DARPA'S LEGACY TAKES FLIGHT: CONTRIBUTIONS TO AERONAUTICS

By Mike Hirschberg

The opening days of Operation Iraqi Freedom proved once again that the United States has the most technologically advanced military in the world. Stealthy F-117 attack aircraft and B-2 bombers eluded enemy air defense networks and eliminated key targets with pinpoint accuracy. Airborne radars tracked moving targets and precision munitions minimized collateral damage. Even during a blinding sandstorm, U.S. forces continued bombing the elite Iraqi Republican Guard forces unabated. Within three weeks, coalition forces had effectively neutralized Iraq's defenses, with very few losses.

Contrast this with the 37,000 U.S. troops and 2,000 aircraft lost in the Korean War. The near-parity loss-exchange ratios during the Vietnam War are likewise a thing of the past. The technological advances in military aircraft over the last 50 years have revolutionized the American approach to warfare.

Stephen Welby, the director of DARPA's Tactical Technology Office, notes that, in part due to the investments that DARPA has made in aviation technology, "We can dominate nearly any country in the world with only a handful of aircraft. We no longer expect to be challenged for air superiority. It is a critical input to the way we fight." Welby says that land forces are dependent on airborne ISR – intelligence, surveillance and reconnaissance – provided by high-resolution synthetic aperture radar (SAR) and moving target indication (MTI) radars. "MTI was a game changer in Operation Desert Storm – and used effectively again in Operation Iraqi Freedom – that enabled the swift defeat of Iraqi forces. Airborne radars and precision weapons are now taken for granted," Welby adds.

The MTI radar on the E-8C Joint STARS and the low probability of intercept radar on the B-2 are both products of the DARPA Pave Mover and TACIT BLUE programs. In addition, modern munitions that DARPA helped bring to fruition include the Advanced Medium-Range Air-to-Air Missile (AMRAAM), the Sensor Fuzed Weapon, Brilliant Anti-Tank (BAT) submunitions, and the Tube-launched and Optically tracked Wire-guided (TOW) anti-tank missile, as well as the Advanced Cruise Missile and the Tomahawk's jet engine.

Many of the key advances that facilitated the revolution in military aviation – including stealth (see sidebar "DARPA's Stealth Revolution"), advanced unmanned aerial vehicles (UAVs), precision munitions, command and control, propulsion, and advanced sensors – are the direct result of investments made by DARPA. Many other DARPA initiatives, including advances in computing power, software technology, and materials science, also contributed indirectly. These technology improvements, as well as development of design tools and methodologies across the industrial base, have left a lasting legacy of DARPA's contributions to aeronautics.

EXPLORING THE LIMITS OF AERODYNAMICS

Beyond the many technology investments that indirectly improved the capabilities of America's military aircraft, DARPA has also sponsored numerous programs over the past 40 years to develop technology demonstrators. As part of DARPA's legacy, these advanced aerodynamic demonstrators have had a significant impact on military aircraft developments.

QUIET BEGINNINGS

When the Army stated a requirement for an acoustically stealthy aircraft for night surveillance over Vietnam in mid-1966, DARPA funded Lockheed to convert two sailplanes based on the Schweizer SGS 2-32. An acoustically insulated and muffled engine was installed and connected to a large, low-speed, high-efficiency tractor propeller connected by a long shaft over the cockpit of each aircraft. With state-of-the-art sensor suites, these aircraft, designated QT-2 (for "Quiet Thruster"), were shipped to Vietnam in mid-1968. Virtually inaudible from the ground, they provided valuable real-time surveillance of enemy movements at

DARPA's aerospace expertise began with work on such relatively unsexy craft as the Lockheed YO-3A, pictured here being flown by NASA. The sailplane-derived wings and quiet wooden propeller are clearly shown.

NASA photo

night. The aircraft were tested extensively, totaling 600 hours of combat flying time. Based on the success of this concept, the Army developed and fielded Lockheed's YO-3A.

The QT-2 was an auspicious beginning to DARPA's involvement in developing radically new aircraft concepts. By using streamlined acquisition capabilities, DARPA was able to quickly and inexpensively meet an urgent Army need and field-test aircraft that not only helped shape an operational aircraft, but also provided valuable military intelligence.

FLYING BACKWARDS

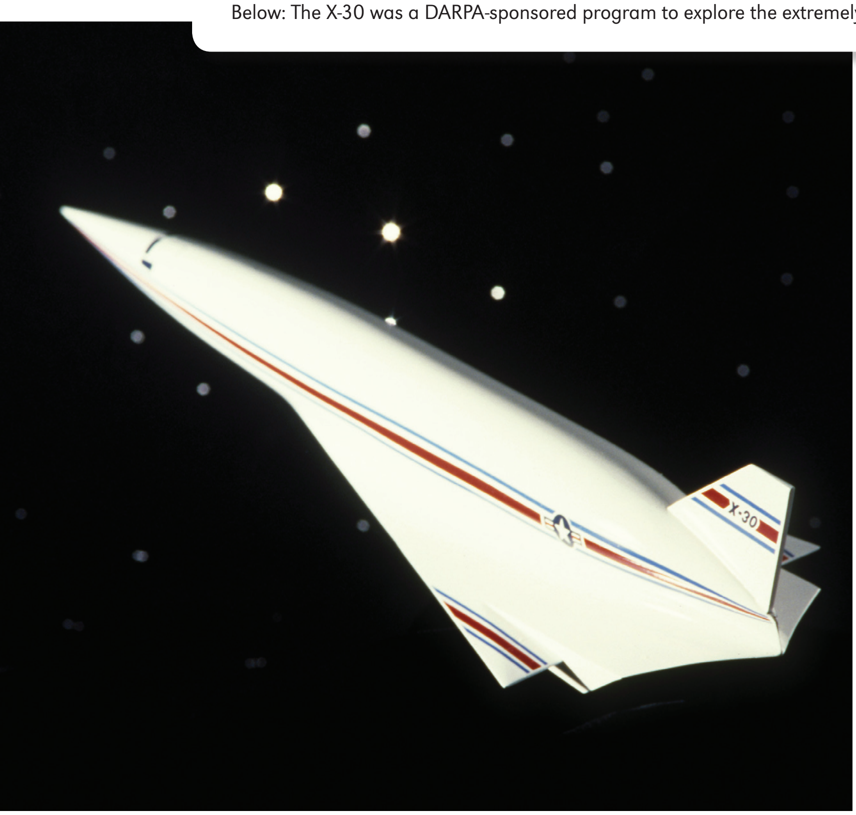
After the QT-2 returned from Vietnam, it was redesignated the X-26B. After the program concluded, there was a long hiatus in X-Planes, not broken until DARPA's X-29 first flew in December 1984. The X-29 was designed to explore forward-swept wing technology for supersonic flight, using advanced composites, aeroelastic tailoring, variable camber wings, and extreme static instability – managed by a digital fly-by-wire flight-control system – to achieve a highly maneuverable, lightweight design.

Beginning in 1976, DARPA and the Air Force funded a series of study contracts, and in December 1981, Grumman Aerospace was awarded a contract to build two demonstrators, designated the X-29.

Although research into forward-swept-wing aircraft had been conducted since World War II, the issue of wing divergence at high speed had never been fully addressed. A forward-swept wing twists with the leading edge up, increasing the angle of attack and

NASA photo

DARPA photo



Above: The X-29 program demonstrated the advantages of a forward-swept wing when the structural and engineering challenges could be overcome. Below: The X-30 was a DARPA-sponsored program to explore the extremely difficult challenges facing a single-stage-to-orbit (SSTO) spacecraft design.

the wing load. At high speeds, this effect would lead to divergence and failure of the wing. A metal wing strong enough to withstand this would have to be so stiff that the weight penalties would negate any performance gains from being swept forward. The X-29 solved this problem by using advanced graphite-composite materials then becoming available, and aeroelastically tailoring the wing to resist twisting under flight loads. The X-29 – the most unstable aircraft ever built – also used a flight-control system that compensated for its instability by sensing flight conditions and continually adjusting the control surfaces up to 40 times per second, enabling impressive maneuverability.

The two aircraft were flight-tested at NASA's Dryden Flight Research Center from 1984 to 1992, for a total of 422 flights. Flights up to Mach 1.48 and angles of attack up to 57 degrees were executed. Analysis of performance data indicated that in one-on-one dogfight situations against conventional fighter aircraft such as the F-15 and F-16, the X-29 would have had a significant advantage because of its ability to routinely achieve high angles of attack. The X-29 also demonstrated about 20 percent less drag at transonic speeds than an equivalent aft-swept wing. Flight tests confirmed that not only was a supersonic forward-swept-wing aircraft feasible, but also that the performance closely matched predictions.

Although Air Force fighter designs embraced DARPA's stealth revolution rather than the high maneuverability promised by forward-swept

Using thrust vectoring and advanced digital flight controls, the X-31 demonstrated revolutionary maneuverability in a wide range of flight regimes.

NASA photos

wings, other X-29 technologies found their way into future aircraft. Advanced composites are being used extensively in military and commercial aircraft. Aeroelastic tailoring is now a standard tool for advanced designs with aeroelasticity concerns, such as the long thin wings of the Global Hawk. And, while no aircraft has approached the instability of the X-29, relaxed stability is now the norm for advanced combat aircraft.

The next X-Plane program that DARPA sponsored was the X-30. DARPA initiated the Copper Canyon program in 1984 to develop a single-stage-to-orbit demonstrator aircraft that would facilitate a dramatic tenfold to a hundredfold reduction in the cost of space launch. The program goal was to develop and demonstrate the key technologies to achieve single-stage space transportation vehicles: an unprecedented level of engine-airframe integration, wherein the airframe and inlet geometry was configured to provide efficient flow field compression for a variable-geometry "dual-mode" ramjet/scramjet (supersonic combustion ramjet) propulsion system that burned liquid hydrogen fuel – which also cooled the engine and inlet surfaces. The X-30 evolved into the National AeroSpace Plane (NASP) program, which was transferred to the Air Force in 1986. Although it was cancelled in 1995, it led to numerous advances, not only in hypersonics, but in many other areas of aeronautics and astronautics research.

The X-31 was a project to explore high angle of attack and high agility to provide tactical advantage in dogfights. The DARPA program was launched in November 1984 under a cooperative agreement among DARPA, the Navy, and the German government, with NASA and the Air Force joining the program in the early 1990s.

Construction of two demonstrator aircraft began in 1988, and first flight was in October 1990. The X-31 used a composite

DARPA's Shaped Sonic Boom Demonstration showed that the heavily modified shape of the F-5 test aircraft also changed the shape of the aircraft's sonic boom. The research could lead to quieter supersonic aircraft.

NASA photo

cranked-delta wing along with a canard and an integrated thrust vectoring system that used three independently controlled vanes exterior to the engine nozzle. The digital flight-control system fully integrated all control effectors over the entire expanded flight envelope. Over the course of the next four-and-a-half years, nearly 600 flights were conducted, during which time many incredible maneuvers were developed, including 360-degree rolls at a 70-degree angle of attack, a controlled flat spin in which the aircraft could depart the maneuver in any heading direction the pilot chose, and "hovering" at altitude with the nose straight up and using thrust vectoring for balance. In the Herbst maneuver, the aircraft was able to emulate the equivalent of a swimmer's "flip turn," achieving a rapid change in heading of up to 180 degrees. In mock close-in combat against fighter aircraft, the X-31 demonstrated kill-to-loss ratios in excess of 30-to-1.

A more recent example of exploring the limits of aerodynamics was DARPA's Shaped Sonic Boom Demonstration (SSBD). In August 2003, two F-5 fighter jets – one of which had an extensively modified fuselage – were flown supersonically over a test range, demonstrating for the first time in flight that modifying an aircraft's shape can change the shape of its sonic boom, thereby reducing loudness. This radical concept may some day lead to quiet supersonic aircraft.

REVOLUTIONARY ROTORS

DARPA has also pushed the limits in many other aircraft technology areas, including advanced rotorcraft. During the Vietnam War, combat search and rescue capabilities were severely limited by the speed of conventional helicopters. Efforts by the Navy to improve helicopter response time led to the X-Wing program, using a synergy of emerging technologies to enable an aircraft with the efficient hover and low downwash capabilities of a pure helicopter and the speed and range of a tactical jet. The X-Wing was conceived as a "stopped rotor" system where the four-bladed main rotor could be used for vertical flight like a conventional helicopter and then stopped in mid-air to serve as an X-shaped fixed wing once adequate forward velocity was attained.

The underlying technology was a revolutionary new class of aerodynamics called circulation control. The circulation control airfoil used quasi-elliptical airfoils with

The X-Wing program sought to combine the vertical takeoff and landing capabilities of a helicopter with the high speed of a tactical jet in one aircraft.

boundary layer control employing tangential blowing to generate over four times the lift coefficient of conventional airfoils. By cyclically varying the air pressure in the extremely stiff, four-bladed rotor/wing, it was possible to eliminate the mechanical complexity of cyclic pitch control and to cancel the sources of higher harmonic vibrations while also producing greatly increased fore-and-aft sector lift to permit conversion to stopped rotor flight with full lift. Furthermore, with circulation control, the symmetric airfoils could develop lift in either flow direction on the retreating side of the disc, independent of the angle of attack, so that the classic problem of retreating blade stall was eliminated.

Other critical technologies – all demonstrated – included a graphite rotor/wing, which at the time was the largest primary graphite aerospace structure ever made; a hub-moment feedback rotor control system, which enabled the high inertia rotor to be controlled during its stopping and starting maneuver (from 100 percent RPM to 0); the second-ever quad-redundant digital flight-control system; and a convertible engine equipped with variable inlet guide vanes installed over the bypass area of a conventional turbofan to shut off the fan thrust, thus converting the engine to a turboshaft engine (to drive the rotor and the circulation control air supply). A circulation control tail boom system was also studied.

In 1984, Sikorsky was awarded a contract for a joint DARPA-NASA effort to fly a demonstrator with a full-scale 50-foot-diameter rotor/wing on the NASA Rotor Systems Research Aircraft. Transonic wind-tunnel tests of a quarter-scale model validated that the X-Wing could achieve over 400 knots. However, in 1988, with the waning of the Cold War, the need for a high-speed, stealthy, penetrating helicopter diminished, and the funding was moved to other priorities, ending the program just prior to flight test.

Nonetheless; the advances in circulation control aerodynamics; variable-speed rotor control; unstable aircraft stability and control; aeroelastic stability; high-thickness tailored graphite-composite wing structures; redundant digital flight controls and software; and low observable technologies for helicopters had significant benefits for later aerospace programs. For example, in the early 1980s, DARPA flight-tested circulation control on a helicopter tail boom to successfully demonstrate the No Tail Rotor, or NOTAR, concept, now produced by MD Helicopters. In addition to eliminating loss of helicopters due to tail rotor strikes and weapons fire, it also dramatically reduces the acoustic signature of a light helicopter – resulting in the world's quietest helicopters.

NASA photo

The STOVL variant of the JSF competition winner, the Lockheed Martin X-35B, boasted a shaft-driven, lift-fan arrangement that was a direct result of the DARPA research into advanced STOVL technologies.

Photo courtesy of TeamJSF

Ten years after the end of the X-Wing, DARPA again began investing in a stopped-rotor concept for high-speed rotorcraft. Boeing's two-bladed X-50 Canard Rotor/Wing (CRW) technology demonstrator was to achieve high-speed cruise by stopping and locking the rotor and using it as a wing to achieve high-speed forward flight. A canard and horizontal tail provided additional lifting and control surfaces to offset the loss of lift when stopping the rotor. Speeds as high as 400 knots were expected from an operational CRW design. Nine flights were made between 2003 and 2006, but, unfortunately, both demonstrators crashed before demonstrating a conversion to fixed-wing mode.

SUPERSONIC AND VERTICAL

By the time the joint U.S./U.K. AV-8B Harrier II became operational in 1985, discussions between the two countries on a supersonic successor to the short takeoff and vertical landing (STOVL) attack aircraft had already begun. In 1988, DARPA joined the effort, commonly referred to as the ASTOVL (for "Advanced STOVL") program.

By 1992, it was recognized that even the most capable existing engines alone could not provide sufficient vertical thrust for the desired payload and range; furthermore, a single engine would be oversized for high-speed flight – creating excessive drag and fuel consumption. As a result, DARPA and the Navy focused on using lift fans to augment vertical thrust and to decouple the location of center of lift from the center of gravity of the aircraft; this was found to be the most feasible method of achieving the world's first practical supersonic STOVL strike fighter. With the removal of the lift fan, the aircraft could also be converted from a STOVL aircraft to a conventional takeoff and landing aircraft. Contracts were awarded to Lockheed and McDonnell Douglas in 1993 to design and build Large-Scale Powered Models (LSPMs) – test beds for their STOVL propulsion systems, including their lift-fan approaches. Soon thereafter, Congress directed DARPA to fund Boeing to study its direct-lift concept as well.

In 1994, Congress merged ASTOVL and what would become known as the Joint Strike Fighter (JSF) program, which included the Navy, Air Force, and Marine Corps. In 1995, Boeing and Lockheed Martin tested their LSPMs, demonstrating their STOVL lift concepts, which had by then been selected for their JSF demonstrators.

During 2001, both companies flight-tested their JSF competitors, the Boeing X-32B using direct lift and the Lockheed Martin X-35B with its shaft-driven lift fan; the latter was the world's first aircraft to combine supersonic-level flight and a vertical landing on the same mission. In October 2001, the Lockheed Martin concept was selected to become the F-35, thus proving DARPA's analysis a decade earlier that using a lift fan was the most efficient way of achieving a supersonic STOVL strike fighter that could also be converted to a common affordable lightweight fighter.

TO BOLDLY GO WHERE NO UNMANNED AIRCRAFT HAS GONE BEFORE

Through 40 years of development efforts, DARPA has helped foment the revolution in unmanned aircraft. Although the military services have not always been successful at fielding UAVs, DARPA programs led to the introduction of the Pioneer, Gnat, Predator, and Global Hawk, as well as micro air vehicles. The explosion in UAVs is due in large part to DARPA's legacy in unmanned systems.

EARLY UNMANNED EFFORTS

In the early 1960s, the Navy began operating the QH-50 Droned Anti-Submarine Helicopter (DASH), capable of carrying antisubmarine torpedoes and giving destroyers the ability to attack enemy submarines far beyond the range of their antisubmarine rockets. As such, it was the first time that a reusable UAV had been developed and operated for attack missions. In the Vietnam War, the QH-50 was often used as a reconnaissance and targeting drone, since there were no submarines to combat.

During 1968-1974, DARPA sponsored several demonstrations with the Army to explore other potential missions for the DASH, including a hunter-killer combination of two drones working together with additional sensors and weapons to find and engage targets. DARPA's Nite Panther program modified several QH-50Ds as day/night surveillance and targeting platforms using a variety of sensor systems and target designators. Under Nite

continued on page 144

The Predator UAV, which contained nearly 15 years' worth of developmental systems funded by DARPA and private investors when it first flew in 1994, evolved out of the Gnat-750 UAV. Here, an RQ-1 Predator UAV prepares for takeoff at Balad Air Base, Iraq, on Sept. 15, 2004, in support of Operation Iraqi Freedom.

Air Force photo by Senior Airman Joshua Strang

Gazelle, QH-50Ds were tested with various armaments, including a minigun, grenade launcher, bombs, bomblet dispensers, and air-to-ground missiles.

Although the DASH tests were successful, the systems were very expensive. In 1971, DARPA began considering lightweight, rugged, inexpensive, model-airplane technology as the basis of small unmanned aircraft, then called remotely piloted vehicles (RPVs). The Mini-RPV program was begun with Ford Aerospace the following year and developed two interchangeable sensor payloads: Praeire was a daylight television-laser target designator, while Calere was a lightweight, forward-looking infrared and laser target designator. The aircraft weighed only 75 pounds and was powered by a modified lawn mower engine; it made its first flight in 1973 under joint DARPA-Army partnership and soon had successfully designated targets for laser-homing bombs delivered by tactical aircraft. Based in part on the results of the Mini-RPV program, the Army initiated an operational system; Lockheed's Aquila, however, was never fielded, as the requirements and costs eventually spiraled out of control. In fact, from the mid-1970s to the late 1980s, the U.S. military failed to develop any new operational UAVs.

DARPA continued development of the Mini-RPV with the Praeire/Calere II, the Praeire IIB, and the Calere III. Several Praeire II systems were acquired by Israel in 1977, and when combined with their existing UAV technology (used extensively in the 1973 Arab-Israeli War), eventually resulted in the Pioneer. As a result, the first post-Vietnam UAV that was fielded with the U.S. military was when the Navy and Marines (and later the Army) purchased the AAI Corporation's Pioneer in 1986. During Operation Desert Storm, the Pioneer flew nearly 300 reconnaissance sorties and was so effective in directing battleship artillery fire that Iraqi soldiers famously surrendered to the Pioneer upon hearing it fly overhead.

LONGER AND HIGHER

In November 1974, Lockheed and its subcontractor, Astro Flight, flew the world's first solar-powered aircraft, the Sunrise I, under DARPA funding. The aircraft had a 32-foot wingspan with 1,000 solar cells. The following September, Sunrise II, with 4,480 photovoltaic cells, reached an altitude of 20,000 feet, limited only by its data link. Astro Flight continued its work on solar power and eventually collaborated with AeroVironment to build the Solar Challenger, the first solar-powered aircraft to carry a human across the English Channel, in 1981.

DARPA then funded AeroVironment's High-Altitude Solar-Powered (HALSOL) flying wing UAV, which first flew in June 1983. Although flown on battery power, it evaluated the effect of wing flexure on solar-cell performance. It reached 8,000 feet and flew for more than an hour, but the conclusion was that the solar-cell efficiency of the time was still insufficient for practical long-endurance flight. It wasn't until nearly two decades later that AeroVironment solar-powered UAVs approached 100,000 feet, with a predicted endurance of days.

Another DARPA/AeroVironment demonstration program, Broomstick, was developed in 1986 to explore the limits of airfoil design and straight-wing, high-lift, high-aspect-ratio aerodynamics. This demonstrator employed 50-percent-thick airfoil sections with circulation control, and used differential blowing to provide lift and control while also efficiently achieving a very lightweight, high-aspect-ratio wing structure. The first flight of the electric-powered demonstrator was in 1987, proving the feasibility of extremely thick airfoils and the ability to control a straight, all-wing planform.

Meanwhile, in 1978, Leading Systems proposed a long-endurance UAV design; DARPA funded flight tests of their Albatross UAV from 1980-1982 to demonstrate the technical feasibility of long endurance for ISR. A scaled-up advanced technology configuration, the Amber UAV, was funded under a joint program with the Navy called Teal Rain. The aircraft first flew in November 1986 and soon set an endurance record of 38 hours and reached altitudes of 25,000 feet.

Unfortunately for Leading Systems, in 1988, Congress – concerned about the failure of the military to deploy UAVs and the direction of UAV development in general – consolidated all UAV developments into a Joint Program Office (JPO). However, the operational concepts focused on short-range and short-endurance tactical operations. As a result, Amber did not transition to the U.S. military; a lower technology export version, the Gnat-750, was designed using the Amber hardware, but with a new, lower performance airframe. But without a customer, Leading Systems went out of business and General Atomics acquired the technology. General Atomics modified a Gnat-750 to the "Whale" configuration – a teardrop-shaped wideband satellite antenna pod carried on top of the Gnat fuselage – and a beyond-line-of-sight demonstration was conducted.

Soon, as a consequence of this test, the operational capability of the Gnat-750 aircraft was recognized to be a "Revolution in Military Affairs," and a rapid competition was held. The Gnat-750 was then modified to incorporate the satellite antenna in the nose. With a stretched fuselage and longer wings, the aircraft became the now-famous Predator UAV, which first flew in July 1994. The so-called "acquisition miracle" of the Predator took place in only about six months, but it contained the developmental efforts of almost 15 years of DARPA and private UAV investments. Today, the Predator family of aircraft are among the most widely produced UAVs in the world. Predators fly in support of Operations Enduring Freedom and Iraqi Freedom, accumulating a total of some 10,000 flight hours per month.

Meanwhile, Boeing was also developing an autonomous long-endurance UAV, dubbed Condor. The huge aircraft with a 200-foot wingspan was powered by two six-cylinder piston engines, with two-stage turbochargers for high-altitude flight and a gearbox to shift the propellers to a higher RPM at these high altitudes. DARPA funded flight tests under the Teal Rain program, with first flight in October 1988. Condor set an altitude record for piston-powered aircraft of 67,028 feet, as well as an endurance record of 58.2 hours. It had an estimated maximum range of 19,000 nautical miles. Condor featured lightweight composite and honeycomb structures, autonomous controls, high-altitude aerodynamics, and a fuel-efficient propulsion system. Although the Navy had planned to buy 50 Condors, the consolidation of the program into the JPO again derailed production plans. But, just as Praeire gave birth to the Pioneer, and Amber led to the Predator family of aircraft, so too had Condor proven the concept for a high-altitude, long-endurance aircraft.

A six-month design competition led to the award of a contract in April 1995 to Teledyne Ryan for their Global Hawk concept, which could simultaneously carry both an electro-optic/infrared and a synthetic radar with moving target indicator modes. After first taking to the air in February 1998, flights of the first two aircraft were so successful and the ISR capability so compelling that three more aircraft were built. The Air Force soon embraced the basic system concept and utilized the (now Northrop Grumman) Global Hawks in numerous military exercises around the world.

Three Global Hawks were deployed to Afghanistan in late 2001 to support Operation Enduring Freedom and later supported Operation Iraqi Freedom. With the ability to fly 1,200 nautical miles and remain on station at 65,000 feet for 24 hours – and the ability to be controlled from anywhere in the world through global communications – the Global Hawk has helped to transform the battlefield by providing incredibly high-resolution imagery. During Operation Iraqi Freedom, the system flew only 5 percent of the Air Force's high-altitude reconnaissance sorties, but accounted for more than 55 percent of the time-sensitive targeting imagery generated to support strike missions. By mid-2007, Global Hawk had flown a total of over 1,000 flights – more than half of which were combat missions – and had amassed more than 10,000 combat hours. Global Hawk is the first UAV that meets the military and the Federal Aviation Administration's airworthiness standards and has been approved to fly regular flights within U.S. airspace, providing, for example, real-time observation of the California wildfires in fall 2007.

STEALTHIER AND DEADLIER

Another major interest for DARPA has been in enabling unmanned aircraft to conduct complex, dangerous missions, including lethal attack over denied enemy territory. Based on studies begun in 1994, DARPA initiated the Unmanned Combat Air Vehicle (UCAV) program in 1998. One of the major goals was to significantly reduce the military's cost per target destroyed; this resulted in revolutionary approaches to cost reductions in development, production, and operations and support. The initial missions selected were suppression of enemy air defenses and deep strike: the most hostile missions possible, ones that would put pilots at extremely high risk.

A development contract was awarded to Boeing in March 1999 for two X-45A demonstrators, with first flight occurring in May 2002. The UCAV program demonstrated one operator controlling two highly autonomous X-45As in flight; the operational goal was for an operator to control as many as four aircraft simultaneously and for them to collaboratively identify and attack targets. Another goal was to take affordable stealth to the next level.

In April 2004, an X-45A autonomously released an inert GPS-guided bomb, directly hitting its target. In July 2005, control of two X-45As was transferred to another operator 900 miles away over satellite control links. The two aircraft also performed coordinated multi-ship attacks on multiple targets, including simulated weapons release and battle

The Northrop Grumman Global Hawk UAV was developed under the DARPA High Altitude Endurance program.

Courtesy of Northrop Grumman

damage assessment against the targets. Computer simulations of up to four UCAVs controlled by a single operator were also conducted.

Meanwhile, DARPA had initiated a Naval UCAV study in June 2000 and Northrop Grumman built a demonstrator aircraft, the X-47A Pegasus, which flew in February 2003. In order to synchronize these separate development efforts, the Joint DARPA/Air Force/Navy Unmanned Combat Air Systems (J-UCAS) program was initiated in October 2003. This program sought to develop an integrated system that incorporated advanced air vehicle designs from Northrop and Boeing with a single common "operating system" to demonstrate the technical feasibility, military utility, and operational value for a networked system of high-performance, weaponized UAVs to effectively and affordably prosecute 21st century Air Force and Navy combat missions.

Despite significant progress, wavering interest from the military services led through a twisting path of development. In November 2005, the management of the J-UCAS program was transferred to the Air Force. The next month, however, the Air Force announced it would withdraw from the program. The Navy assumed responsibility and renamed the program UCAS-D (for "demonstrator"). An award was made in August 2007 for Northrop Grumman to build three X-47B demonstrators with first flight expected in late 2009. The demonstration is intended to show that carrier flight operations can be routinely and safely conducted by advanced unmanned aircraft. An operational capability is envisioned by 2020.

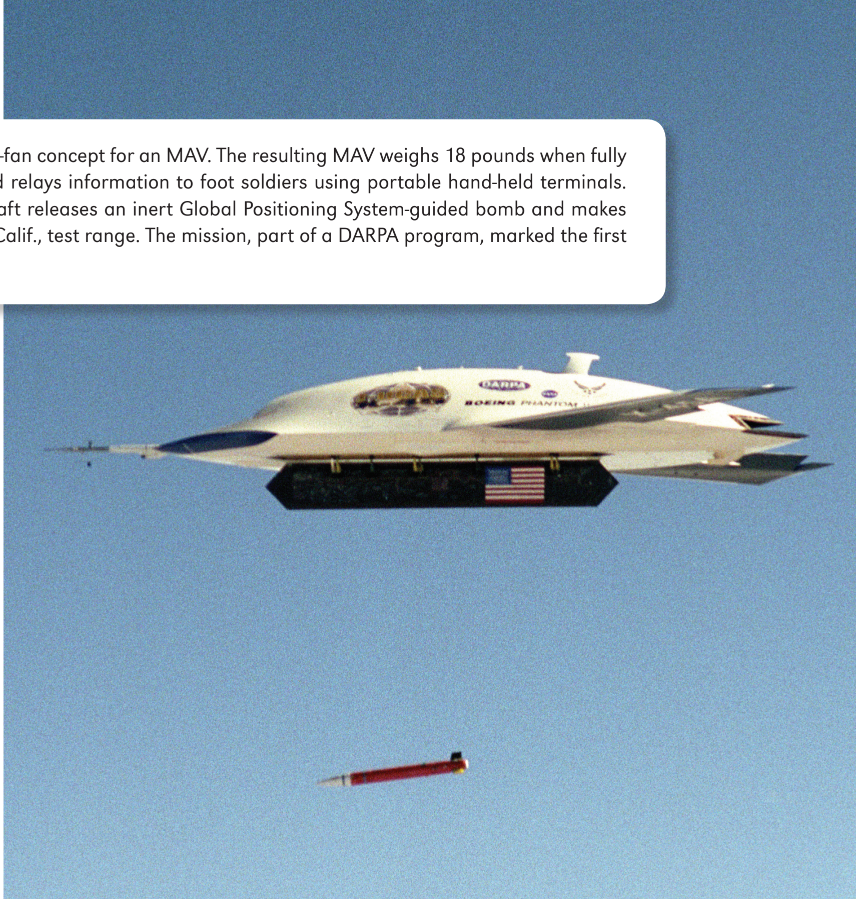
Similarly, an Unmanned Combat Armed Rotorcraft (UCAR) program was initiated in 2001 to develop a highly autonomous advanced helicopter for armed reconnaissance and attack missions. By operating close to its targets, the stealthy UCAR was intended to demonstrate the capability to affordably and effectively identify and prosecute masked ground targets. UCAR was developing the key technologies to enable the next generation of autonomous and collaborative operations: enhanced survivability at altitudes above nap-of-the-earth, low-altitude autonomous flight, and standoff target identification. Despite extremely promising progress, the Army pulled out of the program in late 2004, terminating the effort.

SMALLER AND QUIETER

DARPA has also made significant contributions to miniaturizing sensors and systems to the point of providing significant capability in a vehicle that can fit in your hand. DARPA's Micro Air Vehicle (MAV) program was started in fall 1996 to consider technologies that could be used to develop an airborne system for reconnaissance and surveillance with a maximum dimension of 6 inches. The MAVs were specifically intended to fly autonomously to allow relatively untrained soldiers to use them to scout out what lay beyond the next hill or around a building. From the beginning, however, it was hoped that the MAVs would progress to the ability to operate in more difficult environs, such as urban centers

Below, left: DARPA contracted Honeywell Aerospace in 2003 to develop its ducted-fan concept for an MAV. The resulting MAV weighs 18 pounds when fully fueled and can be carried in a backpack. It has hover and stare capabilities and relays information to foot soldiers using portable hand-held terminals. Below, right: A Boeing Joint Unmanned Combat Air Systems (J-UCAS) X-45 aircraft releases an inert Global Positioning System-guided bomb and makes aviation history at the Naval Air Warfare Center Weapons Division, China Lake, Calif., test range. The mission, part of a DARPA program, marked the first time an unmanned autonomous aircraft dropped a precision bomb.

Photo courtesy of DARPA



NASA photo by Jim Ross

and building interiors. Impressive results were developed, and the constituent technologies were matured over several years, with a few fits and starts.

Although the military utility of the approach led to a size increase, a contract to Honeywell Aerospace in 2003 matured its ducted-fan concept to the point that assessments by several services have confirmed military utility. The Army Division that performed the Military Utility Assessment of the MAV elected to take the Advanced Concept Technology Demonstration residual assets when they deploy in early 2008. Successful experimentation by Navy-led Joint Explosive Ordnance Disposal (EOD) teams with 10 MAV systems (20 airframes) in theater led to a decision to procure systems for development. The Honeywell MAV uses a ducted fan with a 13-inch diameter, and weighs 18 pounds when fully fuelled. It is small enough to carry in a backpack and is equipped with video cameras or infrared sensors that relay information back to foot soldiers using a portable handheld terminal. The MAV can hover and stare, providing a persistent line-of-sight into complex and urban terrain, even under bridges or jungle canopy. The vertical launch and recovery capability enables operations from and to almost any site with no footprint. The Army Future Combat Systems (FCS) Class I UAV is based on the MAV.

A parallel program to MAV has been the Organic Air Vehicle (OAV), which offers a capability to company commanders to detect, track, and engage targets using precision-guided (off-board) weapons. Whereas MAV is backpackable, the OAV is intended to be transportable by Humvee for use at the company level. Standing 65 inches tall and weighing about 150 pounds, the OAV system leverages the MAV autonomous ducted-fan technology, adding obstacle avoidance for safe autonomous flight, remote start for mid-mission perch and stare or "ground loiter," and a small and lightweight mission equipment package with optical and infrared sensors as well as laser ranging and designation on a stabilized gimbal. The OAV technology was developed and demonstrated to support the Army FCS Class II UAV, and may be considered for other military needs as well.

DARPA'S LEGACY CONTINUES

Today, DARPA is building on its impressive legacy of advanced aircraft developments. In the areas of miniaturization, extending endurance, increasing speed, and exploring novel concepts, DARPA continues to push the aerospace community to rethink basic assumptions, seeking high-risk, high-payoff approaches that will lead to revolutionary aircraft designs.

GETTING IT SMALLER

DARPA's efforts to develop small aircraft have continued. Another spin-off from the MAV program is the AeroVironment Wasp. It is a fixed-wing UAV with a 14-inch wingspan, and weighs about a half-pound. It can fly at over 35 mph, and provides unobtrusive, real-time imagery from low altitudes. The Wasp's payload consists of two color video cameras, a GPS sensor, an altimeter, a compass, and a sophisticated autopilot enabling hands-free operation. Wasp prototypes have been evaluated by the military in Iraq. There are a number of variants, including an extended-range version, a variant equipped with infrared sensors, and a version with a collision-avoidance capability.

Meanwhile, the Nano Air Vehicle (NAV) program objectives are to get even smaller: air vehicle systems less than 7.5 cm (about 3 inches) in size, ultra-lightweight (less than 10 grams or one-third of an ounce), and with the potential to perform indoor and calm weather outdoor military missions. The program is exploring novel, biologically inspired conventional and unconventional configurations to provide the warfighter with unprecedented capability for urban mission operations. This effort will push the limits of aerodynamic and power-conversion efficiency, endurance, and maneuverability for very small air vehicle systems. The program is advancing technologies that enable collision avoidance and navigation systems for use in GPS-denied environments and developing efficient methods for hovering flight and deployment or emplacement of sensors.

GETTING THERE FASTER …

With conventional helicopters limited to about 200 mph, DARPA's Heliplane program seeks to develop an air vehicle that combines the vertical takeoff and landing capabilities of a helicopter with the speed and efficiency of a fixed-wing aircraft. The Heliplane demonstrator aircraft is being designed for a 400-mph cruise speed, a 1,000-pound payload, and an unrefueled range of 1,000 miles. The concept marries a reaction rotor (i.e., no transmission) being developed by Groen Brothers Aviation with a modified Adam Aircraft A700 very light jet.

A joint program with the Air Force and NASA, the X-51A Scramjet Engine Demonstrator is intended to prove innovative hydrocarbon-fueled hypersonic-propulsion technology. Using conventional jet fuel, it will operate above Mach 6 and prove technologies for affordable space access and global strike. A ground test of its scramjet engine in July 2007 reached a peak equivalent of Mach 6.5. The Boeing/Pratt &Whitney Rocketdyne vehicle is expected to fly in 2009.

The Hypersonics Flight Demonstration (HyFly) program, a joint effort with the Navy, is another approach to develop and demonstrate advanced technologies for hypersonic flight. The program will demonstrate an air-launched missile with a range of 400 nautical miles, a maximum sustainable cruise speed of Mach 6, and the ability to accurately terminate the missile on a GPS-guided impact target.

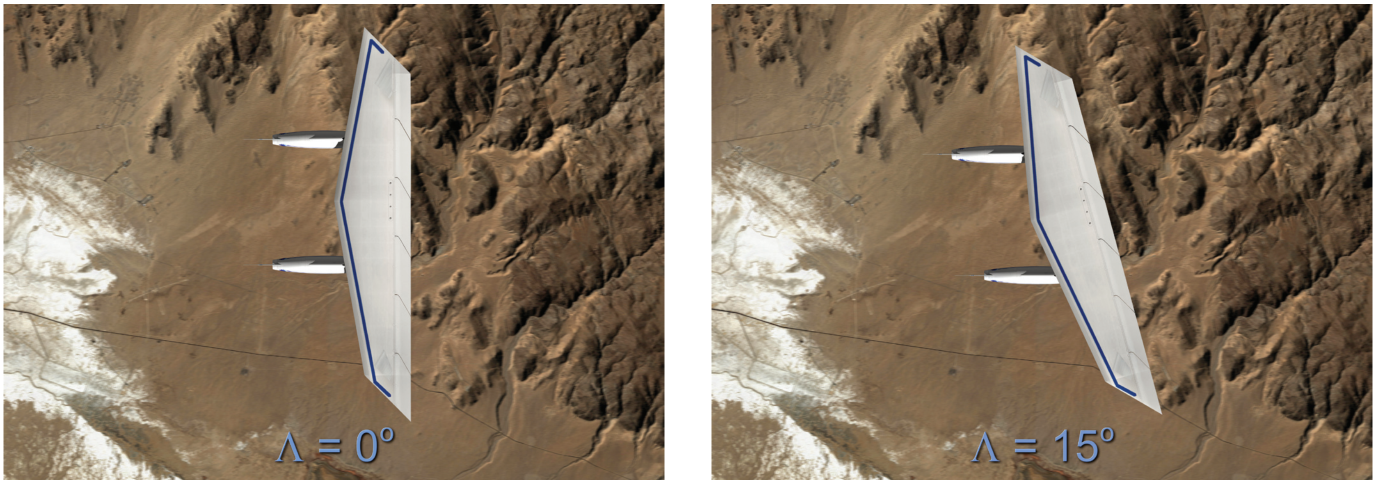
The joint DARPA/Air Force Falcon program is developing and demonstrating hypersonic technologies that will enable prompt global reach missions. The far-term capability is envisioned to entail a reusable Hypersonic Cruise Vehicle, launched from a conventional runway in the continental United States, that is capable of delivering 12,000 pounds of payload at a distance of 9,000 nautical miles in less than two hours.

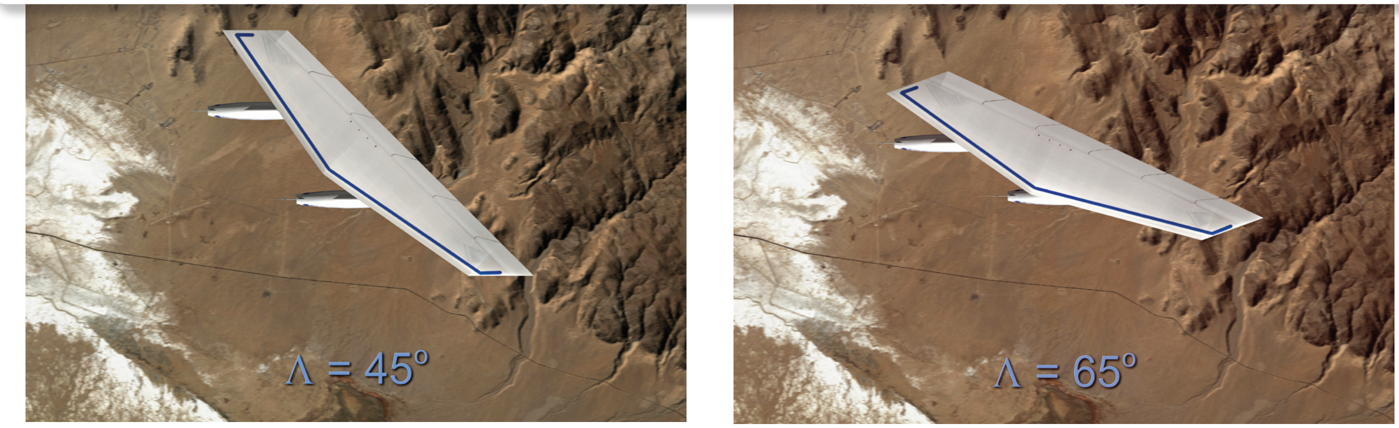
DARPA is also developing and ground demonstrating the propulsion technologies critical to a turbine-based combined-cycle propulsion system within the Falcon Combined-cycle Engine Technology program. These programs will feed into the Blackswift test bed, a reusable hypersonic aircraft that will take off from a conventional runway using turbojets, accelerate to Mach 6 under combined propulsion, decelerate, and make a turbojet-powered landing.

Another approach to getting there quickly is Rapid Eye. This program will develop and demonstrate the ability to deliver a persistent ISR aircraft anywhere in the world within an hour or two. Rapid Eye will be rocket-launched from the United States and can provide surveillance and communications over natural disasters or sudden hot spots. Once over the area of interest, the aircraft will be released, the wings deployed, and the engine started, with the aircraft remaining on station until relieved or the mission is completed.

… AND STAYING THERE LONGER

In 1998, DARPA started a long-endurance UAV program with Frontier Systems – acquired by Boeing in 2004 – with similar range, altitude, and endurance goals as Amber, but capable of vertical takeoff and landing. The A160 Hummingbird is a conventional-looking main-rotor helicopter with a very lightweight and stiff graphite-composite rotor that can vary its rotor speed down to 50 percent of maximum. The technology needed to stabilize and control the A160 rotor system was derived from the X-Wing program. First flight of the A160 was in January 2002, using an automotive piston engine. Four A160 demonstrators have flown to date, and 11 turbine-powered A160Ts are on order. In September 2007, the A160T demonstrated eight hours' endurance with a 1,000-pound payload; the following month, it made a 12-hour flight with a 500-pound payload at





The Oblique Flying Wing, a new X-Plane currently under development by DARPA, can vary the angle of its wing with speed, shifting between an unswept-wing design at lower speeds and a swept-wing design at high speeds. The four images on this page depict the changes in the angle of the wing.

Images courtesy of DARPA

5,000 feet using only a partial fuel load. The objective is to have an endurance of over 18 hours and an altitude capability approaching 30,000 feet. The A160 promises to provide a "vertical takeoff and hover Predator" capability that will permit the use of staring radars, ladars, and other sensors to monitor the real-time evolution of the conflict area in day/night, all weather, camouflaged, and concealed target environments.

The Morphing Aircraft Structures program seeks to advance aircraft performance with concepts designed to change their shape substantially during flight, facilitating aircraft that are aerodynamically and structurally efficient at both high and low speeds. In October 2007, NextGen Aeronautics' MFX-2 demonstrated the ability to independently vary wing area and sweep in flight, characteristics that would enable an operational aircraft with efficient, long-endurance flights as well as a high-speed dash capability.

DARPA is now developing a new X-Plane, the Oblique Flying Wing (OFW). The OFW is an aircraft without a fuselage that can vary the angle of its wing with Mach number: As the aircraft accelerates to supersonic speeds, one side of the wing sweeps forward and the other side sweeps back. This allows for an efficient swept-wing design at high speeds and an unswept wing with excellent low-speed endurance. By varying the sweep of the entire wing asymmetrically, the OFW also allows a structurally efficient wing design, without wing pivots used in other variable-sweep aircraft such as the B-1. The Northrop Grumman OFW X-Plane will be the first supersonic demonstration of an oblique flying wing and the first tailless oblique wing aircraft. The preliminary design of the X-Plane is now under way, with flight-testing planned for the 2011 time frame.

With Global Hawk and other UAVs capable of days of endurance – and some current efforts striving toward a week – DARPA is now looking to the next huge leap: Is it possible to develop an aircraft – with a useful payload of 1,000 pounds and able to generate 5 kW of power – that would be capable of staying aloft for five years? Can the constant cycle of takeoff, landing, and undergoing maintenance be broken? The Vulture program seeks to have a sub-scale demonstrator by 2012 to see if aircraft can be operated like satellites, which have already proven that such long-term reliability is possible. An aircraft operating in this manner could act as a "persistent satellite" that would circle indefinitely over points of interest for future battlefield commanders, providing all the communication and ISR capability they require. The solution to this "DARPA-hard" challenge could be to service the aircraft in flight. While aerial refueling is now commonplace for manned aircraft, in August 2007, DARPA demonstrated autonomous airborne refueling that was described as being more accurate than a skilled pilot.

DARPA and the Boeing Company's A160T Hummingbird unmanned rotorcraft successfully completed a 12-hour test flight on Oct. 12, 2007, recording the aircraft's longest flight to date.

Photo by Keith Skelton, courtesy of The Boeing Company

DARPA'S CONTINUING LEGACY

Since DARPA's first involvement in X-Planes in 1967, the agency has been a sponsor of nearly half of the series, maturing high-risk, high-payoff technologies that could only be tested in flight and transforming theory into reality. Welby explains, "The demonstrators were important because they proved the aircraft concepts were viable, but maybe more important were the design tools. The legacy is not just the demonstrations or the data; much more important is the advancement of the state of the art across the industrial base."

Due to DARPA's efforts in advancing the state of the art of unmanned systems, the world has seen a "democratization" of UAVs – in a few short years, they have been transformed from national or strategic assets to being operated by dismounted squads of soldiers. Welby notes, "Industry is providing UAVs to the military services that are built around DARPA technology investments." He says that DARPA's current efforts continue to be focused on "what are the fundamental limits of aircraft design?"

Will the military in the future deploy an aircraft that can keep a 1,000-pound payload aloft for five years? Will there be aircraft that can change their wing configuration and fly efficiently both very slowly and at supersonic speeds? Will hypersonic vehicles become a reality? The next few decades will show which of the efforts under way today will bear fruit. Countless other "seedling" efforts are under way as well, each one with the possibility to revolutionize some aspect of aeronautics.

Due to investments over the past half-century, "DARPA has a long legacy in aerospace technology," said Welby. And the efforts under way today and tomorrow will continue that legacy for decades to come.