Development of “Aria”, a Compact, Ultra-Quiet Personal Electric Helicopter

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Presented at the Vertical Flight Society, Southwest Chapter, Virtual Event, November 9, 2021
Outline

• Competition Overview and Motivation
• Aircraft Configuration Selection
• Historical Coaxial Personal Helicopters
• Design and Development
  – Coaxial Rotor System
  – Electric Powertrain
  – Flight Dynamics and Control
  – Structural Design and Analysis
• Subscale (1/3rd scale) and Full-Scale Flight Testing
• Lessons Learned
Introduction: GoFly Competition

$2 million X-prize sponsored by Boeing, 3-phases

Phase I: Design, April 2018
10 winners, $20K each

Phase II: Sub-Scale, Feb 2019
5 winners, $50K each

Final Fly-off: Full-Scale, ongoing
1 winner, $1 mil

Initiative to foster the development of safe, quiet, ultra-compact, near-vertical takeoff/landing (VTOL) personal flying devices capable of flying 20 miles while carrying a single person
Aircraft Scoring

**Final Fly-Off Scoring Metrics:**

- **Size**: Linear: 8.5 ft cut-off
- **Noise**: Linear: 87 dBA cut-off (@ 50ft)
- **Speed**: Quadratic: 30 kts min
**Performance Requirements**

**Range**
- 6 laps

**Endurance**
- 20 minutes total flight time
- 10 minutes reserve

Team *Harmony* was formed to innovate solutions, and develop a competitive eVTOL aircraft via scientific approach.

1 of 10 Phase I winners out of 1,300 global competitors

1 of 5 Phase II winners with 1/3\(^{rd}\) Subscale prototype

Developed and flight tested full-scale prototype for Phase III
Aircraft Configuration Selection
Configuration Options

- **Single main rotor**
  - Not compact
  - Tail-rotor noise

- **Tandem helicopter**
  - Not compact
  - Tail-rotor noise
  - Non-ideal space use

- **High disk loading ducted rotors**
  - High noise and low efficiency
  - Duct: High drag and pitch moment

- **Intermeshing rotors**
  - High mechanical complexity

- **Compound heli**
  - Not compact
  - Tail-rotor noise

- **Twin/quad tilt-rotor/wing**
  - Complex transition for speed

- **Tail sitter**
  - Pilot orientation
  - Complex transition

**Excessive noise; Low efficiency**

**Mechanically complex; Reorientation**
Multi-copter: Popular Choice

Not the optimal choice for both maximizing efficiency and minimizing noise

Fundamental Requirements:
- Minimize Disk Loading
- Minimize Blade Tip Speed
Optimal Solution

The Coaxial Configuration has:

- 4.26 times more disk area
- Significantly lower power per unit thrust
- Larger rotors – efficient, high Reynolds Numbers
- Improved safety & space usage – pilot at center of rotors
- Numerous acoustic benefits…
Helicopter Noise Generation Mechanisms

**Mitigated through tip speed reduction**

<table>
<thead>
<tr>
<th>Noise Type</th>
<th>Characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>High-Speed Impulsive Noise</strong></td>
<td>- Tonal noise due to local shock waves in the vicinity of the blades</td>
</tr>
<tr>
<td></td>
<td>- Occurs at high tip Mach numbers</td>
</tr>
<tr>
<td><strong>Steady Loading Noise</strong></td>
<td>- Harmonic noise due to production of lift and drag</td>
</tr>
<tr>
<td></td>
<td>- Low frequency: depends on rotor RPM</td>
</tr>
<tr>
<td><strong>Thickness Noise</strong></td>
<td>- Harmonic noise due to displacement of air by blade</td>
</tr>
<tr>
<td></td>
<td>- Low frequency: depends on rotor RPM</td>
</tr>
<tr>
<td><strong>Insensitive to tip speed reduction</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Broadband Noise</strong></td>
<td>- High frequency: due to airload fluctuations</td>
</tr>
<tr>
<td></td>
<td>- Turbulence induced pressure fluctuations</td>
</tr>
<tr>
<td><strong>Unsteady Loading Noise</strong></td>
<td>- High frequency: due to airload fluctuations</td>
</tr>
<tr>
<td></td>
<td>- Vortex, rotor-to-rotor, rotor-to-structure interactions</td>
</tr>
</tbody>
</table>
**Acoustics: A-weighted Sound**

**A-weighting:** Variation in loudness of sound with frequency as sensed by the human auditory system

- **Low Frequency** perceived as quieter
- **High Frequency** (1,000-5,000Hz) perceived as louder

Coaxial vs. Quadrotor Acoustics

Magnitude $\rightarrow f(\text{Blade Tip Speed})$  
Frequency $\rightarrow f(\text{RPM, No. of Blades})$

<table>
<thead>
<tr>
<th>Coaxial Rotor Configuration</th>
<th>Thrust-matched Quadrotor</th>
</tr>
</thead>
<tbody>
<tr>
<td>Large rotor, low tip speed:</td>
<td>Small rotor, high tip speed:</td>
</tr>
<tr>
<td>Low noise magnitude</td>
<td>High noise magnitude</td>
</tr>
<tr>
<td>Low RPM:</td>
<td>High RPM:</td>
</tr>
<tr>
<td>Low frequency and A-weighted advantage</td>
<td>High frequency and A-weighted disadvantage</td>
</tr>
</tbody>
</table>
Coaxial vs. Quadrotor Acoustics

Acoustic Simulation, Thrust-Matched, Same Footprint

Quadrotor
Unweighted: 106dB
A-weighted: 103dBA

Coaxial Rotor
Unweighted: 74dB
A-weighted: 69dBA

Coaxial: much lower frequency and SPL

Sound Pressure Level (dB)

Quadrotor
457 Hz

Coaxial
65 Hz
Rotor Spacing Experiments

80-20 Rotor Test Stand

Coaxial Rotor

Measurement Microphone

10R Separation Distance

Control Computer
Rotor Spacing Results

25% Radius
Final Configuration Selection

- Coaxial Rotor System
- Rotor Diameter: 8.5ft
- Separation Distance: 25% of Radius
- Pilot placed above rotor system for clear field of view
Historical Coaxial PAVs

De Lackner HZ-1 Aerocycle (1954)
Hiller VZ-1 Pawnee “Hiller” Platform (1955)
GEN H-4 (1999)
First Manned Electric Helicopter (2011)

Kinesthetic Control
Manual Thrust Vectoring

Heavy dependence on pilot skill, cannot utilize SAS
Not the best choice for a PAV
Design and Development

Coaxial Rotor System
Key Rotor Design Tools:

- **In-House Blade Element Momentum Theory (BEMT) Code**
  - Calculates airloads based on rotor parameters
  - Captures radial inflow variation, vortex effects; Pitt-Peters inflow model, forward flight
  - X-Foil® based look-up table
  - Modified to capture coaxial rotor interference using Rand model

- **Helios: Commercial Computational Fluid Dynamics (CFD) Code**
  - Product of HPCMP CREATE™-Air Vehicles programs, high-fidelity analysis for rotary-wings
  - Dual mesh paradigm as basis of CFD aerodynamic solution

- **In-House Acoustics Solver**
  - Predicts rotor noise based on aerodynamic forces generated by CFD simulation
  - Harmonic noise modeled using Ffowcs Williams – Hawkings equation
  - Broadband noise simulated using Brooks, Pope, and Marcolini model
  - SPL, 1/3rd octave frequency spectra, unweighted, A-weighted noise, directivity polar plots

Parametric Study: Minimize forward flight power, minimize noise in hover
Parametric Study: RPM

Lower RPM decreases power

Lower RPM increases angle of attack which decreases stall margin

RPM: 950
Reduced power, 30% stall margin
Higher $\sigma$ decreases power and RPM

Higher $\sigma$ increases AOA, decreases stall margin; increases rotor weight

Solidity: 0.2

Reduced power, weight; good stall margin
Parametric Study: Taper ratio

Taper ratio: 2
Reduced power; good stall margin
Parametric Study: Twist

**Power (HP)**

- $\theta_w = 0$
- $\theta_w = -3$
- $\theta_w = -6$
- $\theta_w = -9$
- $\theta_w = -12$
- $\theta_w = -15$

**Forward speed (knots)**

- $\theta_w = 0$
- $\theta_w = -3$
- $\theta_w = -6$
- $\theta_w = -9$
- $\theta_w = -12$
- $\theta_w = -15$

**Max AOA (°)**

- $\theta_w = 0$
- $\theta_w = -3$
- $\theta_w = -6$
- $\theta_w = -9$
- $\theta_w = -12$
- $\theta_w = -15$

**Twist: -9°**

Reduced power; good stall margin
Parametric Study: No. of Blades

More blades decreases power, diminishing returns for $N_b > 4$

More blades, increased rotor weight

More blades decreases noise: tonal noise decreases with RPM

For given $N_b$ broadband noise increases with AOA

No. of Blades: 4

Reduced power; acoustically optimal Mach No. (0.35)
Parametric Study: Blade Airfoil

**Airfoil Requirements:**

1. High lift to reduce rpm and noise
2. High $C_L/C_D$ to improve performance
3. Thin to reduce thickness noise

- NASA RC(4)-10
- Clark-Y
- Selig S1223
- Chuch Hollinger CH 10
Blade Planform Shaping

Coaxial rotors generate impulsive noise during blade cross-overs

**Straight blades**
Instantaneous blade overlap - strong acoustic effects

**Double-swept blades**
Distributed blade overlap - “de-phase” aerodynamic interactions

**Full-Scale Blade**
5° 20°
R = 62%

4.4 dBA Noise reduction

Swept Blade
Straight Blade

SPL (dBA)

Frequency (Hz)
**Optimal Rotor Design**

**Optimal Rotor Configuration**
- Solidity = 0.2
- Number of Blades = 4
- Rotor Spacing = 0.25R
- Rotor Diameter = 8.5ft
- Optimal Hover RPM = 800
- Optimal Forward Flight RPM = 950

**Optimal Blade Shape**
- Chord = 0.95ft
- Root cutout = 0.35R
- Forward sweep = 5°
- Backward sweep = 20°
- Sweep reversal at 0.62R
- Twist = -9°

Parametric Studies: 269,344 cases analyzed
Optimal Rotor CFD Simulation (Helios)

Hover
Full-Scale Verification: BEMT vs CFD

Hovering flight case

Coax Rotor: CFD vs BEMT

Good agreement: BEMT within 15% of CFD
Optimal Rotor CFD Simulation (Helios)

Forward Flight
Full-Scale Verification: BEMT vs CFD

Forward flight case

Good agreement: BEMT within 10% of CFD
BEMT/CFD Experimental Verification

Subscale rotor blade measurements on in-house hover stand

Good agreement among all within 10%
Aerodynamic Similarity

CFD study on scalability of aerodynamics

**Coefficient of Thrust**

**Full-Scale Model**

**1/3rd Scale Model**

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**Coefficient of Power**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Full-Scale Model</th>
<th>1/3rd Scale Model</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reynolds No.</td>
<td>$9 \times 10^5$</td>
<td>$2 \times 10^5$</td>
</tr>
<tr>
<td>Mach No.</td>
<td>0.27</td>
<td>0.21</td>
</tr>
<tr>
<td>Froude No.</td>
<td>79</td>
<td>104</td>
</tr>
</tbody>
</table>

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Full-Scale Acoustic Prediction

CFD predicted blade loads utilized to simulate noise in hover

Third Octave Analysis of Max Noise Level

Coaxial Rotor Total Noise Directivity Polar
Max Level: 69.8 dB

Predicted Noise: ~70dB @ 50ft
Subscale rotor sound pressure level measurements scaled to Full-Scale sound pressure levels

Experiment: 70.0 dBA, 72.5 dB

Analysis: 69.8 dBA, 74.5 dB
Blade Construction

Blades were manufactured with foam core, carbon fiber skin, fiberglass reinforced root

1. Ply Schedule
2. Core and Root
3. Carbon Fiber Partial Ply
4. Uni-Directional Spar
5. Full Carbon Fiber Ply
Design and Development

Electric Powertrain
Electric Powertrain

**Requirements:**

Quiet, all-electric propulsion system (motor, batteries, controller, etc.)

High-torque, low-speed drive motor

Lightweight, aerospace grade COTS parts

1. Motor and inverter selection and testing

2. Custom high-voltage battery pack development

3. Custom one-stage quiet transmission development
Motor Selection

Motor Architecture Options

Radial Flux Stator

Axis of Rotation

Axial Flux Stator

Axis of Rotation
Motor Selection

Trade-Study: Motor Torque Density

<table>
<thead>
<tr>
<th>Torque (N-m)</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>2</td>
<td>2</td>
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<tr>
<td>4</td>
<td>4</td>
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<td>6</td>
<td>6</td>
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<td>8</td>
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<td>10</td>
<td>10</td>
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<tr>
<td>12</td>
<td>12</td>
</tr>
<tr>
<td>14</td>
<td>14</td>
</tr>
</tbody>
</table>

Axial flux

Radial flux

EMRAX® 208 Axial Flux, Permanent Magnet Motor

Mass: 20.1lbs (9.1kg)
Max Continuous Power: 55 HP (41 kW)
High Voltage: 550V
Air-Cooled
Motor Dynamometer Testing

Dynamometer Interface

Cascadia Motion PM100DZ Controller

Emrax® 208 Motor
Dynamometer Testing Results

Motor efficiency >94% for all flight conditions

Angular Velocity (RPM)
Torque (N-m)

Test data
Axial climb
Hover
Forward Flight
Dynamometer Testing Results

Rapid and Significant Motor Overheating

EMRAX® 228 Axial Flux, Permanent Magnet Motor

Mass: 27.1lbs (12.3 kg)
Max Continuous Power: 83.1 HP (62 kW)
High Voltage: 680V
Air and Water-Cooled

Lack of Sufficient Cooling
Battery Chemistries

Lithium:
Highest energy density
Compact, pouch design

Lithium-Cobalt (LCO): High specific energy, thermal runaway

Lithium-Ion Phosphate (LFP): High specific power, thermal stability

Lithium Manganese Nickel Cobalt (LMNC): In-between performance, used in eVTOL

Lithium-Ion, pouch – based custom battery, high specific power
Battery Design

Lithium-Ion, pouch – based custom battery, high specific power

Battery Architecture:
144-series wired 4-parallel cells

Battery Specifications:
11 kWh
Peak Voltage: 604V
Mass: 200lbs (90.7kg)

Battery Management System:
Individual Cell Voltages
Pack Voltage & Current
6 Temperature Probes

Pack Level Energy Density: 133 Whr/kg
Transmission Type Selection

One-stage reduction drive required to meet low RPM – high torque demands

Belt and Pulley
- Parallel V-belt transmission demonstrated on YO-3A Quiet Star
- Not Compact
- Runout noise
- Heavy support structure
- Meshing noise in timing belts

Chain and Sprocket
- Compact, meshing noise mitigated with tensioner
- Maintenance Intensive
- Mechanically Complex
- Heavy support structure

Gearbox
- Simple, Compact, Reliable
- Noisy

Noise mitigation:
- Helical Teeth
- High-Contact-Ratio Tooth Profiles
- Enclosed Transmission Housings
- Sufficient Lubrication
Custom Ultra-Quiet Gearbox Design

One-stage reduction drive required to meet low RPM – high torque demands

Helical Gear
Custom High-Contact-Ratio Tooth Profile
3.6:1 Gear Ratio
9310 Aircraft Grade Steel

Custom-designed transmission quieter than rotor in operation

Custom Transmission Housing, Nylon 12 GF
Filled with Molybdenum Grease
Flight Control Implementation

Dual rigid rotors, mechanically independent, electronically coupled, swashplates

Control authority, maneuverability, gust tolerance

1/3rd Scale

Top Swashplates

Actuators

Bottom Swashplates

Actuators

Full Scale
Flight Control Implementation

Dual rigid rotors, mechanically independent, electronically coupled, swashplates

Control authority, maneuverability, gust tolerance
Flight Controller

Custom designed Embedded Lightweight Kinematic Autopilot (ELKA-R)

- Tri-axial gyros and accelerometers
- Bi-directional communication
- Tuned PID feedback loop

Embention Veronte® AP: initially utilized on full-scale

- Unreliable for flight control
- Retained for CAN coms, remote sub-system control, sub-system telemetry
Flight Dynamics Modeling

Predict flight characteristics, analyze stability, simulate flight

Aircraft equations of motion: Non-linear
Inertias, mass: CATIA® CAD model
Forces, moments: BEMT, Pitt-Peters inflow
Analysis Code: Texas A&M University Rotorcraft Analysis Code
Linearized Model, Stability

Hover, Forward Flight at 47kts

Linear Quadratic Regular (LQR) Feedback

Hover Model

Forward Flight Model

Real Axis

Imaginary Axis

Open Loop Pole

Closed Loop Pole

STABLE ↔ UNSTABLE

Linear feedback stabilizes unstable modes
Flight Simulations

Simulations demonstrated gust tolerance, tracking
X-Plane® Simulation

Real-time flight simulation
Design and Development

Structural Design and Analysis
Landing Gear Design

ANSYS® FEA, 1-g and 4-g loading
Landing Gear Analysis

1-g Loading

Von Mises: 10.6ksi, Factor of Safety: 1.53

4-g Loading

Deformation after hard landing (similar to FEA predictions)

Maximum Von Mises below yield stress of metal

41.4 ksi < 46ksi
Stress Analysis Examples

Rotor Hub

Transmission Support Structure

FEA utilized extensively to design structurally critical members
Vehicle Testing

Subscale (1/3rd)

Assembled Subscale (1/3rd) PAV – Aria
GTOW: 22lb
Testing Phase 1: Gimbal Stand

Evaluate mechanical system, characterize response, tune flight controller
Testing Phase 1: Gimbal Stand

Evaluate mechanical system, characterize response, tune flight controller
Testing Phase 2: Indoor Tethered

*Flight test assembled vehicle, familiarize pilots, trim and tune controller*
Testing Phase 3: Indoor Free-flight

Demonstrate flight capabilities indoors
Testing Phase 4: Outdoor Free-flight

Demonstrate high-speed forward flight outdoors
Aria vs Quadrotor: Acoustics

Experimentally measure SPL of Aria and thrust-matched quadrotor, same footprint

Quadcopter
85 dBA at 16.7 ft (50 ft / 3)

Aria vs Quadrotor:

- **Aria Rotor**
  - 70.2 dBA
  - 72.5 dB

- **Quadrotor**
  - 85.2 dBA
  - 89.6 dB

Aria rotor system 18dB quieter than quadrotor
Aria vs Quadrotor: Efficiency

Experimentally measured performance

Quadrotor requires 55% more power
Vehicle Testing

Full-Scale Vehicle

Assembled Full-Scale *Aria*
- Empty Weight: 550lb
- Payload Weight: 200lb
Testing Phase 1: Gimbal Stand

Evaluate mechanical system, characterize response, tune flight controller
Testing Phase 1: Gimbal Stand

Evaluate mechanical system, characterize response, tune flight controller
Testing Phase 2: Indoor Tethered

*Flight test assembled vehicle, familiarize pilots, trim and tune controller*
Tethered Hovering Flight Data

Flight controller tuned using body rates and angles

Good agreement between desired and measured
Hover Endurance Flight Data

- Battery Voltage, Current
- Motor, Battery Temps.
- Motor Torque

Sub-system telemetry monitored in real time for all flight tests
Testing Phase 2: Indoor Tethered

Hover flight tests with 165lb payload
Testing Phase 3: Outdoor Tethered

*Flight test vehicle in constrained outdoor environment, measure SPL*
Testing Phase 4: Outdoor Free-flight

Demonstrate flight capabilities outdoors
Team *Harmony* designed, developed and flight tested a subscale and full-scale ultra-quiet coaxial helicopter PAV as part of Boeing GoFly competition – Phase I, II winners

- Ultra-quiet and efficient rotor system
- Rigid rotors with independent collective and cyclic control
- Electronically coupled, dual swashplate
- Electric powertrain with ultra-quiet transmission for low-RPM & high-torque
- 11 kWhr, 600Volt, 200lb, custom battery pack with 144 cells

Team designed, built, and flight tested full-scale aircraft in 10 months
Lessons Learned/Conclusions

- Demonstrated it is possible to significantly quiet rotors (73dBA @ 50ft) without losing efficiency
  - Via tip speed reduction, planform shaping and acoustically tailored blade design

- Endurance is limitation for eVTOL aircraft
  - Size, Noise, Speed constraints met – **not endurance**
  - Longest hovering flight: 8 minutes full-charge, no payload
  - Low energy density of current battery tech (133 Whr/kg @ pack level)

- Reliable, lightweight aerospace grade COTS parts needed for eVTOL
  - Numerous mechanical and electrical issues
  - COTS parts heavy – PM100DZ motor controller
  - COTS autopilots unreliable – Veronte® AP
What next?

Still pursuing the GoFly prize – no winners yet!

- Harmony Aeronautics won Phase 1 Air Force Agility Prime STTR Award (AFWERX Program)

6-month, 150K feasibility study on development of ultra-quiet and efficient propulsors for eVTOL UAMs

- Awaiting Phase 2 Award Results

Ultra-quiet rotor technology broadly applicable to eVTOL aircraft
Thank You