



Lift Where You Need It

Given advances in power generation, storage and control, Distributed Electric Propulsion opens new design opportunities for vertical flight.

By Frank Colucci

With rotors, ducted fans and other lift devices powered through wires, Distributed Electric Propulsion (DEP) can change the shape and performance of vertical takeoff and landing (VTOL) aircraft of many sizes. Advanced Aircraft Company's (AAC) 36 lb (16.3 kg) Hercules unmanned aircraft system (UAS) has a hybrid-power gasoline engine and generator set driving eight outrigger motors with propellers for hover and forward flight. Licensed to AAC, NASA's 62 lb (28.1 kg) Greased Lightning battery-powered UAS has 10 motorized propellers on its tilting wing and tail to transition from rotor-borne VTOL to efficient wing-borne cruise. First flown with a pilot on board last April, the 992 lb (450 kg) e-volo GmbH VC200 Volocopter battery-powered multicopter has 18 electric motors and propellers on a latticed ring and is designed to land safely with four of them out of action. The LightningStrike, a DARPA-funded, 12,000 lb (5,443 kg) unmanned VTOL Experimental Aircraft (VTOL X-Plane), will tap hybrid turboshaft-generator power to turn 24 ducted fans on its tilting wing and canard for speeds of up to 400 kt (740.8 km/h) (see "A Small LightningStrike," *Vertiflite* July/August 2016). Researcher Mark Moore at the NASA Langley Research Center contrasted innovative DEP

NASA now considers the all-electric GL-10 Greased Lightning a UAS technology demonstrator and licensed the design to Advanced Aircraft Company for further development, including a hybrid electric propulsion system. (NASA photo)

designs with helicopters: "DEP means you can put the propulsors anywhere you want on the airframe. This means you can achieve pitch, roll, yaw with direct propulsive force — and a nice moment arm. So the need for cyclic systems completely disappears, along with most of the complexity and vibration."

Joby Aviation in Santa Cruz, California aims to leverage DEP experience it gained with the NASA Leading Edge Asynchronous Propellers Technology (LEAPTech) demonstration to fly its S4 personal VTOL aircraft early next year. LEAPTech ground-tested 18 electric propellers on the leading edge of a wing attached to a truck. Now, Joby is working on the design and construction of the optimized wing, motors and propellers that will fly in 2018 on the all-electric X-57, built under NASA's Scalable Convergent Electric Propulsion Technology Operations Research (SCEPTOR). Replacing the wing on a Tecnam P2006T aircraft, the X-57 "Maxwell" uses 14 electric motors driving propellers mounted on the leading edges of the wing, according to Moore, who is the X-57 principal investigator and NASA's On-Demand Mobility planning lead.

The privately funded S4 introduces

six electric-powered tilting propellers for VTOL and wing-borne flight. "With electric propulsion, it's much more practical to look at distributed propulsion with lots of propellers driven by their own motors," explained Alex Stoll, an aeronautical engineer with Joby. "If you have a bird strike, an electrical failure, or some mechanical failure, you still have lots of other propellers.... We have the ability to really minimize [single] points of failure and put in lots of redundancy, which is great from a safety standpoint."

Bloomberg Businessweek revealed in June that the potential of electric propulsion has also inspired Silicon Valley billionaires to fund several 'flying car' efforts, including guarded programs at Zee.Aero and Kitty Hawk funded by Google co-founder Larry Page. [Kitty Hawk includes the leadership of AeroVelo, who won the AHS Igor I. Sikorsky Human Powered Helicopter Competition in 2013.]

Airbus Group announced in August that it has been working on its Vahana and CityAirbus electric VTOL aircraft. Meanwhile, in late September, Uber revealed that it is looking into VTOL for autonomous passenger transport.

New DEP configurations nevertheless pose power and flight control challenges. Since August 2015, Embry-Riddle Aeronautical University's Eagle Flight Research Center and UAS maker Heurobotics in Daytona Beach, Florida, have logged about 35 vertical flight hours with an all-electric tail-sitter that can autorotate to safety like a helicopter should power fail. "Quadcopters don't do it. An octocopter doesn't do it," observed Dr. Richard "Pat" Anderson, Research Center director and Heurobotics chief scientist. Heurobotics' Mark I octocopter was succeeded by a twin-rotor Mark II vehicle that takes off and lands vertically but quickly transitions to wing-borne flight. Anderson explained, "We leap off the ground and immediately lean over to fly fixed-wing. Direct lift is very costly" in terms of power and cruise efficiency.

The Mark II is designed for agricultural sensing applications and aims to cover about 250 acres on a 20-minute battery charge. "There's nothing that tilts; nothing that rotates; nothing that moves other than the fact that it's got fully articulated rotor blades," Anderson said. "Making it mechanically simple requires making it smart." The Mark II UAS with its model-based parameter identification control system uses differential cyclic for pitch, yaw and lateral translation and is nearly ready to transition from hover to wing-borne flight. "It's completely unstable in every axis," said Anderson. "I'm sort of likening it to a child... It's learning to fly in every direction." The 39 lb (18kg) demonstrator has a useful load of around 40 lb (18 kg) and generates 115 lb (52 kg) of static thrust. A production vehicle optimized for forward flight could be about 30% lighter.

Mark Moore at NASA Langley



Advanced Aircraft Company is near low rate initial production of the Hercules multi-rotor VTOL UAS with a hybrid gasoline-generator propulsion system. (AAC graphic)

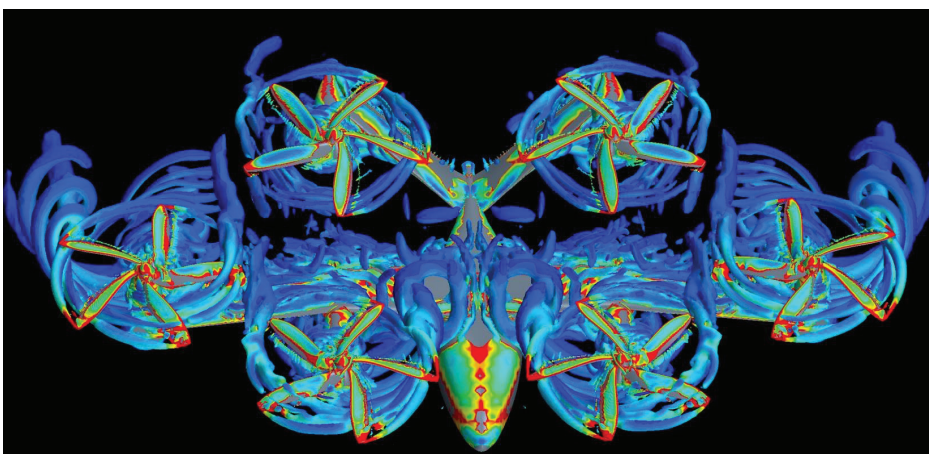
calculated superior lift-to-drag ratios and propulsive efficiencies can make DEP aircraft an order of magnitude more efficient than helicopters. With multiple small motor and propellers instead of heavy gearboxes and driveshafts, plus complex rotor hubs, DEP can also eliminate flight-critical helicopter components and reduce operating costs. Although several electric-powered helicopters have been built, Moore concluded, "Electric helicopters make absolutely no sense. Why would anyone bother with a complex rotor system when you have a scale-free propulsion technology? Why would anyone use an energy-constrained propulsion technology on a grossly inefficient airframe such as a helicopter?"

Power-Packed

The enthusiasm for electric flight stems from the promise of cheap flight, free of the noise and combustion pollutants of "thermal"

engines. In September, NASA released an RFI for an Electrified Aircraft Propulsion Flight Demonstrator meant to reduce carbon emissions. A new DEP VTOL flight demonstrator may stem from private funding. The battery-powered Airbus E-Fan airplane that crossed the English Channel last year and the Aero Electric Aircraft Corporation (AEAC) solar-battery Sun Flyer near first flight are runway-bound aircraft both aimed at the cost-sensitive pilot training market — which tends towards short flights from noise-sensitive local airports. AEAC in Englewood, Colorado targets Sun Flyer energy costs of just \$1 per flight hour. Comparing energy-equivalent costs of electricity and avgas, Mark Moore at NASA Langley figured electricity around half as expensive as general aviation fuel. Platforms with up to 11.8 times the efficiency of helicopters and 50% of the fuel costs translate to energy costs 23.6 times less than those of a helicopter.

Electrically powered vertical flight nevertheless demands both high energy density in batteries and high power density in motors. Alex Stoll at Joby Aviation noted that while turboshafts typically lose efficiency when scaled down, small, lightweight electric motors like those on the S4 retain their high power-to-weight ratios and power efficiencies. "The motor designs are more optimized for the mission," he said. "With large engines, you can't afford to have lots of them." While DEP motors for runway-bound aircraft also need high power-to-weight ratios and energy efficiency, vertical flight may impose special requirements. "One of the main areas where you could see a difference is



The Joby Aviation S4 is a four-seater with six electric-powered tilting propellers that should fly within the next year. (Joby Aviation graphic)



Embry-Riddle University and Heurobotics are collaborating on the all-electric Mark II UAS. The tail-sitting vehicle uses two fully articulated rotors and tips over to transition from vertical takeoff to wing-borne cruising flight. (Heurobotics photo)

in an aircraft with long hover ability, you could have different cooling demands on the motor.... We're not trying to design an aircraft that can hover for a long time."

All-electric aircraft are constrained by battery technology. Researchers at ENAC in Toulouse, France are flying the Volta electric helicopter with separate motors for main and anti-torque rotors. The two-seat demonstrator aims for 10–20 minutes endurance on a battery charge. e-vo, the Volocopter developers in Karlsruhe, Germany, want a 100 km/h (54 kt) multicopter that can fly for at least 30 minutes on a charge. They are already investigating hybrid thermal-electric power to extend endurance and range.

Sikorsky Innovations explored an all-electric Schweizer Model 300C helicopter from 2008 to 2011 and concluded manned electric flight was feasible but not yet practical. The Firefly demonstrator modified by Eagle Technologies in West Chester, Pennsylvania, swapped a 190 hp (142 kW) Textron Lycoming HIO-360 D1A internal combustion engine for a US Hybrid electric motor with digital controller and cockpit monitor. Two lithium ion battery packs weighed about 1,100 lb (0.5 t) and put the Firefly near its maximum gross weight. The projected 5–10 minute flight time was too short to capture meaningful data, and the Firefly program was paused while still in ground acceptance testing. Officially, Sikorsky looks forward to continued development of the technology.

US Hybrid in Torrance, California makes electric motors for a range of ground vehicles, but it had to advance motor and materials technology to meet Firefly power density and cost objectives

with aviation levels of reliability and redundancy. The helicopter motor exceeded 95% efficiency, but unlike an automotive motor that typically accelerates for seconds, a helicopter powerplant operates under continuous load. According to US Hybrid founder Dr. Gordon Goodarzi, "For cars, we usually work on the starting torque to meet vehicle grade capability and acceleration, whereas for vertical lift, we have to keep increasing the torque as RPM increases." The electric helicopter also underscored the challenges of weight and continuous power and posed cooling and vibration challenges.

Alex Stoll at Joby Aviation noted the brushless electric motor to be tested in the first-phase NASA X-57 has a much better power-to-weight ratio than

the Rotax combustion engine in the precursor Tecnam P2006T aircraft. The 50 kg (110 lb) electric motor generates about five times the torque and uses a smaller gearbox than the 225 kg (500 lb) thermal engine, and promises better reliability. "The catch is ... the batteries are extremely heavy compared to gas." Stoll told the AHS Forum that S4 batteries will account for about 35% of takeoff weight versus 21% for payload and 19% for propulsion.

Mark Moore noted that over the past five years, electric motors and controllers have more than doubled in specific power. He concluded, "The only downside of the DEP VTOL aircraft is that they're short-range because of the batteries. But urban ops don't need long range, and a range extender [hybrid thermal engine] can allow longer flight (but the operating cost benefits aren't nearly as compelling)." Moore estimated that batteries for all-electric flight need over 400 W-hr/kg energy density — significantly greater than the 265 W-hr/kg in the best rechargeable lithium batteries today. Battery costs also need to come down to less than half the current \$450 per kW-hr. "We also need larger, high-voltage charging stations that can rapidly charge the bigger batteries that electric aircraft will have." High-voltage charges for the Tesla automobile are rated around 100 kW and restore an 80% charge in about 40 minutes. "We need 350 kW chargers. It just so happens that the DOE [Department of Energy] just started a \$50M program to achieve these exact goals over the next five years."



Distributed Electric Power aircraft, like the Volocopter VC200, package drive motors and propellers without a driveshaft to eliminate transmission losses and give designers new flexibility. (e-vo GmbH photo)

With funding from the US National Park Service, Embry-Riddle Eagle Flight Research Center is turning a Diamond Aircraft HK36 Super Dimona light aircraft into the battery powered E-Spirit of St. Louis to fly in 2017. The demonstrator enables researchers to design battery packs, motors and propulsion control software like systems certified by the Federal Aviation Administration. The YASA 750 electric motor in the all-electric demonstrator will provide 100 hp (75 kW) continuous power or 130 hp (97 kW) peak power. The 3.7 V / 3,400 mA-hr lithium-ion batteries are sized to

provide 90 minutes of endurance, but the high power required on takeoff means actual flying time and power available throughout flight will be less. Pat Anderson explained, "As soon as your battery starts to deplete, you can no longer draw maximum horsepower." Power system controls have to monitor the charge state and temperature of each cell in the lithium ion battery pack for safe, efficient operation. Anderson acknowledged, "There's a lot to learn, and the fully-electric airplane is a lot simpler than the hybrid."

Embry-Riddle researchers are working with the Argonne National Laboratory in Lemont, Illinois, on improved battery technology, but expect only about 3% net growth in specific energy over the next 10 years. "I think there are a lot of people who think the specific energy of batteries is going to grow in leaps and bounds. We're not planning on that," said Professor Anderson. "I think fully electric, to get more than about 15 minutes in any size in pure vertical lift on batteries is difficult. That drives you to a hybrid aerodynamic solution or a hybrid propulsion solution."

Hybrid Hopes

NASA named the GL-10 research platform Greased Lightning for the biofuel engine it planned to use in a series hybrid (engine-generator) propulsion system. Langley researchers built a dozen Greased Lightning models of different sizes. With 10 Scorpion SII-4020-360KV electric motors turning wing and tail props, the biggest has a



The Sikorsky Firefly integrated a Schweizer S-300C helicopter with all-electric propulsion, but excessively short endurance with battery power stopped the program in 2011 during ground acceptance testing. (Sikorsky Aircraft photo)

10.5 ft (3.2 m) span and transitions from vertical flight to efficient cruise at about 35 kt (65 km/h). "Normally, the resulting performance is an average of the two," explained NASA engineer and Greased Lightning lead William Fredericks. "We get the performance of a fixed-wing aircraft and vertical takeoff and landing." Since the first flight last year, the battery-powered test vehicle transitioned 20 times in 41 flights. With four 4,400 mA-hr batteries, hovering flights last about five minutes, or 20 minutes in wing-borne flight. Fredericks founded Advanced Aircraft Company in Hampton, Virginia in October 2015 (continuing part time at NASA) and gained a NASA license to market the Greased Lightning. "There's an aviation saying, 'You never want to design a new aircraft at the same time you design a new propulsion system,'" he said. "For Greased Lightning to be a useful product, to really get long legs, it needs a hybrid electric propulsion system in it.... It's not on hand yet."

Fredericks instead designed the Hercules multi-rotor UAS, both to develop

a hybrid powertrain that will fit Greased Lightning and give his AAC a commercial product that will fund the tilt wing. Hercules begins low rate initial production this year with a gasoline or heavy fuel engine, and a generator set. The hybrid multi-rotor has eight motors on fore and aft booms, each boom covered by pivoting aerodynamic fairings that reduce separation drag. The rotors with their drive motors remain fixed, but unlike typical multi-rotor UAVs that nose-down in forward flight, the Hercules fuselage is tilted to stay nearly level to reduce base drag at 30–40 kt (55–75 km/hr).

The first-generation Hercules has a two-stroke gasoline engine that turns an alternating current generator. A rectifier supplies direct current to the motors while the propulsion system controls throttle the gas engine to maintain steady bus voltage. Significantly, the hybrid multi-rotor also has small battery packs to compensate for power transients and allow soft emergency landings. "Small combustion engines are cantankerous — they're not terribly reliable," noted Fredericks. "When the gas engine quits, the batteries have enough stored energy to allow another two minutes of flight time. You don't lose your expensive aircraft and expensive payload."

LaunchPoint Technologies, Inc. in Goleta, California continues work on a 1.5 kW hybrid power system for Greased Lightning and supports other UAV manufacturers. Dave Paden, company president, explained, "We are developing a family of power systems for VTOL applications, from 1.5 kW all the way up to 40 kW with the immediate focus on the lower end." Pancake-shaped dual-Halbach magnet array motors achieve



The DARPA LightningStrike VTOL X-Plane designed and built by Aurora Flight Sciences will integrate a Rolls-Royce AE1107C turboshaft with Honeywell megawatt generators to provide hybrid electric power for 24 ducted fans. (Aurora graphic)

higher efficiencies than ordinary radial configurations, and carbon fiber used in place of iron enables LaunchPoint designers to eliminate current losses and reduce weight. Paden noted, "In airborne applications, weight and efficiency are king. Direct drive is always desired (no gears), but electric motors are better at higher speeds, and larger-diameter, slow-turning props are more efficient. These two points are in direct competition with each other and force the designers to optimize the complete system. They can't just pick the lightest motor and attach the best propeller." AAC is working with LaunchPoint as the launch customer of their UAS hybrid propulsion system to power Hercules.

Aurora Flight Sciences in Manassas, Virginia is building the LightningStrike hybrid electric VTOL X-Plane for the Defense Advanced Research Projects Agency (DARPA). The big, unmanned aircraft has ducted fans on its tilting canard and wing driven by lightweight, air-cooled, brushless motors from ThinGap in Ventura, California. The custom-made permanent magnet fan motors have composite stators with

embedded electromagnetic conductors for best power-to-weight ratio.

A Rolls-Royce AE 1107C turboshaft from the V-22 tiltrotor powers three Honeywell 1 MW generators mounted on a power gearbox and sends power through the Aurora-designed electrical grid. Rolls-Royce LibertyWorks in Indianapolis, Indiana, designed and developed the LightningStrike Power Generation System (PGS) and power distribution control system. The distribution system synchronizes 24 wing and canard fans throughout the flight envelope and saves weight by eliminating traditional power conditioning and control hardware. Honeywell Aerospace is providing the megawatt generators based on common wound-field aircraft generators. The 280 lb (127 kg) generators incorporate mechanical and electrical conversion features to provide 98% efficiency.

A LightningStrike Copper Bird will ground-test the complete PGS and distribution controls with one-third of the full aircraft propulsion system. According to Kaare Erickson, chief of advanced propulsion concepts at LibertyWorks,

"The LightningStrike engine is not derated for the X-Plane application but will have additional power available should the demonstration technology transition to another airframe platform in future." The extra power margins enable the PGS to generate the full 3 MW up to 15,000 ft (4600 m) altitude. Erickson explained, "The electrical distribution system eliminates the need for additional gearboxes or complex shafting. The integration of multiple fans can provide additional aerodynamic efficiency at the airframe level by freeing up the placement of each individual propulsor or by providing a blown wing effect. As in the DARPA X-Plane, this can enable high hover efficiencies as well as high speed cruise capabilities."

About the Author

Senior contributing editor Frank Colucci has written for *Vertiflite* for the past 20 years on a range of subjects, including rotorcraft design, civil and military operations, testing, advanced materials and systems integration. He can be emailed at rotorfrank@aol.com.



Don't Miss these Exciting Upcoming AHS Technical Meetings!



Technical Meeting on VTOL Unmanned Aircraft Systems

Sponsored by the AHS Arizona Chapter

Mesa, Arizona, USA

Jan. 24-26, 2017

www.vtol.org/unmanned

Technical Meeting on Rotorcraft Handling Qualities

Sponsored by the AHS Redstone Chapter

Huntsville, Alabama, USA

Feb. 22-23, 2017

www.vtol.org/handling