Combined Electric Aircraft and Airspace Management Design for Metro-Regional Public Transportation

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Outline

- Innovation: Hopper Aerial Transport Network
- Technical approach
- Results
  - Conceptual Design
  - Airspace Management Issues
  - Network Design and Simulation
  - Operations and Misc. Tech Issues
- Future Work & Tech Transition
The Innovation

- Investigate technical feasibility of electric aircraft to provide a solution to metro/regional public transportation

Hughes Helibus concept circa 1967 (Courtesy AHS International)
“Hopper” Metro/Regional Aerial Transportation System

- Rotorcraft with electric-propulsion
- Extremely short haul vehicles (<100nm)
- Network of vertiport stations in San Francisco Bay Area
- Different network topologies studied
- An evolutionary build-up of networks studied
Technical Approach

- Network Topology Definition Tool
- RotCFD & Misc.
- NDARC & Hopper Tool
- BaySim
- FACET
Conceptual Design: Hopper/Electric-Propulsion
Redesigned this section of the helicopter and observed effect on gross takeoff weight

Iterate until convergence

Initial Gross Takeoff Weight Guess

Fly Mission

Compute power and energy requirements

Size propulsion system components, compute new gross takeoff weight
NDARC (Phase I) and Stanford Tool (Phase II) Validation Comparison

<table>
<thead>
<tr>
<th>Weight (lbs)</th>
<th>Turboshaft (NDARC)</th>
<th>Turboshaft (Hopper)</th>
<th>Battery Electric (NDARC)</th>
<th>Battery Electric (Hopper)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fuel Weight</td>
<td></td>
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<tr>
<td>Scaled Weight</td>
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<tr>
<td>Passenger Weight</td>
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<tr>
<td>Fixed Weight</td>
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<tr>
<td>Motor/Engine Weight</td>
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<tr>
<td>Battery Weight</td>
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</tr>
</tbody>
</table>

Legend:
- Orange: Fuel Weight
- Turquoise: Scaled Weight
- Purple: Passenger Weight
- Green: Fixed Weight
- Red: Motor/Engine Weight
- Blue: Battery Weight
Ragone Plot: Battery Specific Power vs. Energy

Specific Power (kW/kg)

Specific Energy (W-h/kg)

\[ P_{sp} = 88.818 \times 10^{(-0.01533 \ E_{sp})} \]
\[ P_{sp} = 245.848 \times 10^{(-0.01072 \ E_{sp})} \]
\[ P_{sp} = 245.848 \times 10^{(-0.00763 \ E_{sp})} \]
\[ P_{sp} = 245.848 \times 10^{(-0.00478 \ E_{sp})} \]

- Li-Ion
- 2005 Li-S
- 2008 Li-S
- 2013 Li-S (Projected)
### Sizing Requirements

<table>
<thead>
<tr>
<th>Mission Requirements</th>
</tr>
</thead>
<tbody>
<tr>
<td>Cruise velocity</td>
</tr>
<tr>
<td>Cruise altitude</td>
</tr>
<tr>
<td>Disk Loading</td>
</tr>
<tr>
<td>L/De</td>
</tr>
<tr>
<td>Aircraft Figure of Merit</td>
</tr>
<tr>
<td>Number of passengers</td>
</tr>
<tr>
<td>Range</td>
</tr>
</tbody>
</table>

### Sizing Assumptions

<table>
<thead>
<tr>
<th></th>
<th>Gas</th>
<th>Battery</th>
<th>Hybrid</th>
<th>Fuel cell</th>
<th>Fuel Cell Hybrid</th>
</tr>
</thead>
<tbody>
<tr>
<td>Structural Weight fraction</td>
<td>0.42</td>
<td>0.331</td>
<td>0.37</td>
<td>0.42</td>
<td>0.37</td>
</tr>
<tr>
<td>Fixed Weight</td>
<td>3710</td>
<td>2660</td>
<td>3000</td>
<td>3200</td>
<td>3200</td>
</tr>
</tbody>
</table>
Sample Battery Electric Design Results (25 nm)

- \( W_{\text{gross}}_{2008} \approx 26,640 \text{ lbs.} \)
- \( W_{\text{gross}}_{2013} \approx 22,000 \text{ lbs.} \)
- \( W_{\text{gross}}_{2020} \approx 31,000 \text{ lbs.} \)
- Power and energy improvements make these configurations much more realizable in the near-term.
- Sizing loop diverges for Li-ion technology.

2013 predicted Li-S battery (500 W-h/kg, 1kW/kg)

2008 Li-S battery (336 W-h/kg, 0.67kW/kg)

Li-air near-term (2020 est) (1300W-h/kg, 0.66kW/kg)

Specific energy (Wh/kg)

Specific power (kW/kg)

Gross Takeoff Weight (lbs)
Battery research tends to focus on improving specific energy, sometimes at cost of specific power.

Current technology outperforms future battery trends for most hybrid configurations, because power constraints tend to dominate these design challenges.

The chart illustrates the projected gross takeoff weight (lbs.) of different hybrid configurations for a 30 passenger aircraft. The configurations include projected 2013 Li-S, 2008 Li-S, 2005 Li-S, Li-air, All Electric Li-S, All Electric Li-Air, and Gas Turbine.
Sample Fuel Cell Results

- Similar tradeoff between specific power and specific energy for fuel cell, although harder to quantify.

- Efficiencies for H₂ Fuel Cells usually ~30-60%.

- Recent technology improvements result in cascading weight benefits.

- 1999 technology (Psp~.4 kW/kg) results in gross takeoff weight ~300,000 lbs.
Serial Fuel Cell Hybrid Volume Breakdown (65 nm)
Weight Breakdown (25 nm)
Energy Usage Comparison (Full)

Takeoff Energy for Takeoff (kW-h) vs. Energy/nautical mile (kW-h/nm)

- Gas
- Battery
- Hybrid Turboshaft
- Fuel Cell
- Fuel Cell Hybrid

Energy for Takeoff (kW-h) is represented by blue bars, and Energy/nautical mile (kW-h/nm) is represented by yellow bars.
Gross Takeoff Weight Comparison

- Gas
- Battery
- Hybrid Turboshaft
- Fuel Cell
- Fuel Cell Hybrid

Gross Takeoff Weight (lbs.)

- 25 nautical miles
- 65 nautical miles
Airspace Management Issues
Bay Area Traffic Flows
ATM Focus

• Generate Hopper flight plans to reduce potential conflicts with background traffic
  • Reduce controller workload by avoiding heavily used airspace
  • Adjust flight plans based on time of day as background traffic shifts
• Investigate emerging technologies which could enable Hopper
Traffic Density Maps

Time: 08:00 to 09:00 PST
Altitude 3000 ft to 5000 ft
Fuel: 38.18 kg, Traffic: 31.75 AC–min/hr
Time-of-Day Dynamic Flight Path Routing

- Time: 07:00 to 08:00 PST
  - Altitude: 4000 ft to 6000 ft
  - Fuel: 38.31 kg, Traffic: 41.25 AC–min/hr

- Time: 08:00 to 09:00 PST
  - Altitude: 3000 ft to 5000 ft
  - Fuel: 38.18 kg, Traffic: 31.75 AC–min/hr

- Time: 09:00 to 10:00 PST
  - Altitude: 3000 ft to 5000 ft
  - Fuel: 38.93 kg, Traffic: 45.75 AC–min/hr

- Time: 07:00 to 10:00 PST (specific areas with varying traffic and fuel consumption)

Aircraft—minutes per hour
Traffic Interaction Decrease

Time: 07:00 to 10:00 PST

Traffic Percent Difference Compared to Great Circle

Allowable Fuel Increase [%]

07:00 to 08:00
08:00 to 09:00
09:00 to 10:00
## Domain

<table>
<thead>
<tr>
<th>Domain</th>
<th>Emerging technologies</th>
</tr>
</thead>
<tbody>
<tr>
<td>Communication</td>
<td>Widespread Data Link with limited human oversight</td>
</tr>
<tr>
<td>Ground operations</td>
<td>Precision Departure Release Capability (PDRC)</td>
</tr>
<tr>
<td>Terminal airspace</td>
<td>Traffic Management Advisor (TMA)</td>
</tr>
<tr>
<td></td>
<td>Airborne Dependent Surveillance–Broadcast (ADS-B)</td>
</tr>
<tr>
<td>Weather avoidance planning</td>
<td>Dynamic Weather Routes (DWR)</td>
</tr>
<tr>
<td>Enroute</td>
<td>Airborne Dependent Surveillance–Broadcast (ADS-B)</td>
</tr>
<tr>
<td></td>
<td>Strategic ground-based 4D trajectory planning</td>
</tr>
<tr>
<td></td>
<td>Tactical airborne 4D trajectory execution</td>
</tr>
</tbody>
</table>
Network Design and Analysis
BaySim: Discrete Element Simulation

- Individual passenger and flight agents
- Fast-time simulation of surface and air travel
- PX transition through 12+ daily states from
  - home – work – home
  - Queue up for flights
- Heuristic rules
- Gaussian inputs
- Creates estimates of demand for flights and subsequent inputs for fleet optimization
Network Build-out

- Phase II considers practical network expansion
- Replace Phase I “n x n” network with “ring-spoke”
- How many daily passengers?
  - “Tech Industry” employs 386K workers in Bay Area
  - CalTrain serves roughly 42K passengers per day
  - BART serves roughly 370K passengers per day
- PX Distribution, starting times, workday length
  - 65% Day  4 to 10 AM  7 to 9 hours
  - 20% Swing  1 to 6 PM  7 to 9 hours
  - 5% Graveyard  9 to 2 AM  7 to 9 hours
  - 10% Other  8 AM to 3 PM  4 to 5 hours
Population Improvements

- Extensive use of Census and Zip Code databases
  - Zip codes provide appropriate geographic granularity
  - Zip and Census data readily available via websites (i.e., FREE!)
  - 2010 Census data includes commute and business employment demographics
- Populations within zip codes created via iterative process according to several constraints:
  - Homesite network node != Worksite network node
  - Estimated Flying time < Estimated Driving Time
  - Number of workers at jobsite scaled and limited using local zip code employment statistics
  - Residents and worksites within user-specified distance from station nodes
Dijkstra and Speed Tables

• Each passenger chooses flights attempting to minimize transit time between home and work (including estimates of queue times)

• Dijkstra leg weights (transit times) updated immediately after each flight arrival and best route made available to each passenger before queuing

• Leg transit times from hourly table lookup, based on routes that minimize traffic conflicts with current SJC, SFO, and OAK patterns
BaySim Phase II Sample Movie
Network Statistics

Number of Flights per Day

Average Load Factor

Average PX Queue Delay in Minutes

Average Flight Departure Spacing Delay in Minutes

Results with minimum departure spacing of 60 seconds

Network Energy Usage

Total Energy Use in kW-h: Gas

Total Energy Use in kW-h: Battery

kW-h/(PX-mile): Gas

kW-h/(PX-mile): Battery

Results with minimum departure spacing of 60 seconds
Operations & Misc. Tech Issues
Vertiport Station Operations

Integration with multi-modal public transit

Multi-level, accessible by aircraft-elevator, vehicle storage/hangers

Battery, or energy storage device, depot for recharging, temporary storage, or transfer for disposal

Automated vehicle servicing (e.g. battery or energy storage device, swap-out or recharging)

Morphing, or adaptive, structures for jetblast deflectors, jetways, etc.

All-weather, precision-navigation, network (air traffic) control

Automated service tugs and/or alternate surface mobility for vehicle staging
Rotor Wake Interactions
Preliminary Noise Assessments
• Some of the electric-propulsion models developed are finding their way into Stanford’s SAUVE vehicle conceptual design tool and NASA’s NDARC

• Two NASA TM’s are being drafted for publication

• Internal electric-propulsion discussion within ARMD Rotary-Wing project

• Hopper helps make a case for vehicle/systems autonomy research
Hopper Capabilities

Hopper Vehicle Capability Development Timeline

- Demonstrated to TRL 6
- "Electric Rotorcraft" demonstration
  - Endurance: ½-hr
  - Payload: 1-2 PAX
  - Batteries/power electronics drive not only propulsion electric-motor but fixed and rotating electromechanical actuators as well

- Medium-Lift Electric Demonstration
  - Endurance: 1-2 hours
  - Payload: 6-15 PAX
  - Optionally-piloted/monitored, i.e. semi-autonomous

- Heavy-Lift (Hopper) Demonstration
  - Endurance: 1-2 hours
  - Payload: 15-30 PAX
  - Advanced flight controls and active rotor technology for low noise/vibration for passenger/community acceptance
  - Fully autonomous with dynamic route planning
  - Integration with simulated vertiport station for automated charging/battery swaps/servicing
Concluding Remarks

- Large numbers of medium- to large- A/C are required to serve assumed passenger levels
- Flying and VTOL are energy intensive transportation modes for short distances and, yet, represent a potential way to bypass urban surface transportation congestion
- While originally conceived as "light infrastructure" (no new roads/rail-lines), the vertiport station power requirements and real estate footprints of ramps and terminals may require require more infrastructure than initially anticipated when large numbers of aircraft are involved
  - Trucks will be required if charged batteries are to be delivered to stations (and discharged batteries removed for offsite recharging);
  - high-power electrical transmission must be provided to stations if charging is onsite.
Concluding Remarks, Cont.

- Acoustics and other over-flight issues will require technology innovations and public/neighborhood outreach. Will neighborhood populations accept a new type of traffic noise?
- The development of Discrete Event Simulations has value not only in producing quantitative design tradeoff information, but also in 1) uncovering and examining detailed operational policies surrounding transportation networks, and 2) understanding behavioral and demographic issues for the populations they are intended to serve.
• May be best to operate network independently of other air transport that transits outside of the Bay Area, instead of “actively intermeshing”

• Emerging technological and procedural advances, currently being proposed under the Next Generation Air Transportation System (NextGen), could be leveraged to facilitate the realization of the Hopper concept.
Concluding Remarks, Cont.

• Relatively near-term battery / hybrid / fuel cell technologies could make these short range vehicles realizable within the next 10 years.

• Near-term battery technology (500-600 W h / kg at reasonable power densities) will satisfy power and energy requirements for these short range vehicles: more advanced Li-air batteries will not lead to further weight reductions.
Concluding Remarks, Cont.

- Discrete event simulations and schedule optimizations reveal the possibility of carrying a substantial daily passenger load within the Bay Area.
- Study has identified challenges in integrating Hopper flights and Bay Area commercial traffic that can be partially tackled with Hopper aircraft time-of-day dynamic routing as well as NextGen technologies.