Supplementary Material – Learning Agile Flights through Narrow Gaps with Varying Angles using Onboard Sensing

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Abstract

This supplementary document is organized as follows. Section I introduces the problem to be addressed and presents an overview of our method. Section II presents a detailed quadrotor dynamics model, which is used for quadrotor simulation during policy training. For the detailed methodology and results, please refer to our letter at https://arxiv.org/abs/2302.11233. We refer the reader to the accompanying video for more experiment details at https://youtu.be/HUTWBclayT8.

I. Problem Overview

We assume a quadrotor equipped with a depth camera flying in a workspace with a tilted narrow window on a wall. The quadrotor initially hovers in front of the gap and aims to fly behind. Our approach consists of two subsystems: perception and control, illustrated in Figure 1. The perception system estimates the position and orientation of the gap in the world frame using a single-view image collected by a forward-facing depth camera.

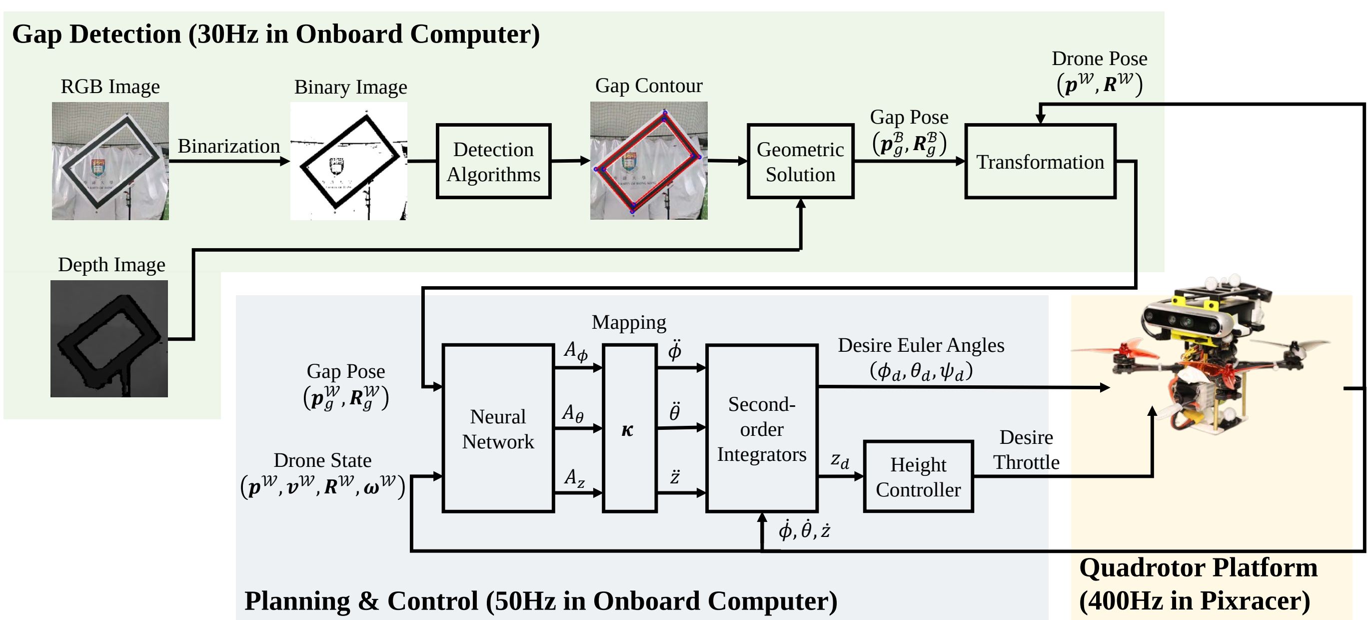

Fig. 1. The overall architecture in physical experiments.

Given the state of the drone and the gap, the control system uses a neural network to generate low-level control commands, which guide the quadrotor to complete the task. During the traversal, the drone has to maximize the distance to the gap edges to minimize the risk of collision. Thus, the planned traverse trajectory should try to intersect the center of the gap while simultaneously attaining the exact orientation of the gap, as illustrated in Figure 2. A precise *SE(3)* planning and control policy for quadrotor is required. We train our model in a self-supervised fashion in a physics simulation environment. In training, we assume the quadrotor and the window can be fully observed with reasonable estimation error.

Variation of gap orientation is also considered. In policy training, we keep the drone facing the gap and omit the yaw angle control. Pitch angles of the gap are ignored, as the gap on a wall usually has a few pitches. Thus, we mainly cope with the variation of roll angle in this paper.

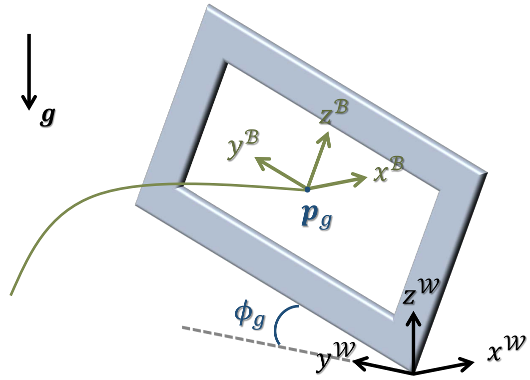

Fig. 2. Traversal Demonstration.

II. Quadrotor Dynamics for Training

To simulate the quadrotor flight and the interaction between the vehicle and the gap for policy training, we formulate quadrotor model in this section. Consider a quadrotor with mass $m \in \mathbb{R}$ and diagonal moment of inertia matrix $\boldsymbol{J} = \mathrm{diag}(I_x, I_y, I_z) \in \mathbb{R}^3$. The dynamic model of the system can be written as

$$\begin{aligned} \dot{\boldsymbol{p}} &= \boldsymbol{v}, & m\dot{\boldsymbol{v}} &= \boldsymbol{R}\boldsymbol{e}_3 f_T + \boldsymbol{R}\boldsymbol{f}_D + m\boldsymbol{g} \\ \dot{\boldsymbol{R}} &= \boldsymbol{R}\hat{\boldsymbol{\omega}}, & \boldsymbol{J}\dot{\boldsymbol{\omega}} &= -\boldsymbol{\omega} \times \boldsymbol{J}\boldsymbol{\omega} + \boldsymbol{\tau}_T + \boldsymbol{\tau}_D \end{aligned} \tag{1}$$

where $\boldsymbol{p} = [p_x, p_y, p_z]^T$ and $\boldsymbol{v} = [v_x, v_y, v_z]^T$ are the position and velocity vector in the world frame. We use rotation matrix $\boldsymbol{R} \in \mathbb{SO}(3)$ to denote the rotation of the quadrotor and $\boldsymbol{\omega} = [\omega_x, \omega_y, \omega_z]^T$ to represent the angular velocity in the body frame. The hat symbol $\hat{\boldsymbol{\omega}}$ denotes the skew-symmetric matrix form of the vector $\boldsymbol{\omega}$. $\boldsymbol{g}$ denotes the gravity vector in the world frame. $\boldsymbol{e}_3 = [0, 0, 1]^T$ is a constant vector in the body frame.

Additionally, f_T and $\boldsymbol{\tau}_T$ denote the vertical body thrust and three-dimensional body torques generated by four rotors. The propeller with rotor speed Ω_i is modeled as a first-order system $\dot{\Omega} = \frac{1}{k_{\mathrm{delay}}}(\Omega_c - \Omega)$, where $\Omega_c \in [\Omega_{\min}, \Omega_{\max}]$ is the commanded rotor speed, and k_{delay} is the time delay constant. Individual motor thrusts f_i are then derived by thrust coefficient k_T as $f_i = k_T * \Omega_i^2$. Thus, body thrust f_T and body torques $\boldsymbol{\tau}_T$ can be calculated as

$$f_T = \sum_{i=1}^{4} f_i, \quad \boldsymbol{\tau}_T = \begin{bmatrix} (f_1 - f_2 - f_3 + f_4) \cdot l/\sqrt{2} \\ (f_1 + f_2 - f_3 - f_4) \cdot l/\sqrt{2} \\ (-f_1 + f_2 - f_3 + f_4) \cdot k_{TQ} \end{bmatrix} \tag{2}$$

where k_{TQ} denotes the ratio of moment coefficient to thrust coefficient, l is the arm length of the vehicle. Air drag is also modeled for aggressive motion. $\boldsymbol{f}_D$ represents air drag force and $\boldsymbol{\tau}_D$ is air drag torque, which are proportional to the square of linear body velocity $\boldsymbol{v}^{\mathcal{B}}$ and angular body velocity $\boldsymbol{\omega}$, respectively, with drag coefficients $\boldsymbol{k}_{f_D}, \boldsymbol{k}_{\tau_D}$.

Overall, the full-state and control input of quadrotor can be given as $\boldsymbol{x} = [\boldsymbol{p}, \boldsymbol{v}, \boldsymbol{R}, \boldsymbol{\omega}]^T$, $\boldsymbol{u} = [f_T, \boldsymbol{\tau}_T]^T$. Additionally, we define the Euler angles of the quadrotor (ϕ, θ, ψ), which can be derived from the rotation matrix $\boldsymbol{R}$.

The parameters of the quadrotor dynamics used in training algorithm are summarized in Table I.

TABLE I
Parameters of Training Algorithm

	Parameter	Value
Quadrotor	m [kg]	1.1
	$\mathrm{diag}(J)$ [kg m^2]	$[0.12, 0.12, 0.22]$
	$[\Omega_{\min}, \Omega_{\max}]$	$[50, 2000]$
	k_T	6×10^{-6}
	k_{TQ}	0.02
	l [m]	0.34
	$\boldsymbol{k}_{f_D}$ [N s^2 m^{-2}]	$[2.9, 2.9, 5.7] \times 10^{-2}$
	$\boldsymbol{k}_{\tau_D}$ [N s^2]	$[3.2, 3.2, 1.7] \times 10^{-3}$