14th Australasian Fluid Mechanics Conference
Adelaide University, Adelaide, Australia
10-14 December 2001

Challenges for Innovation in Aerodynamics

A. J. Smits

Department of Mechanical and Aerospace Engineering
Princeton University, Princeton, NJ 08544, U. S. A.

Abstract

New challenges for innovation in aerodynamics are presented in the context of transonic, supersonic and hypersonic flight, as currently under consideration in the U. S.

Introduction

Over the last 20 years, the emphasis in the commercial aviation industry has increasingly shifted away from building aircraft with better performance (faster, longer-range, more fuel efficient), to building aircraft that are cheaper to make and operate, and are more responsive to customer needs. This has happened in part because natural limits on speed and range exist: the drag rise near Mach one limits the maximum cruising speed, and once the range exceeds half the circumference of the globe there is no specific need for increased range. In addition, with the rise of Airbus and the mergers among U.S. civilian airframe manufacturers, competition has become heavily politicized, with political issus deciding orders more often than manufacturing ones.

Mergers among the military contractors, and the increasing cost of military planes, has led to a similar decline in competitiveness and innovation in the military aerospace industry. As an illustration, the recent competition between Boeing and Lockheed-Martin for the contract to build the Joint Strike Fighter (JSF) has now ben settled in favor of Lockheed-Marting, and it may be another ten years before the next competition will be held. Notably, only Lockheed-Marting and Boeing were judged large enough to be credible bidders on the contract.

In this environment, it seems that innovation in aeronautics would be severely curtailed, and that future improvements may only be incremental, or very limited in impact, and certainly will require only a small number of creative people. However, this view ignores many less visible efforts that continue to drive the U.S. aeronautics industry, large and small, and that will continue to require the talents of the best engineers in a continuing effort to push the boundaries of aeronautics. These challenges exist in developing new transonic, supersonic and hypersonic aircraft, as well as designing innovative new subsonic aircraft, and a whole range of new underwater vehicles.

A prominent example is hypersonic airplane technology. Hypersonic flight has been the goal for almost 40 years of research, and rather than declining in intensity, the current research effort is still very active, with the flight testing of the X-43A, and the NASA initiative on third-generation re-usable launch vehicles. At lower Mach numbers, the problem of sonic boom is also the subject of intensive work, stimulated by a U.S. government proposal for a supersonic business jet, while conventional wisdom on transonic flight has been challenged by Boeing's announcement of the Sonic Cruiser, a plane designed to fly at Mach 0.95. Even at low subsonic speeds, surveillance and communication needs are driving a booming demand for unmanned and autonomous aircraft that are setting new records for endurance and efficiency. These new concepts, covering the entire Mach and Reynolds number range, imbue the field of aerodynamics and aeronautics with continuing excitement.

Figure 1: The Bell Aircraft Corporation X-1-1 in flight. NASA-Dryden photo archives.

Hypersonic Aircraft

For more than 50 years, the X-Series of experimental aircraft, tested and flown by the US Air Force, have pushed the flight envelop in speed, altitude, and duration (Pace, 1995; Miller, 2001). The "XS" designation, originally "XS" for eXperimental Supersonic, applied to a family of experimental aircraft not intended for production but solely for flight research. They were generally the result of a partnership among NASA (originally NACA), the United States Air Force, and a major airplane manufacturer. Probably the most famous X-plane was the first: the Bell X-1, which on the 14th of October, 1947, piloted by Captain Charles "Chuck" Yeager, broke the sound barrier for the first time, reaching Mach 1.015 (figure 1). On the 26th of March, 1948, again flown by Chuck Yeager, it set a new altitude record of 64,0000 ft (19,500 m).

Another famous example was the North American Aviation X-15, which first flew in 1959 (figure 2). This joint program by NASA, the Air Force, the Navy, and North American operated the most remarkable of all the rocket-powered research aircraft. Composed of an internal structure of titanium and a skin of chrome-nickel alloy, the X-15 set new speed records by reaching Mach 4.43 on Mar. 7, 1961; Mach 5.27 on June 23, 1961; Mach 6.04 on Nov. 9, 1961; and Mach 6.7 on Oct. 3, 1967. The airplane also set an altitude record of 354,200 feet (107,900

Figure 2: North American Aviation X-15. NASA-Dryden photo archives.

Figure 3: X-30 NASP (National AeroSpace Plane) model in simulated flight (landing approach); Photographer: JT Heineck; Date: May 21, 1992. Image from NASA/Ames Research Center Document Development Division Customer Services.

m) on Aug. 22, 1963, and provided data on hypersonic air flow, aerodynamic heating, control and stability at hypersonic speeds, reaction controls for flight above the atmosphere, piloting techniques for re-entry, human factors, and flight instrumentation for spaceflight.

The X-15 was the first in a series of X-planes designed to explore hypersonic flight. The most well-known example was the National Aerospace Plane (NASP), designated the X-30 (figure 3). The X-30 had its roots in a highly classified, Defense Advanced Research Projects Agency (DARPA) project called Copper Canyon, which ran from 1982 to 1985. Originally conceived as a feasibility study for a single-stage-to-orbit (SSTO) airplane which could take off and land horizontally, Copper Canyon became the starting point for what Ronald Reagan (1986) called:

> ...a new Orient Express that could, by the end of the next decade, take off from Dulles Airport and accelerate up to twenty-five times the speed of sound, attaining low earth orbit or flying to Tokyo within two hours...

Three of the six critical technologies for the success of the project were related to the propulsion system, which would consist of an air-breathing supersonic combustion

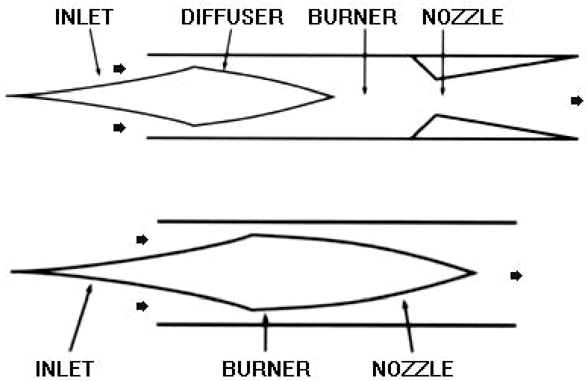

Figure 4: Ramjet and Scramjet configurations, shown in an axisymmetric configuration. Images courtesy of The Aviation History On-Line Museum.

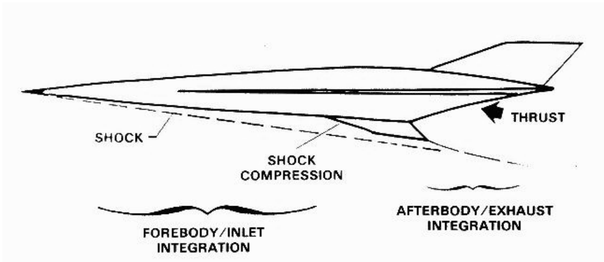

Figure 5: Generic hypersonic aircraft. Image courtesy of John Erdos (GASL).

ramjet, or "scramjet" (United States General Accounting Office, 1988). By carrying only fuel (hydrogen), and using atmospheric air as a source of oxygen, significant savings in weight over conventional rocket technology were anticipated. Ramjets operate by subsonic combustion of fuel in a stream of air compressed by the forward speed of the aircraft itself, as opposed to conventional turbojet engines, which use a separate compressor stage. In comparison to turbojets, ramjets have no moving parts. Scramjets (supersonic-combustion ramjets) are ramjet engines in which the airflow through the whole engine remains supersonic (figure 4). Scramjet technology is challenging because only limited testing can be performed in ground facilities, and the time-of-flight through the engine is extremely short (2 ms or less). Also, the efficiency of the engine depends crucially on the aerodynamics of the airframe which must function as part of the inlet to the engine and form the exhaust nozzle downstream of the engine, which requires complete engine/airframe integration (figure 5).

Other "enabling" technologies included the development of composites and titanium-based alloys which maintain structural integrity at very high temperatures. The enormous heat loads associated with hypersonic flight, sometimes in excess of 1,800°F (1,020°C), require active cooling systems and advanced heat-resistant materials. Speeds greater than Mach 8 can only be achieved through the extensive use of active thermal management. By circulating, and thus heating, the hydrogen fuel through the skin of the vehicle prior to injection into the engine, energy generated through atmospheric drag partly contributes to the engine thrust, enabling it to exceed the Mach 8 thermal barrier. However, the mass and complexity of the thermal management system increases with Mach number, and at some point a rocket stage is needed to complete the ascent to orbit.

It quickly became clear that the original expectations for the program were well beyond the technologies available at the time. As a consequence, the budget and the length of the program grew rapidly. During the first phase of the project, the cost of producing two operational vehicles was estimated at originally at $3.1 billion. Eventually it was estimated that the first test flight of the X-30 might take place in the 2000-2001 period, 11 years behind schedule and 500% over budget (Defense Daily, 1992). It was estimated that many years and a further $10 to $20 billion would have been required for the development of an operational vehicle.

The lack of a clearly defined mission, military or commercial, also helped end the project. Suggestions for possible military applications of a NASP-derived vehicle included space launch, strategic bombing missions, strategic air defense, and reconnaissance and surveillance (Williams, 1986). Analysis of these missions (for example, National Research Council, 1989) suggests that each of these proposed missions was either not within the capability of NASP, or on the wrong time scale, or could be preformed better by other means, such as by satellites.

The Hypersonic Systems Technology Program (HySTP), initiated in late 1994, was designed to transfer the accomplishments made in hypersonic technologies by the NASP program into a technology development program, but on January 27, 1995 the Air Force terminated participation in HySTP.

Nevertheless, research on hypersonic flight continues vigorously with the X-43A Program. The X-43A (part of the Hyper-X Program) is a hypersonic, experimental research vehicle about 12 ft (3.66 m) long with a wing span of about 5 ft (1.52 m) to demonstrate hypersonic propulsion technologies using hydrogen as the fuel (figures 7 and 6). The X-43A is mounted on the first stage of a Pegasus booster rocket (figure 8), and the booster/research vehicle "stack" is launched by NASA's B-52 from altitudes of 17,000 to 43,000 ft (5,200 to 13,100 m) (figure 9). The booster will carry the X-43A to about 100,000 ft (30,500 m), where it will separate from Pegasus and fly under its own scramjet power. For two flights, the X-43A will be boosted to speeds of Mach 7, with another at Mach 10. The test vehicles are not recoverable.

Unfortunately, the first flight of the X-43A on June 2, 2001 failed about 10 seconds after the Pegasus stage fired and no useful data were obtained. The second and third flights may be delayed following the investigation into the cause of the failure.

Re-Usable Launch Vehicles

Hypersonic airplanes may provide a solution the problem of developing a relatively low-cost future Reusable Launch Vehicle (RLV). The space shuttle was intended to provide low cost space access, but current costs for Low Earth Orbit (LEO) are still about $10,000/lb, which is obviously too high for commercial operations. One of the claims made for NASP was as a space launch vehicle, but that promise was never realized, primarily because of technical difficulties. The quest for a truly reusable launch vehicle continues, however, and on July 2, 1996,

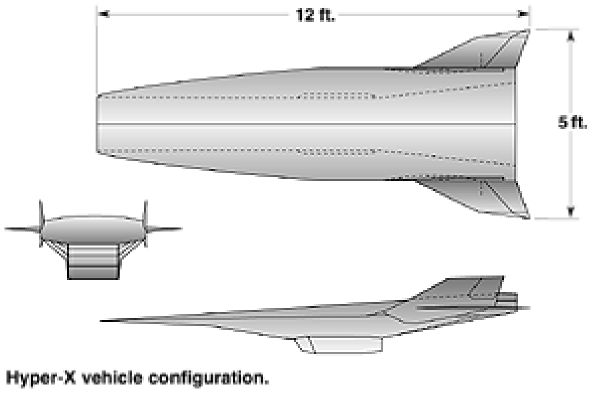

Figure 6: Hyper-X (X-43A) vehicle configuration. Image from NASA/Langley Research Center.

Figure 7: X-43A Hypersonic Experimental Vehicle. Artist concept in flight. Image from NASA/Dryden Flight Research Center Photo Collection.

Figure 8: X-43A/Pegasus "stack" shown attached to its B-52 carrier aircraft . Image from NASA/Dryden Flight Research Center Photo Collection.

Figure 9: Moments after release from NASA's B-52 carrier aircraft, X-43A/Pegasus "stack" is seen before ignition of the Pegasus rocket motor (June 2, 2001). Image from NASA/Dryden Flight Research Center Photo Collection.

NASA selected Lockheed Martin to design, build, and fly the X-33 Advanced Technology Demonstrator test vehicle. The X-33, a half-scale vehicle, featured a lifting-body shape, a new "aerospike" rocket engine, and a rugged metallic thermal protection system (figure 10). It was expected to demonstrate in flight the new technologies needed for a Reusable Launch Vehicle (RLV). The X-33 was to be an unpiloted vehicle, launched vertically like a rocket but landing horizontally like an airplane, and was expected to be capable of reaching an altitude of approximately 50 miles and speeds of more than Mach 11 (http://www.dfrc.nasa.gov/History/x-planes.html). However, in 2001 NASA ceased funding the program, due to cost overruns and technical difficulties.

More recently, NASA has returned to an airbreathing hypersonic airplane concept as the strongest candidate for a Third Generation RLV. The approach is decidedly more cautious than the original NASP program, with a projected flight demonstration in 2020, supported by a strong research and development phase. Success will require significant advances in materials and cooling systems. It is now clear that these vehicles will require multiple engines, one to propel the vehicle to about Mach 4, then to change to a ramjet/scramjet mode until about Mach 12 to 15, where a rocket booster completes the flight path to low earth orbit. This implies gas turbine technology for the supersonic phase, but at Mach numbers greater than achieved so far, since only the SR-71 has achieved gas-turbine powered flight above Mach 3 (figure 11).

Supersonic Flight

In commercial supersonic flight, the two most difficult technical problems are the high-altitude pollution problem which affects the ozone layer, and the sonic boom problem, which has limited current commercial supersonic flights to subsonic Mach numbers over land.

Recently DARPA has stimulated new interest in minimizing sonic boom by supporting the Quiet Supersonic Plat-

Figure 10: X-33 Reusable Launch Vehicle. Artist concept from Lockheed-Martin, image from NASA/Dryden Flight Research Center Archives.

Figure 11: SR71. Image from Lockheed Martin.

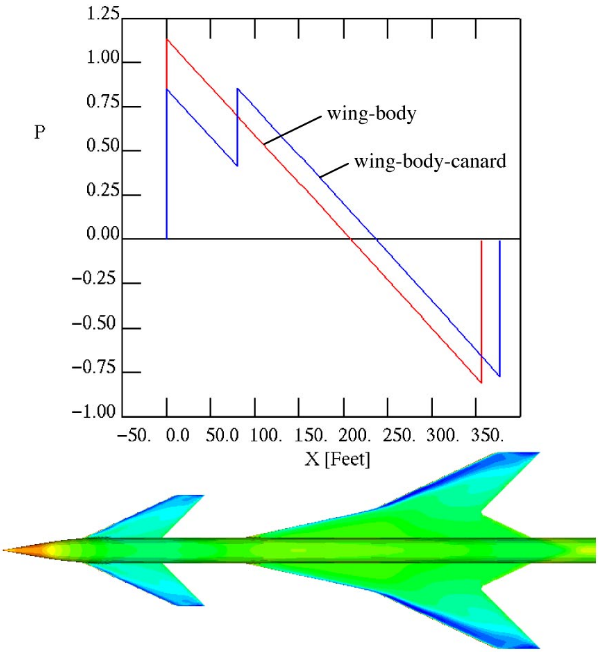

Figure 12: Effect of a canard on the sonic boom pattern. Signatures extrapolated from $H/L = 1.0$. From Martinelli (2001).

form (QSP) program to develop a low-boom, supersonic (Mach 2.4) business jet (100ft, or 30.5m overall length). Proposals include off-body heat addition, and control of shock strength by magneto-hydrodynamic means. One of the most promising techniques for minimizing the peak pressure loads on the ground is aerodynamic design and optimization using CFD. For example, Martinelli (2001) has shown that a canard moves the wing shock aft, preventing coalescence of the nose and wing shock, and reducing the peak ground pressure signature by about 25% over the baseline congfiguration at Mach 2.4 and 60,000 ft (18,300 m) (figure 12). Martinelli also showed that a higher Mach number lengthens the signature without affecting the peak very much, and that lower altitude inhibits the nose/wing shock coalescence but promotes nose shock strength.

What is even more exciting is the use of optimization methods to help design the vehicle shape for low boom. In general, the progress of a design procedure is measured in terms of a cost function I, representative of some appropriate aerodynamic properties, such as drag, target pressure distribution, shock strength, which are functions of the flow-field variables w, and the shape of the boundary, F. Then

$$I = I(w, F),$$

and a change in F results in a change of the cost:

$$\delta I = \left[\frac{\partial I^T}{\partial w}\right]_I \delta w + \left[\frac{\partial I^T}{\partial F}\right]_{II} \delta F \qquad (1)$$

Using control theory, the governing equations of the flow field are introduced as a constraint in such a way that the final expression for the gradient does not require multiple solutions (Jameson *et al.*, 1998). This corresponds to eliminating δw from equation 1.

Suppose that the governing equation R which expresses the dependence of w and F within the flow-field domain D can be written as

$$R(w, F) = 0. \qquad (2)$$

Then δw is determined from the equation

$$\delta R = \left[\frac{\partial R}{\partial w}\right]_I \delta w + \left[\frac{\partial R}{\partial F}\right]_{II} \delta F = 0. \qquad (3)$$

Next, introducing a Lagrange multiplier Ψ, we have

$$\begin{aligned} \delta I &= \frac{\partial I^T}{\partial w}\delta w + \frac{\partial I^T}{\partial F}\delta F - \Psi^T\left(\left[\frac{\partial R}{\partial w}\right]\delta w + \left[\frac{\partial R}{\partial F}\right]\delta F\right) \\ &= \left\{\frac{\partial I^T}{\partial w} - \Psi^T\left[\frac{\partial R}{\partial w}\right]\right\}_I \delta w \\ &\qquad + \left\{\frac{\partial I^T}{\partial F} - \Psi^T\left[\frac{\partial R}{\partial F}\right]\right\}_{II} \delta F. \qquad (4) \end{aligned}$$

Choosing to satisfy the adjoint equation

$$\left[\frac{\partial R}{\partial w}\right]^T \Psi = \frac{\partial I}{\partial w}, \qquad (5)$$

the first term is eliminated, and we find that

$$\delta I = G \delta F, \qquad (6)$$

where

$$G = \frac{\partial I^T}{\partial F} - \Psi^T\left[\frac{\partial R}{\partial F}\right].$$

An improvement can be made with a shape change

$$\delta F = -\lambda G,$$

where λ is small and positive. The variation in the cost function then becomes

$$\delta I = -\lambda G^T G < 0.$$

The process is repeated to follow a path of steepest descent until a minimum is reached.

The power of this approach lies in the fact that equation 6 is independent of δw, with the result that the gradient of I with respect to an arbitrary number of design variables can be determined without the need for additional flow-field evaluations. Also, in the case that equation 2 is a partial differential equation, the adjoint equation is also a partial differential equation. Thus the computational cost of a single design cycle is approximately equal to the cost of two flow solutions, since the adjoint problem has similar complexity. When the number of design variables becomes large, the computational efficiency of the control theory approach over the traditional approach, which requires direct evaluation of the gradients by individually varying each design variable and recomputing the flow field, becomes compelling. In shape optimization, all points defining the vehicle shape are allowed to move, and the number of design variables can be extremely large. In this case, the adjoint method is highly efficient. Two examples are shown in figures 13 and 14. In the first figure, the nose shape is being allowed to vary subject to the condition that the peak in the shock signature is minimized, and in the second the fuselage camber and wing dihedral are allowed to vary with the

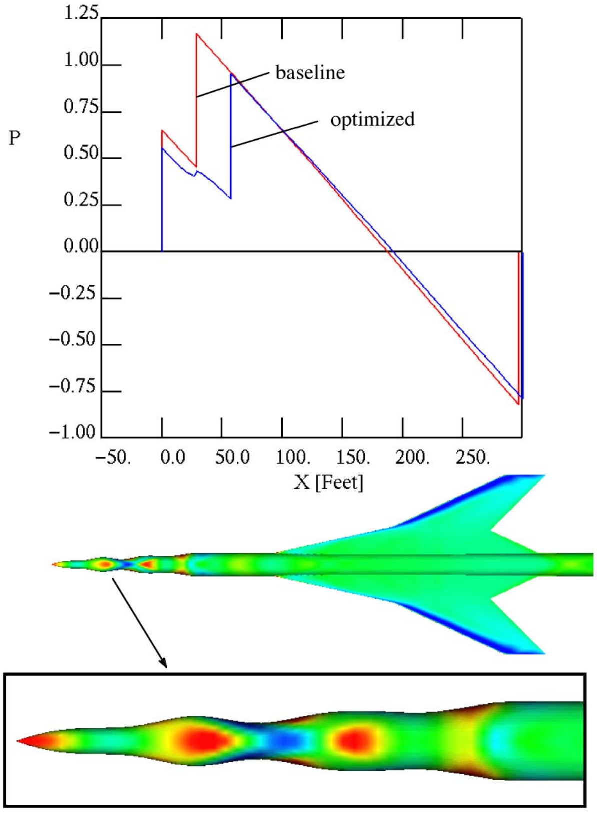

Figure 13: Optimizing nose shapes at Mach 2.4. Signatures extrapolated from $H/L = 1.0$. From Martinelli (2001).

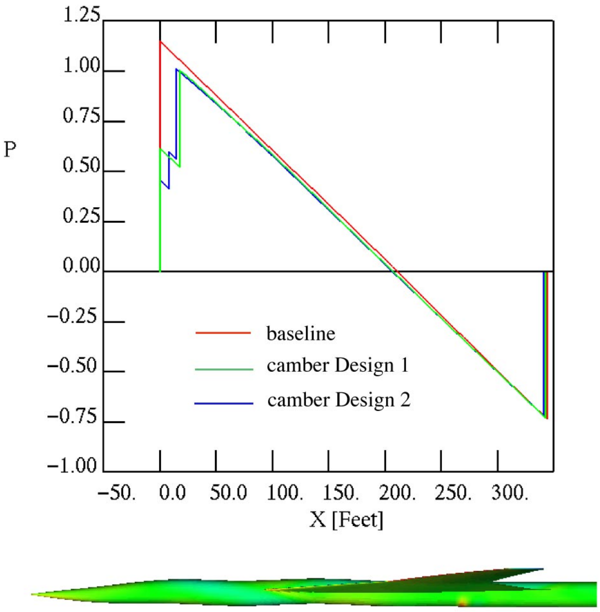

Figure 14: Optimizing camber at Mach 2.4. Signatures extrapolated from $H/L = 1.0$. From Martinelli (2001).

Figure 15: Boeing "Sonic Cruiser." Image courtesy of Boeing Airplane Company.

same goal. Significant improvement in the reducing the peak pressure loading is achieved.

Transonic Flight

The transonic regime, where most commercial transports fly, has also seen some recent innovations. On March 29, 2001, Boeing announced the Sonic Cruiser, which is expected to fly between Mach 0.95 and 0.98 at altitudes of 40,000 ft (13,000 m) with a range of 9000 nautical miles (16670 km) (figure 15). It is anticipated to become part of the fleet in 2007/2008. The concept seems to fly against conventional wisdom, since the drag rise near Mach 1 has limited conventional transports to Mach numbers of about 0.83. According to analysts, development costs are estimated at $9 billion. It is clear that significant aerodynamic challenges must be met before production starts, and aerodynamic optimization techniques will undoubtedly play a major role in the final design. Baseline in May 2001 seemed to be a 767-sized aircraft with 250 seats and a range of 16700 km or more. This would allow Singapore-Los Angeles and Singapore-London flights with time savings of 3 or 2 hours respectively.

Other Interesting Aircraft

Many other novel concepts are in the testing or planning stages. Particular attention is centered on Unmanned (sometimes called "Uninhabited") Autonomous Vehicles (UAV). For example, the Pathfinder, an unmanned, very low speed, solar-powered, high-altitude reconnaissance aircraft, has raised questions regarding low-drag, high-lift low Reynolds number airfoils, as well as structural integrity with very light-weight materials (figure 16). Unmanned vehicles of all types are of intense interest, particularly in recent combat arenas such as Kosovo and Afghanistan, where Predator and Pioneer UAV's were (and still are) widely used (figures 17, 18). Under development is the long-range Global Hawk (figure 19). In another DARPA project, the concept of UAV's has been expanded to include Unmanned Combat Air Vehicles (UCAV), with the X-45A (another X-plane) expecting to fly this summer (figure 20).

AeroVironment's Pathfinder is a remotely controlled, solar-powered flying wing, designed and built as a proof of concept vehicle for a much larger aircraft capable of flying at extremely high altitudes for weeks at a time. Pathfinder is constructed of advanced composites, plastics, and foam, and despite a wingspan of nearly 100 feet (30.5m), it weighs only about 600 pounds (272 kg). The wing is very flexible, which enables it to distribute the load almost entirely along its span. It is propelled by six electric motors, each turning a composite propeller.

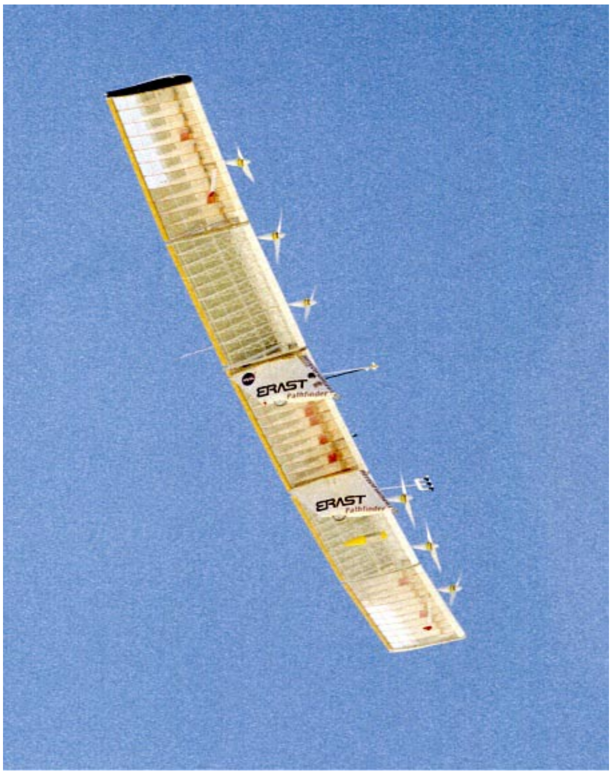

Figure 16: Pathfinder, November 19, 1996. Image from NASA/Dryden Flight Research Center Photo Collection.

Solar arrays provide power during daylight, while stored energy allows two hours of additional flight after dark.

On September 13, 1995 the aircraft achieved a major milestone when it was flown to an altitude of 50,567 ft (15,413 m) during a nearly 12-hour mission. The previous altitude record for a solar-powered aircraft was 14,000 ft (4,267 m).

Pathfinder is one of several unpiloted prototypes under study by a NASA-industry alliance which is helping to develop advanced technologies for aircraft to study the earth's environment during extremely long flights at altitudes in excess of 100,000 ft (30,500 m). Pathfinder flies very slow, within a narrow speed range. Takeoff is at about 17 mph (7.6 m/s), cruise speed is about 21 mph (9.4 m/s), and it climbs at about 150 fpm (0.76 m/s).

The US Air Force Predator aircraft by General Atomics Aeronautical Systems (figure 17) is a high-altitude surveillance aircraft. The new B series (flight testing is in progress) will have increased speeds to allow it to transit and be repositioned quickly to new operating areas to provide reconnaissance and targeting of ground activities (Defense System Daily, Febryuary 6, 2001). A civilian version, ALTAIR, will be developed specifically for scientific and commercial applications that require large payload capacities and operations to 52,000 ft (15,850 m). This aircraft will enable various atmospheric research missions simultaneously while transmitting data in real-time via satellite.

The Pioneer Short Range UAV, a small, propeller-driven aircraft (figure 18), started service in the U.S. Navy in 1985 to provide imagery intelligence for tactical commanders on land and at sea. The prime contractor is Pioneer UAV, Inc., a joint venture of an American and Israeli

Figure 17: Predator. Image courtesy of General Atomics.

Figure 18: Pioneer. Image courtesy of Pioneer UAV.

firms. To date, Pioneer has flown nearly 20,000 flight hours, with 300+ missions during Persian Gulf operations in 1990-91, and missions over Bosnia, Haiti and Somalia, then Bosnia again, and now over Afghanistan (Federation of American Scientists: Intelligence Resource Program).

The Global Hawk High-Altitude, Long-Endurance Unmanned Aerial Vehicle (figure 19) is an Advanced Concept Technology Demonstration (ACTD) designed to provide extended reconnaissance capability, with the ability to operate from anywhere within enemy territory, day or night, regardless of weather. Global Hawk's first flight was from Edwards Air Force Base, CA on 28 February, 1998. The prime contractor is Northrop Grumman Corp. of San Diego CA. Two complementary HAE UAV systems are being developed under this program; a conventional design (Tier II Plus) and an low observable configuration (Tier III Minus). The Tier II Plus air vehicle will be capable of standoff, sustained high altitude surveillance and reconnaissance. Its range is intended to

Figure 19: Global Hawk. Image courtesy of TRW.

Figure 20: X45. Image courtesy of General Atomics.

be up to 3000 nautical miles (5,500 km), with loiter capability of up to 24 hours at altitudes greater than 60,000 ft (18,300 m). It will be capable of simultaneously carrying electro-optical, infra-red, and synthetic aperture radar payloads, and will be capable of both wideband satellite and Line-Of-Sight data link communications (Federation of American Scientists: Intelligence Resource Program).

Finally, there is a growing interest in unmanned combat vehicles. A variety of cost and weight penalties are associated with the presence of a human pilot, including constrained forebodies, large canopies, displays, and environmental control systems. The aircraft's maneuver capabilities are limited by the pilots physiological limits such as g tolerance. Removing the pilot from the vehicle eliminates may of these requirements. The UCAV is expected to be smaller, and simpler aircraft, about half the size of a conventional fighter aircraft, and weighing about one-third to one-fourth of a manned aircraft. At about 10,000 pounds they would weigh two to three times more than a Tomahawk missile (Federation of American Scientists: Military Analysis Network). One of the prime economies is to do with pilot training. Typically 80 percent of the useful life of today's combat aircraft is devoted to pilot training and proficiency flying, requiring longer design lives than would be needed to meet combat requirements. Without the requirement to fly sorties to retain pilot proficiency, UCAVs will fly infrequently. A reduced maintenance design with condition based maintenance, minimized on-board sensors, reduced fluid systems, maintainable signature, and a modular avionics architecture will reduce touch labor in the fashion of commercial aircraft.

The objective of the joint DARPA/Air Force X-45 Unmanned Combat Air Vehicle (UCAV) is to develop a technology demonstrator for unmanned combat vehicles (figure 20). Boeing unveiled the first X-45 prototype on September 27, 2000, revealing a vehicle only 27 ft (8.2 m) long with a 34-ft (9.8 m) wingspan. According to Boeing, it can be stored unassembled in a small container for up to 10 years. It can be restored in one hour, and up to six UCAVs can fit inside a C-17 Globemaster III. Each one will cost about $10 million, about one-third of the cost of a next-generation aircraft such as the Joint Strike Fighter. It is expected to enter the Services in 2010.

Concluding rematks

Despite recent trends in the commercial and military aviation industry, many new concepts continue to be proposed and developed, imbuing the field of aviation with a continuing excitement. The advances have come mostly from military challenges such as the need for high-speed flight, reconnaissance, and force augmentation, but we also see significant spin-offs and new developments in commercial aviation. These projects, and the ones that will surely develop in the future, provide strong motivation for continuing research in aeronautics and aerospace engineering. For those interested in current developments in the military side, the web site of the Federation of American Scientists (http://www.fas.org/) is a wonderful resource.

Acknowledgements

The author's research is supported by the Office of Naval Research, the Air Force Office of Scientific Research, the Defense Advanced Research Projects Agency, and the National Science Foundation. Significat help was received from L. Martinelli, who provided the information on aerodynamic optimization, and who graciously allowed the use of figures 12, 13 and 14.

References

[1] Defense Daily, April 17, 1992, page 103.

[2] Jameson, A., Alonso, J.J., Reuther, J., Vassberg, J.C. and Martinelli, L. Aerodynamic shape optimization techniques based on control theory, AIAA Paper 98-2538, 1998.

[3] Jameson, A., Martinelli, L. and Pierce, N. Optimum aerodynamic design using the Navier-Stokes equations, Journal of Theoretical and Computational Fluid Dynamics, **10**, pp. 213–237, 1998.

[4] Martinelli, L. Private communication.

[5] Miller, J. The X-Planes: X-1 to X-45. Midland Publishing, Hinckley, England, 3rd Ed., 2001.

[6] National Research Council Committee on Hypersonic Technology for Military Applications, Hypersonic Technology for Military Applications, (Washington, National Research Council, 1989), page 12.

[7] Pace, S. X-Planes at Edwards, MBI Publishing Co., Osceola, WI, 1995.

[8] Reagan, R. State of the Union Address, February 4, 1986.

[9] United States General Accounting Office. National Aero-Space Plane: A Technology Development and Demonstration Program to Build the X-30. Report USGAO/ NSIAD-88-122. April 1988, pp. 35–40.

[10] Williams, R. National Aero-Space Plane: Technology for America's Future, Aerospace America, November 1986, pp. 18–22.