An Innovative Algorithm to Estimate Risk Optimum Path for Unmanned Aerial Vehicles in Urban Environments

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Unmanned Aerial Vehicles

- **Unmanned Aerial Vehicles (UAVs)** are widely used in recent years
- The technology of UAVs is growing very fast

In next future, UAVs will be involved in **Smart Cities**
Problem

- Urban areas are a critical scenario
- High population density
- **Safety** must be enforced
An innovative algorithm to estimate risk optimum path for UAVs in urban area

It consists in two phases:

- Risk-map generation
- Risk-aware path planning
Risk-map: definition

- The risk-map assesses the risk in the navigation area
- Two-dimensional cell-based map
- Each cell represents a georeferenced location with an associated risk value
The risk-map is defined considering 4 layers:

- Population Density layer
- Sheltering Factor layer
- Obstacle layer
- No-Fly Zone layer
The risk value defines the risk of flying over the cell.

The risk is computed considering all values inside the hazardous area. With rotary wing aircraft, we assume a ballistic descent:

\[
\begin{align*}
\dot{x} &= -\frac{1}{2} \rho \dot{x}^2 \frac{SC_D}{m} \\
\dot{y} &= -\frac{1}{2} \rho \dot{y}^2 \frac{SC_D}{m} - \frac{g}{m}
\end{align*}
\]

With fixed wing aircraft, we assume an uncontrolled glide descent:

\[x_h = \psi h\]
The risk is defined as the frequency per hour of casualty $f_F$

The risk is computed with a probabilistic risk assessment approach:

$$f_F = A_{exp} \cdot D_p \cdot P(\text{fatality|failure}) \cdot f_{GIA}$$

- $A_{exp}$ is the area exposed to crash
- $D_p$ is the population density
- $P(\text{fatality|failure})$ is the probability that the hit person suffers fatal injuries
- $f_{GIA}$ is the rate of ground impact accidents
We introduce a new formulation to compute the area exposed to crash $A_{exp}$

**Old [Smith, 2000]**

$$A_{exp}^{old}(\gamma) = 2(r_p + r_{uav}) \frac{h_p}{\tan(\gamma)} + \pi(r_p + r_{uav})^2$$

**New**

$$A_{exp}^{new}(\gamma) = \pi(r_p + r_{uav})^2 \sin(\gamma) + 2(r_p + r_{uav})(h_p + r_{uav})\cos(\gamma)$$
Risk-map: crash area

\begin{align*}
A_{\text{exp}} & \quad \text{[m}^2]\end{align*}
**Risk-map: probability of fatality**

\[ P(\text{fatality}|\text{exposure}) = \frac{1-k}{1-2k+\sqrt{\frac{\alpha}{\beta} \frac{\beta}{E_{imp}}}}^{\frac{3}{p_s}} \]

with \( k = \min\left(1, \left[\frac{\beta}{E_{imp}}\right]^{\frac{3}{p_s}}\right) \)

- \( p_s \) is the sheltering factor
- \( E_{imp} \) is the kinetic energy at impact
- \( \alpha \) is the energy required for a fatality of 50%
- \( \beta \) is the energy to have a casualty when \( p_s \) converges to zero

<table>
<thead>
<tr>
<th>Sheltering Factor</th>
<th>Typical Area</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>No obstacles</td>
</tr>
<tr>
<td>2.5</td>
<td>Sparse trees</td>
</tr>
<tr>
<td>5</td>
<td>Trees and low buildings</td>
</tr>
<tr>
<td>7.5</td>
<td>High buildings</td>
</tr>
<tr>
<td>10</td>
<td>Industrial area</td>
</tr>
</tbody>
</table>
Risk-aware Path Planning: definition

The risk-aware path planning searches for the optimal path minimizing the risk to the population

- It considers the risk values in the risk-map
- It is a sample-based algorithm based on the Optimal Rapidly-exploring Random Tree (RRT*)
- RRT* constructs an exploration tree, minimizing the motion cost
The risk to the population is proportional with the flight time.

The motion cost considers both risk values and flight time.

\[ c_m(n_i) = c_m(n_{i-1}) + \int_{n_{i-1}}^{n_i} r(n) \, dt \]
\[ c_m(n_i) = c_m(n_{i-1}) + \frac{r(n_{i-1}) + r(n_i)}{2} \Delta t(n_{i-1}, n_i) \]
Results: risk-map

- uniform population density = 6900 people/km²
- flight altitude = 30 m

<table>
<thead>
<tr>
<th>Specific</th>
<th>3DR Iris+</th>
<th>Parrot Disco</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Quadroter</td>
<td>Fixed wing</td>
</tr>
<tr>
<td>Mass (kg)</td>
<td>1.282</td>
<td>0.75</td>
</tr>
<tr>
<td>Radius (m)</td>
<td>0.35</td>
<td>0.575</td>
</tr>
<tr>
<td>Cruise speed (m/s)</td>
<td>10</td>
<td>12.5</td>
</tr>
</tbody>
</table>
Results: risk-map

Iris+: risk-map

Disco: risk-map

f_r (h⁻¹)

1.2 \times 10^6

3.0 \times 10^7

OBS NFZ

7.0 \times 10^7

45.07° N 7.66° E 7.67° E

45.06° N 7.66° E 7.67° E
Results: minimum risk path

<table>
<thead>
<tr>
<th>Vehicle</th>
<th>Solve time (s)</th>
<th>Flight time (s)</th>
<th>Path length (m)</th>
<th>Motion cost</th>
<th>Average risk (h⁻¹)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Iris+</td>
<td>5.0</td>
<td>114.237</td>
<td>1142.372</td>
<td>1.161⋅10⁻⁸</td>
<td>5.072⋅10⁻⁷</td>
</tr>
<tr>
<td>Disco</td>
<td>5.0</td>
<td>80.544</td>
<td>1006.796</td>
<td>1.883⋅10⁻⁸</td>
<td>8.416⋅10⁻⁷</td>
</tr>
</tbody>
</table>

Equivalent Level of Safety (ELOS) = 1 ⋅ 10⁻⁶ h⁻¹
Conclusions (I)

- The risk-map quantifies the risk of the navigation area and identifies the area where the flight is not allowed.
- Each map cell defines the risk level of flying over the represented location.
- The risk-aware path planning seeks for the minimum risk path in the risk-map.
- The combination of risk-map and risk-aware path planning defines a safe flight mission.
Conclusions (II)

- The proposed approach is a very promising tool, because it is able to define safe flight operations, with a focus on urban environments and public safety.

- Future works include the improvement of the risk assessment, considering different descent events and a more realistic model.

- Also, the path planning can be improved considering kinodynamic constraints and the adaptation to tridimensional environments.
THANK YOU FOR YOUR ATTENTION!

FOR ANY QUESTIONS:
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