systems add too much weight to an aircraft, since they require a complex network of sturdy, heavy parts. Aircraft designers must also remember that
for a linkage system, the amount by which a control surface deflects is proportional to the amount of force the pilot exerts on his controls. For example, pushing the rudder pedals in by an inch may cause the rudder to rotate 10°, so to rotate the rudder by 20°, the pilot would push the pedals two inches. That’s a reasonable set-up for small recreational aircraft, in which linkage systems are still common. But to move the surfaces of a large passenger jet flying at a high speed, the pilot would need to exert a great deal of force. There are methods of overcoming this, such as placing some of the control surface’s area in front of its hinge. When the control system moves the surface slightly, aerodynamic forces on the forward portion help the surface to move even more. Still, linkage-based control systems eventually became a limiting factor in the design of high-performance aircraft.

A popular alternative to purely linkage-based control systems uses hydraulic power to move the control surfaces, as on United 232. The pilot’s controls are still connected to a mechanical circuit of linkages or cables, but that circuit leads to a hydraulic circuit. The hydraulics derive their power directly from the engines, and pumps send pressurized fluid to the control surfaces. Once there, actuators (usually one or more pistons) use the fluid to move the surfaces on demand.

In contrast to purely linkage-based systems, the addition of hydraulics allows for adherence to a fundamental engineering principle: redundancy. It is common practice – and an unwritten requirement for any manufacturer who wishes to actually sell their product – to include two or more independent hydraulic circuits. If one fails, the others can help pick up the slack. Of course, this is of little use in the event of a catastrophic failure such as United 232. But it offers a clear advantage over pure linkage systems, in which the failure of a single rod or cable could render a control surface immobile. The addition of hydraulics also sends vital feedback to the pilot in the event of a malfunction. If the amount of fluid in the reservoir drops below a dangerous level, control of less-critical systems can be deliberately cut, leaving the remaining fluid to perform the most important duties. Cockpits also feature gauges to measure the pressure, temperature, and cleanliness of the hydraulic fluid.

Hydraulic actuators have an impressive power-to-weight ratio, and manufacturers put great effort into reducing the weight of the circuit without sacrificing performance, cost, or safety. The working pressure of the hydraulic fluid (a mineral-based oil) is commonly between 3,000 and 4,000 psi, and this choice has been shown to minimize the required weight. Knowing this, along with the fluid flow rate needed to power the actuators, designers can use relations from fluid mechanics to calculate the minimum allowable pipe diameters for the hydraulic circuit, reducing both weight and manufacturing costs.

**Fly-by-Wire**

The inclusion of hydraulics in newer aircraft revolutionized the aerospace industry by partially replacing the mechanical linkages in control systems. The next logical step was to do away with mechanical linkages altogether, and as early as the 1960s, an experimental class of control systems called “fly-by-wire” was under investigation. One of the first aircraft to reach large-scale production featuring a FBW system was the Concorde [3], which first flew in 1969. That aircraft was famously retired after a fatal crash, which was unrelated to its FBW system.

A fly-by-wire control system is one that uses electrical signals to convey the pilot’s control inputs to the actuators that move the control surfaces. It’s important to note that this does not replace the hydraulic components which had previously supplemented linkage-based systems. Those hydraulics are still needed to drive the actuators; a FBW system simply carries the pilot’s commands to the hydraulic circuit by opening and

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*A hydraulic actuator from the aileron of a Boeing 747. Its impressive size suggests how much force it applies to the control surface, and why a pilot couldn’t do it without the help of hydraulics.*
closing valves associated with each actuator. FBW systems work by way of a feedback loop. The pilot inputs a command that describes where she would like the control surface to move, and the computer relays an appropriate instruction to the actuator. As the actuator moves the surface, an electrical feedback signal reports the surface’s position to the computer, which continuously compares that position to the pilot’s command, and instructs the actuator accordingly. The computer also receives signals related to the instantaneous performance of the aircraft, such as speed, roll rate, and so on. It takes this information into account when instructing the actuator. Once the position reported by the actuator is the same as the pilot’s command, the computer ceases its activity and the process is complete.

![Schematic of a fly-by-wire feedback loop, showing the multiple inputs that the computer receives, and its output to the actuator.](image)

This sounds complex, and it is – in fact, this description is very simple compared to the intricacies of a real-world FBW system. But one of the biggest selling points of such a system is that it is largely software-driven. Since the computers and wiring are installed, the system can be fine-tuned in ways that a mechanical system cannot. Andy Corea, Director of Technology and Capability at BAE Systems (a British aerospace firm) says, “It might take a lot of effort to qualify the hardware and get it established, but [FBW systems] provide a lot of flexibility and make it able to change parameters and refine the vehicle’s performance” [4]. While much of an aircraft’s design is based on elaborate simulations prior to building a prototype, FBW systems allow tests to be carried out on real aircraft, and provide a way to modify aircraft that have already been delivered to airlines if valuable new information comes to light, such as data from an accident.

So how is a fly-by-wire control system designed? Each model of aircraft can operate safely within a certain flight envelope, which is a range of acceptable velocities, altitudes, and air conditions. Leaving the confines of this envelope would either prevent the aircraft from staying aloft or damage the airframe. Wind tunnel experiments provide data for a number of points within the flight envelope, and this data is used to design a “localized” control system that would perform ideally under those conditions [5]. The process is very involved, and beyond the scope of this article. Once the localized control systems are implemented on the aircraft, an array of external probes bridge the gap between the operating points by measuring the current flight conditions.

As with any control system, the safety of a FBW system is a primary concern. The computers and wires that make up the FBW system are triply or quadruply redundant; multiple computers run in parallel and compare their outputs. If one produces a result the others don’t agree with, they automatically override it. The hydraulic components have a similar arrangement, and since the mechanical linkages have been removed, all aspects of a modern airliner’s control system have generous redundancy. With this level of redundancy, the system is expected to be extremely reliable, and studies have confirmed that theory. One such study, by Joanne Bechta Dugan and Randy Van Buren at Duke University [6], examined the rudimentary FBW system of an Airbus A310 and the more modern one of an A320 in terms of the probability of an unacceptable result over the service lifetime of the system. In short, they determined that the A320 in particular, being the newer aircraft, is exceptionally reliable, given reasonable estimates of constant parameters like the rate of permanent hardware faults. Their results suggest it could take up to 100,000 hours – over 11 years – of continuous operation before a single unacceptable result arises. Keep in mind, an unacceptable result doesn’t mean a catastrophic accident; it simply means some deviation from the expected result.

![The results of a reliability study by Dugan and Van Buren, showing the probability of an unacceptable result over the service life of an A320.](image)

**A Philosophical Standoff**

Clearly, the simple addition of a fly-by-wire system is acceptably safe, since it features highly reliable and redundant components. But one aircraft manufacturer in particular has opted to take things a step further, sparking an impassioned debate over the degree to which we should trust a computer’s judgment. Beginning with its narrow-body A320 in 1988, Airbus has outfitted their FBW control systems with “flight envelope protection,” which restricts the aircraft to maneuvering only within its flight envelope. This doesn’t just apply when the
autopilot is switched on; even when the pilot is controlling the aircraft manually, the computer won’t allow him to make a maneuver it deems unsafe. Under normal flight conditions this doesn’t pose a problem, and pilots likely wouldn’t notice the difference. Potential issues arise during an emergency, when a pilot may find himself fiercely tugging on the controls to avoid an obstacle, only to be overridden by his own aircraft.

One school of thought says that allowing the pilot to operate an aircraft outside of its flight envelope is pointless, as doing so would cause major structural damage. Often cited as a counterexample is the case of China Airlines Flight 006, in which the pilot of a Boeing 747 (a non-FBW aircraft) recovered from a catastrophic vertical dive by aggressively leveling the aircraft, introducing forces up to five times the force of gravity (5G) [7], while an Airbus would prevent any maneuver over 2.5G. China Airlines 006 landed safely with no fatalities, though the airframe was badly damaged as a result of leaving the flight envelope. That is, of course, a small price to pay for the passengers’ safety, and the pilot acted commendably under the circumstances. Airbus responded by saying that flight envelope protection would have entirely prevented the vertical dive, which was brought on by the autopilot’s overcompensation for a stalled engine [8].

Boeing’s takeaway from China Airlines 006 was that sometimes, pilots need to do unpredictable things, and no computer should get in their way. Beginning with its 777 series in 1995 and continuing with the 787, Boeing has followed modern trends and installed FBW systems – notably without flight envelope protection. But Airbus is confident that giving the computer system the final word provides a piloting experience that is not only acceptable, but also liberating. Udo Guenzel, an engineering test pilot at Airbus, points out that a pilot, knowing her aircraft will not stray outside its flight envelope, can feel free to make aggressive control inputs to avoid obstacles, instead of trying to judge whether those maneuvers would overstress the airframe [8]. Unless the situation is very dire, then, and no recovery is possible even at the furthest reaches of the flight envelope, taking some judgment out of the pilot’s hands might increase safety substantially.

Even if you take Airbus’s response to China Airlines 006 with a grain of salt, there is no shortage of cases in which flight envelope protection may have saved the day. Consider American Airlines Flight 587, which crashed in 2001 shortly after takeoff in a residential area of New York City, killing 265 people. The National Transportation Safety Board determined that one of the pilots’ excessive inputs to the rudder controls, in an attempt to recover from turbulence, ripped the tail from the body of the aircraft [9]. Questions were raised about the pilot’s training and the sensitivity of the Airbus A300’s rudder controls. Still, one cannot help but wonder if the addition of flight envelope protection to this pre-FBW aircraft could have drastically changed the outcome.

The View from the Cockpit

A common argument against FBW systems is that they prevent the pilot from “feeling” the response of the aircraft through the cockpit controls. This idea dates back to the linkage-based systems of older aircraft, in which aerodynamic forces on the control surfaces applied tension to the cables connecting them to the yoke (a “steering wheel” to control pitch and roll). Taking this tactile feedback out of the equation can be worrisome, since there would be one less way for a pilot to gauge how the aircraft is flying.

As it turns out, this issue has little to do with FBW, and in fact applies equally to any aircraft with hydraulic actuators—that is, any modern passenger jet. Two solutions have been proposed. One is to add a spring to the yoke. The pilot then feels a linearly increasing amount of force as he moves the yoke from its natural position. This is an oversimplification, though, because it does not account for fluctuating air qualities. A better method implements artificial feedback called ‘Q’ feel [1]. Using data from the aircraft’s pressure sensors, ‘Q’ feel imposes a hydraulic resistance force on the yoke that is proportional to the square of the airspeed (so a small change in speed can cause a big change in resistance). This is in keeping with a simple law from fluid mechanics that relates airspeed to the aerodynamic force on the control surfaces [10].

Airbus aircraft, however, which have a side-mounted joystick instead of a yoke, do not feature any artificial feedback.
Is this problematic? Personal preferences aside, a good case can be made for the lack of feedback: with flight envelope protection, it’s no longer needed. The value of tactile feedback is to indicate whether the aircraft is operating unsafely, but an Airbus’s computer limitations make this impossible.

By the Numbers

Fly-by-wire has its advantages, and is clearly being pushed forward by the major players in commercial aviation. Every Airbus since the A320 (the A318, A319, A321, A330, A340, and A380) has featured a FBW control system, as have Boeing’s two most recent lines, the 777 and 787. How have their customers responded?

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<thead>
<tr>
<th>Number in Service</th>
<th>Airbus</th>
<th>Boeing</th>
</tr>
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<tbody>
<tr>
<td>Non-FBW</td>
<td>9231</td>
<td></td>
</tr>
<tr>
<td>FBW</td>
<td>7603</td>
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Passenger aircraft currently in service worldwide, made by two major manufacturers [11].

These data do not present the full picture, just a large portion of it. First, many aircraft from defunct manufacturers like McDonnell Douglas are still flying with major airlines, as are smaller regional jets from companies like Embraer and Bombardier. Eastern European manufacturers like Ilyushin, Tupolev, and Antonov have a significant presence in that region, but very little outside it. Second, it is hard to compare sales of FBW and non-FBW aircraft on fair terms, since FBW is a relatively new creation. Non-FBW products have been available for much longer, and many are still offered, such as the Boeing 737, 747, and 767. Finally, airlines consider more than just the control system when buying an aircraft, so it’s tricky to match sales figures with a conscious choice to adopt or avoid FBW.

However, one thing is abundantly clear: modern customers are comfortable enough with FBW to allow it on a sizeable portion of their fleets. With older aircraft being retired by operators and new offerings from the major manufacturers almost universally featuring FBW, that portion is bound to increase.

The Final Word

With over four decades of history and extensive testing, fly-by-wire control systems in their basic form are a positive step in aerospace engineering. They eliminate the need for heavy, high-maintenance mechanical linkages, and they allow for painless software redesigns throughout the testing phase and regular service. On top of these improvements, FBW systems are at least triply redundant, and have been shown to be exceptionally reliable. These systems are the obvious way forward for the commercial aviation industry, and even more sophisticated electronic systems have outfitted military aircraft with greater agility and maneuverability [5].

Less black-and-white is the issue of assigning ultimate control to either the pilot or the FBW system. Thankfully, there have been very few accidents to give us insight into which design philosophy is superior. Cases like China Airlines 006 and American Airlines 507 are few and far between, leading to the anticlimactic – yet comforting – conclusion that both options are extremely safe. Stringent regulations, careful designs, effective maintenance, and pilot skill have proven to be enough to keep our aircraft in the air, regardless of which fly-by-wire philosophy is chosen.

References

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<http://www.airliners.net/photo/Air-France/Boeing-777-328-ER/1405530/L/>.


<http://commons.wikimedia.org/wiki/File:B747_Inboard_Aileron_Actuator.JPG>.


