Robust autonomous landing of fixed-wing UAVs in wind

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Half time report

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Problem description

Research questions:

1. How can sampling-based motion planning techniques be used to generate landing sequences for fixed-wing UAVs?
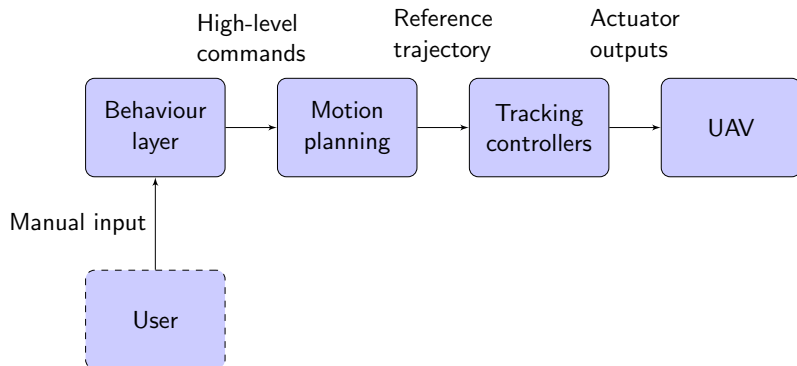2. How can safe landings!!! be guaranteed when taking wind effects into account?

Scope

Figure 1: Components of a general autonomous system

Kinematic model

$$\dot{x}_N = \cos\psi + \cos \tag{1}$$

$$\dot{y}_E = \sin\psi + \sin \tag{2}$$

$$\dot{\psi} = \frac{g}{-}\tan\phi \tag{3}$$

$$\dot{\phi} = f_\phi(\phi - \phi^c) \tag{4}$$

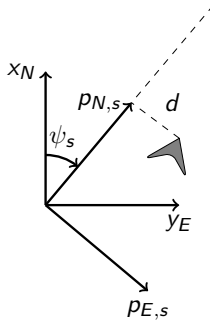# Straight path following in wind

Figure 2: Coordinate frame for straight path following

Straight path following in wind (contd)

$$\dot{d} \equiv \dot{p}_{E,s} = \sin(\psi - \psi_s) + \sin(-\psi_s) \tag{5}$$

$$\dot{\psi} = \frac{g}{} \tan \phi \tag{6}$$

$d \approx 0$, $\dot{d} \approx 0$ means that $\sin(\psi - \psi_s) + \sin(-\psi_s) = 0$ so

$$\equiv -\arcsin\left(\ \sin(-\psi_s)\right) + \psi_s \tag{7}$$
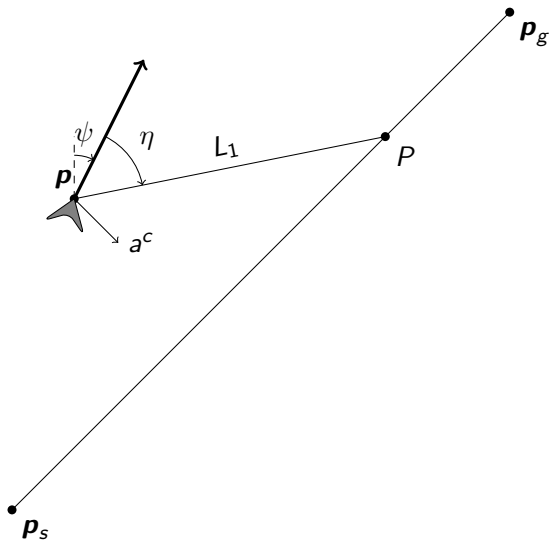
Trajectory following controller

Figure 3: L_1 controller logic

Trajectory following controller (contd)

$$= \begin{bmatrix} \cos \psi \\ \sin \psi \end{bmatrix} + \begin{bmatrix} \cos \\ \sin \end{bmatrix} \tag{8}$$

$$a^c = 2 \frac{V^2}{L_1} \sin \eta, \quad V = \|\| \tag{9}$$

$$\phi^c = \tan^{-1}(a^c/g) \tag{10}$$

State and action set definitions

$$x = (x_N, y_E, \psi) \tag{11}$$

$$u = (p_{N,g}, p_{E,g}) \tag{12}$$

Closed loop system

$(??) + (??) \Rightarrow$

$$\dot{\psi} = \frac{a^c(x, u)}{} \tag{13}$$

Physical constraint: $\dot{\psi} \leq \dot{\psi}_{\mathsf{max}} \Rightarrow$

$$\underline{\dot{\psi}}(x, u) = \begin{cases} a^c(x, u)/ & |a^c(x, u)/| \leq \dot{\psi}_{\mathsf{max}} \\ \mathsf{sgn}(a^c(x, u)/)\dot{\psi}_{\mathsf{max}} & \text{otherwise} \end{cases} \tag{14}$$

$$\dot{x} = f(x, u) = \begin{bmatrix} \cos\psi + \cos \\ \sin\psi + \sin \\ \underline{\dot{\psi}}(x, u) \end{bmatrix} \tag{15}$$

Motion primitives

- Different motion primitives for different wind direction
- Different motion primitives for different wind speeds

Constraints on final course instead of heading where course is defined as

$$\psi_c(x) = \tan^{-1}\left(\frac{\sin\psi + \sin}{\cos\psi + \cos}\right) \tag{16}$$

Optimal control problem

$$\min_{x(t), u, T} \quad J = |d(x(T), u)|^2 + |\psi_c(x(T)) - \psi_d|^2 + \int_0^T dt \tag{17a}$$

subject to
$$\psi(0) = \tag{17b}$$
$$\psi_c(x(0)) = 0, \quad |\psi_c(x(T)) - \psi_d| \leq \Delta\psi_{\min} \tag{17c}$$
$$\dot{x} = f(x(t), u) \tag{17d}$$
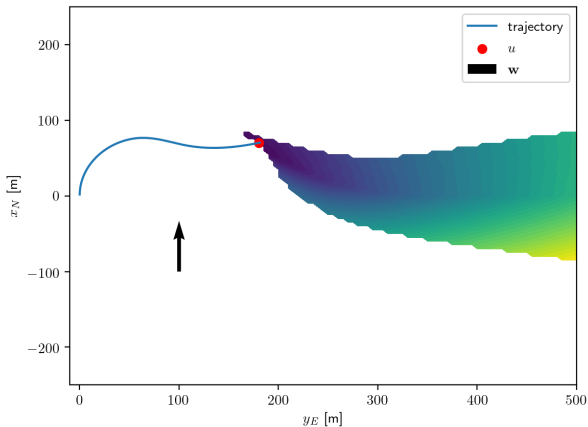$$x(t) \in \tag{17e}$$
$$u \in \tag{17f}$$

Optimal control problem (contd)

Figure 4: J for $= 14$ m/s, $= 5$ m/s, $= 0°$, $\psi_d = 90°$

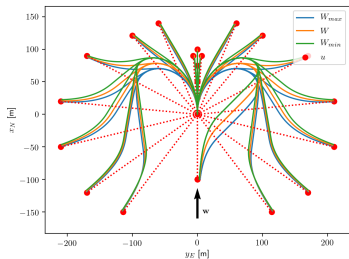# Optimal control problem (contd)

Derivative free optimization methods

$$\min_{x \in \mathbb{R}^n} \quad f : x \to \mathbb{R} \quad\quad\quad (18a)$$

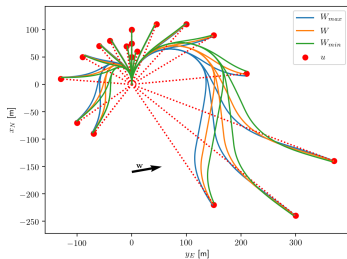$$\text{subject to} \quad x \in_{feasible} \quad\quad\quad (18b)$$

$$(18c)$$

Mesh-Adaptive Direct Search (MADS)

Resulting primitives

(a) $= 0°$ (b) $= 80°$

Figure 5: Motion primitives for different wind directions, $= 5$ m/s

Heuristic function

- States defined in inertial frame
- Cost is distance travelled by UAV in air-relative frame
- Not equal to inertial frame distance if $\neq 0$

Cost for straight line paths

Assuming that $\psi_i = \psi_f =$:

$$V_\parallel = \cos\psi_s(\cos + \cos) + \sin\psi_s(\sin + \sin) \tag{19}$$

$$s_A = \frac{1}{V_\parallel}\|\boldsymbol{p}_{i+1} - \boldsymbol{p}_i\| \tag{20}$$

Cost for arbitrary initial and final heading

- Dubin's path if $= 0$
- No analytical solution if $\neq 0$
- Numerical solutions exist but computationally expensive

Heuristic Look-Up Table

- ▶ Entries for different values of ψ_i from $0°$ to $180°$
- ▶ Different require new HLUT
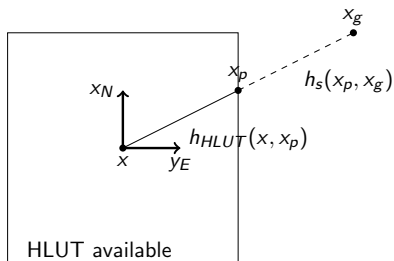- ▶ Generated with Dijkstra's Algorithm using motion primitives

Figure 6: Projection of queries on HLUT
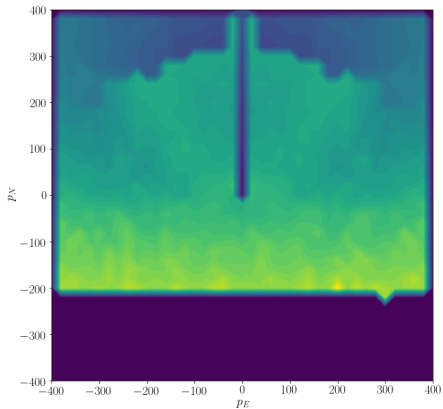
Heuristic Look-Up Table (contd)

Figure 7: HLUT for $\psi_f = 0°$

Landing sequences

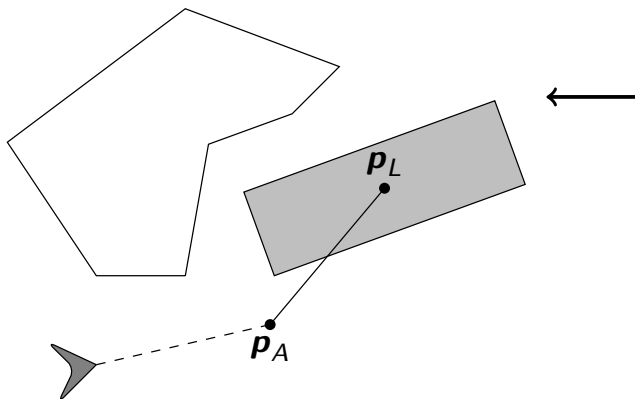Figure 8: Landing sequence definition

Landing sequences (contd)

- ▶ Approach: Descend at rate $\dot{h}$ given by $\boldsymbol{p}_A$ and $\boldsymbol{p}_L$
- ▶ Flare: When below altitude , begin descending at fixed rate
- ▶ Has to enter landing area above altitude h_A

Optimal landing sequence

Objectives:

1. Land as closely to the center of as possible
2. Land against the wind if possible
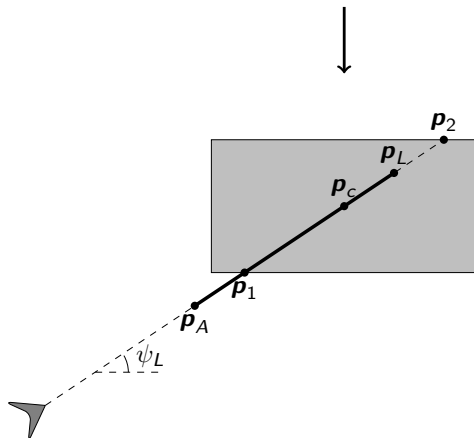
Optimal landing sequence (contd)

Figure 9: Variables to determine optimal landing sequence

Optimal landing sequence (contd)

Divided into two steps:

1. Determine ψ_L
2. Determine $R_a = \|\boldsymbol{p}_A - \boldsymbol{p}_2\|$ and $R_l = \|\boldsymbol{p}_L - \boldsymbol{p}_2\|$

Determining approach direction

$$V_L(\psi) = \cos\psi(\cos + \cos) + \sin\psi(\sin + \sin) \tag{21}$$

$$R_{\min}(\psi) = V_L(\psi)\frac{h_A-}{h_{\max}} \tag{22}$$

$$R_{flare}(\psi) = V_L(\psi) \tag{23}$$

Determining approach direction (contd)

$L(\psi)$: Line from $\boldsymbol{p}_1$ in direction $\psi + 180°$ with length K for some $K \geq 0$

$$\{\psi_L\}_{feas} = \{\psi : (R(\psi) \geq R_{\min}(\psi) + R_{flare}(\psi)) \cap (L(\psi) \notin)\} \quad (24)$$

$$\psi_{L,opt} = \underset{\psi \in \{\psi_L\}_{feas}}{\arg\min} R(\psi) \quad (25)$$

Determining approach parameters

$$\dot{h} = f(R_a, R_l) \tag{26}$$

$$h(R) = h_0 - R \frac{\dot{h}}{V_L} \tag{27}$$

$$R_c = \|\boldsymbol{p_1} - \boldsymbol{p}_2\| \tag{28}$$

Determining approach parameters (contd)

Constraints:

$$h(R_a - 2R_c) \geq h_A \qquad (29)$$

$$h(R_a - R_{flare} - R_l) = \qquad (30)$$

Determining approach parameters (contd)

$$\min_{R_a, R_l} \quad J = R_a^2 + \lambda |R_c - R_l|^2 \tag{31a}$$

$$\text{subject to} \quad R_a, R_l \geq 0 \tag{31b}$$

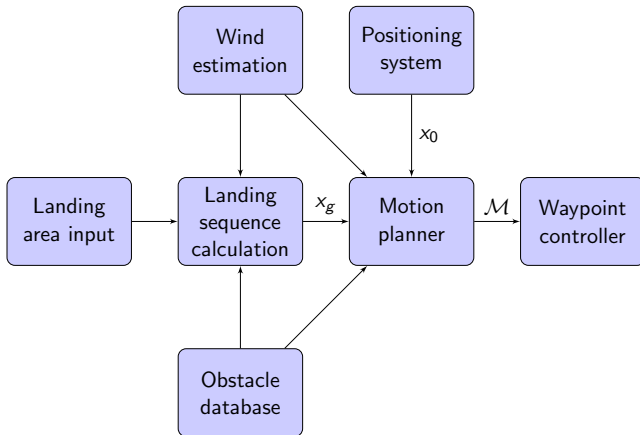$$\dot{h}(R_a, R_l) \leq \dot{h}_{\max} \tag{31c}$$
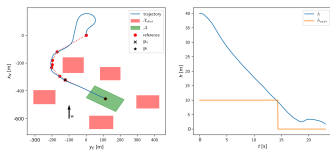
$$(\textbf{??})$$

$$(\textbf{??})$$

System overview
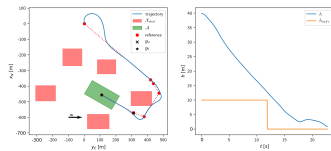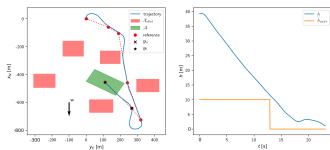

Figure 10: System overview

Results

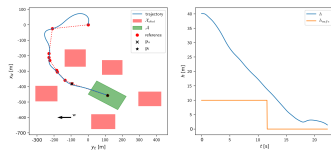(a) = 0°   (b) = 90°

Figure 11: Resulting landing procedures for different wind directions, = 5 m/s

Results (contd)

(a) $= 0°$ (b) $= 90°$

Figure 12: Resulting landing procedures for different wind directions, $= 5$ m/s

Possible improvements

▶ Extend formulation to handle varying winds with the same motion primitive set/HLUT
▶ Investigate admissibility of heuristic (especially projection)
▶ Handle wind variations in landing sequence generation
▶ Estimate wind mean and variance online from measurements