Power System Redundancy Design Trends for All-Electric eVTOL Quadrotors

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Electric vertical takeoff and landing (eVTOL) vehicles promise to enable new Advanced Air Mobility (AAM) missions
- E.g., air taxi, medical transport, cargo delivery, and many more
- Reliability a key challenge for electrified propulsion (EP) and eVTOLs
- Failure rates of power system components predicted higher than vehicle requirements

Redundancy must be part of the solution to comply with FAR 25.1309
- No single failure in a safety critical system (i.e. EP power system) can result in a catastrophic failure condition
- The question is, how much redundancy to meet reliability requirements?
This work proposes analytical techniques to:
- Characterize power system redundancy design space
- Select mass optimal solutions subject to failure rate constraints

Studies focus on power system for NASA Revolutionary Vertical Lift Technology (RVLT), all-electric six passenger quadrotor concept vehicle
- Rotors are RPM controlled, direct drive
- Battery backed DC bus
Reliability defined as probability that 160 kW capability maintained at all rotors, at all times during mission

Enable safe emergency urban landing

Assume power system failure rate shall be $< 10^{-10}$ per flight hour

Support vehicle failure rate $< 10^{-9}$ per flight hour (EASA SC-VTOL-01)

Parameter assumptions generally consistent with previous RVLT work

Assume constant failure rates for components (exponential distribution)

$$R = e^{-\lambda T}$$

<table>
<thead>
<tr>
<th>Variable</th>
<th>Value</th>
</tr>
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<tbody>
<tr>
<td>Minimum Required Rotor Power for Hover (kW)</td>
<td>160</td>
</tr>
<tr>
<td>Mission Duration (h)</td>
<td>1</td>
</tr>
<tr>
<td>Pylon / Cable Length (m)</td>
<td>5</td>
</tr>
<tr>
<td>Electric Machine Specific Power (kW/kg)</td>
<td>13</td>
</tr>
<tr>
<td>Electric Machine Efficiency</td>
<td>0.96</td>
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<tr>
<td>Power Electronics Specific Power (kW/kg)</td>
<td>9</td>
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<tr>
<td>Power Electronics Device Efficiency</td>
<td>0.95</td>
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<tr>
<td>Battery Specific Energy (Wh/kg)</td>
<td>400</td>
</tr>
<tr>
<td>Battery Design Energy (kWh)</td>
<td>275</td>
</tr>
<tr>
<td>Nominal Battery Voltage ($V_{dc}$)</td>
<td>1000</td>
</tr>
<tr>
<td>Nominal Battery Efficiency at Full Load</td>
<td>0.94</td>
</tr>
<tr>
<td>Electric Machine Failure Rate (failures/hr)²</td>
<td>$10^{-6}$</td>
</tr>
<tr>
<td>Power Electronics Failure Rate (failures/hr)²</td>
<td>$5\cdot10^{-6}$</td>
</tr>
<tr>
<td>Battery Failure Rate (failures/hr)³</td>
<td>$3.45\cdot10^{-6}$</td>
</tr>
</tbody>
</table>


Study redundancy design problem for eVTOL power system
- Two objectives: System Mass and System Failure Rate (Reliability)
- Analysis in Electrical Power System-Sizing and Analysis Tool (EPS-SAT)
  - Available via Govt purpose license: https://software.nasa.gov/software/LEW-20017-1

Modeling and Analysis Approach

- Optimal design trend
  - Pareto front / set of non-dominated solutions
- Optimal solution
  - Minimum mass solution subject to reliability constraint
Logical partitioning is into primary and secondary power systems.

Redundancy for both can be “k-out-of-n”

- Primary: $n_1$ and $k_1$
- Secondary: $n_2$ and $k_2$

System reliability is product of primary and four secondaries

$$R_{k-out-of-n}(R, k, n) = 1 - \sum_{m=0}^{k-1} \binom{n}{m} (1 - R)^{n-m} R^m$$

$$R_{sys} = R_{pri} R_{sec}^4$$
Mass Modeling

- Mass of single component (non-redundant) calculated by dividing component rated power by the component assumed specific power (kW/kg)

- Assume that all $n$ parallel redundant components are sized for a fraction $f = 1/k$ times the nominal component rated power
  - Mass is then given by $nf$ times the nominal mass

\[
m_{1-out-of-1} = \frac{P_{rated}}{SpcPow}
\]

\[
m_{k-out-of-n} = nf m_{1-out-of-1}
\]

E.g.,

- “1-out-of-1”
  - $n=1$
  - $k=1$
  - $f=1$

- “2-out-of-3”
  - $n=3$
  - $k=2$
  - $f=1/2$

8
Exhaustive search over all valid solutions in $n_1, n_2, k_1,$ and $k_2$ from 1 to 4

- $n_1$ must be $\geq k_1$ and $n_2$ must be $\geq k_2$

Analysis approach

- Draw lines with a fixed primary power system redundancy design (fixed $n_1$ and $k_1$)
- Each marker represents unique secondary power system design ($n_2$ and $k_2$)

Example showing the mass versus reliability of a power system with non-redundant primary ($n_1 = k_1 = 1$) and varying secondary redundancy

- Non-redundant primary cannot meet reliability requirements as expected
- Trend regions of interest shown
Varying Primary and Secondary Redundancy Design

- Additional primary design curves
- Some suboptimal designs omitted
  - (e.g., 2002, 3003)
- Mass data for select designs
- 3004 primary is optimal feasible soln.
- 2003 is close runner up
  - 10% more mass than 3004
  - 2003 is more conventional, may be more attractive despite additional mass
Zooming in shows that 2004 is the mass optimal feasible design for the secondary power system.

Same for both 3004 and 2003 primary system designs.

Indicates that the secondary power system benefits from a higher degree of redundancy compared to the primary system.

Expected, since secondary strings contain two series components with a higher combined failure rate vs primary strings.
Baseline assumes RPM controlled rotors, no cross-shafting, however:

- Cross shafting (w collective control) adds reliability via mechanical power sharing
- While simpler, RPM control becomes difficult as rotor size (and inertia) increases

No clear winner in general:

- Depends on vehicle size/class

Conducted comparison study:

- Four independent groups of secondary strings
- vs one big collection of them
- Neglecting mass and reliability of gearing/shafting
- Predictions optimistic for cross shafting
Compare the architectures assuming a 2oo3 redundant primary for both

- Zooming out shows the cross shafting has somewhat better Pareto optimal trend
- Zooming in shows that cross shafting makes secondary system more reliable
  - Requires less redundancy allocation (3oo4 vs 2oo4) and 4% less mass vs baseline
- Additional mass/failure rate from cross shafting may or may not eliminate benefit
  - Even if benefit remains, difference may not be enough to matter (for this vehicle)
Conclusions

- Demonstrated integrated reliability and mass modeling in EPS-SAT
- Highlighted design trends for all-electric 6 passenger class quadrotor
  - Mass vs reliability as primary and secondary redundancy designs varied
- Predicted required level of redundancy adds 30-50% more mass vs non-redundant power system architecture
  - 3oo4p/2oo4s is optimal redundancy design for baseline (RPM control)
  - Followed closely by more conventional 2oo3p/2oo4s
- Cross shafting adds reliability and may improve optimal design trend
  - Not clear that difference is enough to override other concerns (control/inertia)
- Results and published approach may help budding eVTOL industry converge more quickly on redundancy designs to meet requirements
Future Work

➢ Modeling approach is fairly simplistic
  ➢ Fidelity could be added especially to mass models

➢ Analysis can also include maintainability
  ➢ Maintainability is huge factor in aircraft feasibility and operations cost