Lift fan labs

DARPA has sponsored two ducted lift fan test efforts aimed at compact vertical take-off and landing aircraft that can fly safely in close quarters

BY FRANK COLUCCI

The Transformer (TX) program of the US Defense Advanced Research Projects Agency (DARPA) has morphed from a flying car into a modular unmanned air vehicle (UAV) that uses ducted lift fans to operate in constrained areas without rotor strike hazards. Lockheed Martin Aeronautics Skunk Works and Piasecki Aircraft are building their subscale powered TX model for wind tunnel tests this autumn. A full-sized, turboshaft-driven demonstrator should fly in 2015. Separate from the Transformer effort, a rejected TX proposal from Aurora Flight Sciences turned into a successful electrically driven ducted-fan demonstration aimed at other vertical take-off and landing (VTOL) platforms. Aurora delivered its lift fan final report to DARPA in late July. Although the company's government-sponsored fan work is done, "Aurora will be using this technology in the future," says program manager and principal investigator Dan Cottrell. "There will be follow-on work; this will have future application."

The DARPA Tactical Technology Office solicits high-risk, high-payoff battlefield technologies through Broad Agency Announcements (BAAs) and transitions successful technologies to military users and industry suppliers. In 2009 a BAA described an ambitious drive-or-fly vehicle that could carry 1,000 lb of cargo or four troops over ambushes and IEDs and travel 250 nautical miles without refueling.

Transformer Phase 1 concept study and Phase 2 preliminary design contracts teamed Lockheed Martin with Piasecki, and AAI Corp. with Carter Aviation Technologies, to design off-road vehicles that could unfold and fly. Protected fans promised vehicles small enough to travel on narrow roads and safe enough to take-off and land vertically near ground personnel and terrain. Lockheed Martin and Piasecki proposed tilting lift fans in a fixed wing to achieve VTOL and cruising flight. The AAI-Carter Slowed Rotor Concept was an autogiro with a jump-started lift rotor, fixed cruising wing and ducted thrust fan.

Lockheed Martin and Piasecki were selected last December to continue Phase 3 prototype development on what is now an Unmanned Aircraft System (UAS) with a lift fan flight module designed to carry cargo, sensors and other interchangeable payloads. Within the TX team, Lockheed Martin Skunk Works is prime contractor and responsible for overall vehicle design, aerodynamics, flight controls and flight testing. Subcontractor Piasecki Aircraft in Essington, Pennsylvania, builds the Flight Module, including the drivetrain, gearboxes and subsystems.

In the 1950s and 1960s, Piasecki's Airgeep transitioned from vertical to forward flight with manual flight controls (see sidebar, overleaf). Today, fly-by-wire flight controls derived from those in the F-35 Joint Strike Fighter (JSF) promise to make a lift fan vehicle

The DARPA Transformer has evolved from a flying off-road vehicle to a modular UAS to carry cargo, vehicles and other payloads


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PIASECKI VZ-80 (AIRGEEP)

Piasecki Aircraft Corp (PiAC) began development of the VZ-8P Airgeep for the US Army under a 1957 Transportation Research Command contract. The first VZ-8P, delivered to the Army in 1958, had two ducted three-bladed fans driven by twin 180hp Lycoming piston engines through a common gearbox. It was subsequently powered by a single Turbomeca Artouste IIB turboshaft. The follow-on VZ-8P(B) Airgeep II flew in 1959 with two 400shp Artouste IIC turboshafts and incorporated an angle rear duct, ejection seats and power-driven landing gear for ground speeds to 35mph.

The Airgeep II, test flown in 1962, had 8ft 2in diameter ducted fans and could hover out of ground effect at 3,670 lb gross weight and fly at speeds to 65kts. Independent fan pitch commanded attitude, and cyclic pitch and steerable vanes on the ducted rotors provided yaw and roll control. Flight tests near the ground revealed that fan downwash gave the pilot good visibility without blinding debris recirculated by open helicopter rotors. The ducted rotor platform was stable and could fly safely under trees and between buildings. Testing concluded in the 1960s.

The Piasecki ducted fan Airgeep was tested by the US Army in the late 1950s and early 1960s

both flyable and flexible. Lockheed Martin Transformer program manager Kevin Renshaw explains, "The ability to use the same flight module with a variety of modular payloads requires the flight control system to be adaptable to differing weights and aerodynamics."

Three F-35 versions each use an onboard model tailored to predict the response from control deflections based on current aircraft state. Common control laws maintain consistent handling qualities across the different aircraft and reduce development costs for the JSF variants. Lockheed Martin plans to implement a similar architecture in an existing flight control computer to control changing Transformer configurations. Following F-35 practice, control and handling qualities simulations will clear software releases for hardware-in-the-loop tests and subsequent flight tests. Skunk Works is testing the first versions of Transformer control software in its flight controls lab.

An operational Transformer will have to be a highly autonomous UAS to work with non-aviator ground troops. The Skunk Works will consequently draw on the work that Lockheed Martin Mission Systems and Training has done on the K-MAX Cargo Resupply UAS deployed to Afghanistan. (See '*Warhorse*', November-December 2011, p28-32.)

The current TX also builds on a patent-pending Piasecki design and concept of operations. Piasecki received US Army study contracts in 2006 and 2008, one for a UAV – Combat Medic Collaboration for Resupply and Evacuation, the other for an Unmanned Ground and Air System for Contaminated Personnel Recovery. The vehicle concepts included a modular ducted fan design with separating flight and ground modules for air and ground mobility. The Modular Air/Road System (MARS-TX) carried over to the unmanned Transformer.

Though TX prototype gross weights and dimensions are still to be revealed, the variable-pitch fans of the Lockheed Martin-Piasecki Transformer should be about the size of those on the manned VZ-8 Airgeep. Small lift fan models have already been tested in Lockheed Martin wind tunnels, and Piasecki is building a one-third scale flight module with drivetrain, fans and tilt mechanism to characterise various thrust, duct angle and control combinations. The model will be anchored to a calibrated reaction frame to measure lift, drag and control moments through the flight regime.

Data from the model will in turn refine the flight control software for the

"TX ENGINEERS WILL ALSO EVALUATE FAILURE MODES AND EMERGENCY PROCEDURES WITH FLIGHT HARDWARE AND SOFTWARE ON THE GROUND TEST STAND"

full-size Transformer prototype. The TX team will assemble and test their full-scale propulsion system drivetrain next year. Duct structure, flight controls and electronics will be added, and tests of the complete system on a ground test stand will measure thrust and control responses. TX engineers will also evaluate failure modes and emergency procedures with flight hardware and software on the ground test stand, then move on to flight test including hover and transition to cruising flight.

ELECTRIC FAN

The Lockheed Martin-Piasecki Transformer will drive its fans with a familiar turboshaft to cut prototyping costs. DARPA early-on acknowledged hybrid electric propulsion as a means to extend the range of a land-air vehicle. A brushless ring motor driving a fan in a duct could also eliminate heavy gears and linkages and scale up or down for different sized vehicles.

Aurora Flight Sciences in Manassas, Virginia, received a Phase I hybrid ducted lift fan contract in August 2010. Under a Phase II option contract from DARPA, late last year Aurora successfully demonstrated an integrated hybrid lift fan system including electric motor, high switching frequency power controller, and 32in diameter fixed-pitch fan. "The technology was interesting to DARPA for several concepts," explains Dan Cottrell. "Aurora has an aircraft called Excalibur. The full-scale version of that would have employed fans of this size."

The turbine-electric hybrid Excalibur with three lift fans flew in 2009. Aurora also drew on earlier fan experience from its GoldenEye-80 UAV. (See *Aerospace Testing International*, March 2007.) The main goal of the DARPA program was to produce a 70kW motor able to generate over 400 lb peak thrust with a 32in diameter ducted fan. Continuous thrust at 40kW was to be about 300 lb. Required performance called for a thin, five-bladed rotor more efficient than that used in the Excalibur. "It boils down to rotor area, the efficiency of system, and total thrust – it's a figure of merit," notes Cottrell.

The lift fan system included the fan and duct and a 4 x 4ft section of a wing to fit within a notional aircraft profile. Program lead and system integrator Aurora was responsible for the lift fan structures and aerodynamics. "We fleshed out the design of the ducted fan," says Cottrell. "We validated our internal tools with standard CFD [computational fluid dynamics] packages." Aurora recruited motor expert ThinGap in Ventura, California, and controller specialist Trust Automation in San Luis Obispo, California, to build the powerful new fan system.

Phase I tests of a re-amped 20kW motor revealed serious limitations with conventional motor designs. "It was limited thermally and in the dielectric strength of the material used in the motor. It couldn't quite get up to the power they needed," recalls Cottrell. Early performance characterization also uncovered the challenges of a motor with low inductance and high commutation rates. "It boiled down to needing its own controller."

Phase II of the hybrid lift fan development bench-tested purpose-built motors with innovative control technologies. Electric car motors of comparable power have liquid cooling. "That's great for a car application; it doesn't make as much sense for electric propulsion for aircraft," says ThinGap principal investigator Evan Frank. The lightweight, air-cooled brushless

URBANAERO AIRMULE

In Israel, Urban Aeronautics has modernized and refined what it calls the fancraft concept with fly-by-wire flight controls and composite structures. The unmanned AirMule demonstrator is currently powered by a 640shp Turbomeca Arriel 1 turboshaft and has been upgraded from four-bladed to six-bladed fans with 20% more lift. A vane control system on the top inlet and bottom outlet of each lift fan duct deflects thrust either in parallel or differentially to generate either pure lateral force or pure rolling moment. The front and back ducts can also deflect air differentially to generate yaw.

The AirMule has ducted fans at the rear for forward thrust. Drag reduction louvers at the front of the forward duct and rear of the aft duct open in forward flight for speeds up to 120kts. The AirMule fuselage functions as an airfoil and generates sufficient lift at high speeds to off-load 50% of the needed lift from the rotors. Since 2011 the AirMule has logged 120 tethered hover and low-speed flights, each lasting 10 to 15 minutes. The aircraft will transition to untethered cruising flight at the end of 2014.

The AirMule fancraft uses fly-by-wire controls and aerodynamic refinements to advance the ducted lift fan concept

The Aurora Excalibur UAS used turbine-electric fan power to take off and land vertically and transition to cruising flight

ABOVE: **Under DARPA contracts, Aurora Flight Sciences conducted a successful high-power test of an electrically powered ducted lift fan applicable to VTOL aircraft**

permanent magnet lift fan motor incorporated an ironless stator to improve the power-to-weight ratio and achieve the required power density. "Essentially the stator design is composite with electromagnetic conductors embedded in it," summarizes Frank.

MOTOR CONTROL CHALLENGES

ThinGap, Trust and Aurora engineers connected their motor and controller to a DC bus to simulate battery power. They measured motor currents on oscilloscopes to compare power-in and power-out, and ran the motor on a computer-controlled dynamometer to monitor temperatures to assess overall motor health. The fan motor control varies fan speed to modulate lifting power. "Rather than controlling the thrust with blade pitch, the motor speed is what drives the thrust output," explains Frank. "The torque – power is torque times speed – is proportional to whatever speed you're operating at. With the push to higher power-to-weight ratios in higher power machines, inductance is getting lower. That makes motor control more challenging."

Lift fan control developer Trust Automation drew on previous experience with a traction drive for an electric vehicle to provide the control for the new motor. "One of the things is to maximize efficiency. You want to have a controller – hardware and software – that's mated to the motor," says Trust vice president of business development Craig von Ilten. "The greatest challenge that needed to be overcome was the low inductance of the motor winding. When you have a very low inductance motor the current in the phase winding collapses very quickly." Compared with the optimized lift fan controller, a non-flying commercial controller working with the same power might be 15% less efficient and potentially three times heavier. "There was a tremendous amount of development and test as the system came together," says Von Ilten.

"RATHER THAN CONTROLLING THE THRUST WITH BLADE PITCH, THE MOTOR SPEED IS WHAT DRIVES THE THRUST OUTPUT"

Aurora ran the integrated controller, motor and fan system on a seesaw test rig with load cells at one end. "Through the geometry of that system we would read thrust through the moment arms into the load cells," says Cottrell. "Aurora and ThinGap worked to balance the motor magnetically and structurally. There are some large loads there, not to mention that the rotor itself is attached to this." Strain gages measured stresses for system safety, and high-definition video cameras recorded the tests.

Test engineers used National Instruments' LabVIEW software to collect their data. "The key data we were looking at was thrust and then power-in and power-out, so we could get efficiency," says Cottrell. In December 2012 the system generated 440 lb hover thrust at 70kW for short bursts and 320 lb continuous thrust at 40kW.

The demonstrated ducted lift fan is not flight-rated hardware or optimized for weight. Cottrell notes, "Aurora has an extensive history of lightweight composite aircraft structures and components, so we know that when this technology is integrated into an aircraft we can address those concerns." ∎

Frank Colucci specialises in writing about rotorcraft design, civil and military operations, test programs, materials and avionics integration