AirEZ

Executive Summary

American Helicopter Society International
32\textsuperscript{nd} Annual Student Design Competition
Graduate Student Team Submission
Overview: AirEZ Vehicle

**Battery**
- 2.04 kW-hr lithium-sulfur battery
- Quick swappable for turn around time

**Proprotors**
- Low maintenance rigid hub
- Variable collective for max efficiency
- Variable RPM for high controllability
- Optimized composite blades

**Emergency Parachute**
- Angled to work in hover and cruise
- Tangle-proof

**Quadrotor Tailsitter Biplane**
- High endurance, high speed, long range, and VTOL capable

**Electronics Suite**
- Robust sense-and-avoid sensor suite
- Redundant communications systems
- HUMS early warning system

**Wing**
- Lightweight composite construction
- Modularized to be easily replaceable

**Delivery System**
- Deliver multiple packages per trip
- Minimal actuators for low maintenance
- Auger based package deployment

**Overview: AirEZ Vehicle**
In response to the AHS Student Design Competition 2015 Request for Proposal for a complete aerial delivery system of systems, the University of Maryland graduate team presents AirEZ, a fully developed logistics system that can be implemented using available state-of-the-art technology.

The AirEZ vehicle is a novel quadrotor-biplane-tailsitter concept with the ability to hover, transition quickly into high speed forward flight, and efficiently transition back to hover for landing. These capabilities have all been demonstrated at a smaller scale at the University of Maryland. The vehicle’s simple structural design enables inexpensive mass manufacturing, leading to a delivery system that can provide 2-hour delivery within a 50 mi x 50 mi region at a cost of only $9.03 per package.

The AirEZ vehicle is outfitted with an advanced sensor package enabling autonomous navigation in the crowded airspace of an urban environment. Package delivery is performed safely and reliably with minimal expense to the logistics company. To demonstrate the viability of this innovative concept, a scaled model was built and successfully tested in different flight modes.
The AirEZ system shows impressive performance in each of the five Measures of Effectiveness (MoE).

**MoE 1: System Acquisition and Yearly Operating Cost**

<table>
<thead>
<tr>
<th>Cost (Millions)</th>
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<tbody>
<tr>
<td>Development</td>
</tr>
<tr>
<td>Acquisition</td>
</tr>
<tr>
<td>Direct Operating (3 yrs)</td>
</tr>
<tr>
<td>Indirect Operating (3 yrs)</td>
</tr>
<tr>
<td>End of Life</td>
</tr>
<tr>
<td>Yearly Operating</td>
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**MoE 2: Packages Delivered Per Vehicle Per Day**

The AirEZ system has been designed using vehicles which carry multiple packages per trip. Utilizing this capability has led to a system in which each vehicle delivers an average of 11 packages per day at a cost of $9.03 per package. Vehicles that can carry only one package per trip reduce the system productivity to 8 packages per vehicle per day (27% worse).

**MoE 3: Number of Deliveries Requiring More Than 90 Minutes**

0 packages weighing less than 5 lb and smaller than 12x12x16 in require more than 90 minutes to deliver.

**MoE 4: Pounds of CO₂ per Delivery Mile Flown**

AirEZ produces 0.067 lb of CO₂ per delivery mile flown. This number is based on the CO₂ emissions for grid-based charging specified in the RFP. When compared to light-duty trucks with CO₂ emissions of 0.814 lb/mi or hybrid cars with 0.331 lb/mi, AirEZ is 92% and 80% better respectively. The choice of batteries as the power plant ensures that AirEZ is an environmentally green reality.

**MoE 5: Mission Success Rate**

Based on detailed simulations, AirEZ boasts an overall mission success rate of 86%, similar to any major carrier’s success rate for express over-night deliveries.
**SYSTEM CAPABILITIES**

### Vehicle Fleet

<p>| | |</p>
<table>
<thead>
<tr>
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<tbody>
<tr>
<td># active vehicles</td>
<td>400</td>
</tr>
<tr>
<td># standby vehicles</td>
<td>80</td>
</tr>
</tbody>
</table>

### Personnel

<p>| | |</p>
<table>
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<tr>
<th></th>
<th></th>
</tr>
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<tbody>
<tr>
<td>Central Command</td>
<td>5</td>
</tr>
<tr>
<td>Maintenance</td>
<td>10</td>
</tr>
</tbody>
</table>

**Delivery radius of action for given payload**

[Map showing delivery radius with payload weight ranges indicated by color codes: up to 5 lbs (light green), up to 12 lbs (blue), up to 15 lbs (pink).]

University of Maryland – Executive Summary
The mission outlined by the RFP is for daily delivery of 5,000 packages across a 50 mi x 50 mi region. The packages are of varying weights, and must be delivered within two hours of being requested. A robust in-house simulation environment was developed by the University of Maryland team to model a typical delivery day and explore the options for system configuration and vehicle capabilities.

Simulations were carried out:
- Vehicle routing strategies for delivering multiple packages per trip
- Use of forward supply locations as waypoints or charging stations
- Shuttle vehicles to move packages to forward locations
- Multiple vehicle designs for differing:
  - Range
  - Package capacity
  - Payload capability

Results from the simulations dictated several key design drivers:
- Multiple packages per trip – reduces number of vehicles by 35% compared to single package per trip
- High speed – ensure packages are delivered within 2 hours, fewer vehicles required, lower maintenance cost
- No forward supply locations – eliminate 50% additional operating costs, for marginal increase in overall energy consumption and acquisition costs

Snapshot of a simulation at one instant in delivery day

- 300 vehicles in air
- 443 package requests
Package Delivery Simulation

Multiple Package Delivery

- Routing strategy is optimized specifically for the delivery mission.
- Package 1 is requested first, but package 3 is delivered first to minimize overall energy consumption.
- All the deliveries are completed within 90 minutes.

Concept of Operation

- New Request (Location, Weight, Size)
- List of Requests/Available Vehicles
- Optimize Route
- Pick up and Pack Packages
- Load to Vehicle
- Assign Packages to Vehicle
- Change Battery
- Cruise/Transition
- Status update/HUMS
- Landing
- Vehicle Return to CW
- Customer

Typical Delivery Day

- Out for delivery
- Loading packages
- Batter exchange/Standy

Number of Requests & Delivery

- Overweight packages
- New request & Delivery Waiting
- New request & Delivery are balanced
- Final request
- Fraction of vehicles (%)
- Number of packages
- Time (hrs)
- Loading packages
- Out for delivery
- Batter exchange/Standy

Vehicles in Different Stages

- First delivery
- Time (hrs)
NOVEL VEHICLE CONFIGURATION

The AirEZ delivery system features a unique quadrotor-biplane-tailsitter configuration demonstrated at the University of Maryland. This design was chosen based on its ability to combine the best aspects of each configuration to meet the goals of the RFP.

Quadrotor
Quadrotor configuration enables efficient hovering flight and exceptional controllability. The unique control options allow for simple hubs with no swashplates and no additional control surfaces to reduce maintenance costs. In addition, ground safety and operational safety are enhanced due to lower kinetic energy of its smaller rotors, and redundant rotor system.

Tailsitter
Achieving the transition from helicopter to airplane mode via a tailsitter configuration rather than a tilt-rotor allows AirEZ to keep a simple, lightweight design. The lack of a complicated and heavy mechanism for tilting rotors or wings ensures that the many hundreds of AirEZ vehicles in the system are easy to maintain.

Biplane
Wings allows AirEZ to achieve the high speed and long range necessary for 2-hour delivery to all points in the service region. The biplane configuration provides the necessary lift in a small footprint. In addition, the wings offload the rotors in forward flight, enabling the rotors to be highly efficient propellers.
The AirEZ vehicle proprotor offers excellent efficiency as a rotor (FM = 0.73) in hover and as a propeller (\(\eta = 0.85\)) in forward flight through the use of variable RPM and adjustable root pitch control. Optimization was achieved through parametric studies on:

- Number of blades
- Chord
- Taper ratio
- Twist rate
-Number of blades
- Chord
- Taper ratio
- Twist rate

- Optimized rotor and propeller designs were combined to produce a proprotor with excellent performance in hover and forward flight
- Balance between FM and propeller efficiency based on needs from the system simulation
- Adjustable pitch rotor allows significant improvement over fixed pitch designs.

### Proprotor Characteristics

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
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<tbody>
<tr>
<td>Radius</td>
<td>1.32 ft</td>
</tr>
<tr>
<td># of blades</td>
<td>2</td>
</tr>
<tr>
<td>Taper ratio</td>
<td>0.25</td>
</tr>
<tr>
<td>Inboard twist</td>
<td>19.8°</td>
</tr>
<tr>
<td>Outboard twist</td>
<td>9°</td>
</tr>
<tr>
<td>Transition radius</td>
<td>0.87R</td>
</tr>
<tr>
<td>Airfoil</td>
<td>SD7032</td>
</tr>
<tr>
<td>Solidity</td>
<td>0.0745</td>
</tr>
</tbody>
</table>

2,684 proprotor blade designs studied

Optimized AirEZ proprotor design
The rigid proprotor hub was designed to allow the collective pitch variation necessary to hover efficiently and cruise at high speeds.
- Linear actuator used to push collective control rod
- Turnbuckles on pitch links allow tracking and balancing of rotors
- Simple pitching mechanism allows easy maintenance for the entire fleet
- Bearing material selected for unique loading of system
  - **PTFE plain pitch bearings** for the low load and low rotation rate condition between blade grip and hub base
  - **Bronze SAE 841plain bearings** for the low pitch link load and high rotation rate condition between actuator rod and pitch link crossbar
  - **Steel ball bearings** (thrust bearing) to take high centrifugal loads

### Proprotor Operating Conditions

<table>
<thead>
<tr>
<th></th>
<th>Hover</th>
<th>Cruise</th>
</tr>
</thead>
<tbody>
<tr>
<td>RPM</td>
<td>1750</td>
<td>750</td>
</tr>
<tr>
<td>Root pitch</td>
<td>33.36</td>
<td>70.34</td>
</tr>
<tr>
<td>Efficiency</td>
<td>FM = 0.73</td>
<td>$\eta_p = 0.85$</td>
</tr>
</tbody>
</table>

- Vehicle can safely land in one motor inoperative scenario using the proven quadrotor control system
- Emergency parachute allows vehicle to safely descend in case of multiple power plant failure
EFFICIENT POWER PLANT

AirEZ is powered by lithium-sulfur batteries that have proven high energy density, while being lightweight, safe, inexpensive and environmentally friendly. Rapidly advancing battery technology enables easy improvements to the system in this future-proof design. As lighter and more powerful batteries become available, battery packs can be upgraded for higher payload and longer range.

The modularity of batteries combined with the hinged battery compartment of the fuselage enable quick power pack changes between missions, minimizing downtime between deliveries and maximizing system productivity.
OUTSTANDING VEHICLE PERFORMANCE

The AirEZ vehicle is able to achieve long-range high speed flight by combining the outstanding hover performance of a quadrotor and the high speed efficiency of a fixed-wing aircraft.

The AirEZ vehicle is deployable in a variety of non-ideal environments, allowing the possibility of system implementation in any urban market across the U.S.

- High hover ceiling 7,900 ft
- Ability to operate in ISA +40°C conditions
- Operate in up to 40 knot winds

**Vehicle Performance**

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>MGTOW</td>
<td>38.5 lbs</td>
</tr>
<tr>
<td>( V_{\text{max}} )</td>
<td>88 knots</td>
</tr>
<tr>
<td>Best Range at GTOW</td>
<td>175 miles</td>
</tr>
<tr>
<td>Max endurance</td>
<td>6 hours</td>
</tr>
<tr>
<td>L/D</td>
<td>4.7</td>
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University of Maryland – Executive Summary
LOW MAINTENANCE STRUCTURE

The RFP specifies an operating life of 300 days per year for three years. On each operating day, the system is active for 10 continuous hours. This leads to a design system life of 9000 hours, resulting 3.15 million cumulative flight hours for the entire fleet. Coupled with the suggested high cost of labor specified in the RFP ($100/hr), special care was taken to ensure that vehicles can be repaired easily and quickly both in the field and offline.

- Aluminum 6061-T6 joints – easy use of standard fasteners and high corrosion resistance for all-weather flight (and treated to prevent galvanic corrosion)
- Carbon fiber composites – components consist of large single piece structures
- UHMW polyethylene package compartment – low cost, low weight, and low friction for easy sliding of package boxes
- Assembled with standard fasteners – very quick assembly and replacement of parts
- Airframe structure consists of 17 major parts for easy storage (8 struts, 4 landing gear stilts, 2 wings, and 3 fuselage sections). This leads to a lower spare parts inventory and easy replacement.
A single AirEZ vehicle can deliver up to 4 packages per trip, a capability that results in higher mission success rate and lower system cost. A light-weight robust mechanism with minimal parts is capable of delivering multiple packages of different sizes upon landing. An advanced onboard sensor suite provides sense-and-avoid capabilities to avoid terrestrial obstacles.

AirEZ utilizes a simple screw conveyor mechanism to push packages through the automatic door. The mechanism also adjusts the lateral CG position after each package is delivered for optimum stability. Adequately sized servos and an interconnect shaft ensure that the mechanism is operable even if one servo fails.
CONTROL STRATEGY

- Vehicle control and stability is achieved using rotor differential RPM
- Airfoil on vehicle struts provides passive stabilization in forward flight
- Proven quadrotor control scheme can be used in both hover and cruise
- No other control surfaces required – minimal complexity & light-weight design

<table>
<thead>
<tr>
<th>Cruise</th>
<th>Roll</th>
<th>Pitch</th>
<th>Yaw</th>
</tr>
</thead>
<tbody>
<tr>
<td>Hover</td>
<td>Yaw</td>
<td>Pitch</td>
<td>Roll</td>
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AirEZ implements a gust attenuation and stability augmentation procedure inspired by the mechanosensory systems of flying insects through use of acceleration sensors distributed across the airframe.
For a tailsitter vehicle, the transition from hover to cruise and vice versa is critical. The transition needs to be quick, efficient, safe, and reliable. The AirEZ transition maneuver has been optimized to be highly efficient and was successfully demonstrated on a scaled vehicle.

**Outbound**
- Optimal transition maneuver executed autonomously based on allowed vertical displacement within FAA guidelines and skyline profile
- Trim analysis used to select efficient flight profile
- Avoids wing stall by transitioning in nearly axial flight
- Transition uses 6.6 hp to move rapidly to stable forward flight, using only 0.8% of the battery capacity for entire maneuver

**Inbound**
- Avoids the altitude gain typical of tailsitter vehicles by using drag from the fuselage, wings and rotors to decelerate
- No additional power required - ensures excess vehicle power can be used for attitude control and stabilization during wing-stall
- Transition uses 3.4 hp and only 0.3% of battery capacity

Root pitch is changed during transition at 23 knots to minimize power. Each transition maneuver is completed within 20 seconds. Simulations with full non-linear vehicle dynamics and experiments with subscale vehicles validates transition procedure.
Overview: Avionics Suite

Forward Flight Camera:
- Obstacle Avoidance
- Dynamic Path Planning

2x Flight Computers:
- Redundant Flight Management
- 16 Processor Cores

Advanced Autopilot:
- 1 oz.
- Accelerometers, Gyros, Barometer, Airspeed Sensor, Battery Voltage Monitor

4x Laser Range Finders
- Precise Altitude Measurement up to 130 ft Range, ±1”
- Eye Safe Laser

Time of Flight Depth Sensor
- Short Range Depth Mapping
- Day/Night Capable

Latas Module:
- Cell Tower Comms
- Air Traffic Management
- Secondary GPS

Radio Mesh Networking:
- Redundant Communication Links
- Multi-Node Range Extension

Differential GPS:
- Sub-meter Positioning Accuracy

WiFi Module:
- Short-Range, Large Bandwidth Transmission

LATAS Module:
- Cell Tower Comms
- Air Traffic Management
- Secondary GPS

Distributed Accelerometers/Transducers:
- Health and Usage Monitoring Systems
- Airspeed and Flow Angle Measurement
- Bio-Inspired Gust Rejection

4x Wide Angle Ultrasound
- Close Range Proximity Sensing

5x LEDs
- 900 Lumens
- 160 ft Visual Range at Night

5x Visual Cameras
- Medium Range Depth Mapping
- Customer Recognition
- Moving Person Detection

Thermal Imager
- Heat Signature Detection

Advanced Autopilot:
- 1 oz.
- Accelerometers, Gyros, Barometer, Airspeed Sensor, Battery Voltage Monitor

Radio Mesh Networking:
- Redundant Communication Links
- Multi-Node Range Extension
The AirEZ Micro:
A scaled vehicle demonstrating feasibility of the full scale design

Utilizes the in-house designed ELKA-R Board
- Microprocessor: Cortex-M4
- IMU: MPU-9150
- 2.4 GHz wireless transceiver
- Loop rate: 1000 Hz
- Mass: 1.7 g
- Thickness: 1 mm
SUMMARY

The AirEZ delivery system has been designed in response to the RFP for an aerial system of systems capable of delivering packages to customers in an urban environment. The University of Maryland AirEZ design utilizes an existing warehouse as a distribution center for a unique delivery concept that is scalable, robust, and cost-efficient.

The AirEZ UAV’s unique quadrotor-biplane-tailsitter configuration fuses the engineering advantages of each of the three concepts:

1) **Quadrotor** – Efficient hover and superior stability
2) **Biplane** – Efficient high speed cruise in a small footprint
3) **Tailsitter** – A mechanically simple design with minimum parts

The ability to carry multiple packages per trip enables a high level of mission success. Additionally, the AirEZ vehicle is stable in gusts and can complete its mission even with a 40 knot headwind.

The innovative use of proven technologies ensures complete operational safety, while a robust and redundant sensor suite enables safe, autonomous flight and delivery in unpredictable urban environments. The capabilities of the AirEZ system represent a paradigm shift in the logistics services market.