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

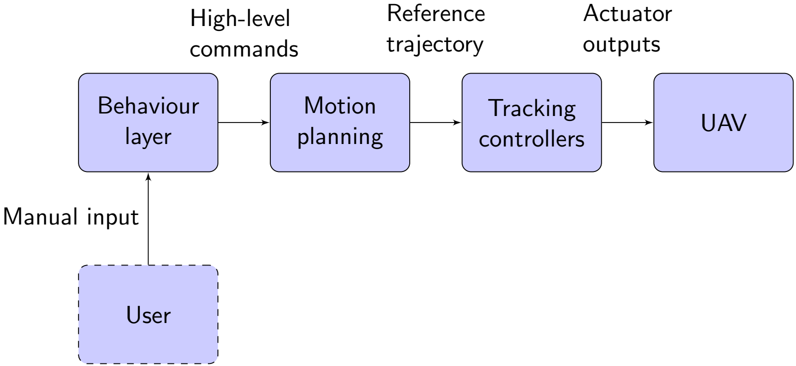


Figure 1: Components of a general autonomous system

Kinematic model

$$\dot{p}_N = V_a \cos\psi + W \cos\psi_w \tag{1}$$

$$\dot{p}_E = V_a \sin\psi + W \sin\psi_w \tag{2}$$

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

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

Straight path following in wind

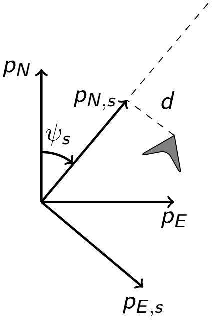


Figure 2: Coordinate frame for straight path following

Straight path following in wind (contd)

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

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

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

$$\psi_{wca} \equiv -\arcsin\left(\frac{W}{V_a} \sin(\psi_w - \psi_s)\right) + \psi_s \tag{7}$$

Trajectory following control law

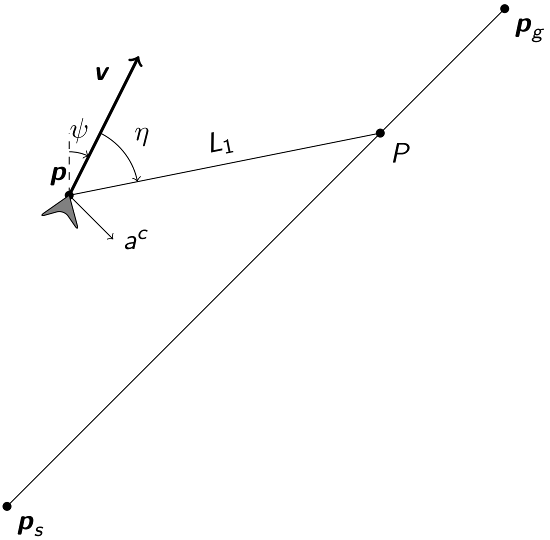


Figure 3: L_1 controller logic

Trajectory following control law (contd)

$$\boldsymbol{v} = V_a \begin{bmatrix} \cos\psi \\ \sin\psi \end{bmatrix} + W \begin{bmatrix} \cos\psi_w \\ \sin\psi_w \end{bmatrix} \tag{8}$$

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

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

State and action set definitions

$$x = (p_N, p_E, \psi) \tag{11}$$

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

Closed loop system

(1) + (10) $\Rightarrow$

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

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

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

Closed loop system (contd)

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

Motion primitives

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

Motion primitives (contd)

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

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

Optimal control problem

$$
\begin{aligned}
\min_{x(t),u,T} \quad & J = |d(x(T),u)|^2 + |\psi_c(x(T)) - \psi_d|^2 + \int_0^T V_a dt && \text{(17a)} \\
\text{subject to} \quad & \psi(0) = \psi_{wca} && \text{(17b)} \\
& \psi_c(x(0)) = 0, \quad |\psi_c(x(T)) - \psi_d| \leq \Delta\psi_{min} && \text{(17c)} \\
& \dot{x} = f(x(t), u) && \text{(17d)} \\
& x(t) \in \mathcal{X} && \text{(17e)} \\
& u \in \mathcal{U} && \text{(17f)}
\end{aligned}
$$

Optimal control problem (contd)

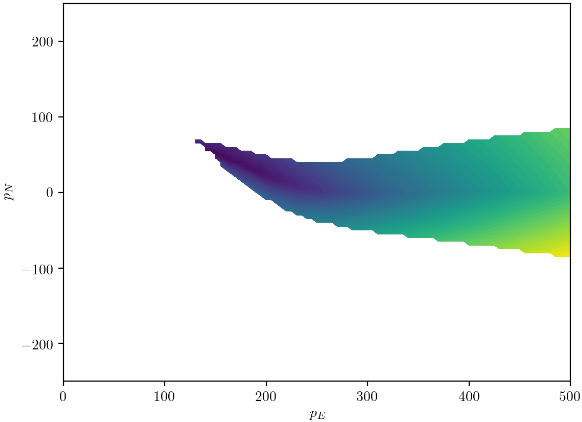


Figure 4: J for $V_a = 14$ m/s, $W = 5$ m/s, $\psi_w = 0^\circ$, $\psi_d = 90^\circ$

Optimal control problem (contd)

Derivative free optimization methods

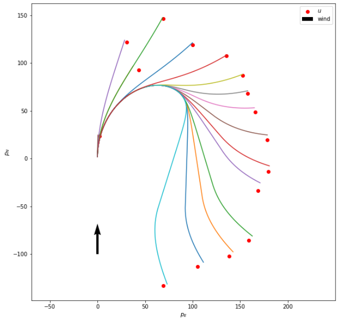
$$\min_{x \in \mathbb{R}^n} \quad f : x \to \mathbb{R} \tag{18a}$$

$$\text{subject to} \quad x \in \mathcal{X}_{feasible} \tag{18b}$$

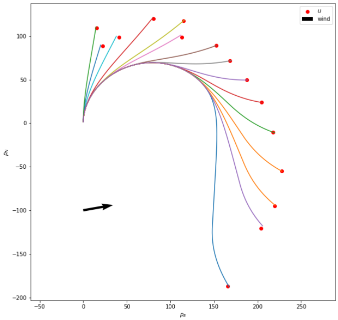
$$\tag{18c}$$

Mesh-Adaptive Direct Search (MADS)

Resulting primitives



(a) $\psi_w = 0°$



(b) $\psi_w = 80°$

Figure 5: Motion primitives for different wind directions, $W = 5$ 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 $W \neq 0$

Cost for straight line paths

Assuming that $\psi_i = \psi_f = \psi_{wca}$:

$$V_{\parallel} = \cos\psi_s(V_a\cos\psi_{wca} + W\cos\psi_w) + \sin\psi_s(V_a\sin\psi_{wca} + W\sin\psi_w) \quad (19)$$

$$s_A = \frac{V_a}{V_{\parallel}}\|\boldsymbol{p}_{i+1} - \boldsymbol{p}_i\| \quad (20)$$

Cost for arbitrary initial and final heading

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

Heuristic Look-Up Table

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

Heuristic Look-Up Table (contd)

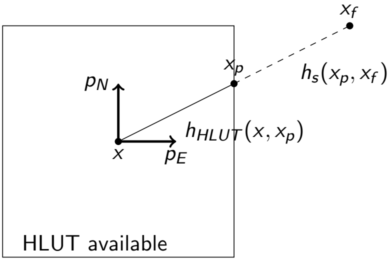


Figure 6: Projection of queries on HLUT

Heuristic Look-Up Table (contd)

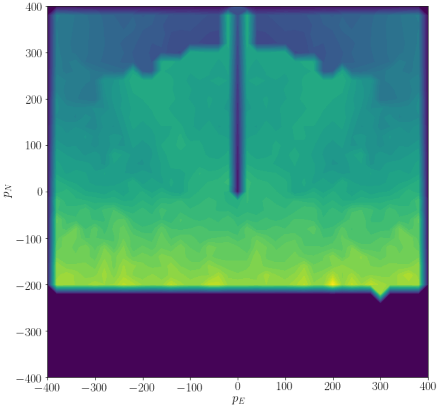


Figure 7: HLUT for $\psi_f = 0°$

Landing sequences

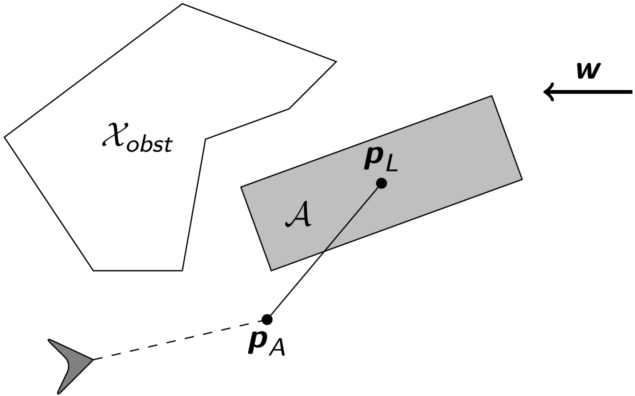


Figure 8: Landing sequence definition

Landing sequences (contd)

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

Optimal landing sequence

Objectives:

1. Land as closely to the center of $\mathcal{A}$ as possible
2. Land against the wind if possible

Optimal landing sequence (contd)

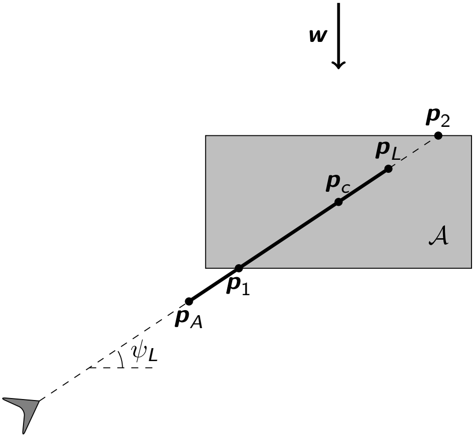


Figure 9: Variables to determine optimal landing sequence

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

$$V_L(\psi) = \cos\psi(V_a \cos\psi_{wca} + W\cos\psi_w) + \sin\psi(V_a \sin\psi_{wca} + W\sin\psi_w) \tag{21}$$

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

$$R_{flare}(\psi) = V_L(\psi)\frac{h_{flare}}{\dot{h}_{flare}} \tag{23}$$

Determining approach direction (contd)

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

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

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

Determining approach parameters

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

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

$$R_c = \|\boldsymbol{p}_{\mathbf{1}} - \boldsymbol{p}_2\| \tag{28}$$

Determining approach parameters (contd)

Constraints:

$$h(R_a - 2R_c) \geq h_A \tag{29}$$

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

Determining approach parameters (contd)

$$
\begin{aligned}
\min_{R_a, R_l} \quad & J = R_a^2 + \lambda |R_c - R_l|^2 && \text{(31a)} \\
\text{subject to} \quad & R_a, R_l \geq 0 && \text{(31b)} \\
& \dot{h}(R_a, R_l) \leq \dot{h}_{max} && \text{(31c)} \\
& \text{(29)} \\
& \text{(30)}
\end{aligned}
$$

System overview

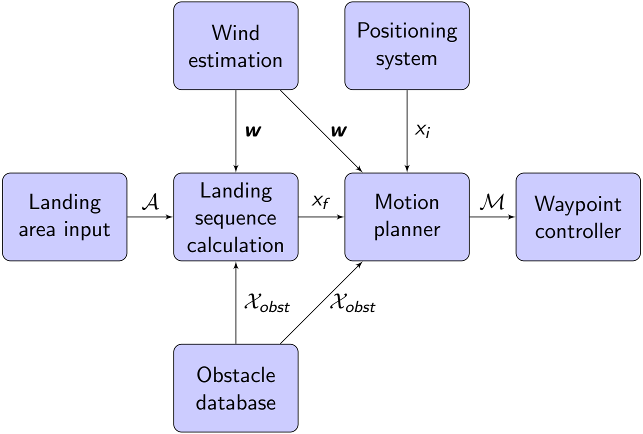
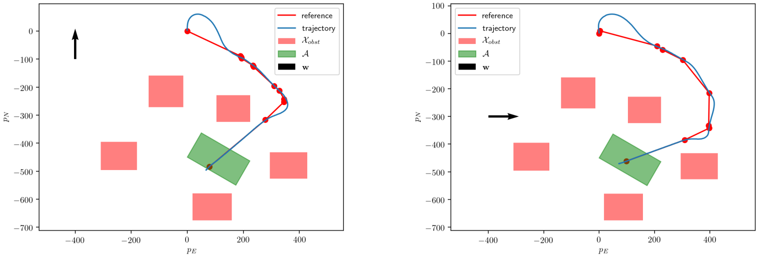


Figure 10: System overview

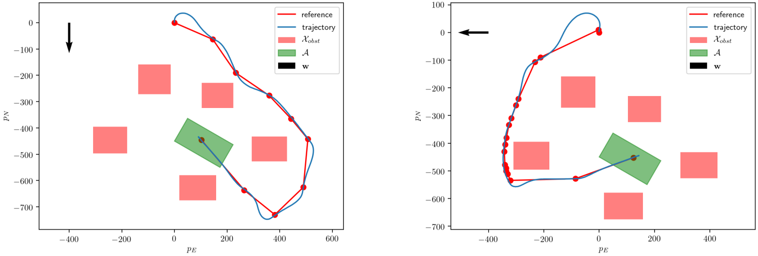
Results



(a) $\psi_w = 0°$ (b) $\psi_w = 90°$

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

Results (contd)



(a) $\psi_w = 0°$ (b) $\psi_w = 90°$

Figure 12: Resulting landing procedures for different wind directions, $W = 5$ 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