Fuzzy Scheduler Workflow (paper_fuzzy.py)

1 Overview

The scheduler follows the structure described in the DCOSS 2020 paper "A Fuzzy Rule-Based Control System for Fast Line-Following Robots": two inputs (X_1 speed, X_2 visible line length) feed six fuzzy rules; the aggregated output is defuzzified to a scalar X^* (range 1–100). The winning output label also maps to a PID gain set and speed cap used by the downstream controller. Membership triangles and PID tuples here are heuristic placeholders; the paper does not publish exact values, so tune them on hardware.

2 Constructing Inputs from Raw Signals (paper formulas)

From Section IV of the paper, the augmented decision vector $x(k)$ contains controllable motor parameters (e.g., wheel speeds). The two fuzzy inputs are normalized as:

$$X_1 = \frac{\max_j x_{j,k}}{|X|} \times 100, \quad j \in [1, \ldots, N] \tag{1}$$

$$X_2 = \frac{L_k}{|L|} \times 100 \tag{2}$$

where:

- $x_{j,k}$ is the commanded speed of motor j at iteration k; $|X|$ is the maximum motor speed (rpm) capability.
- L_k is the length of the currently detected line segment (from vision); $|L|$ is the maximum detectable line length for the camera.

In this repository, the same normalization is applied conceptually, but the numbers can be synthesized (e.g., `test.py`) or derived from the webcam line detector:

- X_1: take the current forward speed command (normalized 0–1), multiply by 100.
- X_2: take the fraction of ROI rows containing line pixels ("len_pct" in `vision.py`) as a percentage.

3 Membership Functions

Triangular membership function:

$$\mu_\triangle(x; a, b, c) = \begin{cases} 0, & x \le a \text{ or } x \ge c \\ \dfrac{x-a}{b-a}, & a < x < b \\ \dfrac{c-x}{c-b}, & b \le x < c \end{cases}$$

Input X_1 (motor speed %)

Label	Triangle (a,b,c)	Notes
Low	$(0,0,40)$	rises to 1 at 0, falls to 0 at 40
Medium	$(20,50,80)$	centered at 50
High	$(60,100,100)$	starts at 60, flat to 100

Input X_2 (line length %)

Label	Triangle (a,b,c)	Notes
Close	$(0,0,50)$	
Far	$(30,100,100)$	

Output sets (speed level)

Labels: LC, LF, MC, MF, HC, HF with triangles:

$$\text{LC} : (0,10,25), \quad \text{LF} : (15,30,45), \quad \text{MC} : (35,50,65),$$
$$\text{MF} : (55,70,85), \quad \text{HC} : (70,85,95), \quad \text{HF} : (85,100,100).$$

4 Rule Base (Table I)

For each input pair (X_1, X_2):

X_1	X_2	Output label
Low	Close	LC
Low	Far	LF
Medium	Close	MC
Medium	Far	MF
High	Close	HC
High	Far	HF

Rule activation uses fuzzy AND as $\min(\mu_{X_1}, \mu_{X_2})$. If multiple rules map to the same output label, fuzzy OR is max of activations (Mamdani max–min).

5 Aggregation and Defuzzification

1. For each sample $x \in [0,100]$ (101 evenly spaced points; increase density if you need finer centroid accuracy), compute the aggregated output membership:

$$\mu_{\text{agg}}(x) = \max_{L \in \{\text{labels}\}} \min\big(\mu_{\text{rule}}(L),\, \mu_L(x)\big).$$

2. Centroid defuzzification:

$$X^* = \frac{\sum_x \mu_{\text{agg}}(x)\, x}{\sum_x \mu_{\text{agg}}(x)}.$$

3. Quantize and clamp: $X^*_{\text{q}} = \min(100, \max(1, \text{round}(X^*, 2)))$.

6 From X^* to Motor Commands

1. Choose the winning label (highest activation) and fetch $(v_{\max}, K_p, K_i, K_d)$ from Table 1.
2. Set base speed v such that $|v| \le v_{\max}$ (cap depends on label).
3. Measure lateral error e from the IR array (weighted centroid); compute PID correction

$$u = K_p e + K_i \int e\,dt + K_d \frac{de}{dt}.$$

4. Mix to wheel commands (normalized):

$$u_L = \mathrm{clamp}(v - u,\ -1,\ 1), \quad u_R = \mathrm{clamp}(v + u,\ -1,\ 1).$$

5. Map to TB6612FNG: direction pins from sign of u_L, u_R, PWM duty $= |u| \times 255$.

Label	$v_{\max}$	K_p	K_i	K_d
LC	0.30	0.80	0.00	0.10
LF	0.35	0.70	0.00	0.10
MC	0.45	0.65	0.00	0.12
MF	0.55	0.55	0.00	0.14
HC	0.65	0.45	0.00	0.16
HF	0.75	0.40	0.00	0.18

Table 1: PID mapping used in this repo (heuristic), aligned with labels from the paper's Table I.

7 Worked Example (X_1=20, X_2=30)

1. $\mu_{\text{Low}}(20) = 0.5$, $\mu_{\text{Close}}(30) = 0.4$; other memberships are 0.
2. Rule Low$\wedge$Close $\to$ LC activates with $\min(0.5, 0.4) = 0.4$.
3. Only LC contributes; its triangle $(0, 10, 25)$ is clipped at 0.4, centroid over $x \in [0, 25]$ yields $X^* = 12.04$.
4. Label LC wins; select PID $(0.30, 0.80, 0.00, 0.10)$.