Design of a Custom Flying-Wing UAV

Aerodynamics · Stability & Control · Composite Structure · Systems Integration

Tyson Ray · Aeronautical Engineering · 2026

Full engineering report — analysis, equations, code, and manufacturing

Span **1.78 m** | Area **0.65 m²** | AR **4.88** | AUW **3.3 kg** | Static margin **8 %** | Ult. load **+6 g** | Cruise **12–14 m/s**

Summary. This report documents the clean-sheet design of a 1.78 m span flying-wing UAV intended as a hands-on platform for guidance, navigation, and control (GNC) engineering. Every dimension is traceable to analysis: planform and airfoil from aerodynamic sizing, control-surface authority and centre of gravity from a vortex-lattice stability model, carbon-fibre spars from a spanwise load analysis at a +6 g ultimate factor, and a fully parametric CAD model that exports 26 print-ready parts for a Bambu H2S. The aircraft carries a complete ArduPilot avionics suite and reserves a centre-of-gravity ventral bay for a future deployable secondary vehicle. The analysis is implemented in Python (AeroSandbox, NeuralFoil, build123d, trimesh); key derivations and code are included throughout.

1 · Configuration & Design Rationale

The flying-wing layout was chosen deliberately. It maximises internal volume and minimises wetted area for a given span, but in exchange it removes the horizontal and vertical tails that normally provide pitch trim and yaw stability. Recovering those functions — through airfoil reflex, wing sweep, washout, elevons, and wingtip drag-rudders — is precisely the engineering content that makes the project valuable as a controls learning platform.

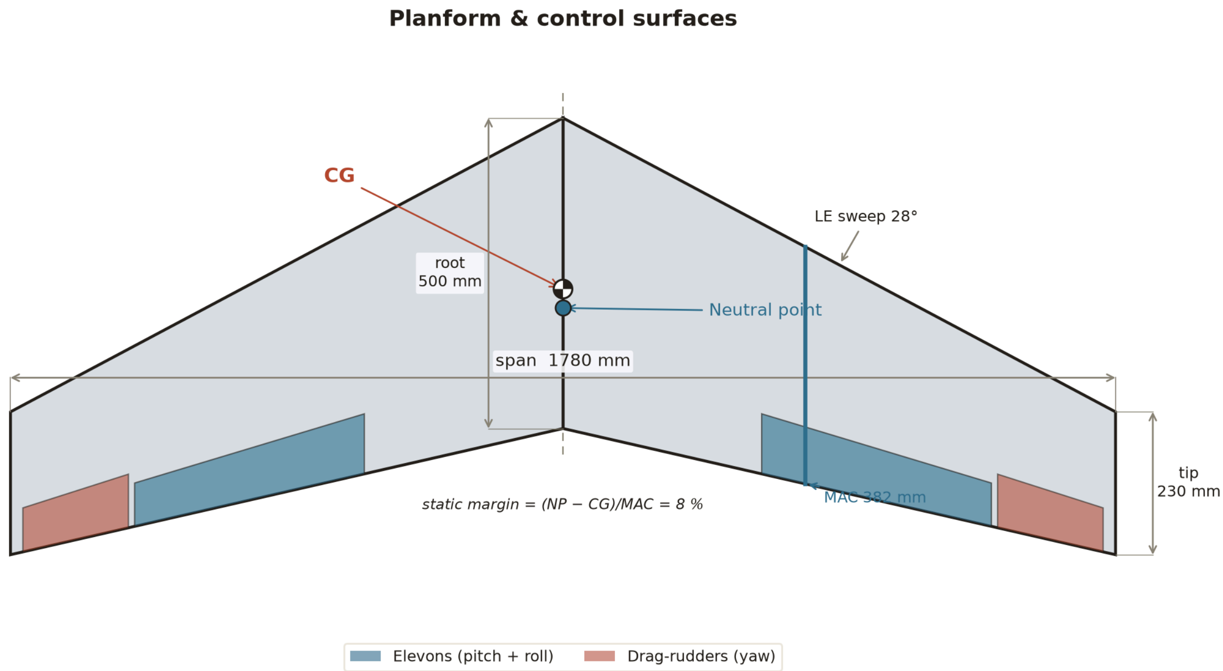

Figure 1: Planform geometry and control-surface layout. Elevons (inboard) provide combined pitch and roll; wingtip drag-rudders provide yaw. The centre of gravity sits 8 % of the mean aerodynamic chord ahead of the neutral point.

The aircraft is a two-piece removable wing mated to a central pod. The pod houses all avionics and the battery; the outer panels carry the control surfaces and bolt onto a carbon joiner tube. Major parameters are frozen in a single `design.json` file that every downstream script reads, so the geometry, the structural model, and the CAD always agree.

Geometry

Span b	1780 mm
Root / tip chord	500 / 230 mm
Taper ratio λ	0.46
Wing area S	0.650 m²
Aspect ratio AR	4.88
Mean aero chord $\bar{c}$	382 mm
LE sweep	28° (¼-chord 24.5°)
Washout	−4°
Airfoil	MH45 (reflexed)

Mass & performance

All-up weight	3.3 kg
Wing loading W/S	50.3 N/m²
Stall speed	9.0 m/s (20 mph)
Cruise envelope	12–14 m/s
Neutral point	306 mm aft of apex
CG (nominal)	275 mm (8 % SM)
Limit / ult. load	+4 g / +6 g
Printed mass	1.63 kg (ASA Aero)
Spars	16×14 + 10×8 CF tube

2 · Aerodynamic Sizing

Planform. For a straight-tapered wing the area, aspect ratio, and mean aerodynamic chord (MAC) follow from closed-form geometry:

$$S = \frac{b}{2}(c_r + c_t), \quad AR = \frac{b^2}{S}, \quad \bar{c} = \frac{2}{3}c_r\frac{1+\lambda+\lambda^2}{1+\lambda} \tag{1}$$

with taper $\lambda = c_t/c_r$. These set $S = 0.650\text{m}^2$, $AR = 4.88$, and $\bar{c} = 382$ mm. The aspect ratio is a compromise: higher AR lowers induced drag, but a flying wing's structure and the sub-2 m span limit cap it near 5.

Speeds. Level flight requires lift equal to weight, so the cruise lift coefficient and the stall speed are

$$C_L = \frac{W}{\frac{1}{2}\rho V^2 S}, \quad V_{\text{stall}} = \sqrt{\frac{2W}{\rho S C(L, \max)}}. \tag{2}$$

At the as-built weight $W/S = 50.3\text{N/m}^2$ and a swept-wing three-dimensional $C(L, \max) \approx 1.0$, giving $V_{\text{stall}} = 9.0$ m/s. This is an honest and important result: the original 20–25 mph (9–11 m/s) cruise target sits right at the stall, so the practical cruise was raised to 12–14 m/s (27–32 mph). To truly cruise at 22 mph the wing would need 35 % more area or 25 % less mass — neither compatible with the component set and span limit.

Reynolds number sets which airfoil data are valid. At cruise

$$\text{Re} = \frac{\rho V \bar{c}}{\mu} = \frac{V \bar{c}}{\nu} \approx 2.9 \times 10^5, \tag{3}$$

a low-Reynolds regime where laminar separation matters; airfoil polars are therefore evaluated with NeuralFoil rather than thin-airfoil theory.

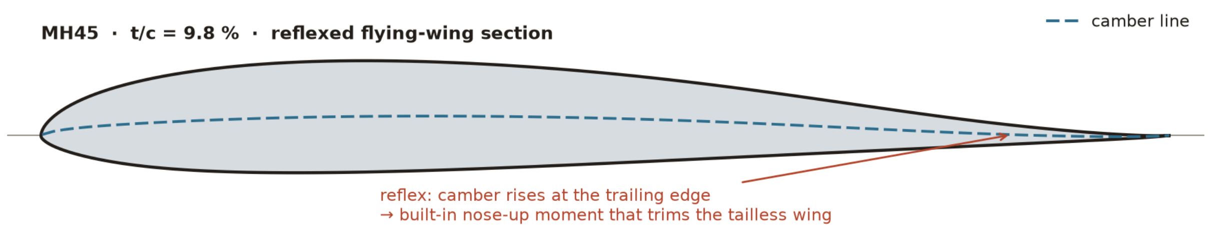

Figure 2: MH45 section. The upward-reflexed camber line near the trailing edge produces a near-zero (slightly positive) zero-lift pitching moment, which is what lets a tailless wing trim at a useful lift coefficient.

Airfoil selection. A flying wing cannot rely on a tail to balance the nose-down pitching moment of a normally-cambered section. The selection therefore screened reflexed sections on three figures of merit — zero-lift moment $C(m, 0)$, maximum lift, and drag at cruise lift — computed directly:

```
import aerosandbox as asb, numpy as np
for name in ['mh45','mh60','mh61','mh62','s5010']:
    af = asb.Airfoil(name)
    a  = af.get_aero_from_neuralfoil(alpha=np.linspace(-4,15,39),
                                     Re=290_000, mach=0.03)
    cl, cm, cd = np.array(a['CL']), np.array(a['CM']), np.array(a['CD'])
    cm0  = np.interp(0.0, cl, cm)          # zero-lift pitching moment
    cd05 = np.interp(0.5, cl, cd)          # drag at cruise CL
    print(name, af.max_thickness(), cm0, cl.max(), cd05)
```

MH45 won: a 9.8 % thick, well-behaved reflexed section with $C(m, 0) \approx -0.005$ (near zero), $C(L, \max) \approx 1.23$, and low cruise drag. The root is thickened to 13.5 % to pass the carbon joiner tube and gain internal volume, blending back to 9.8 % by mid-span.

3 · Stability & Control

Static stability. Longitudinal stability is governed by the position of the centre of gravity relative to the neutral point — the point about which the aerodynamic pitching moment does not change with angle of attack. The non-dimensional distance between them is the static margin:

$$\mathrm{SM} = \frac{x_{\mathrm{np}} - x_{\mathrm{cg}}}{\bar{c}}, \quad C(m, \alpha) = -\mathrm{SM} \cdot C(L, \alpha). \tag{4}$$

A positive static margin makes $C(m, \alpha) < 0$: pitch up, and a restoring nose-down moment results. The neutral point is found numerically by perturbing angle of attack in a vortex-lattice model and measuring how the moment coefficient tracks the lift coefficient:

$$x_{\mathrm{np}} = x_{\mathrm{ref}} - \frac{\partial C_m / \partial \alpha}{\partial C_L / \partial \alpha} \bar{c}. \tag{5}$$

```
def neutral_point(xcg_guess):
    r1 = run(alpha=2.0, xcg=xcg_guess)      # vortex-lattice solve
    r2 = run(alpha=5.0, xcg=xcg_guess)
    dCm_dCL = (r2["Cm"] - r1["Cm"]) / (r2["CL"] - r1["CL"])
    return xcg_guess - dCm_dCL * MAC        # iterate once for accuracy
```

The model places the neutral point 306 mm aft of the apex. A static margin of 8 % was chosen (inside the 5–15 % design band) and sets the target CG at 275 mm. The margin is intentionally low-but-positive: enough to be docile, small enough to keep trim drag and control effort low. A sliding battery tray lets the margin be tuned from 7 % to 11 % during flight testing.

Trim. The wing must simultaneously generate the cruise lift coefficient and zero net pitching moment. This is two equations in two unknowns — angle of attack α and elevon deflection δ_e — solved with a Newton iteration on the vortex-lattice outputs:

$$\begin{pmatrix} C_L(\alpha, \delta_e) - C(L, \mathrm{cruise}) \\ C_m(\alpha, \delta_e) \end{pmatrix} = \begin{pmatrix} 0 \\ 0 \end{pmatrix}. \tag{6}$$

The solution at 25 mph is $\alpha = 12.3°$, $\delta_e = -7.9°$ (trailing edge up). The elevons are therefore mechanically rigged 4° up at neutral so the servos operate near the centre of their travel at cruise.

Control authority. The vortex-lattice model also returns the control derivatives. Elevon power is $\partial C_m / \partial \delta_e = -0.0070$ /deg and $C(m, \alpha) = -0.34$ /rad, leaving roughly a 3× margin between available and required pitching moment even at maximum lift.

Yaw — wingtip drag-rudders. With no fin, yaw control comes from split clamshell surfaces at each tip that open above and below the wing, creating asymmetric drag. Modelling each opened pair as a flat plate of area A deflected by angle θ, the yawing moment and its coefficient are

$$N = C(d, \mathrm{plate}) \cdot q \cdot 2A \sin\theta \cdot y_{\mathrm{arm}}, \quad C_n = \frac{N}{qSb}, \tag{7}$$

giving $C_n \approx 0.023$ per side fully open — strong yaw authority for a tailless aircraft, with minimal pitch coupling because the upper and lower plates cancel in pitch (the B-2 approach).

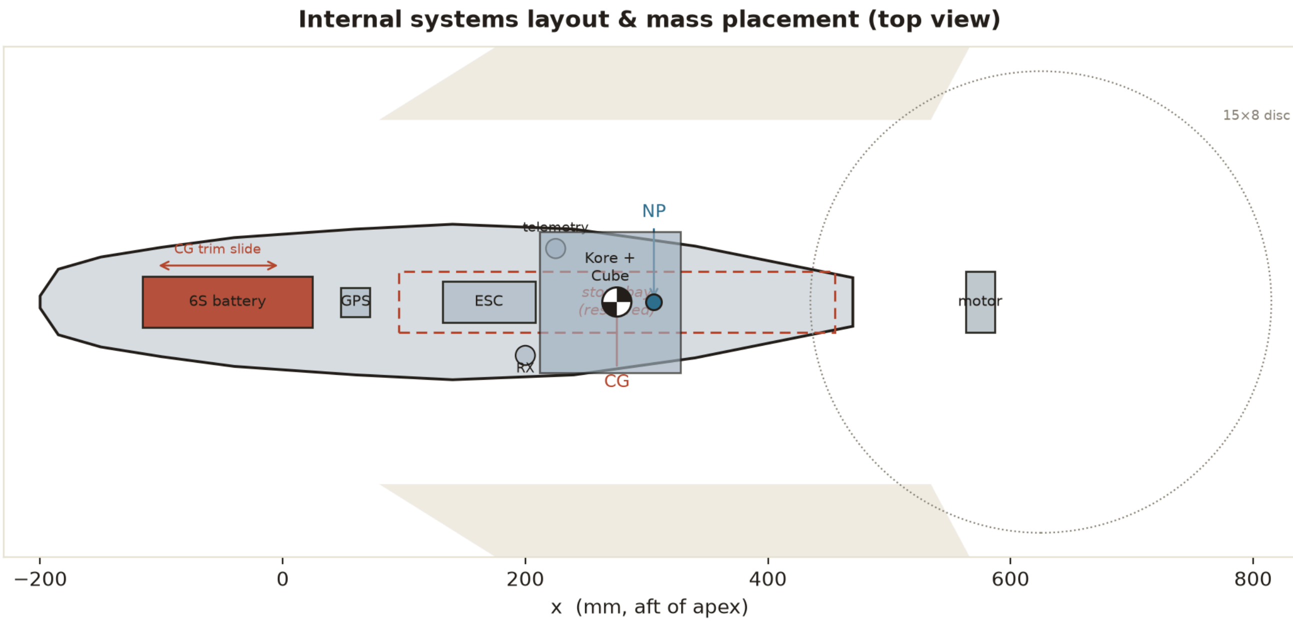

Figure 3: Internal systems layout. Heavy items (battery, motor) sit at the pod extremes; the flight controller sits on the CG. The store bay is centred on the CG so that deploying the future secondary vehicle produces no trim change.

4 · Structural Analysis

Air-load distribution. The spanwise lift is estimated by Schrenk's approximation — the average of the actual chord-proportional loading and an elliptical loading of the same total lift:

$$w(y) = \frac{1}{2}\left[\underbrace{\frac{L}{S}c(y)}_{\text{chord-proportional}} + \underbrace{\frac{4L}{\pi b}\sqrt{1-\left(2\frac{y}{b}\right)^2}}_{\text{elliptical}}\right] \tag{8}$$

evaluated at the ultimate load $L = n_{\text{ult}}W$ with $n_{\text{ult}} = 6$. Integrating inboard from the tip gives the shear and bending-moment envelopes:

$$V(y) = \int_y^{b/2} w(\eta)\,\mathrm{d}\eta, \quad M(y) = \int_y^{b/2} V(\eta)\,\mathrm{d}\eta. \tag{9}$$

```
w = 0.5 * (planform_load + elliptical_load)         # Schrenk, N/m
V = np.array([np.trapezoid(w[i:], y[i:]) for i in range(len(y))])
M = np.array([np.trapezoid(V[i:], y[i:]) for i in range(len(y))])
print("root bending moment:", M[0], "N*m")          # -> 37.7 N*m
```

The root bending moment is 37.7 N · m at ultimate. The figure below shows the full envelopes with the carbon-tube coverage bands overlaid.

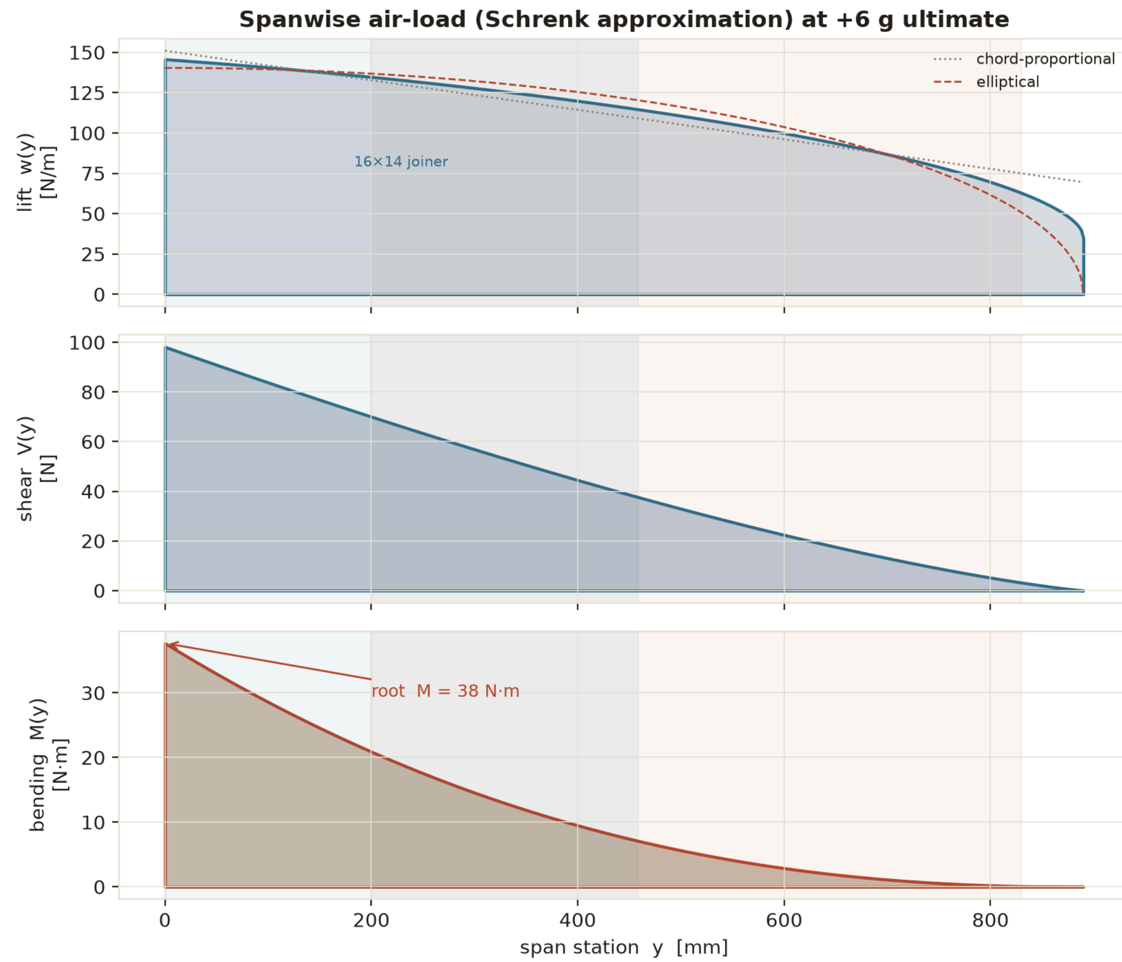

Figure 4: Schrenk air-load, shear, and bending moment along the half-span at +6 g ultimate. Shaded bands show where the 16×14 joiner and 10×8 wing-spar tubes carry load.

Spar sizing. Bending is carried by hollow carbon-fibre tubes. For a tube of outer/inner diameter D/d the second moment of area and the peak bending stress at the outer fibre are

$$I = \frac{\pi}{64}(D^4 - d^4), \quad \sigma = \frac{M \cdot D/2}{I}, \tag{10}$$

and the margin of safety against a conservative allowable $\sigma_{\text{allow}} = 350$ MPa is MS $= \sigma_{\text{allow}}/\sigma - 1$. A 16×14 mm joiner tube through the pod carries the root moment at $\sigma = 226$ MPa (MS $= +0.55$); 10×8 mm tubes carry the outer panels. The hollow section is chosen for its stiffness-to-weight: nearly all material sits far from the neutral axis where it does the most work.

Stiffness. Tip deflection under the +4 g limit load is found by integrating curvature $M/(EI)$ twice along the span; the result is 38 mm, under 5 % of the half-span — stiff enough to preserve the aerodynamic shape in maneuvers.

5 · Mass Properties & CG Closure

The centre of gravity is the mass-weighted average of every component position,

$$x_{\text{cg}} = \frac{\sum_i m_i x_i}{\sum_i m_i}. \tag{11}$$

Because the battery is both the heaviest single item and mounted on a slide, the design inverts this equation to solve for the battery position that places the CG exactly on its 8 %-margin target:

$$x_{\text{batt}} = \frac{x_{\text{cg,target}} \sum_i m_i - \sum_{i \neq \text{ batt}} m_i x_i}{m_{\text{batt}}}. \tag{12}$$

```
m_total = m_fixed + m_battery
x_batt  = (X_CG_TARGET * m_total - moment_fixed) / m_battery
#   -> battery centre at -46 mm; slide ±40 mm spans 7%–11% static margin
```

Component masses flagged as catalogue estimates (flight controller, motor, battery, propeller, harness) are to be weighed and the script re-run before the first flight; the printed-structure mass (1.63 kg) is computed from the CAD part volumes with an ASA-Aero density and infill model, closing the loop between the geometry and the mass budget.

6 · Propulsion & Thrust-Line Geometry

The pusher motor sits on a pylon above and behind the pod. A rigid propeller would force a tall pylon, placing the thrust line far above the CG; at launch speed the resulting nose-down (or nose-up) pitching couple

$$M_{\text{thrust}} = T \cdot d_{\text{cg}} \tag{13}$$

can exceed the available elevon moment, an unflyable corner. The design therefore uses a folding propeller (lower pylon) and tilts the thrust axis 7° so it passes close to the CG, driving $d_{\text{cg}} \to 0$ and decoupling throttle from pitch. The folding blades also fold flat for belly landings, eliminating prop strikes.

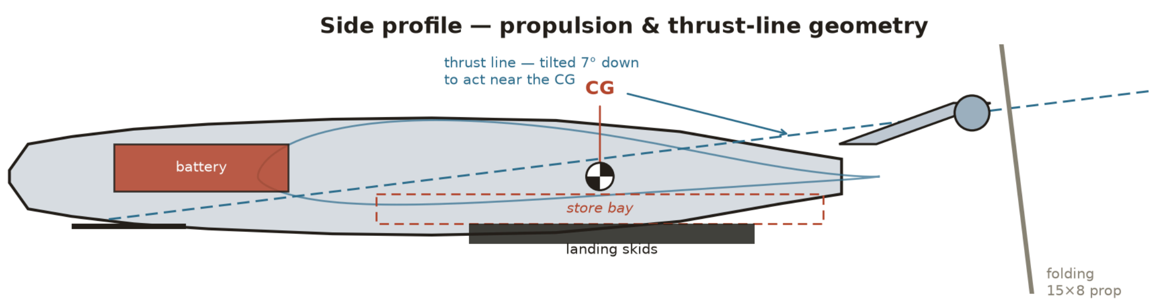

Figure 5: Side profile. The thrust line is tilted to act through the CG; the folding propeller allows a low pylon and a clean belly landing on the printed skids.

A note on power: the 500 Kv motor on 6S with a 15×8 propeller computes to roughly 1.8 kW and 80 A at full throttle — at the ESC's rating. Cruise needs only 15–20 % of this, so the powertrain is intentionally over-provisioned for climb and vertical performance, with a throttle cap enforced in firmware to protect the ESC.

7 · Manufacturing & Validation

The airframe prints on a Bambu H2S (340 × 320 × 340 mm). The wing is split spanwise into segments that each fit the bed, joined over the carbon tubes; the root segment is additionally split chordwise because its 500 mm chord exceeds the bed diagonally. Every exported part is checked automatically for water- tightness and print-fit before it is accepted:

```
import trimesh
m = trimesh.load(stl_path)
assert m.is_watertight                            # closed, printable solid
ext = sorted(m.extents)                           # bounding box, any orientation
assert ext[0] <= 340 and ext[1] <= 320 and ext[2] <= 340
mass = (m.area*wall + m.volume*infill) * RHO_ASA_AERO   # mass model
```

All 26 parts pass: watertight, within the build volume (some rotated diagonally on the bed), and totalling 1.63 kg of ASA Aero — a foaming, UV-stable filament chosen for its low density and outdoor durability.

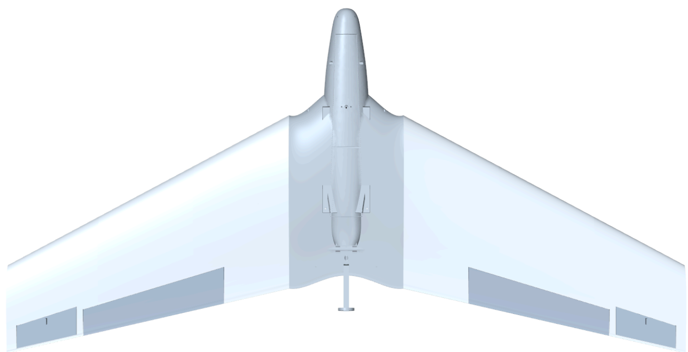

Figure 6: Rendered assembly (underside) showing the printed segments, control surfaces, motor pylon, and the centred ventral store bay.

8 · Flight-Test Plan & GNC Value

The aircraft is flown in stages that double as a controls experiment:

1. **Bench & range checks** — control-surface directions, failsafes, compass and accelerometer calibration.
2. **Powered maiden in stabilised mode** — battery forward (≈11 % margin), drag-rudder yaw mixing disabled, firm hand launch.
3. **Envelope expansion** — characterise the low-speed buffet, trim the cruise, and let the autopilot learn the standing elevon trim.
4. **Yaw & autotune** — progressively enable the drag-rudders, then run ArduPilot AutoTune to identify the pitch and roll rate loops.
5. **CG migration** — move the battery aft toward 8 % margin, re-trimming at each step.

The payoff for GNC practice is the final comparison: the rate and stability derivatives **measured** in flight (and identified by AutoTune) against the values this report **predicted** from the vortex-lattice model. Reconciling predicted and measured dynamics — then tuning the controller around them — is the core daily work of a guidance, navigation, and control engineer, and this airframe was built specifically to practise it.

Analysis stack: Python · AeroSandbox (vortex-lattice) · NeuralFoil (airfoil polars) · build123d (parametric CAD) · trimesh (mesh validation). All figures generated programmatically from the design model; numbers in this report are emitted directly by the analysis scripts.