Regulating arrival UAV flows between the AirMatrix and the droneport using a dynamic carousel circuit

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Agenda

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2) Concepts
   - Droneport
   - Dynamic carousel circuit
3) Research framework
4) Methodology
   1) Simulation
   2) Optimization model
5) Results
6) Conclusion
Background

- The rise of drone operations
- Potential hazards of drone operations in urban area
  - Safety issue (during approach, landing, and takeoff phases)
  - Airspace congestion issue
- Infrastructure for approach and departure drones

Figure 1: Impact on Airspace of manned vs. unmanned operations (statistic estimated by SESAR) [1]

Background

• The rise of drone operations

• Potential hazards of drone operations in urban area
  – Safety issue (during approach, landing, and takeoff phases)
  – Airspace congestion issue

• Infrastructure for approach and departure drones

Figure 2: Accidents by flight phase as a percentage of all accidents (1999-2019) [2]

Background

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Figure 3: Distribution of accidents and incidents of Remotely Piloted Aircraft System (RPAS) vs. commercial air transportation

Background

- The rise of drone operations
- Potential hazards of drone operations in urban area
  - Safety issue (during approach, landing, and takeoff phases)
  - Airspace congestion issue
- Infrastructure for approach and departure drones

How can we provide the secure use of low-altitude airspace during approach and departure phases, for a wide range of applications of drones?

Droneport

Figure 5: Droneport illustration

Figure 6: Carousel circuit surrounding the droneport

Dynamic Carousel Circuit

Higher demand → Larger capacity → Larger carousel circuit

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Research framework

Input
- Demand forecast
  - E-commerce demand
  - Daily commute demand
- Weather data (Future work)

Simulation
- Approaching phase
  - AirMatrix network
- Queuing phase
  - Circular motion along carousel circuit
- Landing phase
  - Carousel circuit
  - M/M/c queuing system
  - Landing gate

Optimization algorithm

Outdoor infrastructure
- Dynamic carousel circuit
- Emergency landing area
- Outdoor navigation system
- Warehouse...

Indoor infrastructure
- Landing gate
- Indoor navigation system
- Taxiways
- Landing pads & charging pads...

Droneport operation
Simulation

1. Initialization
Generating the arrival time, the assigned landing gate, and the residual battery level that follow a Poisson process, random generation, and a normal process respectively

\[
\left\{ \left( t_{v,l}^a, G_v, B_v^l \right) \right\}_{v=1}^{V_e},
\]

\[
t_{(v+1),l}^a = t_{v,l}^a + u_{(v+1)},
\]

\[
G_v = n, n \in N_g.
\]

2. Approaching phase
The mainstream of traffic is from the AirMatrix. The drone will approach the droneport in the same orientation as its assigned landing gate.

Figure 6: Carousel circuit surrounding the droneport
Simulation

2. Approaching phase

This phase selects available virtual blocks to the approaching drones from the AirMatrix and minimizes the total travel time and the battery consumption. Hungarian algorithm is implemented to solve this assignment problem.

\[
H(t) = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1Y} \\ h_{21} & h_{22} & \cdots & h_{2Y} \\ \vdots & \vdots & \ddots & \vdots \\ h_{X1} & h_{X2} & \cdots & h_{XY} \end{bmatrix} = [h_{xy}] \tag{4}
\]

\[
h_{xy} = \tau_{xy} + B_x', \tag{5}
\]

\[
x = N_v'(t)(1), N_v'(t)(2), \ldots N_v'(t)(X), \tag{6}
\]

\[
y = N_b'(t)(1), N_b'(t)(2), \ldots N_b'(t)(Y), \tag{7}
\]

\[
N_v'(t) = \{\{v, l\}, l \in N_a : \alpha_i^v(t) = 1, \forall v \in V_a\} \tag{8}
\]

\[
N_b'(t) = \{j \in N_b : \alpha_j^v(t) = 0, \forall v \in V_a\} \tag{9}
\]
Simulation

3. Queuing phase
The carousel circuit acts as an approaching pattern to reduce the collision risk.

4. Landing phase
Each landing gate is equipped with a simple M/M/c queuing system, which has c servers with arrivals following a Poisson process and service times observed to be an exponential distribution.

Figure 8: Geometric depiction of the cubic trajectory from the metering fix Point 6 on the carousel circuit to the landing Gate 6.
Simulation

5. Residual endurance estimation model

A residual endurance estimation model is developed based on the model designed by Hwang et al. [9]. The capability of this model is expanded to calculate the residual endurance of a multirotor UAV with the remaining battery level as an input.

Optimization Model

Output: optimum circuit radius, flight speed along the carousel circuit, and circuit altitude.

Constraints:

- All the drones from the AirMatirx network can join the carousel circuit without hovering above the droneport airspace. The value of fail means the number of drones that are not assigned to any available virtual blocks during approaching phase.
- The remaining battery levels of the landed drones $B_r'$ are higher than 5%.

Objective function

$$
\min \sum_{v \in V_c} \tau_{v,lm_v} + \tau_{v,m_v m_g} + \tau_{v,m_g n} + \beta \cdot \left( B_{v,lm_v}' + B_{v,m_v m_g}' + B_{v,m_g n}' \right) \\
\text{s.t. fail} = 0, \\
B_r' > 5%.
$$
Results

Table I. Important parameters employed in the simulation

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Symbol</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Time separation</td>
<td>$t_s$</td>
<td>3 sec</td>
<td></td>
</tr>
<tr>
<td>Landing gate service time</td>
<td>$t_g$</td>
<td>1 sec</td>
<td></td>
</tr>
<tr>
<td>Flight speed (phase 1, 3)</td>
<td>$U_{at}$</td>
<td>10 m/s</td>
<td></td>
</tr>
<tr>
<td>AirMatrix altitude</td>
<td>$h_a$</td>
<td>70 m</td>
<td></td>
</tr>
<tr>
<td>Landing gate altitude</td>
<td>$h_g$</td>
<td>40 m</td>
<td></td>
</tr>
<tr>
<td>Total arriving drones</td>
<td>$D$</td>
<td>5000</td>
<td></td>
</tr>
<tr>
<td>Nominal capacity</td>
<td>$C_0$</td>
<td>32000 mAh</td>
<td></td>
</tr>
<tr>
<td>Rated discharge time</td>
<td>$T_0$</td>
<td>0.2 hr</td>
<td></td>
</tr>
<tr>
<td>Battery voltage drop gradient</td>
<td>$k$</td>
<td>1.2</td>
<td>V/hr</td>
</tr>
<tr>
<td>Fully charged voltage</td>
<td>$V_0$</td>
<td>49 V</td>
<td></td>
</tr>
<tr>
<td>Standard voltage</td>
<td>$V_S$</td>
<td>22.2 V</td>
<td></td>
</tr>
<tr>
<td>Peukert’s coefficient</td>
<td>$p$</td>
<td>1.05</td>
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</tr>
<tr>
<td>Discharge fraction</td>
<td>$\lambda$</td>
<td>0.7</td>
<td></td>
</tr>
</tbody>
</table>

Table II. Simulation results under different arrival rates

<table>
<thead>
<tr>
<th>Arrival rates (drones/hr)</th>
<th>Circuit radius (m)</th>
<th>Flight speed (m/s)</th>
<th>Altitude (m)</th>
<th>Fails</th>
</tr>
</thead>
<tbody>
<tr>
<td>Optimized</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>5000</td>
<td>70.709</td>
<td>3.0039</td>
<td>12.804</td>
<td>0</td>
</tr>
<tr>
<td>5000</td>
<td>60</td>
<td>3</td>
<td>12</td>
<td>921</td>
</tr>
<tr>
<td>6000</td>
<td>70.709</td>
<td>3.0039</td>
<td>12.804</td>
<td>0</td>
</tr>
<tr>
<td>7000</td>
<td>70.709</td>
<td>3.0039</td>
<td>12.804</td>
<td>467</td>
</tr>
</tbody>
</table>

Peak hour demand: 14360

3-level circuit

Arrival rate used in simulation: 5000

Figure 9. The drone service curve (a) with optimized dynamic carousel circuit; (b) without optimized dynamic carousel circuit.
Conclusion

• Droneport
  – a service facility providing a safe operation environment for heterogeneous drones
  – diverging from a recent trend, the design of droneport focused more on air traffic control and regulation enforcement

• Dynamic carousel circuit
  – act as a traffic pattern that manages drones coming in and coming out of the droneport
  – adjustable radius based on predicted demand

• Carousel circuit simulation model
  – equipped with a residual endurance estimation model and cubic trajectory planning
  – able to find an optimum circuit radius according to current demand

Future work

• Multi-level and multi-lane circuits with transition rules applied between each level
• Weather uncertainty
Q&A

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