SEE ME, HEAR ME, TOUCH ME, FEEL ME

AIRCRAFT NAVIGATION AND GUIDANCE MAY GIVE YOU A SENSE OF WHERE YOU ARE, BUT SENSORS GIVE YOU A SENSE OF WHO AND HOW YOU ARE, AND FLEXIBLE, CONTROLLABLE SKINS LET YOU ADAPT TO THE ENVIRONMENT.

By Bill Schweber, Executive Editor

The first airplanes had no skin, just wings covered with fabric. Soon, designers enclosed the fuselage, first to cut down on wind resistance and, eventually, to hold passengers in the now-familiar aluminum tube. But aircraft were still primarily flying tubes.

As aircraft became faster, more powerful, and more complex, advances in sensor and instrumentation technology improved, and designers adapted them to monitor vital aircraft parameters, such as engine performance and some airframe issues. But systems displayed whatever data these sensors collected only to the crew, so most of it was lost afterward, unless the crew members took notes. The exception was test aircraft—which might have extra instrumentation, including data recorders—but such systems were limited in scope and capability.

Fast-forward to the 21st century. Today's commercial aircraft have thousands of built-in sensors, various data recorders, and even a complex ground-based infrastructure that captures algorithms and databases to use this data. This instrumentation advance continues to real-time linking of a continuous flow of data to ground-based management systems.

Figure 1 The Airplane Health Management program extensively monitors the aircraft in flight and, while in flight, relays information to ground personnel, so necessary maintenance work can start as soon as the plane stops (courtesy Boeing Commercial Airplanes).

Aircraft enhancements go beyond adding more passive sensors to every nook and cranny. The aircraft skin is no longer just an enclosure; it's a framework for antennas as well as special sensors that check on the integrity of the structure itself. And these enhancements may go beyond using the skin primarily as a rigid structure with adjustable flaps. The skin will have actuators that change its flying characteristics to meet the changes in flying conditions, such as speed and mission.

I'M OK, I'M PRETTY SURE...

A commercial airliner, such as the Boeing 777, has lots of sensors—as many as 40,000; half are associated with the engines. Making immediate and long-term sense of this data torrent means that aircraft manufacturers must do more than show these readings to the carrier's air or ground crew. Boeing Commercial Aircraft group has planned a three-step AHM (Airplane Health Management) strategy that combines collected data, communication links, data storage, and advanced diagnostic and predictive algorithms (**Figure 1**). The company supports this strategy with an extensive database that it bases on readings collected from hundreds of aircraft and millions of hours of experience (see **sidebar** "Health management turns data into knowledge.")

AT A GLANCE

▷ Much more than just flying machines, today's aircraft include thousands of sensors monitoring every aspect of performance and integrity.

▷ The aircraft's skin is not just an enclosure, it's an active and increasingly smart part of the design, incorporating antennas, sensors, and more.

▷ Tomorrow's aircraft will have advanced algorithms to judge and report on their health and may be able to morph their shape for different roles.

Phase I of the AHM program started field tests in October, and testing involving Boeing 747 and 777 aircraft in the American Airlines and Air France fleets will continue through March 2004. In this phase, the aircraft's central maintenance computer sends faults, error conditions, and other data to the ground in real time, via a secure Web site (www.MyBoeingFleet.com) and network that air carriers can access. (You can tour the site at www.boeing.com/commercial/aviationservices/myboeingfleet/index.htm.) The ground system, which knows the details of that aircraft's configuration, tells the mechanic what is wrong and the likely source of the problem. (For example, the power unit on Bus A is malfunctioning.) The ground-based software uses an extensive knowledge base of past problems and fault trees, as well as a minimum-equipment list for that aircraft, so that it can match the aircraft's condition with the planned travels of that aircraft, as well as the needs of the carrier, which uses the information for routes and schedules. In this way, it minimizes the overall impact of problems, which can range from minor to severe and from potential to actual.

In Phase II, the AHM system will use snapshots of data taken during normal operation and report it in real or near-real time. This information will allow Boeing and air carriers to anticipate problems before they occur, based on historical data and patterns. For example, a certain rate of rise in a bearing's temperature may mean that the bearing is degrading and that an operator should check it in the next 100 hours, but it is not an immediate crisis. Phase III moves from taking snapshots of data to sending a continuous stream of data to the ground.

HEALTH MANAGEMENT TURNS DATA INTO KNOWLEDGE

Airplane-health management, also called IVHM (integrated vehicle-health management), seeks to turn the good and the bad news of the sensor-laden aircraft into mostly good news. The proliferation of sensors and built-in test means that more raw data is available to the air and ground crews, but turning this data into meaningful information and drawing valid conclusions from it is also increasingly difficult. Many of the reported faults—from 20% for simple aircraft to as much as 88% in some naval-aircraft studies—were false alarms, sensor failures, or "cannot-duplicate" events (**references** A and B). Such false alarms are costly in time, dollars, and availability.

IVHM builds knowledge with formal, structured framework using raw data and built-in-test results, as well as information about the aircraft from designers, crew, and maintenance staff. It is a multiple-perspective approach encompassing:

- built-in test, which provides diagnostics, based on fault thresholds;
- diagnostics, which determine the status or capabilities of a component;
- prognostics, which is predictive diagnostics, to determine the remaining life span of a component;
- health monitoring, which provides ongoing assessment of component status; and
- health management, which bases decisions on diagnostics and prognostics.

Combining this information with correlation understanding, "gray-scale" assessments (sort of like fuzzy logic), parameter drift and degradation during service life, event-sequence analysis, and other analysis modes, as well as with the operational requirements for the aircraft and maintenance resources, IVHM advances the proper diagnostics, matches them to needs, and minimizes misleading or incorrect decisions.

IVHM is not limited to commercial aircraft. Military and research (experimental and secret) aircraft are applying the same method but with major differences. Commercial aircraft benefit from the law of large numbers, with data from many aircraft and hours. The military has fewer vehicles to use as data sources and flies fewer hours; research aircraft have even less of each factor. Furthermore, the mission, support resources, and logistics for military and research aircraft also differ greatly from those of commercial aircraft.

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A. Hooks, Dean and Chris Reisig, "Integrated Vehicle Health Management (IVHM)," NDIA Fifth Annual Systems Engineering Conference, Boeing Phantom Works, October 2002.

B. Schweikhard, Keith A, W Lance Richards, and John Theisen "Flight Demonstration of X-33 Vehicle Health Management System Components of the F/A-18 Systems Research Aircraft," NASA TM-2001-209037, December 2001.

The communication links require additional bandwidth from the in-flight aircraft; to supplement the links, the onboard maintenance computer dumps data onto an onboard optical disk that the ground crew removes and sends to the AHM personnel. The air carriers have access to all data and conclusions using the secure Web portal that Boeing operates for them. This portal allows the carriers to make their own assessments and decisions about what to do next, minimizes schedule disruption, and maximizes maintenance efficiency.

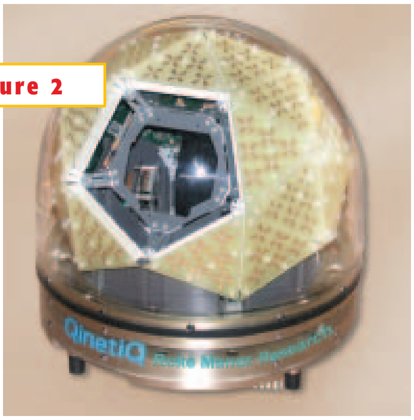
Based on its enormous knowledge of the aircraft design and operation, the system further looks at data trends, false alerts (a major problem with so many sensors), rate changes, and combinations of sensed parameters. The goal is to point to prioritized conclusions about problems and their severity, matching the data with the aircraft specifics, generation, route commitment, and unique configuration.

PLAYING THE SKIN GAME

Antennas and their proliferation demonstrate how aircraft designers must use the surface of the aircraft for more than just physical enclosure. Beyond conventional voice links, aircraft have several radar systems, ground-data links, direct-to-satellite links, GPS navigation, jamming systems for military aircraft, and more. (Automobiles are not much better: General Motors estimates that a 2004 Cadillac with all options will have at least 17 antennas, and collision-avoidance radar is yet to come.)

To make the skin into an electronic element, engineers are investigating advanced conformal-antenna designs that meet both mechanical and electrical requirements. Although conformal antennas are not new, the frequencies and bandwidths they must support are new, and higher frequencies mean that the inherent curves and dimensions of the skin affect them more. The Air Force Research Laboratory antenna division is looking at a conformal array that you could embed in the wing root and wrap around the wing (**Reference 1**). This 5.45-GHz array for radar uses 116 microstrip patch antennas spaced at half a wavelength; in a test, the antennas were alternately excited in the direction of the main beam, which was forward and 45° above the horizon. They achieved near-side lobes of 13 dB down from the main beam with 10 elements active, which improved to 9 dB more below the main beam when 15 elements were active. Because of the leading-edge curve, only eight elements were effective, but simulations and scale-model tests indicate that this antenna can produce high-quality beams at most angles.

Figure 2



Active arrays provide electronically steered antennas with a wide angle of coverage as needed yet can conform to the aircraft skin, such as this "smart-skin" unit from Rowe Manor Research Ltd.

Keeping an aircraft linked to a satellite is another challenge because of the varying and random angles between the two bodies. You can build a moving parabolic reflector that you place under the skin, but this approach is mechanically complex and consumes depth. Using active arrays, designers now have another option. Rowe Manor Research (www.roke.co.uk) bases an SHF-band electronically steerable antenna on a modified dodecahedron with 40 identical triangle tiles, each containing six active cross-dipole elements (**Figure 2**).

This topology provides many active elements for any steering direction, as well as fairly uniform performance for most of the upper part of the hemisphere. Coverage is 360° in azimuth, from -10 to $+90°$ in elevation, with left-hand polarization on transmission and right-hand polarization on receive. Digitally controlled 3-bit phase shifters drive the antenna; the active circuitry is implemented as monolithic-microwave ICs with low-noise amplifiers for receiving and power amplifiers for transmitting. The phase shifters provide ±22.5° angular resolution, and the antenna provides 20-dBm output power, 10-dB gain, and a noise figure of less than 4.5 dB.

Of course, no surface is safe from designers' longing looks. The vertical stabilizer, or tail, of the aircraft is another promising area. NASA's Dryden Flight Research Center (www.drfc.nasa.gov) has tested a "smart-skin" antenna in the

MY NERVES ARE GETTING FRAYED

Internal wiring-harness failures, due to wire chafing from airframe flexing, contribute to wiring failure and have been implicated in several crashes and other incidents. This chafing, which develops over a long period of time, can cause wiring failure. Such failure is bad but rarely catastrophic, because of the redundancy built into aircraft controls. However, chafed insulation can lead to arcing, with a 3- to 4-msec vapor of the arc-forming plasma reaching 3000 to 10,000°C. This heat can, in turn, cause fire and even explosions, especially near or in the fuel tanks if vapors linger (**Reference A**). Checking for cable chafing and breaks involves visual inspection, which means crawling inside aircraft ducts or removing panels.

However, a recent technique (US patents 6,265,880 and 6,275,050) uses an optical fiber that is spiral-wound around the harness and then covered with Teflon tape (**Reference B**). To test, you connect the end of the fiber to an optical time-domain-reflectometry test set, which assesses the integrity of the fiber and the severity and location of any cracks. You associate any fiber problems with the condition to chafing of the underlying harness. Advantages of this approach are that it is nonintrusive and nonelectrical, and you can retrofit it onto aircraft; in addition to using the approach with wire harnesses, you can also use it for monitoring hydraulic and pneumatic hoses and lines.

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A. "Circuit Breakers are not Enough," *Aviation Week & Space Technology*, Aug 21, 2002, pg 72.

B. "Preempting Aircraft Wiring Failures," *AFRL Technology Horizons*, March 2002, pg 28, www.afrlhorizons.com.

tail of the F/A-18, basing it on developments from the US Air Force Wright Laboratory, Northrop-Grumman Corp, and TRW's Aviation Systems Division (**Reference 2** and **Figure 3**). This antenna, for air-to-air and air-to-ground links, may replace the conventional blade antenna; it provides a 15- to 25-dB improvement in SNR performance at 65 MHz, a more symmetrical radiation pattern, a lower radar signature, and reduced drag. The key to this type of antenna is the use of materials with suitable electrical and structural properties—in this case, thermoset materials with low-loss, high-conductivity electrical properties that stimulate current flow and have the high strength necessary to survive the severe loads.

GPS navigation is now a must on aircraft, but to receive the signals, the aircraft needs yet another antenna. Mitre Corp (www.mitre.org) has developed a concentric, two-element adaptive-array antenna using microstrip elements. Including the mounting flange, this antenna (US patent 6,597,316 B2) measures 7 inches square and weighs just 589g without its radome. The antenna's passive elements, which target active adaptive electronics, are made from high-dielectric-constant substrates, which also feature temperature-stable performance.

Another concern of the aircraft is assessment of the flying situation, looking at factors such as flow angle, side slip, and angle of attack. Engineers at Dryden have flight-tested a system that uses conventional strain gauges mounted on a 5×2.5×3-cm aerodynamic fin, similar to those tufts of yarn attached to an aircraft in a wind tunnel, to measure the local flow angle (**Reference 3**). The electrical readings from the gauges are correlated with known readings to convert this force-measurement data to a flow angle. Future implementations may use fiber-optic strain gauges for smaller size and reduced wiring.

For angle of attack and side slip, researchers are looking at a combination of L-shaped probes and four dual-channel pressure transducers (**Reference 4** and **Figure 4**). The transducers measure the Pitot-tube and static pressures from the probes and send these readings to an onboard computer via an RS-422 interface. An algorithm then uses the differential pressure reading to calculate, in real time, the angle of attack and side slip factors. Designers have flight-tested this system under different flight conditions to refine both the probe configuration and the algorithms. Its performance has been comparable to or better than the standard instrumentation, even at angles of attack reaching 90°; one goal of the program is to improve measurements at angles greater than 45°.

Then there is stress. It is not only a psychological phenomena and the subject of numerous stories in the popular press, on TV, and in medical journals, but also a serious mechanical issue. Airframes are subject to both static stress from fixed loads and dynamic stress from vibration and flight motion. This stress, in turn, can initiate crack growth in the structural members and skin of the aircraft and make these cracks grow. For this reason, aircraft undergo extensive, complex stress tests in development to assess their service life in hours, under normal and occasionally extreme conditions. If the aircraft maker wants to extend the airframe life via upgrades and improvements, it must repeat these tests, at great cost in dollars and time, using elaborate test setups (**references 5** and **6**). Even after aircraft enter service, maintenance depots periodically test high-stress areas with a variety of techniques, such as eddy currents, ultrasonic waves, and fluorescent dye checks.

An alternative to stress testing is to use in-place sensors mounted in the critical areas of the aircraft, to continuously monitor cracks and their growth. (Note that small cracks are common occurrences and allowed, up to a point!) If you could embed these sensors into key locations and high-stress points, you could monitor the airframe and skin during its operational life and thus determine whether high local stress levels were causing cracks to start and grow. Boeing is reportedly planning to employ this technology in its next-generation 7E7 aircraft, using, for example, solid-state magnetic sensors based on GMR (giant magnetoresistance) and SDT (spin-dependent tunneling) as part of advanced eddy-current probes (**references 7** and **8**). Some stress consequences are related to neither the aircraft skin nor the structural members (see **sidebar** "My nerves are getting frayed").

Figure 3

The vertical stabilizers in NASA's F/A-18 Systems Research Aircraft are no longer mirror images of each other, now that a smart-skin antenna is mounted on the tip of the right vertical (courtesy NASA Dryden Flight Research Center).

Figure 4

For improved angle-of-attack and side-slip measurements, this under-the-nose view of a modified F-18 Systems Research Aircraft shows two L-probes. Behind the L-probes are angle-of-attack vanes; below them are the aircraft's standard pitot-static air-data probes (courtesy NASA Dryden Flight Research Center).

All of these sensors add to the wiring burden of the aircraft, which adds weight and volume to the design, even with extensive multiplexing; installation time for every sensor's wiring is also a problem. Developers have created wireless sensors for some uses, such as smoke detection. Securaplane Technologies (www.securaplane.com) offers an approved system, now installed in Southwest Airlines 737s and other aircraft, that uses spread-spectrum wireless technology (**Figure 5**). The company can retrofit this system to existing aircraft or install it in new ones during manufacturing.

With all the electrical activity within the aircraft, it is obviously a difficult EMI and RFI environment for any wireless installation. The vendor expected a 20- to 25-dB SNR, but first installations achieved only 15 dB (**Reference 9**). By relocating the central control unit within the fuselage, it was able to reach a 40-dB SNR. (The code for the system is classified at Level C—critical but not essential to the aircraft survival.) The company wants to extend its time-, weight-, and space-saving wireless system to other Level C sensors in the aircraft, such as those related to general security.

It's not just internal aircraft conditions that need checking. Wing icing can lead to severely degraded performance, so an ice-protection system from Cox and Co (www.coxandco.com) combines thermal anti-icing and mechanical deicing to keep surfaces clear of ice (**Reference 10**). This system, which is in production for the Raytheon Premier I business-jet horizontal stabilizer, heats the leading edge of the airfoil to prevent ice from forming. Beyond the leading edge, a mechanical system expulses the ice. The two-part system uses less energy than other in-place systems and provides equal or better deicing performance.

I WANT A MAKEOVER, TOO!

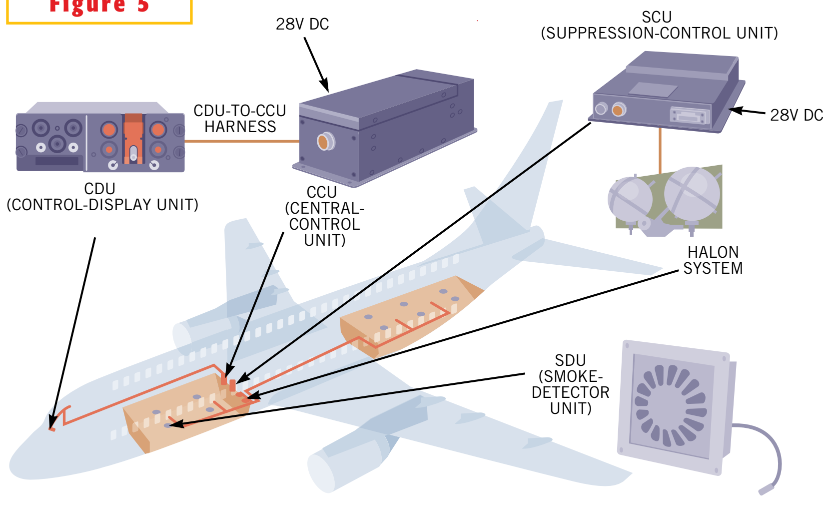
If you have ever looked outside the window of an aircraft, you know that the wings flex and twist in flight. As airplanes get faster, carry heavier loads, or do stomach-churning combat maneuvers, this flexing and twisting becomes unavoidable, despite the aircraft's designed-in strength. The extremes of such bending—which can occur along or across the wing—can compromise the performance and stability of the aircraft. The wing also has built-in rigid control surfaces (flaps) that the pilot controls to change the shape of the airfoil and so control the aircraft.

But birds, which were the initial models for heavier-than-air flying machines, do not have rigid wings or flaps. As the Wright brothers noted, birds change the shape of their wings, and their various curvatures, by deliberately bending them and adjusting the feathers that form the leading, trailing, and tip sections. In fact, the original Wright Flyers used a patented cable-driven total-wing-warping technique to control their aircraft's surfaces, rather than distinct control surfaces and flaps. Can next-generation mechanical aircraft do the same?

Researchers are exploring the possibilities of such an approach as a way to turn the problem of wing flexing into the answer to the problem. Such research is made possible by advances in materials science, actuators, and the complex computer controls needed to manage the dynamically changing wing shape (**Reference 11**). The AAW (active aeroelastic wing) program, jointly run by the US Department of Defense, NASA's Dryden Flight Research Center, and Boeing Phantom Works, is using a modified Navy F/A-18A aircraft as the test vehicle (**Figure 6**). In theory, elastic wings could be lighter than their stiffened counterparts and could offer more surface to control and divert airflow. The flexible wing can control the twist and alter the wing arch (camber) to change the airfoil itself.

Modeling such a wing is difficult, and finding actuators that can implement the changes is another challenge. Researchers are considering building wings from

Figure 5



Spread-spectrum wireless links can replace wired links for some aircraft functions, such as the smoke-detector system from Securaplane Technologies.

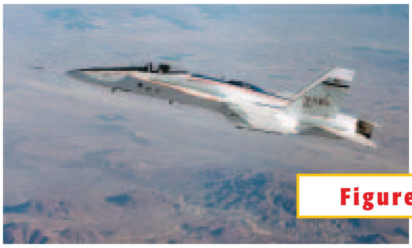


Figure 6

Flight check using a modified F/A-18A evaluates how differential deflection of the inboard and outboard leading-edge flaps affect the handling qualities, as part of the Active Aeroelastic Wing program at Dryden Flight Research Center (courtesy NASA Dryden Flight Research Center).

Figure 7

An artist's rendering of the 21st Century Aerospace Vehicle, sometimes nicknamed the Morphing Airplane, shows advanced concepts that NASA and other organizations are considering for aircraft design (courtesy NASA Dryden Flight Research Center).

lightweight yet strong composite materials, building piezoelectric materials into the composite layers. When you apply a voltage to the piezo material, its dimensions change very slightly, thus implementing the necessary micromotion. Because you would embed the piezo material throughout the surface,]these small shape changes over a wide area would add up to enough overall warping to be significant and useful.

But why stop at just wing warping, reinventing what the Wright brothers did but for a subsonic and supersonic world? Aircraft need different overall shapes, depending on their speed, load, and mission, with high-lift wings at low speeds and swept-back, lower lift, lower drag wings at higher speeds. Just as some birds tuck back their wings when going into a dive, it would be a competitive advantage if an aircraft could dynamically adjust its wings to match a flight situation. (A precedent for this scenario does exist: The F-111 fighter used a mechanical yoke to move the craft's wings from barely swept back for takeoff and landing, to a full sweep-back position for cruising.)

Instead of just moving one element, researchers are looking to change the overall envelope of the aircraft. In some ways, this change will make the aircraft's skin and internal frame more humanlike. After all, human skin, supported by muscles, bones, and ligaments, contains us and provides overall enclosure integrity yet is somewhat flexible and stretchable to adapt to our differing instantaneous needs. And it does so without compromising its basic mission (**Figure 7**).

Finally, there's the nip and tuck. One way to change shape is to discard things you no longer need, such as test packages or special sensor assemblies. Instead of conventional mechanical attachments, you could use an electrically releasable epoxy from EIC Laboratories (www.eiclabs.com), which bonds two conducting surfaces with enough strength to withstand Mach 2 flight. When it's time to slim down or remove the package, you pass a current through the material, and the epoxy cleanly releases the package.

Future aircraft will not be the metal-based, relatively fixed machines that we know today. Already, many of the aircraft subassemblies and surfaces use carbon-graphite composite materials. As we learn to incorporate controlled change into these materials, perhaps the shape shifting and morphing designs of many science-fiction stories will become less fantasy and more reality.□

ACKNOWLEDGMENT

Thanks to Robert Manelski, director of Boeing Commercial Aviation Services' Aircraft Health Management program, for his insight and expertise.

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REFERENCES

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