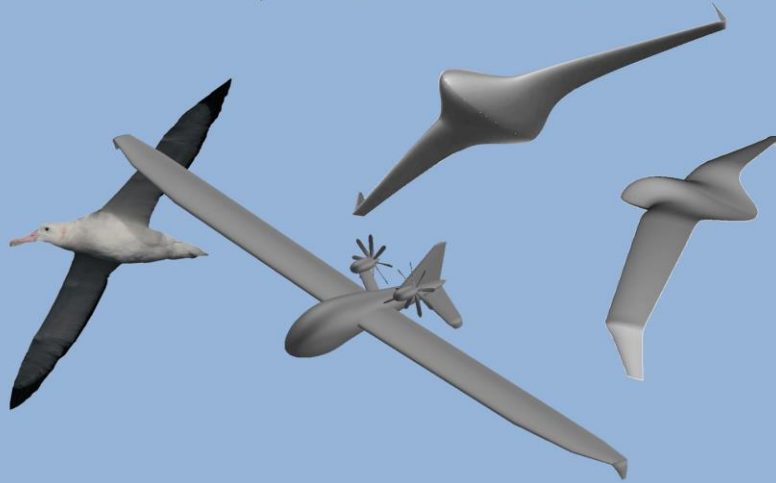**Future Direction: Increased Autonomy**
Extracting Energy From an Atmosphere in Motion
J. Philip Barnes   *12 Dec 2014*
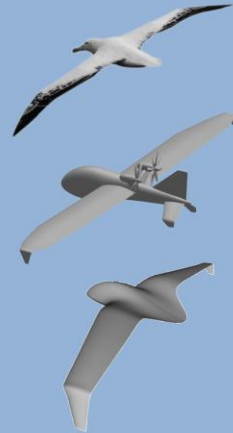
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In parallel with steady gains in battery energy and power density, the coming generation of uninhabited aerial vehicles (UAVs) will enjoy increased range, endurance, and operational capability by exploiting energy gain from atmospheric motion. Here we refer to optimal and/or intelligent motion of the vehicle within an atmosphere which is itself in motion. Specifically, we will learn from the birds in exploiting vertical "wind" in the form of updrafts via thermals, wave lift, or ridge lift, or in exploiting horizontal wind in the form of its vertical gradient.

Presentation Contents

- Purpose: Enhance UAV range, endurance, and operational capabilities

- How: Extract energy from atmos. motion
    - Optimal or intelligent maneuvering
    - With the atmosphere itself in motion

- "Regen": Regenerative electric flight
    - Extract energy from updrafts if available
    - Propeller/turbine "windprop" & motor-gen.

- "Dynasóar": Dynamic soaring
    - Extract energy from the wind gradient
    - Learn from the wandering albatross

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Our focus is on increasing UAV range, endurance, and operational capabilities by extracting energy from an atmosphere in motion.

With regenerative-electric flight, a "regen" will takeoff with its propeller, and upon encountering an updraft, take time out to regenerate by operating the propeller as a turbine, and the electric motor as a generator. Also, we can call upon additional operational capabilities afforded by regeneration near the end of the flight.

In contrast, with dynamic soaring, what we shall term a "dynasóar" will emulate the wandering albatross by exploiting the vertical gradient of horizontal wind. Whereas for the wandering albatross the wind gradient varies as a "profile" with elevation above the water, for the dynasóar in the Jetstream, the wind gradient is largely constant.

Regenerative-electric Flight

"Regen" : Regenerative-electric Flight

- Enhanced range & time
- Steep descent option
- Landing thrust reversal
- Ground wind recharge

Features & Enablers
- Thermal / ridge lift
- High L/D, low sink
- Sym. rotor airfoils
- DC boost converter
- Propel. ~ high RPM
- Turbine ~ low RPM

Updraft | "Clean" sink rate | Windprop Effect

$$\dot{z}_t = u - n_n \frac{D}{L} V \left[1 + (\varepsilon - 1)\frac{T}{D} \right]$$

"Total Climb" | "Total Sink"

$\varepsilon \equiv$ "Exchange Ratio," as applicable:
- turbine *system* efficiency ~71%
- 1 / propeller *system* efficiency
- 0 for pinwheeling (no exchange)

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Like a soaring bird, this "regen," or ***regenerative electric aircraft***, extracts energy from vertical atmospheric motion. But whereas the soaring bird simply maintains its *potential* energy, the regen goes a step further to gain *internal* energy. Regeneration is possible when the updraft exceeds the regen's clean sink rate, where "clean" represents the "windprop" system removed.
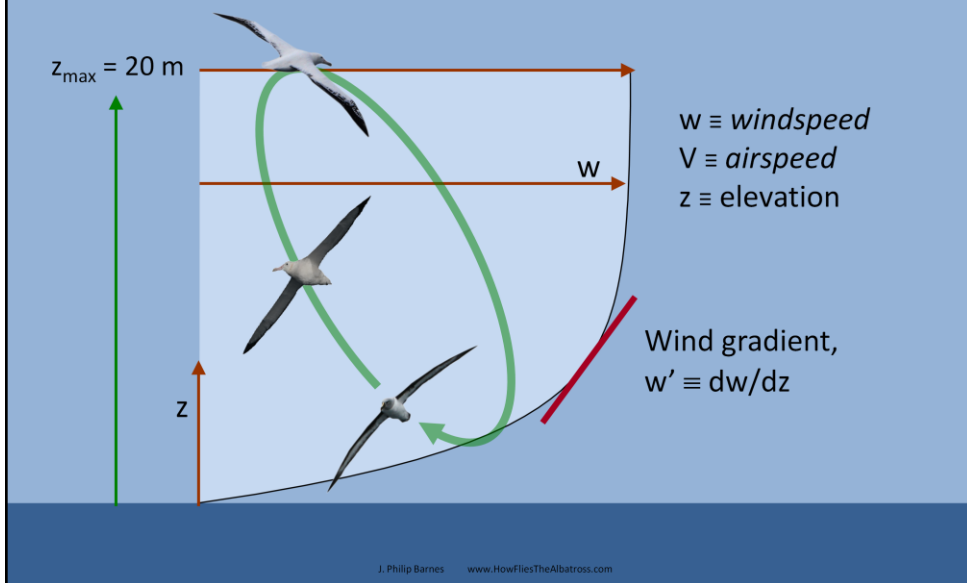
With the regeneration capability, the UAV can enjoy increased range, endurance, steep descent where necessary, ground-roll thrust reversal, and ground recharge in the wind. Apart from uplift, key enablers for the regen include high lift-to-drag ratio, low wing loading, and symmetric rotor airfoils which can be shown to offer similar peak efficiency for both operational modes. An additional key enabler is a *DC boost converter*, borrowed from ground EV *regenerative-braking* technology to enable efficient bi-directional control of electrical power.

The system-level formula at lower left, applicable for any operational mode including pinwheeling, relates the updraft velocity (u), "clean sink rate" (windprop removed), and system bi-directional efficiency to the rate of change (dz_t/dt) of total specific kinetic, potential, and battery-stored energy. This formula, also applicable for cruising or maneuvering at load factor (n_n) and corresponding lift/drag ratio (L/D), reveals the requirements for efficient aerodynamics, powertrain efficiency, and low wing loading.

Dynamic Soaring

Exploiting the wind profile and local gradient

Flight kinetic energy is increased via Dynamic Soaring Rule

$z_{max} = 20$ m

w

$w \equiv windspeed$
$V \equiv airspeed$
$z \equiv elevation$

Wind gradient,
$w' \equiv dw/dz$

z

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Let's take a look at the wind profile far out at sea. Although the "boundary layer" shape looks quite familiar, we may be surprised to learn that its height is perhaps 20-meters. We conclude that the albatross uses the local gradient (dw/dz) of the wind profile to maintain dynamic soaring. Exchanging kinetic and potential energy in each zoom maneuver, the albatross maintains its total energy overall with each cycle, typically including a 3-g pull-up into the wind every 12-sec or so.

Clearly, intelligent maneuvering via dynamic soaring is somehow providing a thrust which overall offsets the drag. Let's now quantify that thrust which, as we might expect, depends on the wind gradient (dw/dz) and the orientation of the albatross, relative to the wind.

Dynamic Soaring ~ Force Diagram

Isaac Newton

φ
L
V ---------- D
γ
ψ
mẇ
mg
w
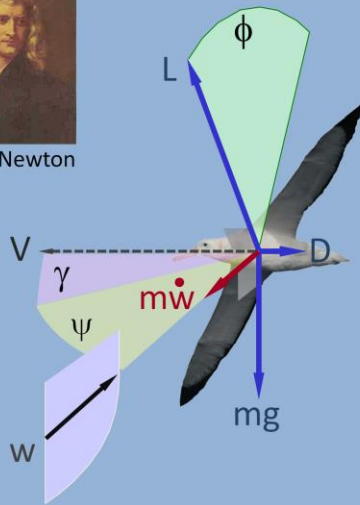
Dynamic Soaring Force Vector **(F)** = m(dw/dt), directed upwind

Dynamic Soaring Thrust , T = **F·V**

Isolate dynamic soaring thrust (ignore weight & drag for now)

$T = m\ dV/dt$
$\quad = m\ (dV/dw)\ (dw/dt)$
$\quad = m\ \cos\gamma\ \cos\psi\ (dw/dt)$
$\quad = m\ \cos\gamma\ \cos\psi\ (dw/dz)\ (dz/dt)$
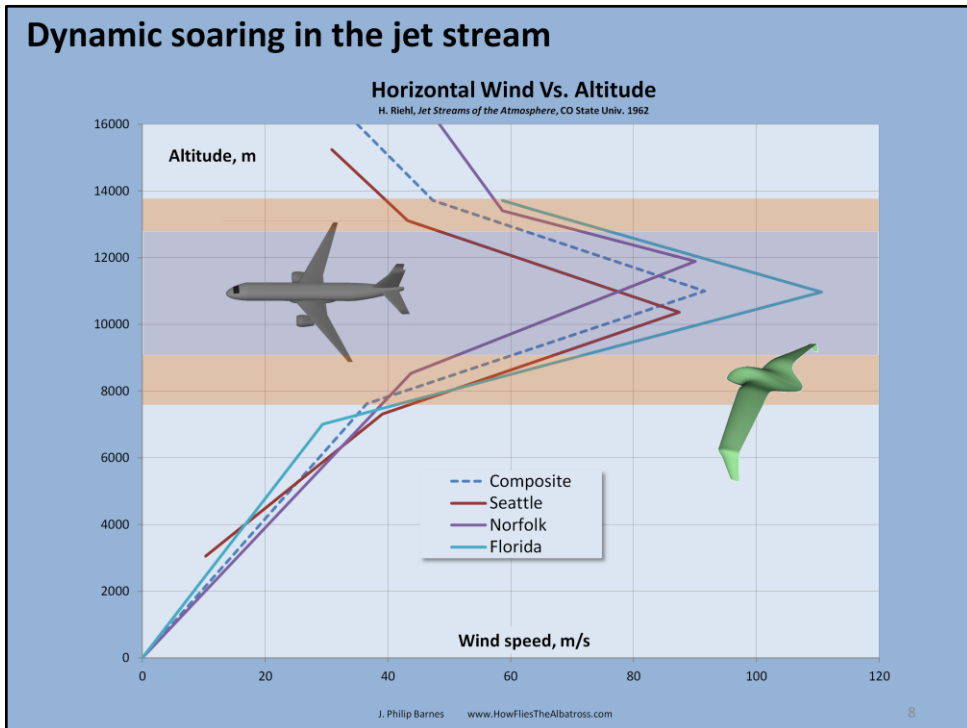$\quad = m\ \cos\gamma\ \cos\psi\ w'\ V\ \sin\gamma$

Thrust proportional to airspeed, wind gradient, climb angle, and airspeed-to-wind "alignment"

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With the albatross shown at an arbitrary orientation, we show all the forces, including in particular the dynamic soaring *force*. This vector, of magnitude [m(dw/dt)], remains steadfastly level and pointed directly upwind. The component of that force aligned with the airspeed vector constitutes dynamic soaring *thrust*.

Since the wind profile is fixed, only by moving vertically within the wind profile does the albatross experience the rate (dw/dt) and the resulting dynamic soaring thrust. To quantify the thrust, we momentarily ignore both weight and drag. Then applying Newton's Law along the flight path, we find that the dynamic soaring thrust is proportional to the mass (m), wind gradient (w'), airspeed (V), flight path angle (γ), and a "cosine product." The latter becomes negative when the albatross turns downwind, whereby the dynamic soaring thrust remains positive if the albatross descends downwind.

For the albatross, the dynamic soaring thrust has the same effect as a "strap-on jet pack," with thrust varying throughout each dynamic soaring cycle. It would appear that nature's jet engine has been around for 50 million years.

Dynamic soaring in the jet stream

Horizontal Wind Vs. Altitude

H. Riehl, *Jet Streams of the Atmosphere*, CO State Univ. 1962

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We are naturally led to ask if terrestrial dynamic soaring is feasible. Here we restrict ourselves to dynamic soaring over flat terrain, as the albatross maintains its total energy overall over a flat, waveless sea. Unfortunately, we learn that wind gradients near the ground are usually inadequate to support UAV dynamic soaring. However, in the Jetstream, the highly-repeatable wind gradient, based on the data shown above, is thought to be sufficient to support the dynamic soaring of a fast and sleek UAV.

Of course, a dynasóar UAV must avoid outright the commercial transport cruising altitude band, and it must at all altitudes have reliable collision-avoidance autonomy. Fortunately, a 1-km band for dynamic soaring is available at an altitude near 8.5 km.

"Dynasóar" ~ Dynamic soaring in the jet stream

Notional conditions
• Altitude < 9 km
• Mach ~ 0.7
• L/D ~ 25

Basic feasibility test:
w' (V/g) (L/D) sin γ cos ψ > 1

The formula above, from our "Learning From the Birds" presentation at www.HowFliesTheAlbatross.com, gives a first assessment of dynamic soaring feasibility, where the product of wind gradient, airspeed, lift-drag ratio, climb angle, and alignment cosine must exceed unity by a sufficient margin to accommodate crosswind turns and other losses. Pending forthcoming simulations, we predict that a "dynasóar" must exhibit a lift-drag ratio (L/D) exceeding 25 and must attain a maximum speed approaching 0.7 Mach number. This entails high wing loading.

One of the many extraordinary aspects of dynamic soaring is its favoritism for high weight (actually wing loading), a result of its demand for high velocity. Indeed, a given successful dynamic soaring aircraft can be rendered unsuccessful by reducing its weight below a certain threshold. The weight of the wandering albatross, in relation to its wingspan and wing area, has been optimized over 50 million years to best enable wind-profile penetration without preventing running-and-flapping takeoff from the water.

Summary

- Increased UAV range & endurance via energy extracted from atmos. motion
  - Learn from the birds

- "Regen" exploits updrafts if available
- High L/D, *low* wing loading
  - Useful option: steep descent
  - Ground-roll reverse thrust
  - Ground recharge facing upwind

- "Dynasóar" exploits the wind gradient
- High L/D, *high* wing loading
  - Climb into the wind ; descend with wind
  - Jetstream dynam. soar. simulation pending
  - Future vision: "albatross" UAV among waves
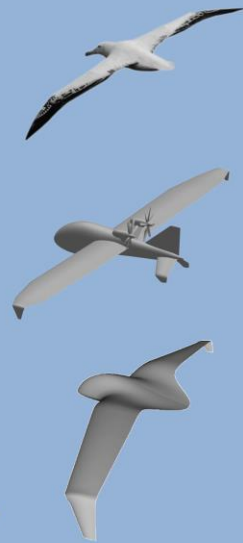
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We showed two methods of extracting energy from atmospheric motion to enhance UAV range and/or endurance. The first method is called regenerative electric flight and the second is called dynamic soaring. Both methods require high lift-to-drag ratio, but whereas the "regen" wants to float, the "dynasóar" wants to penetrate.

Finally, we naturally ask if regeneration and dynamic soaring be combined. Here we note that regeneration has the effect of increasing drag by 50 to 200%, as discussed in our forthcoming AIAA paper on the "regen" topic. However, a "pinwheeling" windprop has a much smaller drag impact, so a "regen-dynasóar" might propel itself to operational altitude, and then pinwheel its rotor(s) as it conducts dynamic soaring maneuvers. Alternatively, it could be deployed from a parent aircraft.

We predict that *regen-electric flight* will be first on the scene as we wait for safe Jetstream *autonomous dynamic soaring* technology. But we envision that in the not-too-distant future, a UAV will emulate the wandering albatross above and among the heaving waves at sea.

About the Author

Phil Barnes has a Master's Degree in Aerospace Engineering from Cal Poly Pomona. He is a Principal Engineer and 33-year veteran of air vehicle and subsystems performance analysis at Northrop Grumman, where he presently supports both mature and advanced tactical aircraft programs. Author of several SAE and AIAA technical papers, and often invited to lecture at various universities, Phil is presently leading several Northrop Grumman-sponsored university research projects including an autonomous thermal soaring demonstration, passive bleed-and-blow airfoil wind-tunnel test, aircraft parametric geometry modeling, and flight simulation with Blender 3D software.

Outside of work, Phil is the world's leading expert on dynamic soaring of the wandering albatross, and he is pioneering the science of regenerative-electric flight.