Executive Summary Report (ESR)

For OSIP Early Technology Development activity

Project: Bio-Inspired Morphing Wing UAV for deployment from HAPS and Orbit (BIOUAS-HALO-21)

ESA Contract N.: 4000134261/21/NL/GLC/ov

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ESA STUDY CONTRACT REPORT

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ESA CONTRACT No 4000134261/21/NL/GLC/ov	SUBJECT Executive Summary Report (ESR)		CONTRACTOR Stellar Advanced Concepts Ltd
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ABSTRACT:

This Executive Summary report is part of an OSIP Early Technology Development activity.

It represents the summation of the Design, Development and Testing of a prototype novel Unmanned Air Vehicle (UAV) demonstrator with a bio-inspired wing for spanwise folding and a Launch System for a high-altitude deployment.

Project entitled: Bio-Inspired Morphing Wing UAV for deployment from HAPS and Orbit (BIOUAS-HALO-21)

The purpose of the report is for formal summary of the activities, conclusions and recommendations of the project, for ESA review and public dissemination.

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1. Abbreviations and Nomenclature

Abbreviation	Meaning
AFRL	Air Force Research Laboratory
AoA	Angle of Attack
BIOUAS	Bio-inspired Unmanned Aerial System
CoM	Center of mass
COTS	Commercial off the shelf
CPNI	Centre for the Protection of National Infrastructure
C-UAS	Counter Unmanned Aerial System
EDL	Entry, Decent and Landing
ESA ACT	European Space Agency - Advanced Concepts Team
ESCD	Emerging Security Challenges Division
HALO	High Altitude Low Opening
HAPS	High Altitude Platform System
JSaRC	Joint Security and Resilience Centre
NATO	North Atlantic Treaty Organisation
OSIP	The Open Space Innovation Platform
PLA	Polylactic acid 3D Printing material
PLATFORM	An unmanned vehicle intended for additional payloads
SAR	Search and Rescue
STANAG	Standardization Agreement, NATO standardization document
Stellar AC	Stellar Advanced Concepts Ltd
SWaP-C	Size, Weight, Power and Cost design criteria
TRL	Technology Readiness Level
UAS	Unmanned Aerial System
UAV	Unmanned Aerial Vehicle
XFLR5	An analysis tool for airfoils, wings and planes operating at low Reynolds Numbers

2. Introduction

Humanity has long sought to understand how birds manoeuvre with agility and grace. Fundamental to this is ability is **spanwise, out-of-plane and asymmetric wing morphing.** This applies to all tetrapod flying animals, the birds, bats and pterosaurs. In birds, this aspect was studied by Leonardo di ser Piero da Vinci as shown below by a compilation of three margin sketches [1]. The goal of this project was to progress the state-of-the-art in this underdeveloped aspect of wing technology towards a flight capable demonstrator.

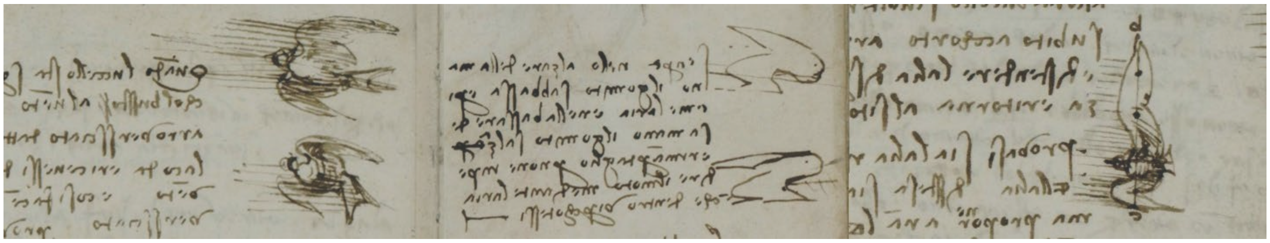


Figure 1 – Compilation of sketches from Leonardo's Codex on the Flight of Birds, 1505-6, Royal Library of Turin [1]

The purpose of this Executive Summary is to provide an overview of the activities that led to the successful implementation of this project titled, *Bio-Inspired Morphing Wing UAV for deployment from HAPS and Orbit*, an **OSIP Early Technology Demonstrator project focusing on advancing morphing wing technology**. To concord with existing acronyms in relevant technology domains, the compound acronym BIOUAS-HALO-21 was used, derived from Bio-inspired Unmanned Aerial System for High Altitude, Low Opening, with kick-off year being 2021. It was conducted in line with ESA ACT's conception of bio-inspired design [2].

2.1 Applicable documents

The following table specifies the applicable documents to better understand the technology development focus of the project: a morphing wing capable of span extension and out-of-plane folding, inspired from academic studies of the peregrine falcon flight control and morphology. See References for full citations.

Ref.	Title	Publisher	Date
[AD.1]	*ESA ACT: Biomimetics - A new approach to space system design*	*European Space Agency*	*2006*
[AD.2]	*Aerodynamics of the Cupped Wings during Peregrine Falcon's Diving Flight*	*Open Journal of Fluid Dynamics*	*2014*
[AD.3]	*Vortices enable the complex aerobatics of peregrine falcons*	*Nature -Communications Biology*	*2018*
[AD.4]	*Peregrine Falcon's Dive: Pullout Maneuver and Flight Control Through Wing Morphing*	*AIAA Journal*	*2021*
[AD.5]	*A review of avian-inspired morphing for UAV flight control*	*Progress in Aerospace Sciences*	*2022*

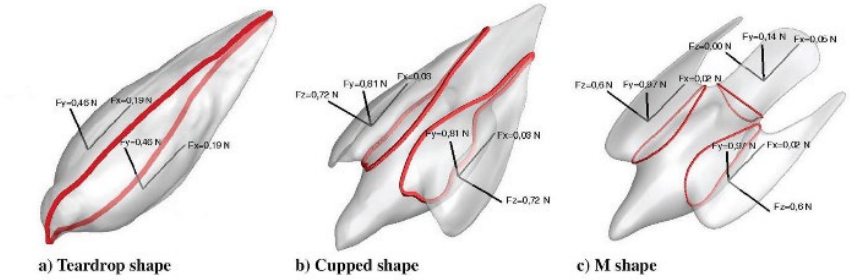
2.2 Reference documents

The following project documents, although not part of this document, amplify or clarify its contents and were completed as part of the project's Design Phase, Development Phase, and Testing Phase.

Ref.	Doc ID	Title	Issue	Date
[D1]	*BIOUAS-HALO-21-TR – 01*	*Technical report WP1*	*2*	*17/11/2021*
	BIOUAS-HALO-21-TR – 02	*Technical report WP2*	*2*	*17/11/2021*
[D2]	*BIOUAS-HALO-21-TR – 03*	*Technical report WP3*	*1*	*23/06/2021*
	BIOUAS-HALO-21-TR – 04	*Technical report WP4*	*1*	*23/06/2021*
[D3]	*BIOUAS-HALO-21-TR – 05*	*Test design report WP5*	*1*	*14/11/2022*
	BIOUAS-HALO-21-TR – 06	*Final test report WP6*	*1*	*14/11/2022*

2.2 Project Background Overview

The project demonstrates a proof-of-concept of a next generation bio-inspired morphing wing **inspired by academic research of the Peregrine Falcon morphology** ([3], [4], [5], [6]). Asymmetric span morphing has previously been demonstrated for UAV roll control via in-plane partial span change [7]. This design has full bird-like span change and a unique out-of-plane modality. This offers novel drag reduction characteristics when made to form an airflow channel in conjunction with a fixed surface such as the fuselage, in "cupped wing" flight [4]. It affords the stowage envelope of avian-like wing folding for semi-autonomous tube-launch deployment. **This project developed a prototype Unmanned Aerial Vehicle (UAV) and Launch System for applications utilising high-altitude deployment;** from a plane, balloon, HAPS or after re-entry from Orbit after a deceleration phase. After a descent the UAV can loiter at altitude for Earth Observation (EO) and descend again at speed. Applications include Maritime Search and Rescue (SAR), survey of natural disaster zones, planetary exploration and UAV operations in high winds.



a) Teardrop shape b) Cupped shape c) M shape

Figure 2 – Peregrine wing folding morphology with aerodynamic forces from academic study, Image taken from [6]

3. Bio-inspired UAV and Launch System design

3.1 System overview

In the final flight demonstrator design (Figure 3), wing extension and contraction is driven directly by an electro-mechanical rotational servo at the wing root, with an additional servo inside the fuselage providing dihedral actuation. As in Figure 2, It can morph into M shape and fold ~90 degrees downwards against the fuselage **to meet the stowage volume requirements of a NATO Sonobuoy Dispenser STANAG** launch tube.

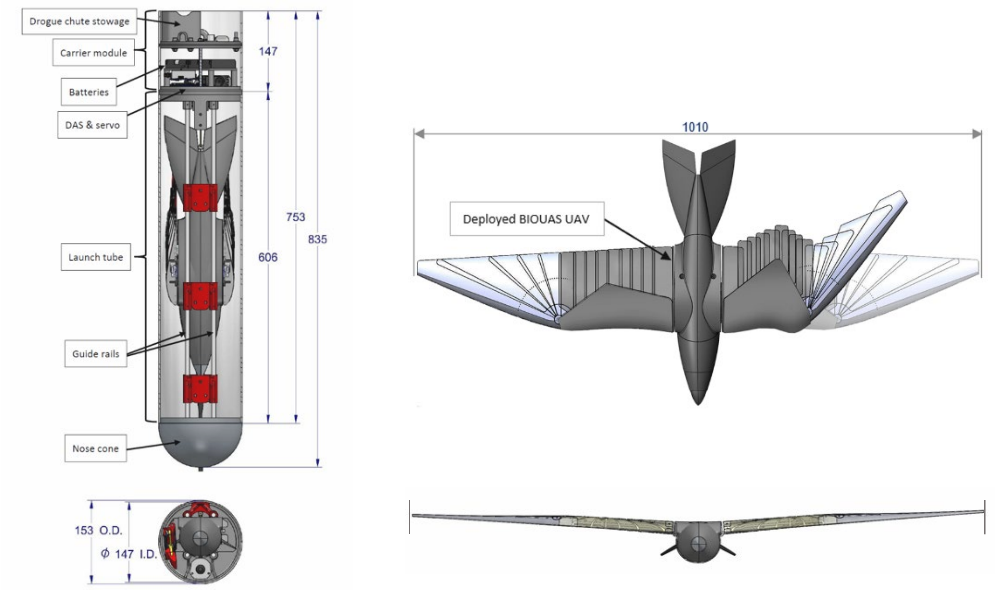


Figure 3 – Final design schematic of UAV and Launch System, (left) UAV stowed, (right) after deployment

The demonstrator can descend with wings in the stowed position for lowest drag, in teardrop shape, and fly in intermediate wing states. The **wing construction consists of a main linkage, an upper and lower set of synthetic feathers conforming to a custom airfoil, with an elastomeric or telescoping inner half of the leading edge** (a synthetic propatagium). It has points of rotation about the shoulder, elbow and wrist which also advances state-of-the-art based on a recent academic review (compare Figure 4 & 5).

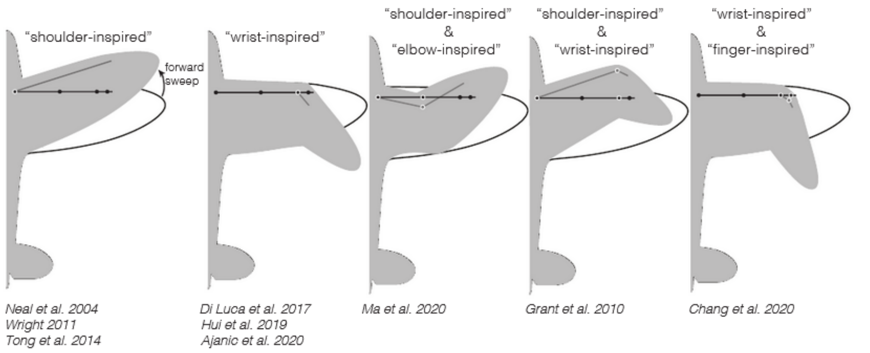


Figure 4 - Simplified renditions of the different UAV implementations of avian-inspired wing sweep morphing. Note that the wing or fuselage shapes are not necessarily representative of the individual UAV designs. Image taken from [7]

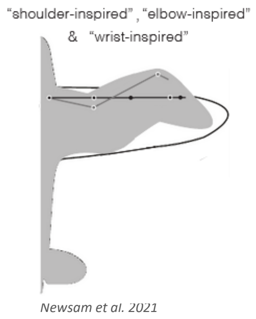


Figure 5 – Simplified rendition of Project Demonstrator

3.2 Main wing linkage range of motion

The basis for the project was Stellar AC's TRL 4 Lab Demonstrator of a viable four-bar linkage mechanism and compatible non-linear telescoping surface approach. Both subsystems are similar to birds' arm and feather structures and development **targeted and achieved at least a 5:1 extension ratio from compressed to fully extended span as an integrated wing**. These were developed and integrated together, with COTS RC plane components and a bespoke fuselage. The moving Centre of Mass (COM) of the morphing wing was analysed by CAD analysis tools (Solidworks) and checked against physical compressible wing model prototypes.

Figure 6 – Range of main load-bearing mechanism with transition states used in flow testing

3.3 Airfoil design and optimisation

A specialized airfoil, named RVB-5, was designed and optimized using XFLR5 with the goals to yield the required lift (L) at the lowest coefficient-of-lift (Cl), and at the lowest angle-of-attack (AoA) as possible while maintaining the thinnest profile toward the trailing edge of the airfoil, which is an essential factor in allowing simplicity in manufacturing and allowing the feathers to overlap when folding.

The airfoil cross-section transitioned toward the wing root into an Eppler E186 airfoil cross-section to allow for thicker loadbearing member and aid compressibility whilst retaining good overall performance, and relatively thin profile.

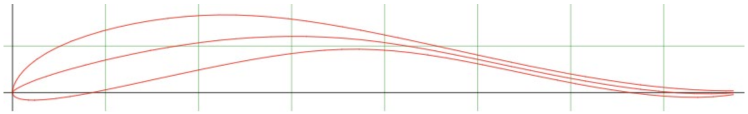


Figure 7 – Custom airfoil RVB-5

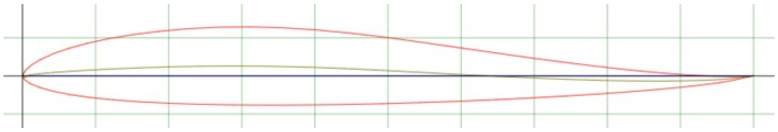


Figure 8 – Eppler E186 airfoil cross-section used at wing root

3.4 Wing profile analysis at full and intermediate extension

The wing was modelled, analysed, and optimized in XFLR5 along with the RVB-5 airfoil for lifting line, downwash, induced drag, and viscous drag for AoA range of -1.0 to 1.0. For both 0° and 1° AoA, which is the optimal operating range for the required Cl at 25m/s, and maximum gross weight of 3.5kg, the bell-curve lifting lines were maintained with the desirable downwash for a flying wing.

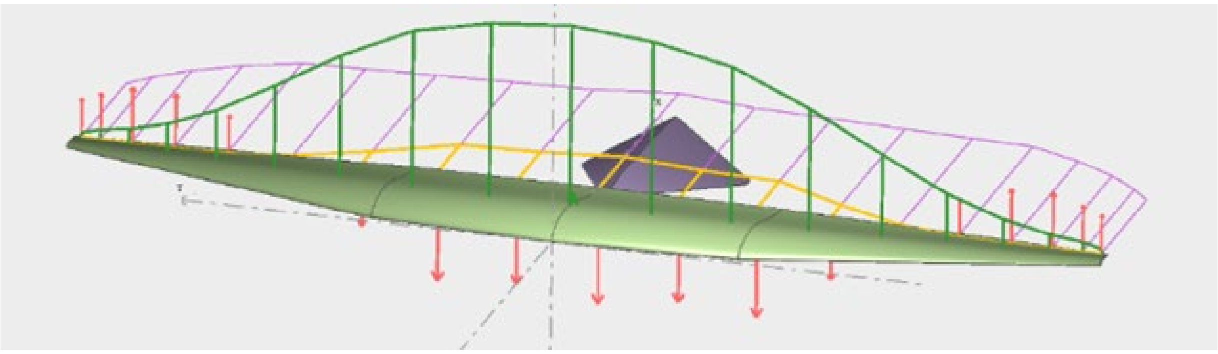


Figure 9 – Lifting lines at 1° AoA and full wing extension

The demonstrator design can dynamically extend and retract the left and right wing to provide roll control via a non-symmetrical lift, or both wings can be extended and retract together to increase or decrease airspeed. Analysis in intermediate wing retraction still exhibited good lift and pitch stability.

3.5 Flow tank testing at maximally compressed, intermediate and full extension

The opportunity of flow tank testing was offered courtesy of *City, The University of London*. This was conducted on a rigid-body semi-span test article having three interchangeable wing states, typical for initial evaluation of novel wing platforms [8], [9], [10]. Due to the law of similitude, water testing allows for a relatively smaller model at slower speeds whilst being comparable to real flight conditions.

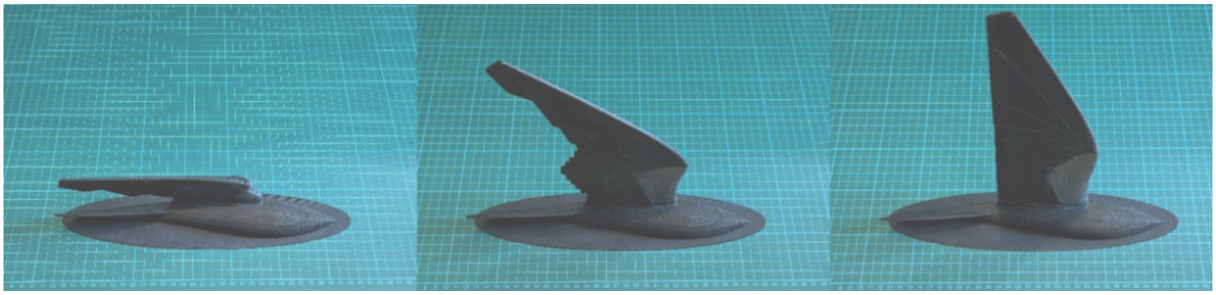


Figure 10 – Composite photograph of test article in three wing states used in flow testing

The test article was developed in PLA material at 60% scale using rapid prototyping from the UAV CAD files using additive manufacturing (Ultimaker S5). Three wing models states were in the maximally compressed, mid extension (~45 degree leading edge) and full extension positions as in Figure 10 above..

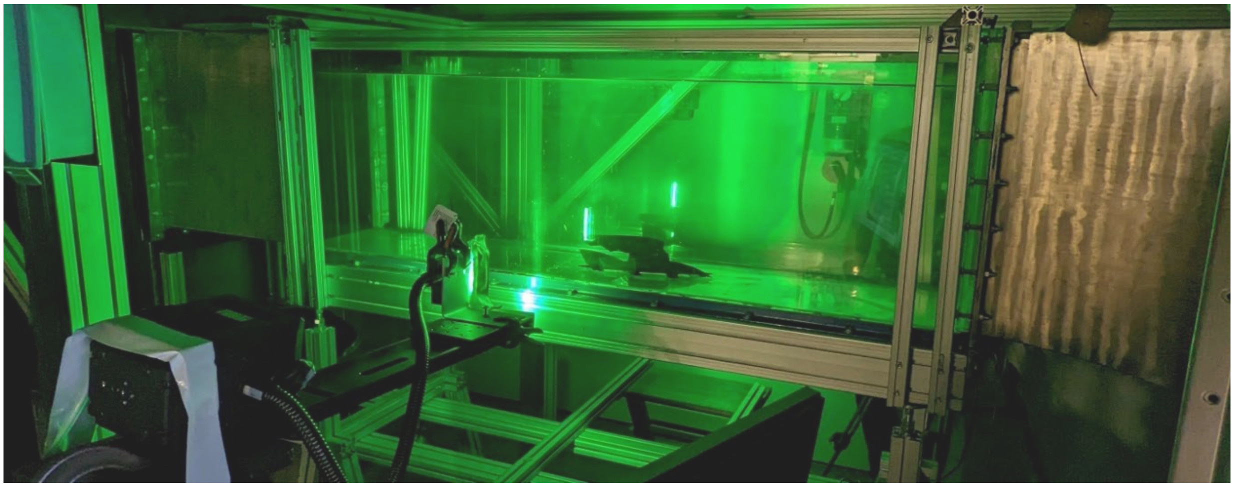


Figure 11 – Photograph taken during Semi-span flow tank testing of maximally compressed M shape flight mode wing

3.6 Integration test of full-scale morphing wing UAV and Launch System

Manual release testing was conducted on the prototype UAV primarily to ensure effectiveness of the UAV and Launch System interfaces, mechanical release, and gravity deployment. Of specific interest was to assess the friction of UAV parts in contact with the Launch System guide rails during deployment and the stability of the stowed UAV in the Launch System.

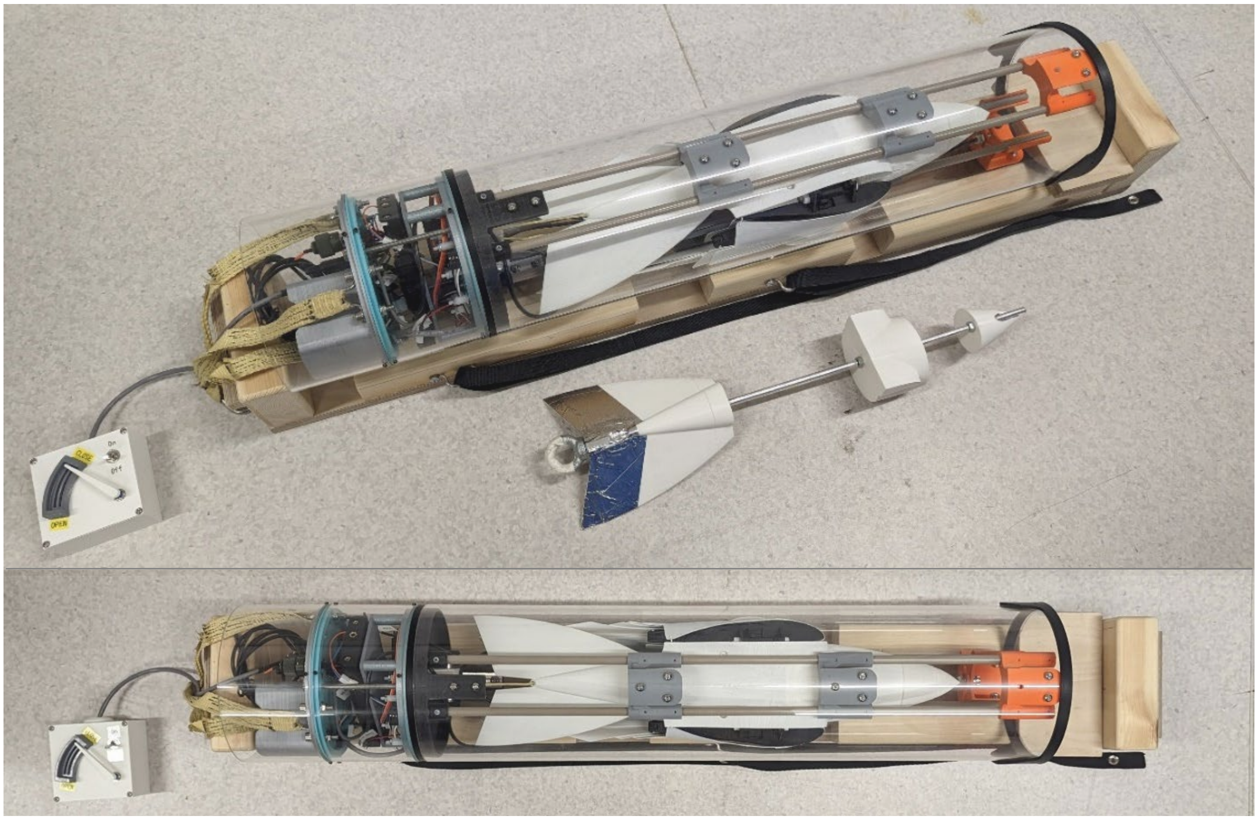


Figure 12 – (Top) Prototype UAV in Launch System alongside the developmental dummy UAV, (Bottom) Top

4. Conclusions and recommendations

Project Conclusions: This document summarised the technology development of a flight capable nature inspired mission adaptive wing, with greater geometry re-shaping than any so far produced. The wings integrated full span asymmetric morphing airfoils and rolling out-of-plane when compressed. A short testing campaign was executed to de-risk structures & mechanisms before flight testing and generate more data on the aerostructure characteristics effecting flight control. Flow testing demonstrated tip vortex at full and intermediate wing extension and vortex lift generation at maximum compression, in concord with prior analysis of the peregrine falcon. Flight testing is to be conducted after project completion as priority was given to the availability of flow tank testing. Given the requirement of rapid design and manufacture, the test article was of sufficient quality and proved effective for initial flow testing. Notable points:

- **Complexities of developing nature inspired structures are becoming mitigated by additive manufacturing, SWaP-C subsystems and new materials**. Robotic wing systems require lightweight high-strength actuators. This project would have benefited from COTS lightweight long-stroke linear actuators which could not be sourced during the design phase.
- Most work to date in nature inspired flight systems is led by aerodynamics (surface first), rather than being led by biomechanics (structures & mechanisms). From experience prototyping tetrapod wing systems, we would recommend prototyping starts with the equivalent of the musculoskeletal structure (linkages and actuation) prior to development of the wing cover system.
- Morphing structures give additional difficulty in terms of design communication. To formalise wing design descriptions a universal tetrapod flight-limb morphing schema was developed. This was designed to be future compatible with most tetrapod wing planforms and wrist actuation.
- **Over the coming decades, morphing wing UAVs will likely become the dominant form of small ‘fixed wing’ UAVs with quick launch-return cycles**, primarily due to the fast deployment and re-stowage capability. This presents User benefits but also introduces potential hazards of misuse of the technology which should be kept under review by relevant parties.
- Future projects on morphing wing systems of this type may benefit from initial development as a VTOL contra-rotating propeller platform. At the time of the project, the availability of COTS propulsion systems of this type was limited.

Exploitation planning: ESA OSIP programme supports technologies with viable route to commercialisation and real-world impact, therefore the activity of the BIOUAS-HALO-21 project included exploitation planning. Discussions regarding SAR UAV product evaluation were held with the UK Maritime & Coastguard Agency who conduct a test programme for SAR using second generation autonomous systems, UKSAR2G. Meetings were held with relevant UK agencies, ONR and AFRL with respect to SAR and border monitoring applications. One future application of the wing system is countering malicious UAS use (C-UAS) by derivative highly manoeuvrable interception UAVs [11]. This was analysed as part of NATO Emerging Security Challenges Division (ESCD) C-UAS exercises and discussed with UK CPNI & JSaRC organisations. **This technology could form part of a long-term solution to protecting airports, areas of mass congregation and national infrastructure from accidental or malicious UAV use**.

Scientific exploitation: This flight demonstrator may be the world’s first air vehicle capable of tetrapod type full-span structural wing morphing, offering an experimental platform for a broad array of research areas: extreme collision avoidance manoeuvre; passive and dynamic gust mitigation; flight in strong winds; machine Learning controlled flight through woodland & urban canyons and through apertures like the goshawk (Accipiter gentilis); peregrine (Falco peregrinus) type interception [6]; glide bounding [12]; and plunge diving (cross-domain manoeuvre) in the manner of cormorants (Phalacrocorax carbo). It may also provide a basis for experimental studies on pterosaur biomechanics, forelimb and on-water take off [13].

Evolution has proven tetrapod wing load bearing morphology can support large flying animals, with the largest pterosaurs estimated to be greater than 250 kg. Studies suggest that of the largest flying animals, Pelagornis sandersi used dynamic soaring, while Argenthavis magnificens, Pteranodon, and Quetzalcoatlus used thermal soaring [14].

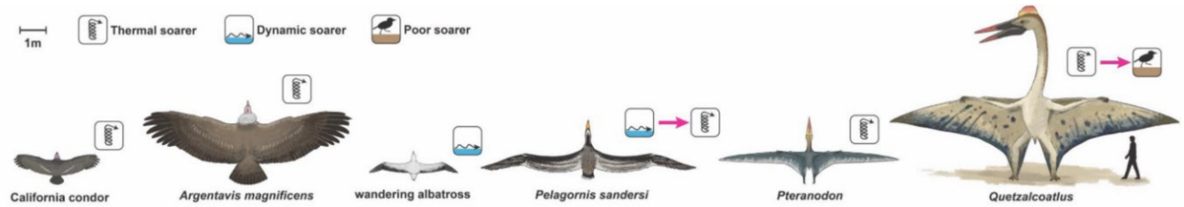


Figure 13 – Size comparison and soaring styles of large flying animals. Adapted image from Y. Gota, K. Yoda et al. [14]

For the space sector, potential applications are: planetary probe design [15]; Mars gliders utilising the Prandtl-D planform [16]; novel EDL platforms for recovery of scientific payloads and manufactured items from orbit; and next generation atmospheric sampling aerosondes. These concepts can be disseminated at events such as the International Planetary Probe Workshop (IPPW).

Figure 14 – Concept image of final project demonstrator prototype as an unpowered aerosonde glider

Acknowledgments and Conflicts of Interest

We would like to acknowledgments the significant contribution of project Subcontractor, Vorticity Limited, who developed the Launch System, high-altitude airdrop operation design and analysis. We would particularly like to acknowledge the support of Prof. Christoph Bruecker for discussions regarding this technology and for the execution of flow tank testing at *City, The University of London* (City). We would like to thank the Stellar AC's 2022 summer intern, Henry Wall, and Alden Midmer, for assisting with flow tank testing, and City's Chief Workshop Engineer, Keith Pamment, students Sergio Rosardo and Omar Selim.

The project Contractor (author) Stellar Advanced Concepts Ltd is owner of a relevant patent in wing morphing filed prior to the project and intends for future commercialisation. Since this technology is nature inspired, we hope conclusions regarding the broad viability of this wing technology are self-evident and endeavours were made to deliver unbiased project reporting despite commercial interest in this technology. For further information about the project, potential applications or press pack, please contact Stellar Advanced Concepts Ltd at info@stellar.ac.com or via our website www.stellar-ac.com.

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