Quad-Rotor Bi-Plane Tailsitter
For OSW Operations and Maintenance

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University of Maryland
Quad-Rotor Bi-Plane Tailsitter for OSW Operations and Maintenance

- In response to 32nd AHS Design Competition (2015)
  - Deliver 5,000 packages per day
  - Operate vehicles for 10 hours a day
  - Packages are of varying weight (<.5 lbs to >10 lbs)
  - 2 hour delivery window
  - 90% of packages fit in 12x12x16 in box

- Large scale, high endurance quad rotor biplane
- Approximately 6 feet wing span
- Fuselage designed to hold 12x12x16 in box
- Can sling load higher weight payloads
- 55 kts cruise and 80 mile range
- 38 lb GTOW with 5 lb package and batteries (20.6 lb empty weight)
- 12 lb payload has 29 mile range (sacrificing some batteries)
- Estimate $75K to buy and operate one vehicle for 3 yrs (for 480 vehicle fleet)
Quad-Rotor Bi-Plane Tailsitter for OSW Operations and Maintenance

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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

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

- **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

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

- **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
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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.
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**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.
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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
- 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.
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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 841 plain 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>η&lt;sub&gt;p&lt;/sub&gt; = 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
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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.
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**3 Year Estimated CO₂ Emissions and Costs**

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.
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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.

<table>
<thead>
<tr>
<th>Performance</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise speed</td>
<td>55.0 kts</td>
</tr>
<tr>
<td>Maximum speed</td>
<td>87.7 kts</td>
</tr>
<tr>
<td>Best endurance speed</td>
<td>24.3 kts</td>
</tr>
<tr>
<td>Best range speed</td>
<td>32.1 kts</td>
</tr>
<tr>
<td>Max vertical load factor</td>
<td>3.0g</td>
</tr>
<tr>
<td>Max endurance</td>
<td>7.2 hr</td>
</tr>
<tr>
<td>Max range</td>
<td>210.0 mi</td>
</tr>
<tr>
<td>Figure of merit (Hover)</td>
<td>0.74</td>
</tr>
<tr>
<td>Prop efficiency, $\eta_p$</td>
<td>0.85</td>
</tr>
</tbody>
</table>
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Overview: Avionics Suite

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

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

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Advanced Autopilot:
- 1 oz.
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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

Differential GPS:
- Sub-meter Positioning Accuracy

WiFi Module:
- Short-Range, Large Bandwidth Transmission

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

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

4x Wide Angle Ultrasound
- Close Range Proximity Sensing

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

Thermal Imager
- Heat Signature Detection

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

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

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
### Quad-Rotor Bi-Plane Tailsitter for OSW Operations and Maintenance

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#### Table 14.2: Avionics Weight, Power, and Cost Breakdown

<table>
<thead>
<tr>
<th>Component</th>
<th>Type</th>
<th>#</th>
<th>Weight (oz)</th>
<th>Total Weight</th>
<th>Size</th>
<th>Power (W)</th>
<th>Total Power</th>
<th>Cost ($)</th>
<th>Total Cost ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Autopilot</td>
<td>MP2128^2^</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>1.6&quot; x 3.9&quot; x 0.4&quot;</td>
<td>1 W</td>
<td>1 W</td>
<td>$1,300</td>
<td>$1,300</td>
</tr>
<tr>
<td>CPU</td>
<td>ODROID-XU3 Lite</td>
<td>2</td>
<td>2.3</td>
<td>4.7</td>
<td>3.7&quot; x 2.8&quot; x 0.7&quot;</td>
<td>5 W</td>
<td>10 W</td>
<td>$95</td>
<td>$190</td>
</tr>
<tr>
<td>Transceiver</td>
<td>RFD-900+</td>
<td>1</td>
<td>0.5</td>
<td>0.5</td>
<td>1.2&quot; x 2.2&quot; x 0.5&quot;</td>
<td>1 W</td>
<td>1 W</td>
<td>76</td>
<td>76</td>
</tr>
<tr>
<td>LATAS</td>
<td></td>
<td>1</td>
<td>3.9</td>
<td>3.9</td>
<td>3&quot; x 2&quot; x 1&quot;</td>
<td>1 W</td>
<td>1 W</td>
<td>$100</td>
<td>100</td>
</tr>
<tr>
<td>Visual Cameras</td>
<td>MatrixVision</td>
<td>6</td>
<td>0.6</td>
<td>3.8</td>
<td>1.4&quot; x 1.3&quot; x 1.6&quot;</td>
<td>2 W</td>
<td>12 W</td>
<td>$50</td>
<td>300</td>
</tr>
<tr>
<td>LED Lights</td>
<td>Fenix E35UE</td>
<td>5</td>
<td>0.5</td>
<td>2.5</td>
<td>0.9&quot; dia x 1.5&quot;</td>
<td>4 W</td>
<td>22 W</td>
<td>$15</td>
<td>75</td>
</tr>
<tr>
<td>FLIR Camera</td>
<td>FLIR Lepton</td>
<td>1</td>
<td>0.1</td>
<td>0.1</td>
<td>0.4&quot; x 0.5&quot; x 0.2&quot;</td>
<td>1 W</td>
<td>1 W</td>
<td>$300</td>
<td>300</td>
</tr>
<tr>
<td>IR Depth Sensor</td>
<td>Soft Kinetic DS363A</td>
<td>1</td>
<td>1.8</td>
<td>1.8</td>
<td>3.1&quot; x 0.5&quot; x 0.6</td>
<td>2 W</td>
<td>2 W</td>
<td>$150</td>
<td>150</td>
</tr>
<tr>
<td>Laser Range Finder</td>
<td>LIDAR Lite</td>
<td>4</td>
<td>0.6</td>
<td>2.3</td>
<td>0.8&quot; x 1.9&quot; x 1.4&quot;</td>
<td>0.5 W</td>
<td>2 W</td>
<td>$90</td>
<td>360</td>
</tr>
<tr>
<td>Ultrasonic Range Finder</td>
<td>LV-MaxSonar-E20</td>
<td>4</td>
<td>0.2</td>
<td>0.8</td>
<td>0.6&quot; x 0.8&quot; x 0.8</td>
<td>0.3 W</td>
<td>1 W</td>
<td>$15</td>
<td>60</td>
</tr>
<tr>
<td>Solid State Drive</td>
<td>SAMSUNG 500GB USB 3.0 Portable SSD T1</td>
<td>1</td>
<td>1.0</td>
<td>1.0</td>
<td>2.8&quot; x 2.1&quot; x 0.4&quot;</td>
<td>2 W</td>
<td>2 W</td>
<td>$200</td>
<td>200</td>
</tr>
<tr>
<td>Pressure Transducers</td>
<td>MPXS500DP</td>
<td>4</td>
<td>0.3</td>
<td>1.2</td>
<td>1&quot; x 1&quot; x 0.5&quot;</td>
<td>0.1 W</td>
<td>0 W</td>
<td>$7</td>
<td>28</td>
</tr>
<tr>
<td>Gust Accelerometers</td>
<td>ADXL34S</td>
<td>16</td>
<td>0.05</td>
<td>0.8</td>
<td>1&quot; x 0.5&quot;</td>
<td>0.05 W</td>
<td>1 W</td>
<td>$3</td>
<td>48</td>
</tr>
<tr>
<td>HUMS</td>
<td>MK20DX256 CPU</td>
<td>4</td>
<td>0.1</td>
<td>0.4</td>
<td>1.4&quot; x 0.7&quot;</td>
<td>1 W</td>
<td>2 W</td>
<td>$20</td>
<td>80</td>
</tr>
<tr>
<td>Antennas</td>
<td></td>
<td></td>
<td>2.4</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td>$39</td>
<td></td>
</tr>
<tr>
<td>GPS Antenna</td>
<td>ANN-MS active GPS antenna</td>
<td>1</td>
<td>1.5</td>
<td>1.5</td>
<td>1.9&quot; x 1.6&quot; x 0.5&quot;</td>
<td>0 W</td>
<td>0 W</td>
<td>$15</td>
<td>15</td>
</tr>
<tr>
<td>Transceiver Antennas</td>
<td>2dBi Right Angle Monopole (RPSMA)</td>
<td>2</td>
<td>0.3</td>
<td>0.5</td>
<td>0.4&quot; (Dia.) x 2.1&quot;</td>
<td>0 W</td>
<td>0 W</td>
<td>$5</td>
<td>10</td>
</tr>
<tr>
<td>WiFi Antenna</td>
<td>IEEE 802.11b/g/n w/ Dual band antenna</td>
<td>1</td>
<td>0.4</td>
<td>0.4</td>
<td>2.7&quot; x 0.9&quot; x 0.3&quot;</td>
<td>0 W</td>
<td>0 W</td>
<td>$14</td>
<td>14</td>
</tr>
<tr>
<td>Total</td>
<td></td>
<td></td>
<td>27.0</td>
<td></td>
<td></td>
<td>57.2 W</td>
<td></td>
<td>$3,306</td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Component description</th>
<th>Weight (lb)</th>
<th>% Empty Weight</th>
<th>zcg (in)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 Wings</td>
<td>1.91</td>
<td>9.3%</td>
<td>24</td>
</tr>
<tr>
<td>2 Rotor Group</td>
<td>1.91</td>
<td>9.3%</td>
<td>28.1</td>
</tr>
<tr>
<td>Blades</td>
<td>0.84</td>
<td>4.1%</td>
<td>28.1</td>
</tr>
<tr>
<td>Hubs</td>
<td>1.07</td>
<td>5.2%</td>
<td>28.1</td>
</tr>
<tr>
<td>5 Electric Motor Group</td>
<td>4.4</td>
<td>20.8%</td>
<td>27.0</td>
</tr>
<tr>
<td>BLDC Motors</td>
<td>3.9</td>
<td>18.9%</td>
<td>27.2</td>
</tr>
<tr>
<td>Electronic Speed Controllers</td>
<td>0.5</td>
<td>1.9%</td>
<td>25.5</td>
</tr>
<tr>
<td>3 Fuselage</td>
<td>4.5</td>
<td>21.8%</td>
<td>21.1</td>
</tr>
<tr>
<td>Forward structure</td>
<td>1.2</td>
<td>5.8%</td>
<td>30.2</td>
</tr>
<tr>
<td>Center structure</td>
<td>2.4</td>
<td>11.6%</td>
<td>20.3</td>
</tr>
<tr>
<td>Air structure</td>
<td>0.9</td>
<td>4.4%</td>
<td>11.1</td>
</tr>
<tr>
<td>4 Landing gear group</td>
<td>2.1</td>
<td>10.2%</td>
<td>13.9</td>
</tr>
<tr>
<td>Upper Struts</td>
<td>0.55</td>
<td>2.7%</td>
<td>26.0</td>
</tr>
<tr>
<td>Lower Struts</td>
<td>0.65</td>
<td>3.2%</td>
<td>7.0</td>
</tr>
<tr>
<td>Landing Stilts</td>
<td>0.8</td>
<td>3.9%</td>
<td>13.0</td>
</tr>
<tr>
<td>Elastomeric Spring</td>
<td>0.1</td>
<td>0.5%</td>
<td>0.5</td>
</tr>
<tr>
<td>7 Package Dropoff System</td>
<td>0.55</td>
<td>2.7%</td>
<td>23.2</td>
</tr>
<tr>
<td>Servos</td>
<td>0.25</td>
<td>1.2%</td>
<td>13.3</td>
</tr>
<tr>
<td>Augers</td>
<td>0.11</td>
<td>0.5%</td>
<td>11.8</td>
</tr>
<tr>
<td>Drive Shafts and Gears</td>
<td>0.19</td>
<td>0.9%</td>
<td>11.8</td>
</tr>
<tr>
<td>Door structure</td>
<td>0.5</td>
<td>2.4%</td>
<td>11.8</td>
</tr>
<tr>
<td>6 Electronic System</td>
<td>5.36</td>
<td>27.9%</td>
<td>28.1</td>
</tr>
<tr>
<td>Sense and Avoid</td>
<td>2.53</td>
<td>12.3%</td>
<td>20.5</td>
</tr>
<tr>
<td>Parachute</td>
<td>2.75</td>
<td>13.3%</td>
<td>35.1</td>
</tr>
<tr>
<td>HUMS</td>
<td>0.03</td>
<td>0.1%</td>
<td>26.9</td>
</tr>
<tr>
<td>Gust Rejection</td>
<td>0.05</td>
<td>0.2%</td>
<td>13.9</td>
</tr>
<tr>
<td><strong>Empty weight</strong></td>
<td><strong>20.63</strong></td>
<td><strong>100%</strong></td>
<td><strong>24.4</strong></td>
</tr>
<tr>
<td><strong>Battery</strong></td>
<td>12.85</td>
<td></td>
<td>28.12</td>
</tr>
<tr>
<td><strong>Package</strong></td>
<td>5</td>
<td></td>
<td>11.8</td>
</tr>
<tr>
<td><strong>Gross weight</strong></td>
<td><strong>38.48</strong></td>
<td></td>
<td><strong>24.0</strong></td>
</tr>
</tbody>
</table>
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- MS Thesis (Chris Bogdanowicz) sorted out control issues
Quad-Rotor Bi-Plane Tailsitter for OSW Operations and Maintenance

• **Built 1/5<sup>th</sup> scale demonstrator**

**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
Quad-Rotor Bi-Plane Tailsitter for OSW Operations and Maintenance

- **MS Thesis (Chris Bogdanowicz)**
  
  [Online video](#) – built 1/5\textsuperscript{th} scale model in two weeks
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• Potential Collaboration
  - Combine with other means of advanced sensing on-blade, LIDAR

• Potential OSW Applications
  - Blade inspection, repair
  - Survey rotor wakes
  - Quick transport of parts
  - Paint tower?

• Team Approach
  - University
  - UAV Manufacturer
  - Government Labs
  - OEM / Operator

• Still to do
  - Determine possible sensor / maintenance packages
  - Station out at substation or on land?
  - Size vehicle for OSW applications
  - Build half-scale / full-scale vehicle?
  - How many vehicles?

  ➢ FAA regulations