A Discussion on Automatic Take-off and Landing Approaches for Airborne Wind Energy Systems

AIRBORNE WIND ENERGY CONFERENCE 2024

24–26 April, Madrid

Sérgio Vinha, Gabriel M. Fernandes, Fernando A.C.C Fontes

SYSTEC–ISR, Faculdade de Engenharia, Universidade do Porto, Portugal

svinha@fe.up.pt , gabriel.fernandes@upwind.pt , faf@fe.up.pt

Abstract

A scalable, robust, and cost-effective airborne wind energy system (AWES) should rely on a completely autonomous operation, including a fully automatic launch and landing scheme.

The take-off and landing (TOL) schemes are significantly different for AWES with soft wings and with rigid wings, and in each of these systems a consensual specific scheme is yet to be established (see e.g. [1]).

In this work, we study different automatic TOL (ATOL) techniques for fixed-wing aircraft, with self-propulsion, to be used in ground-gen AWES:

VTOL: Vertical TOL like usual multicopters;
HTOL: Linear-Horizontal TOL as a common airplane, but with the tether fixed to the fuselage;
CTOL: Circular TOL with the tether fixed to an anchorage point in the center of the circular motion and to the wing of the aircraft.

For each scheme, we evaluate a range of criteria:

- Peak on-board power;
- Consequent additional on–board mass;
- Ground area needed;
- Facility to relaunch;
- Possibility to reuse existing technology.

These characteristics are examined for various aircraft dimensions, with scaling factor indexed by the wingspan.

Evaluation of the ATOL Techniques

For a fair comparison, we established several requisites for the 3 techniques:

- The system needs to take-off in all wind directions;
- The aircraft employs propellers that are used for take-off;
- The ground-station does not assist the kite in the take-off.

In the case of the CTOL system, we have used as basis a small–scale prototype developed within the UPWIND project [2,3].

Lift coefficient	c_l	= 1
Drag coefficient	c_d	= 0.1
Climbing rate	c_r	= 0.1
Propeller efficiency	η	= 0.7
Target height	h	= 100 [m]
Energy density of on-board batteries	E_batt	= 720000 [J/kg]
Power density of on-board motors	E_mot	= 2500 [W/kg]

Design parameters considered for the take-off evaluation of the different methodologies for a kite with mass (m) and wingspan (b).

Peak On-board Power – P_ob Additional On-board Mass – Δm

VTOL: The kite needs to lift its own weight, with a desired climb velocity V_c = 1 ms^{-1}. This imposes a specific on-board power and additional on-board mass:

$$P_{\mathrm{ob}\bullet} = \frac{m+\Delta m}{\eta}\left[\sqrt{\frac{(m+\Delta m)g}{2\rho A_\mathrm{prop}}+\frac{V_\mathrm{c}^2}{4}}+\frac{V_\mathrm{c}}{2}\right]$$

$$\Delta m_\bullet = P_\mathrm{ob}\left[\frac{h}{V_\mathrm{c}E_\mathrm{batt}+\frac{1}{E_\mathrm{mot}}}\right]$$

HTOL/CTOL: the kite needs to follow a desired forward velocity (that depends on the mass of the kite) and climb velocity (defined by the climbing rate), while in the air, which are similar for both techniques:

$$P_{\mathrm{ob}\ominus,\odot} = \frac{(m+\Delta m)g\frac{c_\mathrm{d}}{c_\mathrm{l}}+c_\mathrm{r}}{\eta}\left[\sqrt{\frac{F_T g}{2\rho A_\mathrm{prop}}+\frac{V_\mathrm{fwd}^2}{4}}+\frac{V_\mathrm{fwd}}{2}\right]$$

$$\Delta m_{\ominus,\odot} = P_\mathrm{ob}\left[\frac{h}{V_c E_\mathrm{batt}+\frac{1}{E_\mathrm{mot}}}\right]$$

These criteria were derived from [1], and are displayed here for comparison.

Required Ground Area for Take-off

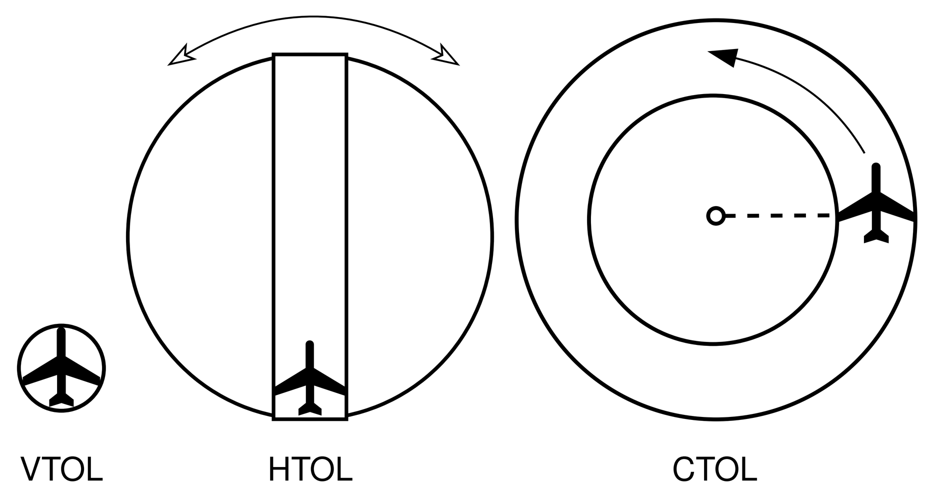
VTOL: The vertical take-off can be performed with all possible angles between the wing and the wind speed direction. The area considered is a circle with radius of half the kite's wingspan.

HTOL: The on-board power is also used to accelerate the kite on ground. The kite needs to reach a certain velocity (v) that creates enough lift [1], dependent on the acceleration (a). The length (L) required to take-off is:

$$L=\frac{v^2}{2a}=\frac{v^3\,(m+\Delta m)}{2P_{\mathrm{ob}\ominus}} \quad \text{with} \quad a=\frac{P_{\mathrm{ob}\ominus}}{v\,(m+\Delta m)}$$

For safety precautions, we considered a runway with twice the length needed for take-off, that can rotate 360°, suitable for all wind directions. The land occupied is a circle with diameter (L).

CTOL: The land occupied is the area of an outer circle with radius $4.5b$ minus the area of a inner circle with radius $3.5b$. These radius dimensions were defined as in [2].



Schematic of the area required for take-off in each technique.

The area occupied (A) for each scheme is as follows:

VTOL: $A_\bullet = \frac{b^2}{4}\pi$
HTOL: $A_\ominus = L^2\pi$
CTOL: $A_\odot = \left[(4.5d)^2-(3.5d)^2\right]\pi$

Scaling of the Kite Mass

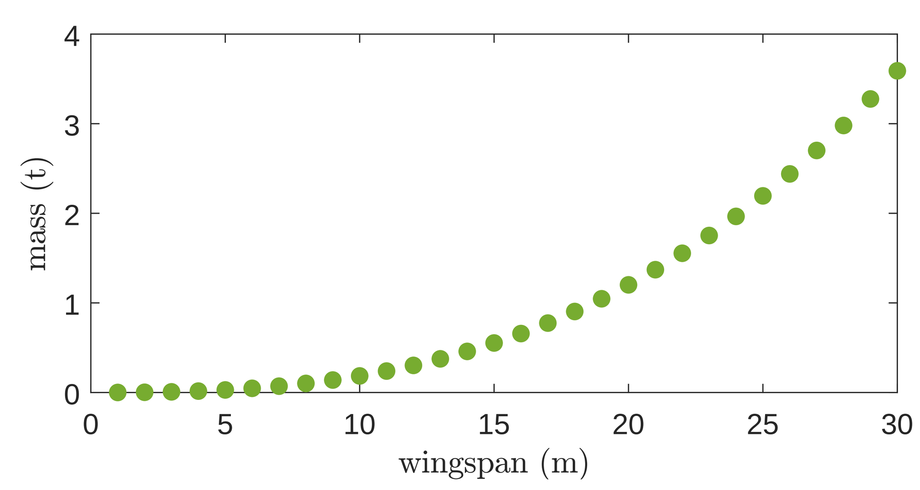
According to [4], the aircraft mass m can be scaled following simplified geometric scaling laws relative to wingspan b.

$$m_\mathrm{scaled} = m_\mathrm{ref}\left[\frac{b_\mathrm{scaled}}{b_\mathrm{ref}}\right]^k$$

We selected the Ampyx AP2 reference model [5], with:

$$m_\mathrm{ref} = 36.8\,\mathrm{kg}, \quad b_\mathrm{ref} = 5.5\,\mathrm{m} \quad \text{and} \quad k = 2.7,$$

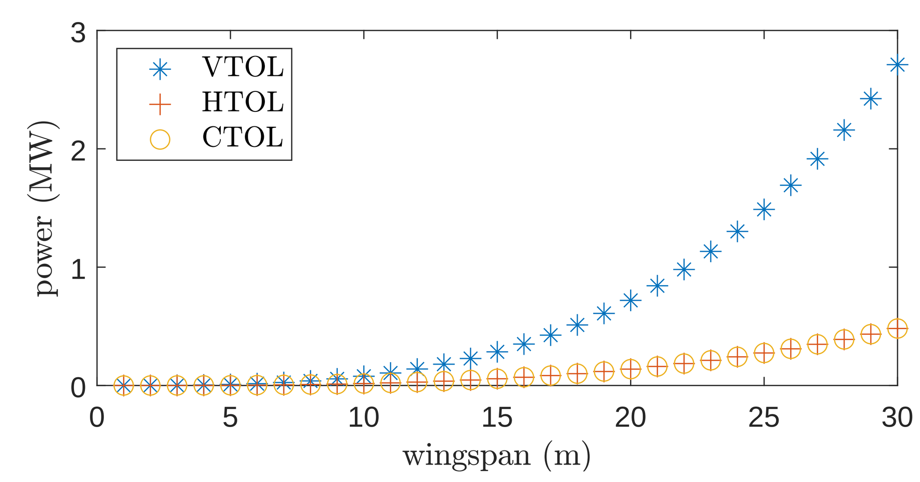
for positive scaling effects and weight savings with size.



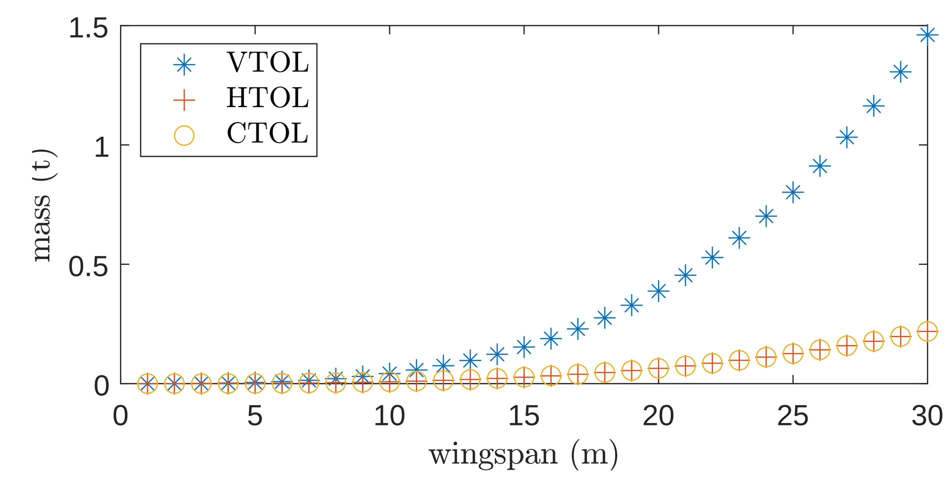
Scaled mass as a function of the wingspan.

Evolution of the Criteria

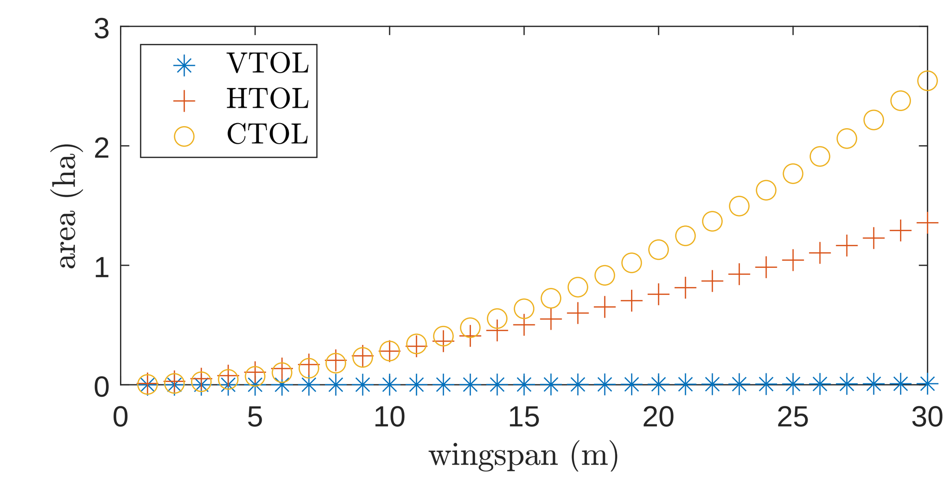
Using the scaling equation, we plotted the evolution of the different criteria for a range of wingspan [1;30] meters.



On–board peak power as a function of the wingspan for each scheme.



Additional on–board mass as a function of the wingspan for each scheme.



Area required for take-off as a function of the wingspan for each scheme.

Discussion

VTOL:

- 👍 Less ground area needed;
- 👍 Facility to re-launch;
- 👍 Easy to re-use existing technology (e.g. from drones);
- 👎 Peak power and additional mass (only useful if a fly-gen system is used).

HTOL:

- 👍 Easy to re-use existing technology (e.g. from aircraft);
- 👍 Low peak power and additional mass for climbing.
- 👎 Medium ground area needed (the take-off speed, capable of generating sufficient lift, has to be attained within the runway length);
- 👎 Difficult to re-launch (the aircraft needs to rotate to be pointed to the runway after landing).

CTOL:

- 👍 Facility to re-launch (infinite runway);
- 👍 Low peak power and additional mass for climbing;
- 👎 Considerable ground area required for large wingspans;
- 👎 Difficult to re-use existing technology (requires further research on the topic).

	VTOL	HTOL	CTOL
On-board power	-	+	+
Additional mass	-	+	+
Ground area	++	-	-
Easy to restart	+	-	++

Evaluation in several aspects for each methodology.

References

[1] L. Fagiano and S. Schnez. *On the take-off of airborne wind energy systems based on rigid wings.* Renewable Energy, vol. 107, pp. 473–488, July 2017.
[2] S. Vinha, G. M. Fernandes, H. T. Nguyen, M.C.R.M. Fernandes and F.A.C.C. Fontes. *Automatic Circular Take-off and Landing of Tethered Motorized Aircraft.* In Proceedings of ECC24 - European Control Conference 2024. Available: http://arxiv.org/abs/2402.10603.
[3] G. M. Fernandes. *Take-off and Landing of Autonomous Flying Wings in Airborne Wind Energy Systems.* MSc thesis, U. Porto, July 2023. Available: https://repositorio-aberto.up.pt/handle/10216/152670.
[4] M. Sommerfeld, M. Dörenkämper, J. De Schutter and C. Crawford. *Scaling effects of fixed-wing ground-generation airborne wind energy systems.* Wind Energy Science, 7(5), 1847-1868. 2022.
[5] Giovanni Licitra. *Identification and optimization of an airborne wind energy system.* PhD Thesis. Universität Freiburg, 2018.

Acknowledgements

We acknowledge the support of FCT/MCTES-PIDDAC, through projects KEFCODE, DOI:10.54499/2022.02320.PTDC, and UPWIND-ATOL, DOI:10.54499/2022.02801.PTDC and 2021.06313.BD.