A Connectivity Aware Path Planning for a fleet of UAVs in an Urban Environment

Nouman Bashir, Saadi Boudjit, and Gabriel Dauphin

Monday, 16 December

Problem statement

Safety as the main concern

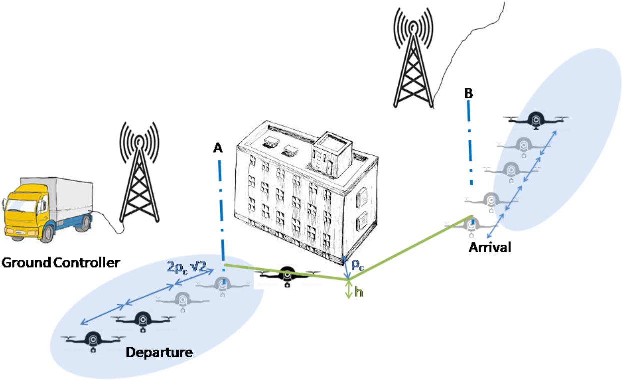


Table of Contents

1. Description of the proposal
1.1 Path planning problem
1.2 Using safe distance to prevent UAV-obstace collision
1.3 Fleet of UAVs

2. Introducing the discussion
2.1 Issues that could be solved
2.2 Questionning the use cases

1.1. Path planning as an optimization problem

- $\mathcal{O}$ set of obstacles
- Ω set of non-obstacle points
- $\mathtt{A}$ Departure
- $\mathtt{B}$ Arrival
- $\mathcal{P}$ Path starting in $\mathtt{A}$ and finishing in $\mathtt{B}$

`Safety remains the main concern`

$$\mathbb{P}_1 : \quad \begin{cases} \text{Find } \mathcal{P} \\ \text{Minimizing length}\,(\mathcal{P}) \\ \text{Subjected to } \mathcal{P} \subset \Omega \end{cases}$$

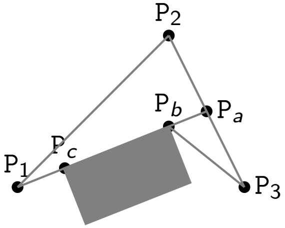
$\mathbb{P}_1$ is feasible if $\mathtt{A}, \mathtt{B} \in \Omega$ and Ω is connected.

1.1. Obstacles are represented by their corners

- $\text{Corner}(\mathcal{O})$ corners of all obstacles
- $\mathcal{P} = \bigcup_{k \leq K} \overline{\text{P}_k \text{P}_{k+1}}$

$$\mathbb{P}_2 : \quad \begin{cases} \text{Find } \text{P}_k \\ \text{Minimizing } \sum_{k \leq K} \text{P}_k \text{P}_{k+1} \\ \text{s.t. } \text{P}_k \in \text{Corner}(\mathcal{O}) \end{cases}$$

$\mathbb{P}_2$ is equivalent to $\mathbb{P}_1$.

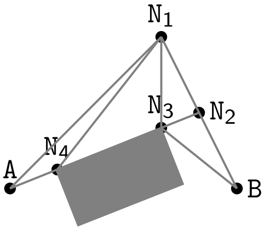


Only for obstacles modeled as polygons.

1.1. Using the Dijkstra algorithm

Defining a graph

- $\mathcal{N} = \text{Corner}(\mathcal{O})$
- $(\texttt{N}_1, \texttt{N}_2) \in \mathcal{E} \Leftrightarrow \overline{\texttt{N}_1\texttt{N}_2} \in \Omega$
- $\mathcal{W}(\texttt{N}_1, \texttt{N}_2) = \texttt{N}_1\texttt{N}_2$



Dijkstra algorithm

- Repeat with BFS order
  - Discover neighboring connection
  - Update minimal distance
  - store previous node

1.2. Using a safe distance

Notations

- ρ_C safe distance
- $\mathtt{V}_t$ prescribed position at time t
- $\mathtt{M}_t$ true position of UAV at time t
- $\mathcal{D}(\mathtt{N}, \mathtt{N}') = \mathtt{NN}'$ Euclidean distance

What ρ_C models

- Trajectory overshoot
- Position uncertainty
- Obstacle's location uncertainty

Navigation system

$$\mathtt{M}_t\mathtt{V}_t < \rho_C$$

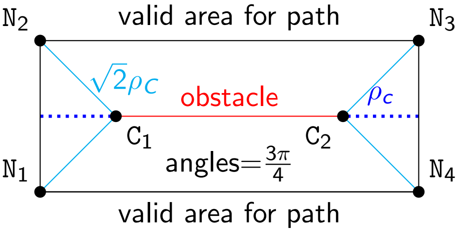
Path constraint

$$\mathcal{D}(\mathcal{P}, \mathcal{O}) \geq \rho_C$$

$$\mathtt{M}_t\mathtt{V}_t < \rho_C \text{ and } \mathcal{D}(\mathcal{P}, \mathcal{O}) \geq \rho_C \quad \Rightarrow \quad \mathtt{M}_t \in \Omega$$

Notations

- $\overline{C_1C_2}$ obstacle
- C_1, C_2 corners
- N_1, N_2, N_3, N_4 interest points



Suboptimal solution

trade-off: sharper turn $\leftrightarrow$ more distant interest points

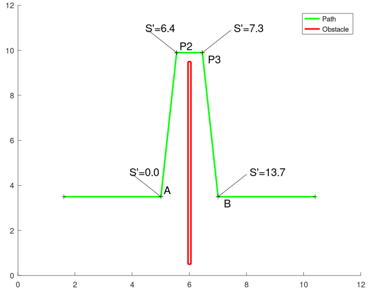
Notations

- $$L_k = \sum_{k'+1 \le k} \mathtt{P}_{k'}\mathtt{P}_{k'+1}$$
- $$\overrightarrow{\mathtt{R}}_{\mathtt{N}}^{\mathtt{N}'}(s) = \begin{cases} 0 & \text{if} \quad s \le 0 \\ s\overrightarrow{\mathtt{NN}'} & \text{if} \quad s \in [0,1] \\ \overrightarrow{\mathtt{NN}'} & \text{if} \quad s \ge 1 \end{cases}$$

Prescribed position

$$\mathtt{V}_t = \mathtt{A} + \sum_k \overrightarrow{\mathtt{R}}_{\mathtt{P}_k}^{\mathtt{P}_{k+1}} \left(\frac{S_t - L_k}{L_{k+1} - L_k} \right)$$

with $S_t = vt$ or $= \int_0^t v(\tau)\, d\tau$ (varying speed).



1.3. New problem statement

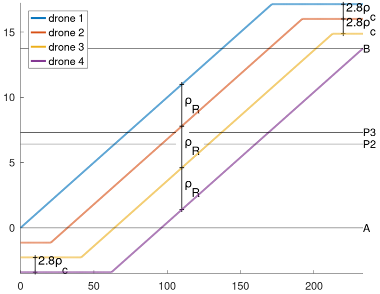
Notations

- N number of UAVs
- V_{nt} prescribed position of the n^{th} UAV.

Minimize N

subjected to

- at least one UAV reaches $\mathtt{B}$
- UAV-obstacle collision avoidance
  $$\mathcal{D}\left(\mathtt{V}_{nt}, \mathcal{O}\right) \geq \rho_C$$
- avoid UAV-UAV collision avoidance
  $$\mathcal{D}\left(\mathtt{V}_{nt}, \mathtt{V}_{n+1,t}\right) \geq 2\rho_C$$
- faultless radio-connectivity
  $$\begin{cases} \mathcal{D}\left(\mathtt{V}_{nt}, \mathtt{V}_{n+1,t}\right) \leq \rho_R \text{ and} \\ \left(\mathcal{D}\left(\mathtt{A}, \mathtt{V}_{1t}\right) \leq \rho_R \text{ or} \right. \\ \quad \left. \mathcal{D}\left(\mathtt{B}, \mathtt{V}_{1t}\right) \leq \rho_R\right) \end{cases}$$

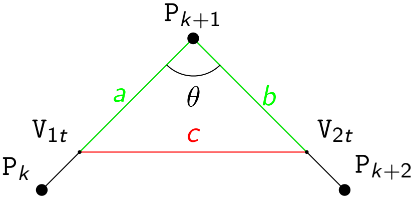


1.3. New path bending constraint

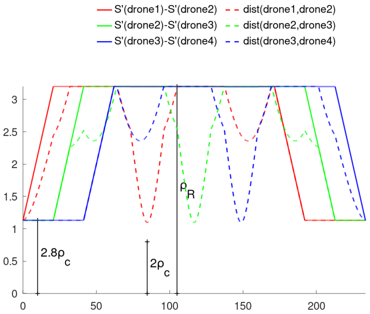
$$\left|\left\langle \overrightarrow{\mathtt{P}_k\mathtt{P}_{k+1}}, \overrightarrow{\mathtt{P}_{k+1}\mathtt{P}_{k+2}} \right\rangle\right| \leq \frac{\pi}{2}$$

$$\Rightarrow \left[\begin{array}{c} |S_{nt} - S_{n+1,t}| \geq 2\rho_C\sqrt{2} \\ \Rightarrow \mathtt{V}_{nt}\mathtt{V}_{n+1,t} \geq 2\rho_C \end{array} \right]$$

where $S_{nt} \approx S_t - (n-1)(\rho_R - 2\rho_C)$



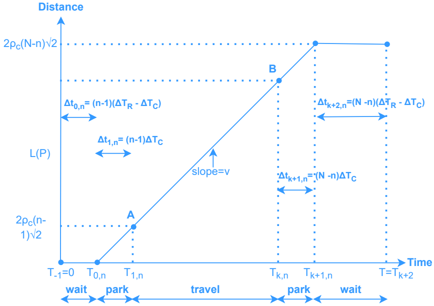
$$\theta \geq \frac{\pi}{2} \Rightarrow c \geq \frac{a+b}{\sqrt{2}}$$



ρ_C models also time uncertainty

- Departure and arrival (angles and distance)
- No self-crossing path are permitted (minimal length of line segments)
- Adapt Dijkstra algorithm (w.r. to supplementary constraints)
- Necessity to organize the energy shortage return
- Necessity to address the failure cases
- Extension to 3D

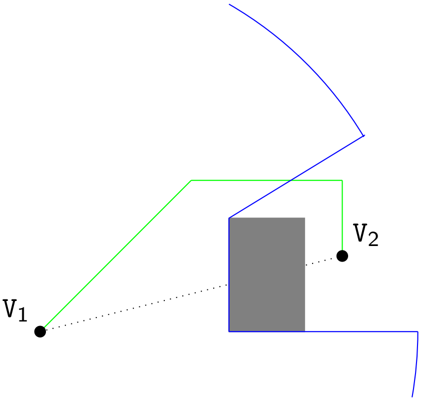
- Adapt to real-time control system



Oversimplified assumption

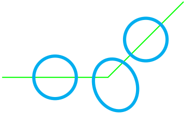
$\mathtt{M}_{nt}\mathtt{M}_{n+1,t} \leq \rho_R \Rightarrow$ communication

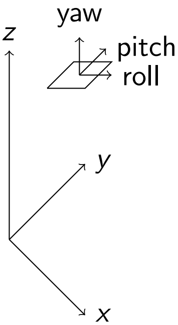
- Decrease ρ_R s.t. the assumption remains true
- Adapt the threshold on $\mathtt{M}_{nt}\mathtt{M}_{n+1,t}$ and on $|S_{nt} - S_{n+1,t}|$ to the local position.



Following a suggestion of Amine Mouhamed OUAMRI

Take into account the overshoot





- perfect roll, pitch and even yaw.
- high speed in $\frac{d}{dt}x$, $\frac{d}{dt}y$ and $\frac{d}{dt}z$.

- z depends on obstacles
- High uncertainty on x and y.
- Delay between orders and action
- Battery issue (low capacity and r.o.of.o)

Experiences done by Amine Mouhamed OUAMRI

Low-cost UAVs could be inappropriate

2.2. Adapting to unknown or moving obstacles

Obstacles ⇒ Sensors ⇒ Path Planning ⇒ Navigation System

- A necessity in outdoor applications
- Very challenging (birds, wind turbines)

- Safety
- Cost
- Regulations will appear

2.2. Are there convincing use cases?

1. What can UAVs do?
    - witness
    - communicate
    - high cost of the payload
2. Other technologies (often indoor)
    - Deploying fixed sensors
    - Articulated robot
    - Pick and place robot
    - Wheeled robot
3. Safety, an important issue $P[_{\text{accident}}] < 10^{-4}$?
    - cost/benefit viewpoint
    - except for military applications

Let the discussion start!