雷达到触觉映射模型

1 Laser-to-Haptic Mapping Model

1.1 Laser Scan Representation

The 2D laser scanner outputs a sequence of $N = 1440$ measurement points per revolution. Each measurement is represented as

$$\mathbf{p}_i = \left(\theta_i^{\mathrm{raw}},\, d_i^{\mathrm{raw}}\right), \quad i = 1, \ldots, 1440, \tag{1}$$

where θ_i^{raw} and d_i^{raw} denote the raw angle and distance values, respectively.

The corresponding physical quantities are defined as

$$\theta_i = \frac{\theta_i^{\mathrm{raw}}}{100} \ \text{(deg)}, \qquad d_i = \frac{d_i^{\mathrm{raw}}}{100} \ \text{(m)}. \tag{2}$$

By sensor convention, $\theta_i = 0^\circ$ corresponds to the backward direction of the user.

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1.2 Angular Coordinate Normalization

For intuitive spatial perception, the angular reference is shifted such that the forward direction corresponds to 0°:

$$\theta_i' = \mathrm{mod}(\theta_i - 180^\circ,\, 360^\circ)\,, \tag{3}$$

where $\mathrm{mod}(\cdot, 360^\circ)$ maps the angle into the interval $[0, 360^\circ)$.

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1.3 Field-of-View Selection

Only the forward 270° field of view is considered for haptic feedback:

$$\theta_i' \in [-135^\circ,\ 135^\circ], \tag{4}$$

while measurements outside this interval are discarded.

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1.4 Angular Sectorization

The effective angular range is uniformly divided into $M = 8$ sectors, corresponding to eight linear vibration actuators. Each sector covers an angular width of

$$\Delta\theta = \frac{360^\circ}{M} = 45^\circ. \tag{5}$$

The sector index associated with measurement i is computed as

$$k(i) = \left\lfloor \frac{\theta_i' + 180^\circ}{\Delta\theta} \right\rfloor, \quad k \in \{0, 1, \ldots, 7\}. \tag{6}$$

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1.5 Risk Distance Extraction

For each sector k, a set of valid distance measurements is defined as

$$\mathcal{D}_k = \{d_i \mid k(i) = k,\ 0 < d_i \le d_{\max}\}, \tag{7}$$

where $d_{\max}$ denotes the maximum reliable sensing range.

The representative distance of sector k is chosen as the minimum distance,

$$d_k = \begin{cases} \min \mathcal{D}_k, & \mathcal{D}_k \neq \varnothing, \\ d_0, & \mathcal{D}_k = \varnothing, \end{cases} \tag{8}$$

which reflects the most conservative (highest-risk) obstacle estimate.

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1.6 Distance-to-Intensity Mapping

Let d_0 denote the distance at which vibration starts, and d_1 the distance corresponding to maximum vibration intensity ($d_1 < d_0$). A normalized risk intensity is computed as

$$x_k = \text{clip}\left(\frac{d_0 - d_k}{d_0 - d_1},\ 0,\ 1\right), \tag{9}$$

where $\text{clip}(x, 0, 1)$ limits the value to the interval $[0, 1]$.

To enhance sensitivity to near-field obstacles, a nonlinear shaping function is applied:

$$a_k = x_k^{\gamma}, \qquad \gamma > 1. \tag{10}$$

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1.7 Temporal Smoothing

To suppress rapid fluctuations, an exponential moving average (EMA) filter is employed:

$$A_k(t) = (1 - \alpha)\, A_k(t-1) + \alpha\, a_k(t), \qquad 0 < \alpha < 1. \tag{11}$$

A dead-zone threshold $A_{\min}$ is further applied to eliminate low-amplitude vibrations:

$$\tilde{A}_k = \begin{cases} 0, & A_k < A_{\min}, \\ A_k, & A_k \geq A_{\min}. \end{cases} \tag{12}$$

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1.8 PWM Output Mapping

Finally, the filtered intensity is mapped to a pulse-width modulation (PWM) duty cycle. Assuming a timer resolution of $\text{PWM}_{\max} = 999$, the output for sector k is given by

$$\text{PWM}_k = \left\lfloor \tilde{A}_k \cdot \text{PWM}_{\max} + \tfrac{1}{2} \right\rfloor, \quad k = 0, \ldots, 7. \tag{13}$$

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1.9 Overall Mapping Summary

Combining the above steps, the laser-to-haptic mapping for the k-th actuator can be summarized as

$$\mathrm{PWM}_k = \left\lfloor \mathrm{EMA}\left(\left[\mathrm{clip}\left(\frac{d_0 - \min \mathcal{D}_k}{d_0 - d_1}, 0, 1 \right) \right]^{\gamma} \right) \cdot 999 \right\rfloor . \tag{14}$$