Tandem-Propeller eVTOL Aircraft for Penetrative Rescue Operations

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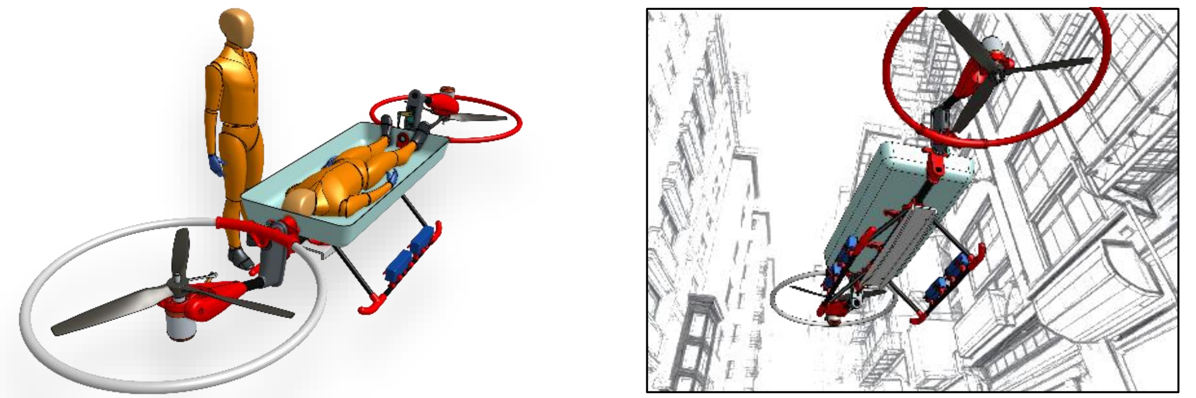
INTRODUCTION

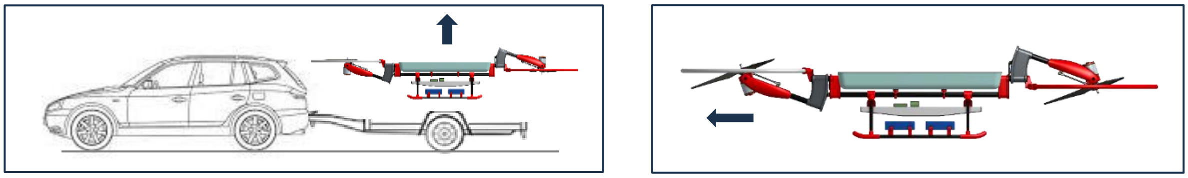
This paper introduces and describes the narrow-platform, tandem-propeller *Ariel*, an emergency-response, autonomous or remotely-piloted eVTOL air vehicle having the ability to carry the injured and supplies through dense, obstacle-laden environments. A proposed – and successfully tested (at 35%-scale) – solution to the GoAERO Prize challenge, the *Ariel* is controlled in roll by the projections of propeller gyroscopics and drag torques which arise from their instructed longitudinal tilting. Such enabling of dual-propeller hovering and flying in a tandem arrangement allows features well suited to emergency response (Fig. 1), which are described in the following.

With one propeller in front of the patient/payload and the other behind, medics and ground personnel have direct access to them without the risk of injury (Fig. 1 (a)). Because of it's narrowness yet having a relatively large total disc area for practical operations, the *Ariel* is not only suitable for flying in dense environments (Fig. 1 (b)), but is roadable (towable on a trailer) and ready to fly without assembly (Fig. 1 (c)). And, because the propellers tilt, it can remain perfectly level while flying forward, and take off and land vertically from steep inclines (Fig. 1 (d)).



(a) *Ariel* configuration permits direct access to patients/ payloads by ground personnel.

(b) Its narrow platform allows penetration of dense environments, and …



(c) … roadability, with readiness to take off on arrival.

(d) With tilting props, it remains level in horizontal flight, and takes off vertically from inclined surfaces.

Figure 1. Images (a) through (d) depict some features of *Aiel* tandem-propeller suited to emergency response.

AIRCRAFT TECHNICAL OVERVIEW

The *Ariel's* counter-rotating, fixed-pitch propellers are directly driven by variable-speed electric motors affixed to gimballed mounts, which can be independently tilted in all directions by servos to effect aircraft control, lift and propulsion. Situated between the two propellers – and roughly in the same plane as their tilt axes – is the main payload volume, which is sized to accommodate a supine or prone human patient longitudinally. Because of the control method employed by the aircraft – which is described in the next section – payloads do not have to be placed low to enable good hover stability, and medics can comfortably attend to the carried patient, and loaders can readily add and remove payload.

As on many multi-rotor eVTOL aircraft, a flight controller aboard the *Ariel* receives signals from the onboard attitude sensors, and the command signals from either the autonomous navigation system or remote human pilot. It combines them appropriately and sends the mixed signals to the tilt servos and the prop-motor speed controls to ensure stability of the aircraft at all times during commanded flight.

Configuration Reasoning

It is reasoned that an emergency-response flyer should be narrow in planform to better penetrate obstacle-laden or dense environments such as forests, urban areas, and mountainous terrain. Referring to Fig. 2, for a given vehicle width, then, lift propellers arranged in tandem will allow their maximum possible diameter, D_m, giving a dual-propeller or bi-rotor total disc area of $0.5\pi D_m^2$. In comparison, a quad-rotor's propeller diameter will be only about $0.5D_m$, and the total disc area is then $0.25\pi D_m^2$ – half the bi-rotor's. For the same take-off weight, therefore, the quad-rotor's hover endurance will be much less. And, though its empty weight might in fact be half the bi-rotor's – making its empty-weight disc loading the same – the quad-rotor must carry the same equipment and payload as the bi-rotor, and therefore its operational disc loading will always be higher and it's endurance always less.

The one obstacle normally excluding bi-rotors from eVTOL operations is their apparent lack of hover stability (in roll for a tandem bi-rotor), but, as will be shown, this has been more than overcome with the use of the propellers as gyroscopes – such that there are in fact control advantages to using bi-rotors.

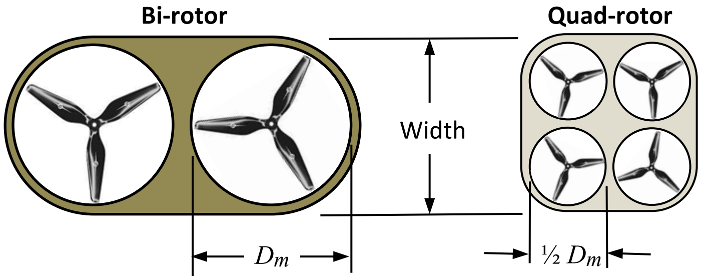


Fig. 2. Quad-rotor propeller diameter and total disc area are half that of same-width bi-rotor's.

STABILITY AND CONTROL IN HOVER

The following describes control of the tandem bi-rotor in hover, which is achieved solely by the manipulation of its counter-rotating propellers' spin rates and spin-axis directions, i.e., their tilting in any direction. A brief description of the tilting mechanisms employed in the *Ariel* is deferred to the next section.

Part of the aforementioned manipulation varies the propeller thrusts $\boldsymbol{T_{1,2}}$ (Fig. 3) for adequate pitch control (from differential magnitudes) and yaw control (from differential lateral tilting), but which is not adequate for its roll control. There are, however, two other control elements deriving from propeller tilting which, taken together, can effectively manage roll of tandem-rotor aircraft, and these are explicated in the next subsection.

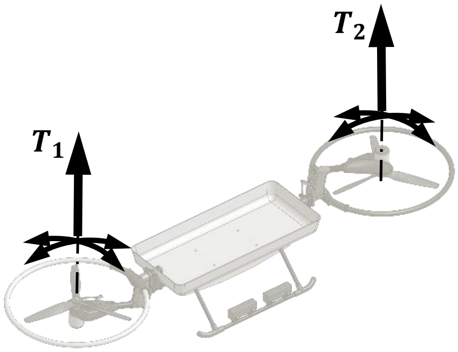


Fig. 3. Varying only aerodynamic vectors provides insufficient bi-rotor control authority in hover. Inertial moments are required as well.

Roll Control from Gyroscopics and Drag Torques: Opposed (Longitudinal) Tilting

Due to its mass moment of inertia (MMoI) about its spin axis, a propeller generates a gyroscopic moment while it is being tilted – a much greater one than that needed to perform the tilting. The moment's direction, using the right-hand rule, is perpendicular to the propeller's spin and tilt axes (or vectors), and its magnitude is the product of its MMoI (I_R), its spin speed (ω), and its tilt rate (β'). Referring to Fig. 4, roll ϕ of the Flyer is dynamically controlled by the propellers' projected (on axis x-x') gyroscopic moments $I_R\omega_i\beta'$ arising from their simultaneous longitudinal tilting at rates β' in opposite directions – commonly referred to as *opposed tilting*.

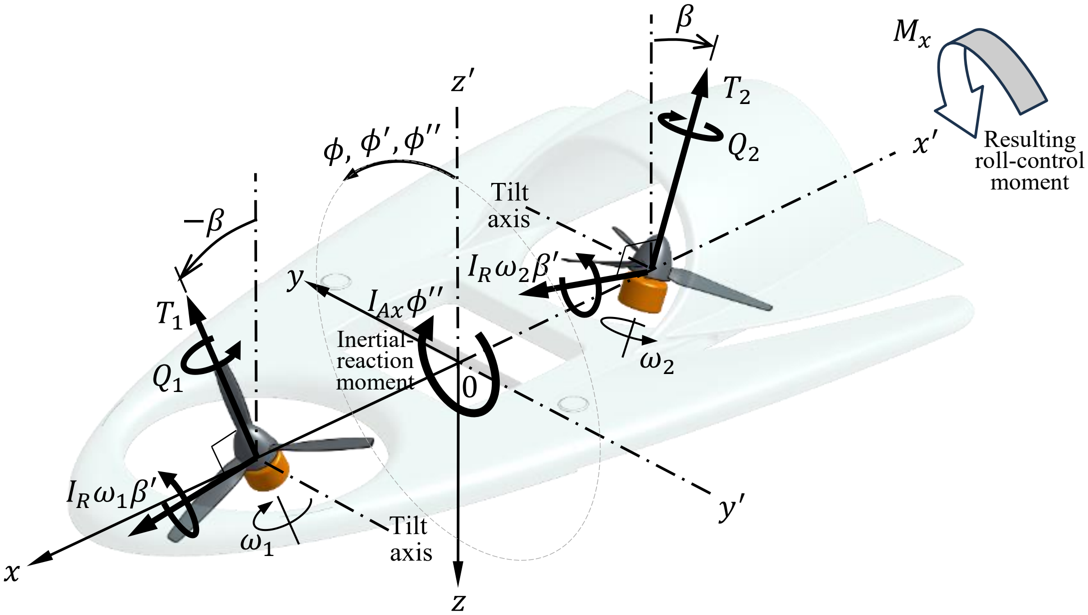


Fig 4. Schematic showing control of roll $\boldsymbol{\phi}$ using projections (on axis xx') of gyroscopic moments $\boldsymbol{I_R\omega\beta'}$ and drag torques $\boldsymbol{Q}$ from the propellers' simultaneous tilting $\boldsymbol{\beta}$ in opposite longitudinal directions (opposed tilting).

The full roll-control moment, M_x, is completed by adding the projected (again, on axis x-x') drag-torque reactions Q_i acting on the aircraft. Assuming in this simple study that the parameters ω_i and Q_i are identical for the two propellers – now referred to as parameters ω and Q respectively – gives the full roll-control moment as

$$M_x = 2I_R\omega\cos\beta\cdot\beta' + 2Q\sin\beta \cong 2(I_R\omega\beta' + Q\beta) \qquad (\beta < 15°) \qquad (1)$$

Roll Stability

The equation of motion in roll derives from equating the control moment M_x to the aircraft's inertial-reaction moment $I_{Ax}\phi''$. Assuming a simple proportional sensor-and-tilt-servo controller of the form $\beta = -k_{\phi p}\,\phi$, where $k_{\phi p}$ is its gain, the equation of motion in terms of ϕ becomes

$$\frac{I_{Ax}}{2k_{\phi p}}\phi'' + I_R\omega\phi' + Q\phi = 0 \qquad (2)$$

which is second-order, with positive, non-zero coefficients, and so represents a stable system. Note that simultaneous lateral tilting (for thrust vectoring about the center of gravity) have not been taken into account in this simple roll-control analysis. Note also that there are no external moments acting on the aircraft, which would otherwise appear on the right side of Eqn. (2).

Minimum Roll-Servo Speed

In the following, only opposed longitudinal tilting controls roll. Adding collective lateral tilting for thrust-vectoring assist will relax the requirements generally. To implement roll stability practically, the longitudinal-tilt servos' speeds should be greater than the system's undamped natural frequency, obtained from the square root of the ϕ and ϕ''-coefficient ratio in Eqn. (2):

$$f_n = \sqrt{\frac{2k_{\phi p}Q}{I_{Ax}}} \qquad (3)$$

Data from the 35%-scale prototype and estimated full-scale parameter values will be used to give values for f_n (and for I_R in Eqn. (4)) in the final paper.

Minimum Propeller Mass Moment of Inertia and Tilt-Servo Torque

Oscillations disappear when the system is critically- or over-damped (damping ratio in Eqn. (2) ≥ 1), whose desirability gives one an idea of the propellers' required spin inertias I_R:

$$I_R \geq \frac{1}{\omega}\sqrt{\frac{2I_{Ax}Q}{k_{\phi p}}} \qquad (4)$$

Offset Payloads without Thrust Vectoring

A payload of weight W_P and offset laterally by distance u can be balanced – and roll equilibrium maintained in the steady state – by the drag-torque roll components resulting from an equal and opposite longitudinal tilt β of the propellers (Fig. 5). Using the exact relation in Eqn. (1) and equating moments acting about the longitudinal axis gives

$$(M_x =) \quad 2Q\sin\beta = uW_P \qquad (5)$$

A simple static thrust-torque relation for a group of geometrically similar, fixed-pitch propellers – or of a single propeller whose speed can be varied – is

$$Q = c_q R\cdot T \qquad (6)$$

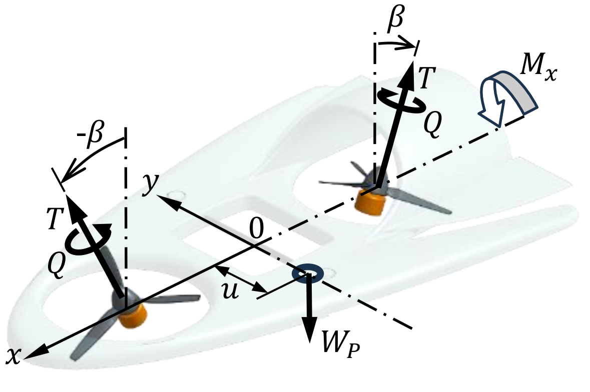


Fig. 5. Balancing laterally offset payload with drag-torque roll-components $Q\sin\beta$.

where R is the propeller tip radius, and the unitless coefficient c_q is specific to the type (= 0.2 for 3-bladed Master Airscrew propellers used by the prototype). If T_0 is the hovering thrust of each propeller before the offset payload is applied, then its hovering thrust T with the added payload is

$$T \ = \ \left(T_0 \ + \ \tfrac{1}{2}W_P\right)/cos\beta \tag{7}$$

Eliminating T in (6) with (7), and with the result eliminating Q in (5), produces the relation for tilt angle β in terms of the GoAERO payload parameters and initial conditions:

$$tan\beta \ = \ \frac{u{\cdot}W_P}{c_q R(2T_0 + W_P)} \tag{8}$$

(Values obtained from Eqn. (8) for the full-size aircraft will be tabulate in the final paper)

Collective Lateral Tilting for Thrust-Vector Roll Assist and Special Roll Ops

Another element of roll control is thrust vectoring via the propellers' simultaneous lateral tilting in the same direction (angle γ in Fig. 10) – referred to simply as collective lateral tilting. Such thrust vectoring can simply effect lateral motion of the aircraft independently of roll or, with a low aircraft center of mass relative to the propeller tilt axes (distance h in Fig. 6), supplement the roll-control moment M_x of Sect. 3.1. From Fig. 6, this thrust-vectoring roll-control moment is

$$M_{Tx} \ = \ 2hTsin\gamma - 2I_P\gamma'' \tag{9}$$

where I_P is the MMoI of the propeller pod resisting its tilting – a potentially destabilizing element which must be minimized or accounted for. In general, collective lateral tilting γ and opposed longitudinal tilting β can be combined (electronically) in several ways to provide

- increased roll, coupled with lateral motion.
- lateral motion without roll.
- stationary roll, i.e., propeller disks remain in horizontal plane

Finally, it is noted that the drag torques and gyroscopic moments from the two propellers cancel one another during collective lateral tilting.

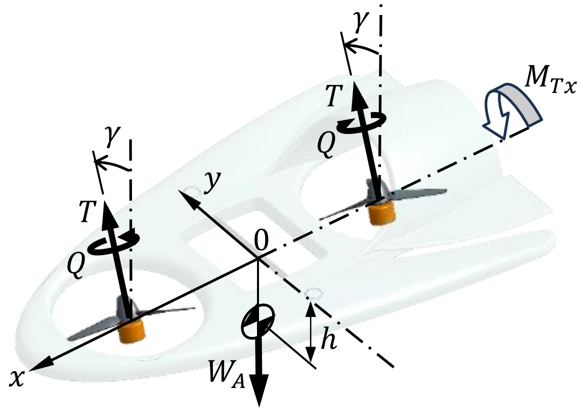


Fig. 6. Lateral thrust vectoring from collective lateral tilting for supplemental roll control, and implementing roll-less lateral motion and stationary rolls.

Pitch Stability: Help from Yaw

Achieving pitch stability with variable propeller speeds in a tandem bi-rotor is somewhat more complex than in a quad-rotor. In the latter, the propeller inertia I_R is usually as small as possible while still providing the required thrust. In a tandem bi-rotor, however, the minimum I_R is governed by Eqn. (4) and is quite large in comparison. This would normally preclude any possibility of stabilizing pitch using typical eVTOL prop-motors, but there is, however, a saving grace: a net yawing moment on the aircraft will result from the prop-motors attempting to speed one propeller up and slow the other down to pitch the aircraft. The ensuing yawing motion will be picked up by the onboard sensor and negated by the instructed differential tilting of the lateral-tilt servos. This tilting just so happens to create gyroscopic pitching moments which supplement the intended pitch, and so a large propeller I_R can be acceptable. (A more detailed analysis with data will be shown in the final paper).

PROPELLER TILTING MECHANISMS

There are many ways to mount and gimbal propellers and their motors so that they can be tilted in all directions, away from their nominally-vertical spin axes. In the method chosen here the mounting structures are largely oriented longitudinally so as to minimize frontal area and drag, and to connect directly to the structural 'spine' at the airframe centerline (please see the following Structures section). Figure 7 is a detailed side view of the *Ariel's* rear tilt-arm assembly, with the inset showing the front tilt arm to be identical in construction, only upside down (being CW and CCW, only the propellers are different). All four tilt axes of the two propellers are in the same, single horizontal plane when neutral, as signified by the dashed lines in Fig. 7 and its inset. Both propellers are able to tilt backward 20 deg. and forward 90 deg. Lateral tilting for both is +/- 25 deg. Figure 8 shows the rear propeller being typically tilted forward and laterally.

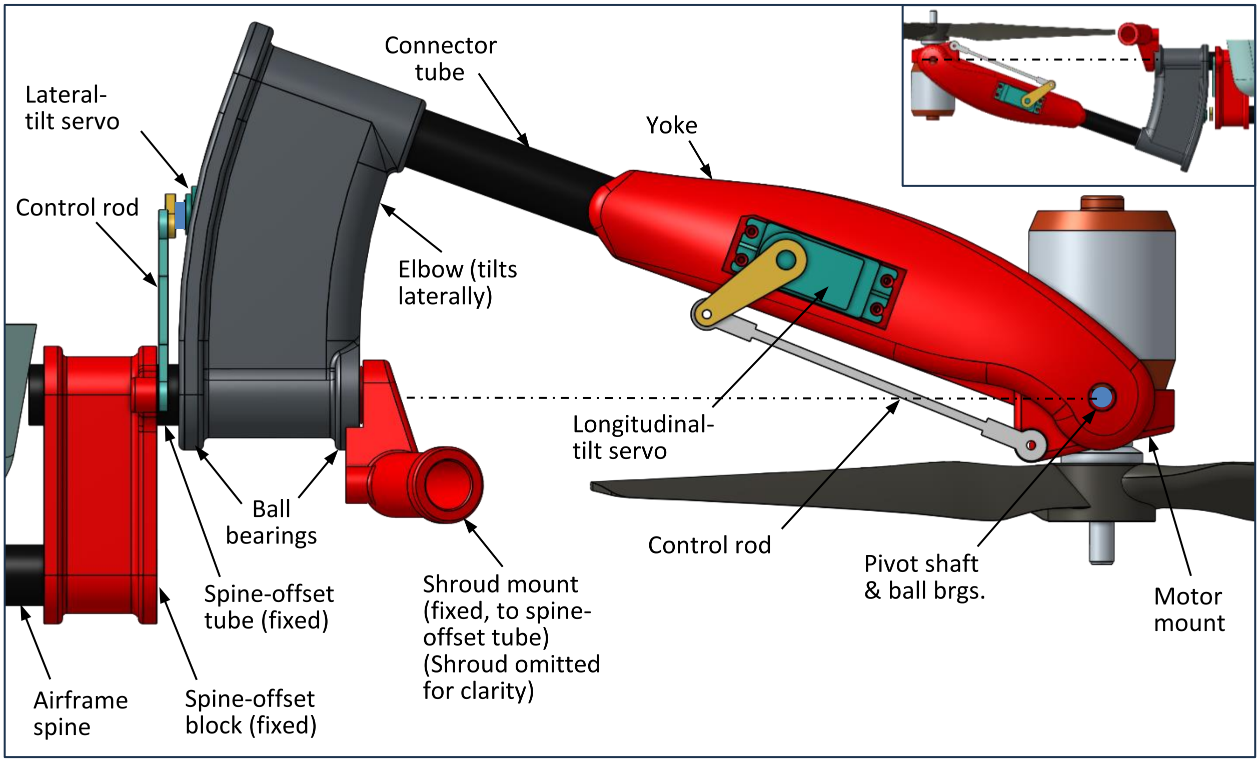


Fig. 7. Detailed side view of *Ariel* tandem-rotor's rear tilt-arm assembly mounted to (and rotating about) airframe's spine-offset tube. Inset shows front tilt-arm assembly to be identical, just upside down.

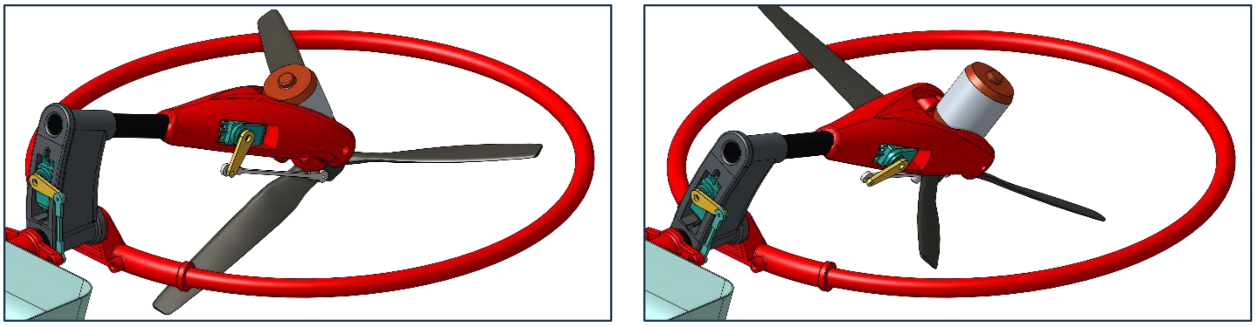


Fig. 8. *Left*: Rear propeller tilted longitudinally. *Right*: Rear propeller tilted laterally.

STRUCTURES

The airframe structure of the *Ariel* 35%-scale prototype is comprised of carbon fiber tube (black items in Fig. 9) and 3D-printed ABS fittings (red items) – all affixed together, with a central 'spine' tube as the main, connecting element. The corresponding materials for the full-scale aircraft will be drawn structural tubing and machined fittings of 7075 aluminum. The raised spine-offset tubes – about which the tilt-arm assemblies and propellers tilt – are needed for the 35%-scale prototype only. With this demonstrator model having minimal battery mass, the offsets ensure that any added payload (placed in the payload tray (Fig. 10)) does not raise the aircraft center of gravity above the propeller tilt axes; the aircraft does employ lateral tilting for thrust vectoring to supplement roll control. Without these offsets, the tilt-arm assemblies rotate directly on and about the spine.

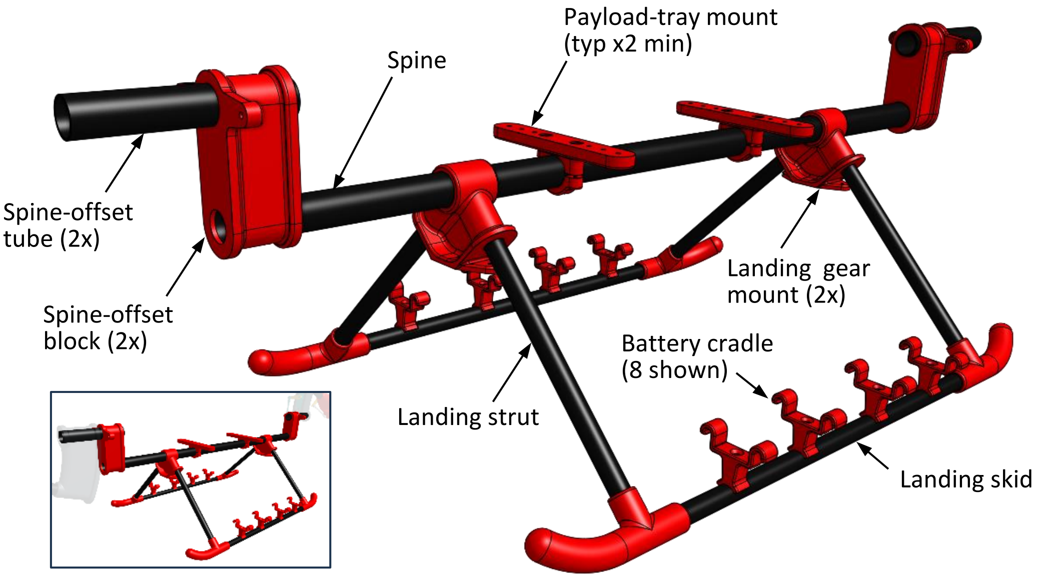


Fig. 9. Airframe structure of 35%-scale *Ariel* tandem-rotor. Carbon tubing is black and ABS fittings red.

To reduce the airframe structural requirements, the flight batteries are secured atop the landing skids (Fig. 10). This also helps keep the aircraft center of gravity low to compensate any oversized payloads, and helps provide a large MMoI about the roll axis (I_{Ax}) to reduce the servo speed requirements (Eqn. (3)). The payload and its tray are supported by the airframe spine via the dedicated mounts. The much lighter electronics table is fastened to the underside of the landing gear mounts

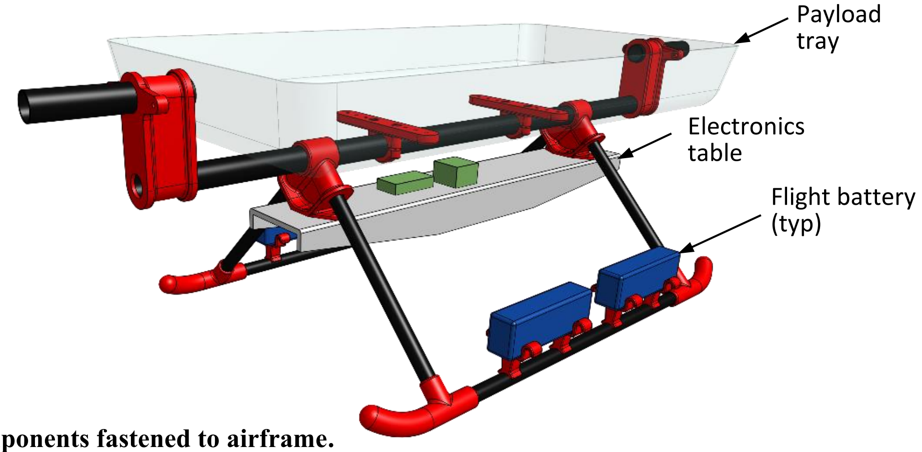


Fig. 10. Major components fastened to airframe.

PREDICTED PERFORMANCE

Hover Endurance

(Equations and their derivations will be in the final paper. Figure 11 is a hover endurance plot based on those equations for 4 ft. propellers and was submitted with the GoAERO Stage 2 Design Report. There is, however, a strong likelihood of increasing the diameters to 6 ft. to achieve better performance while keeping the aircraft roadable (less than 8.5 ft. in width), and this change will be reflected in the final report.)

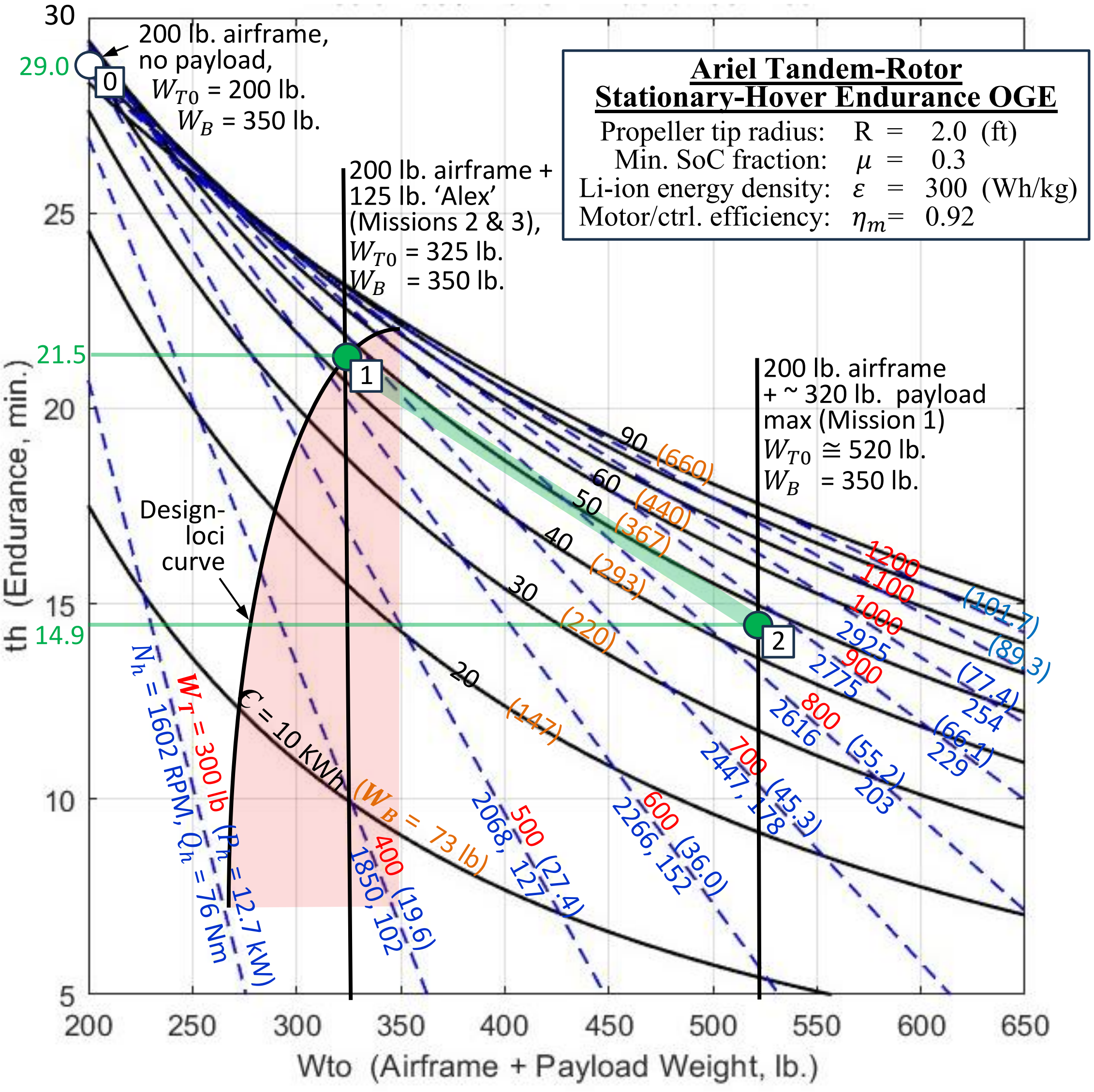


Fig. 11. Stationary-hover endurance prediction for full-size *Ariel* tandem-rotor.

TESTING TO DATE: 35%-SCALE PROTOTYPE

A 35%-scale Ariel prototype has been built and successfully tested (Fig. 1), and has passed the 5.4 lb. GoAERO Stage 2 payload requirement. Specifications for the prototype are below.

Specifications:

Overall length:	70” (1.78m)
Propellers:	16x10” or 17x9” 3-bl. Master Airscrew, (1) CW, 1 (CCW)
Prop-motors:	(2) Leopard 5065-7T 380kv, 3S-9S, 1814W max., brushless outrunner
Tilt Servos:	(4) HiTec D955TW, 0.19 sec/60º, 251 oz-in @4.8V
ESCs:	(2) Red Brick 200A, 2S-7S LiPo (7.4V-25.9V) with 5V BEC
Batteries:	(4) 3S 2200mAh LiPo in 2S2P = 6S (22.2V) 4400mAh, **1.75 lb**. total wt.
Flight Controller	Ardu Pilot Mega (APM) with Arduino 1280 + IMU
a/c weight empty:	7.75 lb.
a/c weight w/ batteries:	9.5 lb.
Max payload to date:	5.4 lb.
Max total weight to date:	14.9 lb.
Total power @ 14.9 lb:	1400 W
Endurance at @ 14.9 lb.:	4 min.

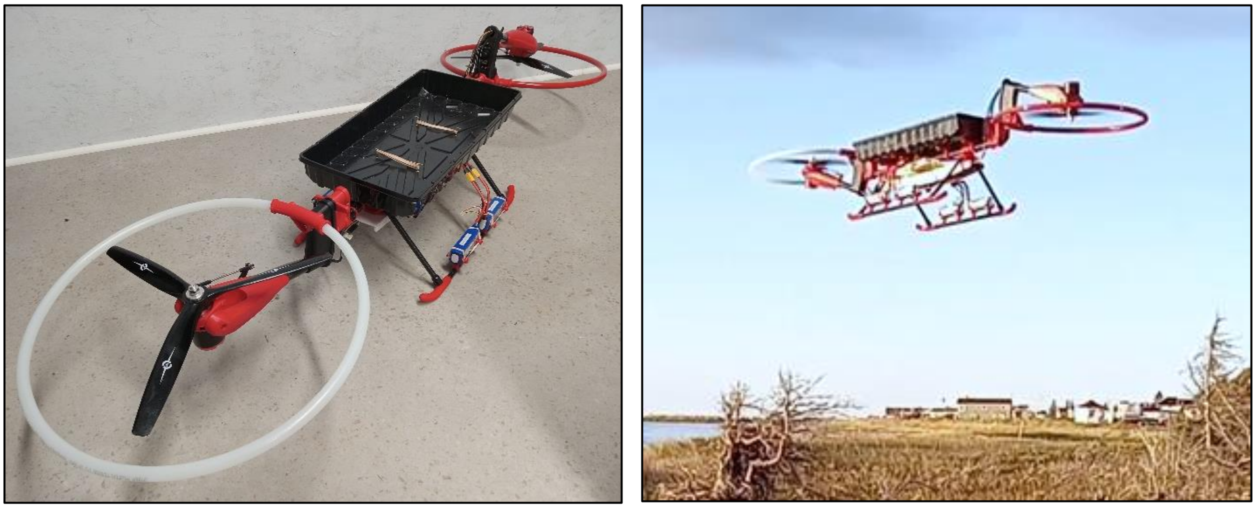
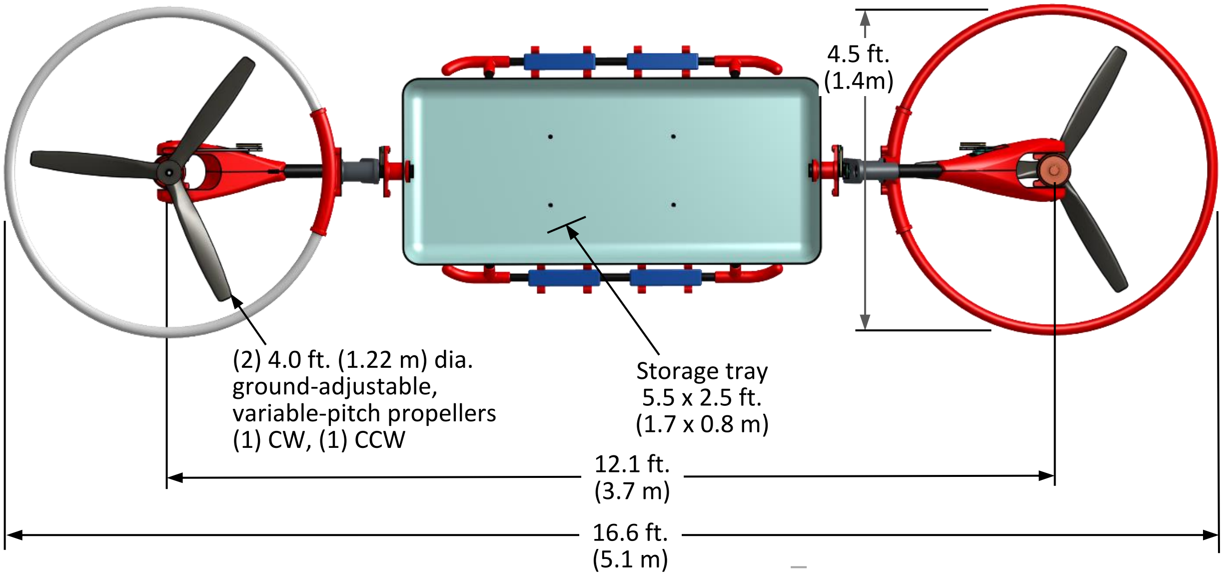


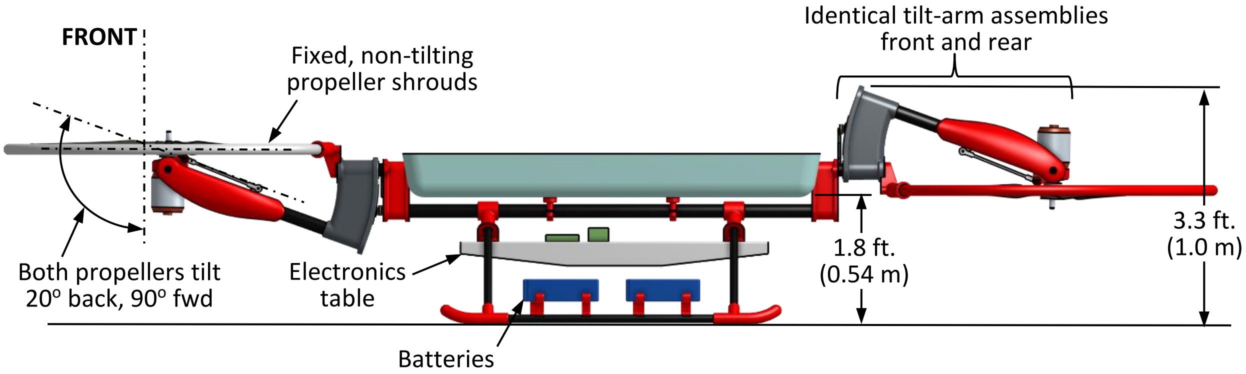
Fig. 12. ***Left*****: 35%-scale *Ariel* prototype. Right: Video still of prototype in flight.**

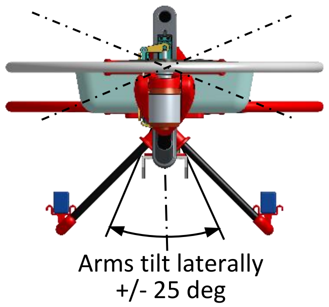
FULL-SIZE *ARIEL* SPECIFICATIONS AND DRAWINGS

Specifications for GoAero Prize, Missions 1,2 & 3

Empty wt:	200 lb (125 kg)	
Li-Ion batt.	350 lb (160 kg) @ 300 Wh/kg	(Magnix)
Disc area:	25.1 ft^2 (2.33 m^2) total	
Motors:	(2) 60 kW rated ea	(Magidrive 75, wt ~15 kg ea)
Propellers	(2) 4-ft 3bl, CW/CCW, >1.6 kg ea	(Sensenich custom)
Tilt servos:	(4) 220 Nm & 65^o/sec ea	(Lynxmotion LSS-P-M1, 4.5 kg)
Endurance:	21.5 min. hover w 125 lb 'Alex' -	Missions 2 & 3
	14.9 min. hover w 320 lb -	Maximum Mission 1 payload







Front View