

ON ROBUSTNESS OF VISION-LANGUAGE-ACTION MODEL AGAINST MULTI-MODAL PERTURBATIONS

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ABSTRACT

In Vision–Language–Action (VLA) models, robustness to real-world perturbations is critical for deployment. Existing methods target simple visual disturbances, overlooking the broader multi-modal perturbations that arise in actions, instructions, environments, and observations. Here, we first evaluate the robustness of mainstream VLAs under 17 perturbations across four modalities. We find (1) actions as the most fragile modality, (2) Existing visual-robust VLA do not gain robustness in other modality, and (3) π_0 demonstrates superior robustness with a diffusion-based action head. To build multi-modal robust VLAs, we propose RobustVLA against perturbations in VLA inputs and outputs. For output robustness, we perform offline robust optimization against worst-case action noise that maximizes mismatch in flow matching objective. This can be seen as adversarial training, label smoothing, and outlier penalization. For input robustness, we enforce consistent actions across input variations that preserve task semantics. To account for multiple perturbations, we formulate robustness as a multi-armed bandit problem and apply an upper confidence bound algorithm to automatically identify the most harmful noise. Experiments on LIBERO demonstrate our RobustVLA delivers absolute gains over baselines of 12.6% on the π_0 backbone and 10.4% on the OpenVLA backbone across all 17 perturbations, achieving 50.6x faster inference than existing visual-robust VLAs, and a 10.4% gain under mixed perturbations. Our RobustVLA is particularly effective on real-world FR5 robot with limited demonstrations, showing absolute gains by 65.6% under perturbations of four modalities. Code and demo videos available at <https://anonymous.4open.science/r/RobustVLA-283D>.

1 INTRODUCTION

Vision–Language–Action (VLA) models are a class of robotic foundation models that enable flexible, general, and dexterous manipulation through vision–language inputs (Zhong et al., 2025; Sapkota et al., 2025). Trained on diverse, internet-scale robot data, VLAs can perform cross-embodied, general-purpose control in real-world settings (Kim et al., 2025; Black et al., 2024; Bjorck et al., 2025). Despite these advances, VLAs remain vulnerable to a wide range of multi-modal uncertainties encountered in practice, including those in observation (*e.g.*, sensory noise, camera errors), action (*e.g.*, sensorimotor noise, unexpected disturbances), environment (*e.g.*, external forces, distracting objects), and language (*e.g.*, synonymous or ambiguous instructions).

Recent work has begun to explore the robustness of VLAs, but efforts remain limited in scope. VLATest (Wang et al., 2025) primarily evaluates VLA robustness against visual perturbations, focusing on uncertainties in environment transitions and observations. For enhancing robustness,

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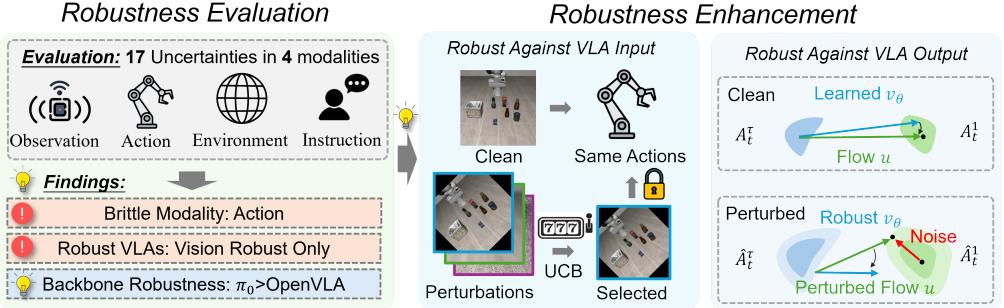


Figure 1: Framework of our paper. We evaluate VLA robustness under 17 uncertainties across 4 modalities. Based on the findings, we enhance robustness against both VLA inputs and outputs.

BYOVLA (Hancock et al., 2025) mitigates irrelevant visual details by identifying, segmenting, and inpainting them using large vision–language models, while GEVRM (Zhang et al., 2025) improves robustness to common visual corruptions such as color jitter through model-based planning. However, these methods are restricted to visual robustness, leaving their effectiveness against multi-modal uncertainties untested. Moreover, both approaches rely heavily on external large models, leading to substantial computational overhead.

To better understand the robustness of VLAs beyond visual uncertainties, as shown in Fig. 1, we evaluate and enhance the robustness of VLAs to multi-modal perturbations. We begin by evaluating the robustness of mainstream VLAs against 17 uncertainties across four modalities. Our findings are threefold: (1) action is the most fragile modality, (2) existing visual-robust VLAs do not show improvements in other modalities, and (3) π_0 (Black et al., 2024) demonstrates superior robustness with a diffusion-based action head and outperforms OpenVLA (Kim et al., 2025) by its large and diverse training corpus. Based on these results, we recommend that robust VLAs focus on robustness in all modalities and build on π_0 backbone as a starting point.

Building on evaluation results, we propose RobustVLA, which handles multi-modal uncertainties in both VLA inputs and outputs. RobustVLA is based on the π_0 backbone and generalizes naturally to OpenVLA. For robustness against VLA output, we derive the worst-case action deviation from the flow-matching objective, then match the action head with both the original and worst-case action distributions. This process can be seen as a combination of flow matching with noisy action distributions, label smoothing, and outlier penalization. For robustness against VLA inputs, we ensure that the noise does not alter the semantics of the current state, so the optimal action remains invariant. We thus regularize the objective to maintain consistent output actions across diverse input perturbations. To balance the various types and modalities of perturbations, we frame the problem as a multi-armed bandit and employ the upper confidence bound (UCB) algorithm (Auer, 2002) to select the most harmful perturbation for training. On LIBERO benchmark, RobustVLA achieves absolute gains of 12.6% on the π_0 backbone and 10.4% on the OpenVLA backbone across 17 perturbations, reaching 50.6x faster inference speed than existing visual-robust VLAs and achieving a 10.4% gain under mixed perturbations. In real-world deployment on the FR5 robot with limited demonstrations, RobustVLA further shows absolute gains of 65.6% under perturbations spanning four modalities.

Contributions. Our contributions are twofold. First, we evaluate the robustness of VLAs under various multi-modal noise and offer suggestions for improving robustness of VLAs. Second, we propose RobustVLA against input and output noise perturbations, which delivers robust gains across 4 modalities and 2 backbones in both simulation and real-world settings.

2 RELATED WORK

Vision-Language-Action (VLA) Foundation Models. Vision-Language-Action (VLA) models serve as foundational systems for robotics, integrating vision, language, and control. Recent approaches can be categorized into two primary types. Autoregressive VLAs leverage large pretrained VLMs and generate discrete action tokens in an autoregressive manner (Brohan et al., 2022; Zitkovich et al., 2023; O’Neill et al., 2024; Kim et al., 2025; Pertsch et al., 2025; Qu et al., 2025). These action tokens are then decoded into low-level, executable actions. In contrast, diffusion-based VLAs generate continuous, high-frequency, multi-modal action distributions by outputting action sequences

through a diffusion-based action head (Team et al., 2024; Li et al., 2024; Black et al., 2024; Bjorck et al., 2025). While these models excel in general-purpose embodied decision-making tasks, their robustness remains a significant concern. Existing research on robust VLAs primarily focus on visual input. For instance, VLATest (Wang et al., 2025) demonstrates that current VLAs are vulnerable to various visual corruptions. To mitigate visual perturbations, BYOvla (Hancock et al., 2025) removes model-sensitive features in visual inputs using VLM-based segmentation and inpainting, while GEVRM (Zhang et al., 2025) addresses common visual corruptions, such as color jitter, through model-based planning. However, these robust VLA methods focus solely on visual inputs and fail to account for multi-modal uncertainties in real-world. Furthermore, all of these approaches rely extensive assess to external large models, leading to substantial computational overhead.

Robust Decision Making. Before the advent of VLAs, robust decision-making was primarily explored within the framework of RL, specifically through robust MDPs (Nilim & El Ghaoui, 2005; Iyengar, 2005). Uncertainties in these settings can arise from various components of MDPs, including environment transitions (Pinto et al., 2017; Mankowitz et al., 2019), actions (Tessler et al., 2019), states (Zhang et al., 2020; 2021), and rewards (Wang et al., 2020). In environments with simulators available, RL agents can learn robust policies through minimax optimization against worst-case adversaries. However, in the case of VLAs, only offline datasets are available, akin to the settings of behavior cloning (Schaal, 1996) and offline RL (Levine et al., 2020). Achieving robust decision-making in the absence of an interactive environment is more challenging, as policies under uncertainty may lead to actions outside the distribution of the original dataset, causing OOD transitions. Consequently, robustness is typically achieved in such settings for states (Shen et al., 2020; Yang et al., 2022; Rigter et al., 2022) and environment transitions (Panaganti et al., 2022; 2023; Seo et al., 2024), with the goal of retaining the original policy despite deviations. However, two major challenges remain when applying these techniques to VLAs. First, it remains unclear how to robustly handle a diverse range of perturbations, with existing methods achieving robustness only against a limited set of environmental uncertainties (Agrawal et al., 2023). Second, it is yet unknown how to achieve action-robust offline RL, as OOD transitions are inevitable in real-world scenarios.

3 EVALUATING THE ROBUSTNESS OF VLAs

In this section, we evaluate the robustness of mainstream VLAs by first presenting the problem formulation, then detailing the experimental setup, and finally summarizing the main findings.

Problem Formulation. We model the decision process of VLAs as a Partially Observable Markov Decision Process (POMDP) (Kaelbling et al., 1998), defined as a tuple $G = \langle \Psi, \mathcal{S}, \mathcal{O}, O, \mathcal{A}, \mathcal{P}, R, \gamma \rangle$. Here, Ψ is the space of language instructions, \mathcal{S} is the state space, \mathcal{O} is the observation space, O is the observation emission function, \mathcal{A} is the action space, $\mathcal{P} : \mathcal{S} \times \mathcal{A} \rightarrow \Delta(\mathcal{S})$ is the transition function, $R : \mathcal{S} \times \mathcal{A} \times \Psi \rightarrow \mathbb{R}$ is the reward function.

We follow a practical formulation similar to π_0 (Black et al., 2024). At $t = 0$, a language instruction $\psi \in \Psi$ was given. At time t , the robot operates in state $s_t \in \mathcal{S}$, observing 2-3 RGB images and the language instruction $\mathbf{o}_t = \{o_t^1, \dots, o_t^n, \psi\} = O(s_t)$. The robot takes an action chunk $A_t = [a_t, a_{t+1}, \dots, a_{t+H}]$ according to its policy $\pi(A_t | \mathbf{o}_t)$. The policy takes observation as input and partial observability is implicitly encoded via historical input in VLMs. The environment proceeds to $s_{t+1} \sim \mathcal{P}(\cdot | s_t, A_t)$ and receive reward $r_t = R(s_t, A_t, \psi)$. $\gamma \in [0, 1]$ is the discount factor.

Robustness under uncertainties. We define test-time uncertainties for VLAs as $\omega \in \Omega$, with $\Omega = \{\Omega_\psi \subseteq \Psi, \Omega_o \subseteq \mathcal{O}, \Omega_a \subseteq \mathcal{A}, \Omega_p \subseteq \mathcal{P}\}$ the uncertainty set that perturbs instructions, observations, actions and environments, respectively. Given a task ψ , the robustness of VLAs is defined as:

$$J^{\text{robust}}(\pi, \psi) = \mathbb{E}_{\omega \sim \Omega} \left[\mathbb{E}_{s_0 \sim \rho_0} \mathbb{E}_{\pi, \omega} \left[\sum_{t=0}^{\infty} \gamma^t r_t \mid s_0, \psi \right] \right]. \quad (1)$$

3.1 EXPERIMENT SETTINGS

Evaluated Algorithms. We consider OpenVLA (Kim et al., 2025), π_0 -FAST (Pertsch et al., 2025) and π_0 (Black et al., 2024) as representative of autoregressive and diffusion-based VLAs, using their publicly released checkpoint. For robust VLA methods, we consider BYOvla (Hancock et al., 2025) on π_0 backbone. Due to the lack of publicly available code and insufficient implementation details, we were unable to reproduce GEVRM (Zhang et al., 2025) for fair comparison.

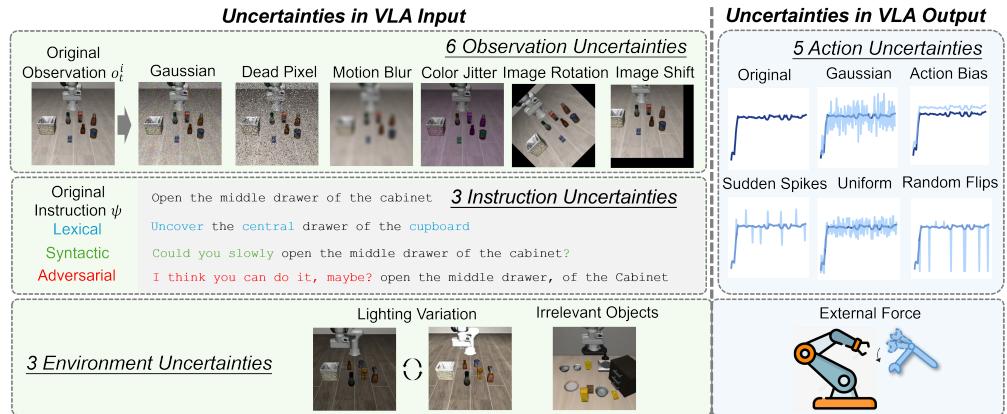


Figure 2: Overview of 17 uncertainty types spanning observation, environment, instruction, and action modalities, used in our evaluation of VLA robustness.

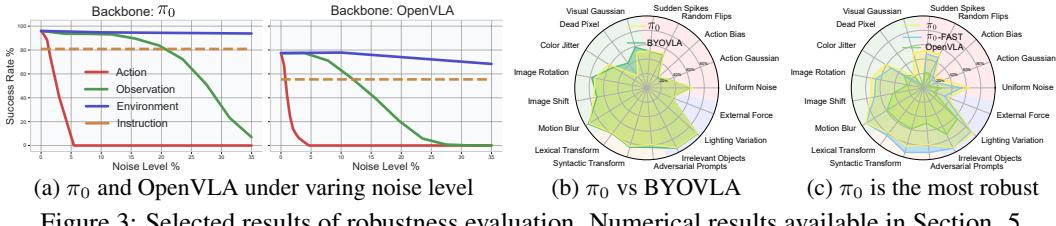


Figure 3: Selected results of robustness evaluation. Numerical results available in Section. 5.

Evaluated Uncertainties. We consider 17 perturbations in action, observation, environment and instructions, see Fig. 2 for visualization. **Action uncertainties** capture sensorimotor noise, actuator wear, and unexpected disturbances in VLA output, modeled by 5 types: uniform noise, Gaussian noise, action bias, random flips and sudden spikes. **Observation uncertainties** arise from sensory noise and camera error that affect VLA input, with 6 variants: Gaussian noise, dead pixel, motion blur, color jitter, image rotation and image shift. **Environment uncertainties** contains 3 types of external influences, with external force in VLA output, irrelevant objects and lighting variations in VLA input. **Instruction uncertainties** represent 3 linguistic variability in VLA input, including lexical transformations at the word level, syntactic transformations at the sentence level, and adversarial prompts with ambiguity and distraction. See details in Appendix. A.

Evaluation Process. For robustness evaluation, we apply each uncertainties to our evaluated algorithms. We use LIBERO benchmark suite (Liu et al., 2023) for evaluation, following their official settings. Due to space limit, we report crucial experiment results that support our findings in this section and leave numerical results to Section. 5.

3.2 EXPERIMENT RESULTS

We present our key findings below with corresponding experiment results.

Action is the most fragile modality. We first evaluate the robustness of all modalities with varying noise level. We unify noise level for all modalities as the percentage of the maximum allowable value in each modality. As shown in Fig. 3a, as the magnitude of noise increases, the robustness of action drops drastically. For example, the success rate of π_0 are reduced to 52.4% under noise 0.05 (2.5%), and fails completely at 0.1 (5%). This is in stark contrast compared with action-robust RL, where noise are often set to 0.1 or higher (Tessler et al., 2019). An explanation from offline RL theory (Levine et al., 2020) is that VLA policies trained on fixed datasets are especially vulnerable to action errors: a single mistake can drive the rollout off-distribution, causing errors to accumulate quadratically with the horizon, whereas in online RL the accumulation is only linear since interaction allows partial correction. In contrast, we find VLAs more robust against uncertainties in VLA input, while non-robust against observations only at high uncertainties.

Existing visual-robust VLAs do not show improvements in other modalities. Next, we investigate the robustness of BYOVLA, an off-the-shelf visual-robust VLA that identify and replace the sensitive regions in visual input. As shown in Fig. 3b, BYOVLA improves performance under Gaussian noise

by 7.3% and dead pixels by 22.3%, yet the average gain across all visual corruptions is only 4.0%. Moreover, we observe no measurable improvement (+0.0%) in non-visual modalities. These results suggest that existing visual-robust VLAs fall short under multi-modal uncertainties.

π_0 **demonstrates superior robustness with a diffusion-based action head.** As shown in Fig. 3c, π_0 outperforms OpenVLA and π_0 -FAST by 27.9% and 5.1%, respectively. Since π_0 and π_0 -FAST share the same VLM backbone, the performance gap highlights the robustness advantage of the diffusion-based action head over the autoregressive FAST tokenizer. OpenVLA performs even worse, likely due to both its smaller and less diverse training dataset and the limitations of its autoregressive action head. These findings motivate us to focus subsequent robustness-enhancing methods on the π_0 backbone with its diffusion-based action head.

4 ROBUSTVLA

To counter multi-modal uncertainties, we propose RobustVLA, a framework that enhances robustness against both VLA inputs and outputs. RobustVLA is based on π_0 and naturally extends to OpenVLA.

4.1 ROBUSTNESS AGAINST VLA OUTPUTS

Ensuring robustness against action output can be hard, since we are equipped with an offline dataset, and any action noises inevitably make subsequent transitions OOD. In our paper, build on π_0 backbone with diffusion-based action head, we first derive ℓ_p bounded worst-case action noise by maximizing the flow matching loss, then performing robust optimization against such noise.

Preliminaries: VLAs with Conditional Flow Matching Action Head. Given empirical observations $A^0 \sim \pi^0$ and $A^1 \sim \pi^1$, a flow defines an Ordinary Differential Equation (ODE) $dA^\tau = v(A^\tau, \tau)dt$ on $\tau \in [0, 1]$, with v the velocity field to push A^0 to A^1 , following the path defined by the ODE (Lipman et al., 2022). In VLA, $\tau = 0$ corresponds to a simple action distribution $A_t^0 = \epsilon \sim \mathcal{N}(0, \mathbf{I})$, and flows to an action from the dataset $A_t^1 \sim p(\cdot | \mathbf{o}_t)$, $(A_t^1, \mathbf{o}_t) \in \mathcal{D}$ at $\tau = 1$. Assuming linear-Gaussian transformation, the action at time τ is formulated as $A_t^\tau = \mathcal{N}(\tau A_t^1, (1 - \tau)\mathbf{I})$. To accelerate the learning process, rectified flow (Liu, 2022) assume linear ODEs for straight flow which is easier to model and compute. The action at time τ is then a linear interpolation $A_t^\tau = \tau A_t^1 + (1 - \tau)A_t^0$. The goal is to learn a velocity field $v_\theta(A_t^\tau, \mathbf{o}_t)$ parameterized by θ to match the rectified flow $u(A_t^\tau | A_t) = A_t^0 - A_t^1 = \epsilon - A_t^1$. This yields the objective of π_0 (Black et al., 2024):

$$\min_{\theta} \mathcal{L}_{\pi_0}^\tau = \mathbb{E}_{p(A_t^1 | \mathbf{o}_t), q(A_t^\tau | A_t^1)} \|v_\theta(A_t^\tau, \mathbf{o}_t) - u(A_t^\tau | A_t^1)\|^2. \quad (2)$$

Worst-Case Action Noise. We define worst-case action noise in VLAs as an ℓ_p -bounded noise that maximally reduces the success rate. In RL, this is typically approximated by a value function, which estimates the quality of the current state-action pair. However, in VLA, estimating action quality is more challenging due to the behavior cloning nature, long horizons, sparse rewards, and complex environmental dynamics. Fortunately, offline demonstrations (\mathbf{o}_t, A_t) provide actions that are more likely to lead to success and can be learned through flow matching. Therefore, we use the loss of the flow matching objective, $\|v_\theta(\hat{A}_t^\tau, \mathbf{o}_t) - u(\hat{A}_t^\tau | \hat{A}_t^1)\|^2$, as an empirical measure of action quality.

Formally, we define the perturbed action as $\hat{A}_t^1 = A_t^1 + \delta$, where a noise δ is added action noise. In this noisy flow, the perturbed action at time τ is $\hat{A}_t^\tau = \tau \hat{A}_t^1 + (1 - \tau)A_t^0$, and the perturbed rectified flow is $u(\hat{A}_t^\tau | \hat{A}_t^1) = u(A_t^\tau | A_t^1) - \delta$. Plugging this into the original π_0 objective, we got:

$$\begin{aligned} \delta &\in \arg \max_{\delta} \mathbb{E}_{p(A_t^1 | \mathbf{o}_t), q(\hat{A}_t^\tau | \hat{A}_t^1)} \|v_\theta(\hat{A}_t^\tau, \mathbf{o}_t) - u(\hat{A}_t^\tau | \hat{A}_t^1)\|^2 \\ &= \arg \max_{\delta} \mathbb{E}_{p(A_t^1 | \mathbf{o}_t), q(\hat{A}_t^\tau | \hat{A}_t^1)} \|v_\theta(\hat{A}_t^\tau, \mathbf{o}_t) - u(A_t^\tau | A_t^1) - \delta\|^2. \end{aligned} \quad (3)$$

Here, the noise on $v_\theta(\hat{A}_t^\tau, \mathbf{o}_t)$ perturbs the action input, enforcing Lipschitz continuity of v_θ to stabilize action outputs under perturbations. Noise on $u(\hat{A}_t^\tau | \hat{A}_t^1)$ maximizes loss in the direction $v_\theta(\hat{A}_t^\tau, \mathbf{o}_t) - u(A_t^\tau | A_t^1)$, where velocity field and rectified flow diverge the most. In practice, we compute δ via PGD (Madry et al., 2017), a gradient-based attack method.

Robustness Against Action Noise. With the worst-case action noise δ , enhancing robustness against worst-case δ requires minimizing the conditional flow matching objective against the worst-case

noise. To stabilize the result without noise, we additionally maintain the original π_0 objective, which provides optimal tradeoff between robustness and accuracy (Zhang et al., 2019):

$$\min_{\theta} \mathcal{L}_{\pi_0}^{\tau} + \mathcal{L}_{out}^{\tau} = \min_{\theta} \left[\mathcal{L}_{\pi_0}^{\tau} + \lambda_{out} \max_{\delta} \mathbb{E}_{p(A_t^1 | \mathbf{o}_t), q(\hat{A}_t^{\tau} | \hat{A}_t^1)} \|v_{\theta}(\hat{A}_t^{\tau}, \mathbf{o}_t) - u(\hat{A}_t^{\tau} | \hat{A}_t)\|^2 \right], \quad (4)$$

where λ_{out} is a hyperparameter to control the balance between flow matching without perturbation and the robustness against noisy VLA output.

Remark 1. Robustness against action noise can be understand as flow matching against both clean and noisy action distribution. The model continues to match the clean distribution sampled from $p(A_t | \mathbf{o}_t)$ while additionally accounting for an adversarially perturbed alternative $p(A_t + \delta | \mathbf{o}_t)$. Training with such perturbations prepares the model for test-time noise and improves robustness.

Remark 2. Robustness against action noise can also be interpreted as a form of label smoothing (Müller et al., 2019). Injecting noise into actions makes the learned flow less certain, discouraging overconfident decisions and overfitting to specific actions. This yields better generalization and encourages more stochastic behavior that covers a wider range of plausible actions, a property shown to support robust decision-making in practice (Eysenbach & Levine, 2021).

Remark 3. Robustness against action noise can be understand by penalizing outliers. Recall the noise δ approximately points in the direction $v_{\theta}(\hat{A}_t^{\tau}, \mathbf{o}_t) - u(A_t^{\tau} | A_t^1)$, where the velocity field and rectified flow mismatch the most. Consequently, any mismatch during training is amplified quadratically by δ in the MSE objective of flow matching. The objective therefore acts to penalize outliers that the VLA cannot fit well, improving performance on corner cases and reducing non-robust failure modes.

Generalizing to Autoregressive VLAs. For VLAs that outputs discrete action tokens, take OpenVLA as an example, we perturb the actions before binning to maximize its cross entropy loss, with robust objective following Eqn. 4. The perturbations are constrained so that the action output remains within the original bin and its adjacent bins. This ensures that, even when errors occur, the outputs stay in the neighborhood of the correct action and the worst-case robustness is improved.

4.2 ROBUSTNESS AGAINST VLA INPUTS

Next, we study robustness to noisy VLA inputs. These noises can have different types in varying modalities. We observe that these perturbations do not alter the underlying task semantics, so the optimal action should remain unchanged. We therefore encourage the flow-matching objective to produce similar actions under perturbed inputs. To automatically handle diverse observation types, we cast the perturbation selection as a multi-armed bandit problem and use an upper confidence bound (UCB) algorithm (Auer, 2002) to identify the most harmful noise for adversarial training.

Robustness to Single Noise. Given a VLA policy $\pi(A_t | \mathbf{o}_t)$, input variation can stem from various sources, including sensory noise and camera error in observation, or irrelevant objects, lighting variations in external environment. Although inputs may vary, the robot’s underlying state does not change. That is, the robot operates in the same physical world to execute the same task. Consequently, the optimal actions should remain unchanged. For an input perturbation $\omega^i \in \Omega$, we define the flow-matching objective under each input noise as:

$$\min_{\theta} \max_{\omega^i} \mathbb{E}_{p(A_t | \mathbf{o}_t), q(A_t^{\tau} | A_t^1)} \|v_{\theta}(A_t^{\tau}, \omega^i(\mathbf{o}_t)) - u(A_t^{\tau} | A_t)\|^2. \quad (5)$$

Here, we adversarially select ω^i to simulate worst-case inputs. If the input noise is fixed, we leave it unchanged. This objective is inspired by state-perturbation techniques in offline RL (Shen et al., 2020; Yang et al., 2022). Now, it remains unknown how to balance many perturbations automatically.

Balancing Various Noises. While RobustVLA targets robustness against a broad set of perturbations, it remains unclear *which* perturbation types contributes most to overall performance. For instance, simple Gaussian noise can be easy to defend, yet confer little robustness to more complex noises. Assigning fixed weights to each perturbation type is possible, but manually tuning the weight for each uncertainty can be time-consuming. We therefore seek to automatically maximize overall robustness by adaptively selecting the input perturbation at each training iteration.

This selection problem can be naturally formulated as a multi-armed bandit, with the goal of maximizing the overall robustness of the VLA policy. At each training step n , the algorithm

selects an uncertainty $\omega^i \in \Omega$ to train the objective in Eq. 6. The UCB algorithm (Auer, 2002) provides a principled way to solve multi-armed bandits. Given the times each uncertainty has been explored as $\omega^i(n)$ at n^{th} training iteration, the uncertainty is selected as:

$$\omega_*^i = UCB(\Omega, n) = \arg \max_{\omega^i \in \Omega} \left[r_n(\omega^i) + \alpha \sqrt{\frac{\log(n)}{\omega^i(n)}} \right], \quad (6)$$

where $\alpha > 0$ is the exploration coefficient. To prioritize robustness, we define the reward as the increase in the flow-matching loss induced by the perturbation, *i.e.*, the gap between the noisy and clean objectives for the same (\mathbf{o}_t, A_t) pair:

$$r_n(\omega^i) = \mathbb{E}_{p(A_t|\mathbf{o}_t), q(A_t^\tau|A_t^1)} \|v_\theta(A_t^\tau, \omega^i(\mathbf{o}_t)) - u(A_t^\tau|A_t)\|^2 - \|v_\theta(A_t^\tau, \mathbf{o}_t) - u(A_t^\tau|A_t)\|^2. \quad (7)$$

To stabilize the reward, we apply z -score normalization with the mean and standard deviation maintained by an exponential moving average, with a decay factor of 0.9. Equipped with the UCB-selected uncertainty type ω_*^i , the training objective against diverse input noise becomes:

$$\min_{\theta} \mathcal{L}_{\pi_0}^\tau + \mathcal{L}_{in}^\tau = \min_{\theta} \mathcal{L}_{\pi_0}^\tau + \lambda_{in} \max_{\omega_*^i} \mathbb{E}_{p(A_t|\mathbf{o}_t), q(A_t^\tau|A_t^1)} \|v_\theta(A_t^\tau, \omega_*^i(\mathbf{o}_t)) - u(A_t^\tau|A_t)\|^2, \quad (8)$$

where λ_{in} balances the π_0 loss and the input robustness term. Finally, to enhance local smoothness of VLAs, we add a ℓ_p bounded observation noise η to maximize the flow matching loss of \mathcal{L}_{in}^τ computed via PGD (Madry et al., 2017), which works well empirically. For **autoregressive VLAs**, we apply the perturbation to observations and then map to action tokens, the remaining procedure is unchanged.

Overall RobustVLA Loss. Finally, we combine robustness to input and output perturbations with the π_0 objective. Let λ_{in} and λ_{out} be hyperparameters that weight the input- and output-robustness terms within \mathcal{L}_{in}^τ and \mathcal{L}_{out}^τ , respectively. The overall training objective is:

$$\min_{\theta} \mathcal{L}_{RobustVLA}^\tau = \min_{\theta} \mathcal{L}_{\pi_0}^\tau + \mathcal{L}_{in}^\tau + \mathcal{L}_{out}^\tau. \quad (9)$$

The pseudocode of our RobustVLA is given in Appendix. D

5 ROBUSTVLA EXPERIMENTS

Experiment Setting. Consistent with the robustness evaluation in Section 3.1, we assess all methods under the same 17 perturbations using the LIBERO benchmark and its recommended setup. We conduct our main experiment on π_0 backbone due to its superior robustness compared with OpenVLA. We compare BYOvla (Hancock et al., 2025), an off-the-shelf robust VLA method designed for visual uncertainties as our baseline. Our approach is termed *RobustVLA*. For our main experiments, we also consider two ablations of our RobustVLA remove either input or output regularization for better understanding, denoted RobustVLA w/o in and RobustVLA w/o out, respectively. We also evaluate our RobustVLA on the OpenVLA backbone under the same setting. *All reported improvements are absolute gains in success rate, expressed in percentage points.*

Implementation Details. We follow the default training recipe for π_0 and OpenVLA as recommended in their original codebase. For our RobustVLA, we set λ_{in} , λ_{out} as 1, action noise δ as 0.03, and observation noise η as 8/255. All baselines use the same set of hyperparameter and implementations. We leave additional implementation details in Appendix. B.1. Code available at <https://anonymous.4open.science/r/RobustVLA-283D>.

5.1 ROBUSTVLA ON π_0 BACKBONE

RobustVLA is more robust on π_0 backbone. We compare RobustVLA against all non-ablated baselines under 17 perturbations. As shown in Table. 1, RobustVLA gains higher robustness on all 17 perturbations, outperforming π_0 by 14.0% and baseline BYOvla by 12.6% on average robustness. Under clean conditions without perturbation, RobustVLA remains competitive with π_0 (95.5% vs. 96.0%), showing robustness gains do not come at the expense of clean performance.

Analysis on ablations. We further compare RobustVLA with ablated variants that remove input regularization (*Ours w/o in*) or output regularization (*Ours w/o out*). RobustVLA achieves higher

Table 1: Average success rate (%) under 17 noise types on LIBERO tasks, evaluated on π_0 backbone.

Noise Modality	Noise type	π_0	BYOVLA	Ours w/o in	Ours w/o out	RobustVLA (Ours)
w/o Noise		96.0	95.2	96.0	94.9	95.5
Action	Uniform Noise	63.5	62.0	67.3	66.8	69.8
	Gaussian Noise	31.4	32.1	36.3	31.9	36.0
	Action Bias	23.0	21.2	44.9	37.0	42.3
	Random Flips	52.7	51.6	56.9	54.0	58.7
	Sudden Spikes	51.7	51.1	58.5	52.7	59.7
Observation	Gaussian Noise	51.4	58.7	55.7	94.5	93.8
	Dead Pixel	20.8	43.1	40.8	90.8	93.8
	Motion Blur	93.7	95.2	94.1	95.0	95.5
	Color Jitter	61.7	54.2	53.9	58.7	69.5
	Image Rotation	73.3	77.7	64.1	94.0	94.4
Environment	Image Shift	74.6	70.4	63.2	89.2	92.7
	External Force	37.1	37.3	39.0	37.9	40.8
	Irrelevant Objects	93.1	93.7	91.2	89.9	94.2
Instruction	Lighting Variation	94.3	95.0	94.6	94.3	95.6
	Lexical Transform	78.7	79.5	81.5	77.7	91.3
	Syntactic Transform	84.7	85.8	84.0	82.3	93.9
	Adversarial Prompts	79.2	80.1	75.7	72.2	80.2
	Average	62.6	64.0	64.8	71.7	76.6

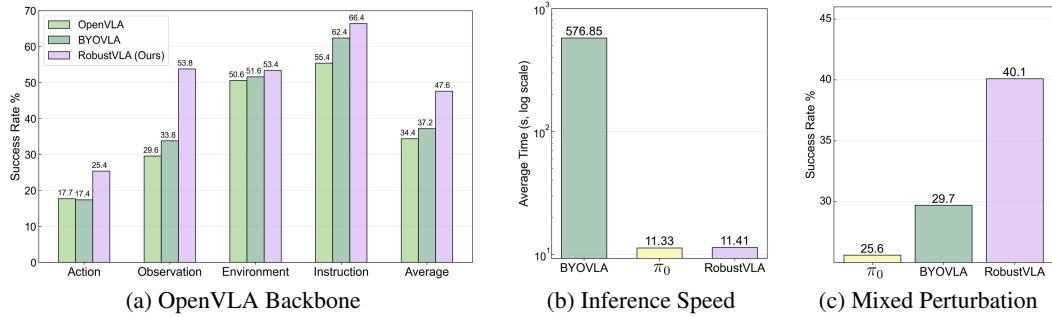


Figure 4: RobustVLA improves robustness on the OpenVLA backbone, achieves fast inference speed, and withstands mixed perturbations.

robustness than both ablations in 14/17 perturbations. This suggests **robustness aimed at one modality can also benefit others**. To explain, output robustness helps counter action drift induced by input noise, whereas input robustness improves generalization to the unseen transitions induced by action noise. As an evidence, even without input regularization, *Ours w/o in* retains notable gains on Dead Pixel, an observation perturbation. Similarly, removing output regularization, *Ours w/o out* still gains robustness on Uniform Noise and Action Bias, two perturbations on actions. These results implies multi-modal robustness as a promising route toward generally robust VLAs.

5.2 DISCUSSIONS

In this section, we demonstrate that RobustVLA is consistently effective on the OpenVLA backbone, achieves greater computational efficiency than the visual-robust BYOVLA, and maintains robustness under mixed perturbations applied on input and output.

RobustVLA is also robust on OpenVLA backbone. Beyond π_0 , RobustVLA is also consistently effective on the autoregressive-based OpenVLA. As shown in Fig. 4a, RobustVLA improves average robustness by 13.2% over OpenVLA, surpasses the baseline BYOVLA by 10.4%, demonstrating the effectiveness of RobustVLA across diffusion-based and autoregressive VLAs. The detailed numerical results are presented in Appendix C.1.

RobustVLA is computationally efficient. As shown in Fig. 4b, RobustVLA achieves a per-episode inference time of ~ 11 s, comparable to π_0 since they share the same architecture and parameter size. In contrast, RobustVLA is $50.6\times$ more efficient than BYOVLA, a visual-robust VLA method. This large gap arises because BYOVLA relies on the backpropagation step of Grad-CAM (Selvaraju et al., 2017) to identify sensitive visual regions of current VLAs and makes repeated calls to external LLMs to modify these regions, resulting in significant computational overhead.

RobustVLA is robust against mixed perturbations applied on input and output. To test this, we randomly sampled one uncertainty in VLA input and one uncertainty in VLA output, from categories defined in Fig. 2. We test the results on π_0 backbone, with random seed fixed to ensure all baselines were tested under the same set of uncertainties. As shown in Fig. 4, RobustVLA achieved a 14.5%

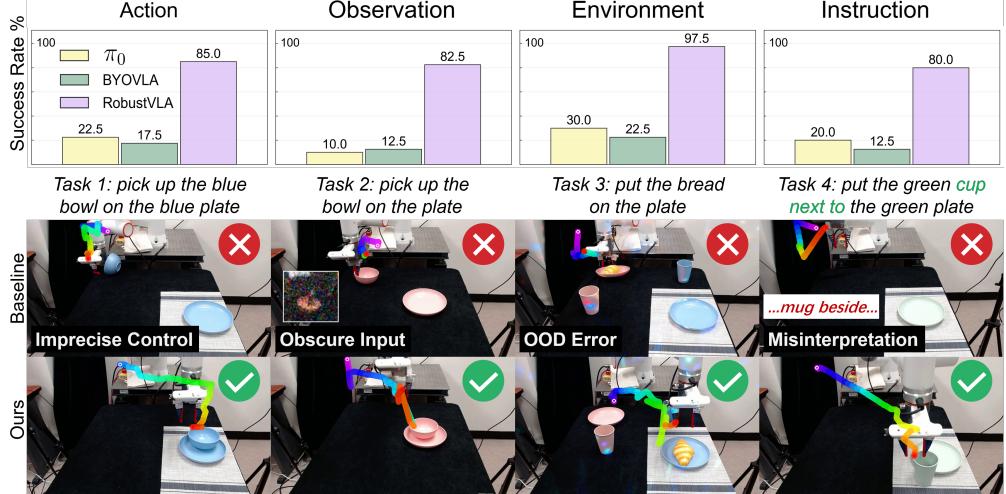


Figure 5: Real-world robustness results. Our RobustVLA is highly effective with scarce demonstrations, while baselines fail due to imprecise action control, obscure observation input, OOD observation and language misinterpretations.

higher robustness than π_0 and gains 10.4% robustness than baseline BYOvla. These improvements are statistically significant ($p < 0.001$, paired-sample t-test).

5.3 REAL-WORLD EXPERIMENTS

Real-world setup. We deploy VLAs on a Fairino FR5 robotic arm with a Hitbot Z-EFG-C50 gripper. Visual inputs are provided by a ZED2 external camera and an Intel RealSense 435i wrist-mounted camera. We design four tasks to assess real-world performance: (1) pick up the blue bowl on the blue plate; (2) pick up the bowl on the plate with randomized colors; (3) place the bread on the plate; and (4) place the green cup next to the green plate. These tasks test VLA’s capability on basic grasping, semantic generalization, deformable object manipulation, and spatial reasoning. For each task, we fine-tune π_0 with 25 demonstration trajectories.

Real-world noise. We design physical noise sources for robustness evaluation. For environmental noise, we vary lighting by adding a neon bubble and introduce irrelevant objects into the testing scene. For action noise, we perturb motor calibration and introduce interference in serial communication. For instruction noise, we use a speech recognition model to process human speech containing dialects, unusual word order, or irrelevant content. For observation noise, we apply the same perturbations as in simulation. However, we omit *external forces* since they could physically damage the robot. For each noise modality, we conduct 10 trials per task and report aggregated results over 4 tasks.

Real-world performance. As shown in Fig. 5, RobustVLA is highly effective in real-world deployment, surpassing the best baseline by 65.6% in success rate. We attribute this to the limited number of real-world trajectories available for fine-tuning. Unlike large and diverse simulation datasets such as LIBERO, laboratory-collected data are costly and offer limited state coverage, leading baseline VLAs to overfit demonstrations and fail under perturbations. In contrast, by anticipating noise during training, RobustVLA anticipates potential noise during training and remains robust to unexpected real-world disturbances. See per-task results in Appendix C.2.

Failure Analysis. Finally, we analyze the failure mode of baselines, aggregating π_0 and BYOvla due to their similar behaviors. As illustrated in Fig. 5: (1) under *action* uncertainties, baselines exhibit imprecise control, resulting in the gripper unable to grasp the bowl precisely and occasionally knocking the bowl over; (2) under *observation* uncertainties, input noise obscures the visual signal, making the robot unable to identify the object clearly; (3) under *environment* shifts, the added neon light produces a severe illumination change that renders observations OOD; and (4) under *instruction* noise, speech parsing errors lead to misinterpretation, making robots placing the cup “beside” the table. In contrast, RobustVLA remains reliable in most trials, achieving consistent success in the real world. Demo videos available in our codebase.

6 CONCLUSION

In this paper, we evaluate and enhance the robustness of VLA models under multi-modal uncertainties. We evaluate mainstream VLAs against 17 perturbations across four modalities, showing that actions are the most fragile, existing visual-robust VLAs fail to generalize beyond vision, and π_0 the most robust backbone with a diffusion-based action head. Building on these insights, we propose RobustVLA, a unified framework against input and output perturbations. For output robustness, we perform offline optimization against worst-case action noise that maximizes flow mismatch. For input robustness, we enforce consistent actions across semantically equivalent inputs and automatically identify the most harmful perturbation using UCB. On LIBERO, RobustVLA delivers absolute gains of 12.6% on π_0 and 10.4% on OpenVLA across 17 perturbations, achieves 50.6x faster inference than visual-robust VLAs, and improves robustness by 10.4% under mixed perturbations. In real-world tasks with limited demonstrations, RobustVLA achieves absolute gains of 65.6% under four modalities of perturbations.

7 ETHICS STATEMENT

Our research focuses on evaluating and enhancing the robustness of VLA models. By systematically studying their vulnerabilities under diverse uncertainties and proposing methods for robustness improvement, our work assists researchers and engineers in developing and deploying VLAs in environments where safety, stability, and reliability are critical. We emphasize that our study does not introduce new adversarial attack techniques, and is designed to provide constructive insights that strengthen the trustworthiness of embodied AI systems.

8 REPRODUCIBILITY STATEMENT

We have open sourced all our code for robustness evaluation and enhancement in <https://anonymous.4open.science/r/RobustVLA-283D>. Additional experiment details are available in Appendix A and B.

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APPENDIX FOR "ON ROBUSTNESS OF VISION-LANGUAGE-ACTION MODEL AGAINST MULTI-MODAL PERTURBATIONS"

Declaration of LLM usage. We use LLM to polish text only and authors have carefully checked all contents in the paper.

A EVALUATION UNCERTAINTIES

To systematically evaluate the robustness of VLAs, we consider uncertainties in actions, observations, environment, and instructions. For each type of uncertainties, we first relate it to practical sources of uncertainty in real-world, provide a formal definition, and describe the implementation details.

As defined in Section. 3, we define robustness of VLAs against perturbations $\omega \in \Omega$, where $\Omega = \{\Omega_\psi, \Omega_o, \Omega_a, \Omega_p\}$ corresponds to language, observation, action and environment dynamic, respectively. The perturbed variables are denoted as $\hat{\psi}$, \hat{o}_t , \hat{A}_t , and $\hat{\mathcal{P}}$.

A.1 ACTION UNCERTAINTIES

In this paper, we consider 5 action noises related to sensorimotor noise, actuator wear and unexpected perturbations. A summary of these threats are available at Table. 2. Formally, we use $\mathbf{A}_t \in \mathbb{R}^d$ to denote the action vector produced by the policy at time step t , where $A_{t,i}$ is its i -th component. We use $\hat{\mathbf{A}}_t$ (with components $\hat{A}_{t,i}$) to denote the perturbed action after injecting noise. We describe details of each noise below.

Table 2: Summarization of action uncertainties.

Uncertainty Type	Mathematical Formulation	Practical Sources
Uniform Noise	$\hat{A}_t = A_t + \epsilon, \quad \epsilon \sim \mathcal{U}(-\sigma, \sigma)^d$	Sensorimotor Noise
Gaussian Noise	$\hat{A}_t = A_t + \epsilon, \quad \epsilon \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I})$	Sensorimotor Noise
Action Bias	$\hat{A}_t = A_t + \sigma \cdot \mathbf{1}$	Actuator Wear
Random Flips	$\hat{A}_{t,i} = \begin{cases} 1 & \xi_i < p \wedge \zeta_i < 0.5 \\ -1 & \xi_i < p \wedge \zeta_i \geq 0.5 \\ A_{t,i} & \text{otherwise} \end{cases}$	Unexpected Perturbations
Sudden Spikes	$\hat{A}_{t,i} = \begin{cases} A_{t,i} + \sigma \cdot \text{sign}(\xi_i) & \xi_i < p \\ A_{t,i} & \text{otherwise} \end{cases}$	Unexpected Perturbations

Uniform Noise. Uniform noise is a random perturbation uniformly distributed within a fixed interval. It simulates sensorimotor noise, such as bias in motor response or random interference in sensor measurements. In the evaluation, the value of σ was set to 0.04.

$$\hat{A}_t = A_t + \epsilon, \quad \epsilon \sim \mathcal{U}(-\sigma, \sigma)^d$$

Gaussian Noise. Gaussian noise is a random perturbation drawn from a normal distribution, with fluctuations centered around zero. It simulates sensorimotor noise such as sensor thermal noise, micro-vibrations, or irregular actuator responses. In the evaluation, the value of σ was set to 0.3.

$$\hat{A}_t = A_t + \epsilon, \quad \epsilon \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I})$$

Action Bias. Action bias introduces a fixed offset across all action dimensions, resulting in consistent deviations from the intended control signal. It models actuator wear over time, or calibration drift and joint zero-point misalignment. In the evaluation, the value of σ was set to 0.03.

$$\hat{A}_t = A_t + \sigma \cdot \mathbf{1}$$

Random Flips. Random flips replace selected action components with extreme values, creating abrupt deviations from normal behavior. This mimics unexpected disturbances such as sudden shocks from external disturbances, communication bit flips or actuator sticking and slipping. In the evaluation, the probability p was set to 0.05.

$$\hat{A}_{t,i} = \begin{cases} 1 & \xi_i < p \wedge \zeta_i < 0.5 \\ -1 & \xi_i < p \wedge \zeta_i \geq 0.5, \quad \xi_i, \zeta_i \sim \mathcal{U}(0, 1) \\ A_{t,i} & \text{otherwise} \end{cases}$$

Sudden Spikes. Sudden spikes are abrupt, high-amplitude perturbations that occur with a certain probability. They simulate unexpected perturbations such as actuator jitter, control signal surges, or abrupt shocks in the mechanical system. In the evaluation, the probability p was set to 0.05 and the spike magnitude σ was set to 1.

$$\hat{A}_{t,i} = \begin{cases} A_{t,i} + \sigma \cdot \text{sign}(\xi_i) & |\xi_i| < p, \quad \xi_i \sim \mathcal{U}(0, 1) \\ A_{t,i} & \text{otherwise} \end{cases}$$

A.2 OBSERVATION UNCERTAINTIES

In this paper, we consider 6 observation noises related to sensory noise and camera error. A summary of these threats are available at Table. 3. Formally, we use $\mathbf{o}_t \in \mathbb{R}^{H \times W \times C}$ to denote the observation (image) received by the policy at time step t , where $o_{t,i,j}$ denotes the pixel intensity at location (i, j) . We use $\hat{\mathbf{o}}_t$ (with components $\hat{o}_{t,i,j}$) to denote the corrupted observation after injecting noise. We describe details of each noise below.

Table 3: Summarization of Observation Uncertainties

Uncertainty Type	Mathematical Formulation	Practical Sources
Gaussian Noise	$\hat{o}_t = \text{clip}(o_t + \epsilon, 0, 255), \quad \epsilon \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I})$	Sensory Noise
Dead Pixel	$\hat{o}_{t,i,j} = \begin{cases} 255 & \xi_{i,j} < p \wedge \zeta_{i,j} < 0.5 \\ 0 & \xi_{i,j} < p \wedge \zeta_{i,j} \geq 0.5 \\ o_{t,i,j} & \text{otherwise} \end{cases}$	Sensory Noise
Motion Blur	$\hat{\mathbf{o}}_t = \mathbf{o}_t * G_\sigma$	Camera Error
Color Jitter	$\hat{\mathbf{o}}_t = \mathcal{S}_\alpha \circ \mathcal{C}_\beta \circ \mathcal{B}_\delta(\mathbf{o}_t)$	Sensory Noise
Image Rotation	$\hat{o}_t[i, j] = o_t[R_\theta^{-1}(i, j)]$	Camera Error
Image Shift	$\hat{o}_t[i, j] = o_t[i - \Delta i, j - \Delta j]$	Camera Error

Gaussian Noise. Gaussian noise is an additive perturbation where pixel values fluctuate around the mean according to a normal distribution. It simulates sensory noise including thermal fluctuation, dark current, and stochastic variations in imaging sensors. In the evaluation, the noise standard deviation σ was set to 70.

$$\hat{\mathbf{o}}_t = \text{clip}(\mathbf{o}_t + \epsilon, 0, 255), \quad \epsilon \sim \mathcal{N}(\mathbf{0}, \sigma^2 \mathbf{I}_{HWC})$$

Dead Pixel. Dead pixel noise is an impulsive perturbation that forces certain pixels to extreme values (0 or 255). It simulates sensory errors such as dead pixels, stuck pixels, or bit errors in image transmission. In the evaluation, the corruption probability p was set to 0.1.

$$\hat{o}_{t,i,j} = \begin{cases} 255 & \xi_{i,j} < p \wedge \zeta_{i,j} < 0.5 \\ 0 & \xi_{i,j} < p \wedge \zeta_{i,j} \geq 0.5, \quad \xi_{i,j}, \zeta_{i,j} \sim \mathcal{U}(0, 1) \\ o_{t,i,j} & \text{otherwise} \end{cases}$$

Motion Blur. Motion blur is a smoothing perturbation introduced by spatial convolution with a Gaussian kernel. It simulates camera error include shake, defocus, or object motion relative to the

camera. We denote the blur standard deviation by σ , the convolution kernel size by K , and the kernel half-width by $k = \frac{K-1}{2}$, so that the kernel spans indices $u, v \in [-k, k]$. In our evaluation, we set $\sigma = 1$ and $K = 5$.

$$\hat{\mathbf{o}}_t[i, j] = \sum_{u=-k}^k \sum_{v=-k}^k G_\sigma(u, v) \mathbf{o}_t[i - u, j - v], \quad G_\sigma(u, v) = \frac{1}{2\pi\sigma^2} e^{-\frac{u^2+v^2}{2\sigma^2}}$$

Color jitter. Color jitter is a composite perturbation that adjusts image brightness, contrast, saturation, and sharpness. It simulates sensory errors like uneven gain in CMOS/CCD, lighting variation, white balance errors or automatic camera gain fluctuations. In the evaluation, the maximum perturbation factor was set to 0.4 for all adjustments.

$$\hat{\mathbf{o}}_t = \mathcal{S}_\alpha \circ \mathcal{C}_\beta \circ \mathcal{B}_\delta(\mathbf{o}_t)$$

where \mathcal{B}_δ , \mathcal{C}_β , \mathcal{S}_α represent the brightness, saturation, and sharpness enhancement functions, respectively. Their intensity parameters δ, β, α are independent random perturbation factors sampled based on `max_factor` = 0.4.

Image rotation. Image rotation is a geometric perturbation that rotates pixels around the image center. It simulates camera error induced by robot tilting, changes in camera orientation, or misalignment in the mounting system. In the evaluation, the rotation angle θ was randomly sampled within a bounded interval $[-\sigma_\theta, \sigma_\theta]$. In the evaluation, the value of σ_θ was set to 20°.

$$\hat{\mathbf{o}}_t[i, j] = \mathbf{o}_t[R_\theta^{-1}(i, j)], \quad R_\theta = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix}, \quad \theta \sim \mathcal{U}(-\sigma_\theta, \sigma_\theta)$$

Image shift. Image shift is a translation perturbation that displaces pixel coordinates by offsets proportional to the image dimensions. It simulates camera vibrations, miscalibration, or abrupt movements during perception. We denote the maximum shift fraction of the image dimensions by Δ_{shift} . In the evaluation, the value of Δ_{shift} was set to 0.15.

$$\hat{\mathbf{o}}_t[i, j] = \mathbf{o}_t[i - \Delta i, j - \Delta j], \quad \begin{aligned} \Delta i &\sim \mathcal{U}(-\Delta_{\text{shift}} H, \Delta_{\text{shift}} H) \\ \Delta j &\sim \mathcal{U}(-\Delta_{\text{shift}} W, \Delta_{\text{shift}} W) \end{aligned}$$

A.3 ENVIRONMENTAL UNCERTAINTIES

Environment uncertainties consider external influences. This can happen either in VLA input and output. In this paper, we consider external force in VLA output. For VLA input, we consider addition of irrelevant objects and lighting variations. This results in 3 environment uncertainties in total.

External Force. External force represents an exogenous disturbance applied directly to the robot's body or joints, rather than an error in its internal control signals. Unlike *action uncertainties*, which arise from sensorimotor noise or actuator imperfections affecting the executed commands, external forces originate from the environment and perturb the robot independently of its control policy. Such disturbances occur in real-world settings when a human pushes the robot, when the robot collides with obstacles, or when it interacts with moving objects in a cluttered environment. These forces are inherently non-deterministic in both timing and magnitude, making them a critical source of uncertainty during deployment. In the evaluation, we apply an external force $\mathbf{F}_{\text{external}}$ in addition to the control force $\mathbf{F}_{\text{control}}$:

$$\mathbf{F}_{\text{total}} = \mathbf{F}_{\text{control}} + \mathbf{F}_{\text{external}} \quad \text{where} \quad \mathbf{F}_{\text{external}}(t) = \begin{cases} \mathbf{F}_0 \cdot \mathbf{d} & t \in [t_i, t_i + \Delta t_i] \\ \mathbf{0} & \text{otherwise} \end{cases} \quad (10)$$

Here, \mathbf{F}_0 denotes the disturbance magnitude and \mathbf{d} the direction vector. We set $\mathbf{F}_0 = 200$ N along $(1, 0, 0)$ (x-axis), with each application lasting 5 ± 2 timesteps and occurring at random intervals of 40–50 steps to emulate unpredictable external perturbations.

Irrelevant Objects. To evaluate the robustness of VLA models, we introduced additional distractor objects into the environment. Specifically, during task execution we placed assets drawn from unrelated tasks in close proximity to either the target object or the designated goal location. The number of distractors was fixed to three. We note that, in our experiments, this setting already

approaches the upper bound supported by the LIBERO environment: adding more distractors frequently leads to spatial conflicts during initialization.

Lighting Variations. Lighting variation is an observation-level uncertainty caused by fluctuations in natural or artificial illumination. Such changes may occur in real-world settings due to moving light sources, shifting daylight, or shadows cast by dynamic objects in the environment, all of which can significantly alter the visual appearance of a scene. To simulate these effects, we adopt the Phong reflection model, where the total intensity at a surface point is given by:

$$I = I_a + I_d + I_s, \quad (11)$$

$$I_d = k_d \cdot I_{\text{light}} \cdot \max(0, \mathbf{n} \cdot \mathbf{l}), \quad (12)$$

with I_a , I_d , and I_s denoting the ambient, diffuse, and specular components, k_d the diffuse reflection coefficient, \mathbf{n} the surface normal, and \mathbf{l} the direction vector to the light source.

In our evaluation, the illumination intensity I_{light} was sampled from a Gamma distribution $\text{Gamma}(k, \theta)$ with parameters $k = 1.0$ and $\sigma^2 = 1.0$, producing both subtle and dramatic variations. To further emulate dynamic conditions, the light direction was updated every 3 simulation steps, with the azimuth angle $\theta \sim \mathcal{U}(0, 2\pi)$ while fixing the elevation at 45° .

A.4 INSTRUCTION UNCERTAINTIES

In this paper, we consider 3 uncertainties, including word-level lexical transform, sentence-level syntactic transform and adversarial prompt with ambiguous or irrelevant transformations. Examples of our added uncertainties are available in Table. 4. We describe details of each noise below.

Table 4: Examples of instruction uncertainties transformations compared to the original instruction.

Type	Instruction
Original	pick up the black bowl between the plate and the ramekin and place it on the plate
Lexical Transform	Retrieve the ebony bowl situated between the dish and the ramekin and deposit it onto the dish
Syntactic Transform	Could you pick up the black bowl that is between the plate and the ramekin, and then place it on the plate with care?
Adversarial Prompt	I think you can do IT, maybe? pick up the black bBBowl, between the plate and the ramekin and place it on the plate

Lexical Transform simulates real-world variations in word usage, encompassing phenomena such as dialectal differences and synonym substitutions. This dimension introduces surface-level perturbations to characters or words while preserving core semantics and syntactic integrity. These transformations probe model resilience against lexical noise encountered in everyday communication.

Syntactic Transform addresses structural flexibility inherent in human language expression. It modifies phrase ordering, sentence patterns, and grammatical constructions, clause insertion, or punctuation alterations—without altering propositional meaning. This dimension tests model robustness against grammatical reconfigurations that retain identical semantic content.

Adversarial Prompts evaluates model sensitivity to contextual noise and communicative distractions. It introduces semantically irrelevant content (e.g., social media tags, extraneous clauses), accidental error(OCR misrecognition, keyboard typos) , or adversarial manipulations (sentiment polarity flips) while maintaining surface fluency. This dimension mimics real-world scenarios where core information must be discerned amidst misleading signals.

B TRAINING SETTING

B.1 IMPLEMENTATION DETAILS

This appendix details the implementation details used throughout our experiments. These settings were found to be effective and robust in our empirical evaluations. We provide them here to facilitate reproducibility and to serve as a reference for future work.

B.1.1 BASE TRAINING PARAMETERS

The foundational training hyperparameters for our models are summarized in Table 5. For training RobustVLA on the π_0 benchmark, we maintained consistency with the original π_0 setup in terms of batch size and total training steps. To optimize computational efficiency, we employed a hybrid training strategy: the action expert (a 300M parameter Gemma model) was fully fine-tuned, while the Vision-Language Model (VLM) component was trained using Low-Rank Adaptation (LoRA). A similar LoRA-based approach was adopted for training OpenVLA models but with minor modifications to balance GPU memory usage and training efficiency.

Table 5: Base training hyper-parameters.

Parameter	RobustVLA on π_0	On OpenVLA
Batch Size	32	16
Training Steps	30,000	30,000
Action Expert Tuning	Full Fine-tune	-
VLM Tuning	LoRA	LoRA

B.1.2 UCB EXPLORATION PARAMETERS

The parameters for the Upper Confidence Bound (UCB) exploration strategy are listed in Table 6. The UCB algorithm encourages the agent to explore less-visited states by adding an exploration bonus to the value estimate. This bonus is inversely proportional to the visit count, promoting a balance between exploiting known rewarding paths and exploring new ones.

ucb_exploration_coeff: This coefficient controls the weight of the exploration bonus in the UCB calculation. A higher value encourages more exploration. We set it to 1.0 as a standard baseline.

ucb_window_size: This defines the size of the sliding window used to calculate recent visit counts. A finite window size allows the agent to "forget" old visits and re-explore states that haven't been visited recently, which is crucial in non-stationary environments.

ucb_ema_decay: This parameter sets the decay rate for an Exponential Moving Average (EMA) used to smooth the visit counts. A decay of 0.9 places more weight on recent visits, making the exploration bonus more adaptive to recent policy changes.

ucb_min_samples: The minimum number of samples required for a state before the UCB bonus is applied. This prevents underexplored states with very few samples from having an excessively high and uncertain bonus.

It is important to note that while these specific values were used effectively in our experiments, they were not extensively optimized. The UCB framework is highly extensible and possesses significant potential for task-specific optimization. Beyond the commonly used enhancement mechanisms, the UCB components can be easily augmented or pruned to suit particular tasks or application scenarios.

Table 6: UCB exploration hyperparameters.

Parameter	Value
ucb_exploration_coeff	1.0
ucb_window_size	100
ucb_ema_decay	0.9
ucb_min_samples	10

B.1.3 ADVERSARIAL TRAINING PARAMETERS

The parameters for adversarial training, which includes both action-space and observation-space (image) perturbations, are provided in Table 7.

adv_epsilon (ϵ): This is the maximum allowed perturbation magnitude, defining the ℓ_∞ norm ball around the original input (action or image) within which the adversarial example must lie. A larger ϵ creates a stronger but potentially less stealthy attack.

pgd_steps: The number of iterative steps used to generate the PGD attack. More steps typically lead to a more powerful adversarial example within the given ϵ constraint, as the attack can better orient itself towards the steepest ascent of the loss function.

pgd_alpha: The step size for each iteration of the PGD attack. It determines how much the perturbation is updated in each step. It is typically a fraction of ϵ .

loss_weight (λ): This is the weight coefficient used to balance the input and output losses, which determines which measurement our optimization focuses more on for robustness.

While parameters below are generally not highly sensitive in our preliminary study, we offer the following guidance: the perturbation limits defined by `adv_epsilon_action` and `adv_epsilon_image` should not be set excessively large. We observed that even small adversarial perturbations during training are sufficient to confer strong robustness against larger noises during evaluation. To enhance the effectiveness of adversarial training, increasing the number of PGD steps (`pgd_steps_*`) is a recommended strategy. However, this improvement comes at the cost of increased GPU memory consumption and longer training times.

Table 7: Adversarial training hyperparameters.

Parameter	Action Space	Observation Space
adv_epsilon	0.03	8/255
pgd_steps	3	3
pgd_alpha	0.01	2/255
λ	1	1

C DETAILS OF EXPERIMENTAL RESULTS

Due to space constraints in the main text, which focused primarily on experimental results and model performance across various robustness categories, more detailed data and secondary observations could not be included. Therefore, we provide in this appendix complementary details of our experimental outcomes to facilitate a more comprehensive understanding of this work.

C.1 DETAILS OF OPENVLA EXPERIMENTAL RESULTS

We conducted comprehensive tests on OpenVLA, BYOVLA, and our enhanced RobustVLA models across our benchmark tasks. While the results analyzed by type of uncertainty have been discussed in detail in the main text, we provide the complete data details of our tests in Table 8.

C.2 DETAILS OF REAL-WORLD EXPERIMENTAL RESULTS

We present in Fig. 6 the specific task success rates of various methods under different uncertainties for different tasks. Furthermore, by analyzing the robot’s performance, we have preliminarily identified the causes of failures in baseline models under different robustness conditions, as well as the advantages exhibited by our method:

Action Uncertainty. The baseline often suffers from imprecise control, such as jitter and control errors, leading to misalignment in grasping and frequent task failures. In contrast, RobustVLA exhibits strong tolerance to such disturbances, enabling stable task execution. As shown in Fig. 5, while the baseline exhibits large-amplitude oscillations and severe localization deviations, RobustVLA reduces jitter to a minor level and consistently completes the tasks.

Table 8: Average success rate (%) under 17 noise types on LIBERO tasks, evaluated on OpenVLA backbone.

Noise Modality	Noise type	OpenVLA	BYOVLA	RobustVLA
Action	Uniform Noise	25.4	24.2	37.6
	Action Gaussian	7.4	8.3	10.1
	Action Bias	11.8	12.6	24.9
	Random Flips	21.6	20.3	25.4
	Sudden Spikes	22.2	21.5	28.8
Observation	Visual Gaussian	0.8	1.5	60.9
	Dead Pixel	21.6	25.1	68.9
	Color Jitter	31.0	37.3	38.1
	Image Rotation	22.3	26.3	26.6
	Image Shift	42.9	46.6	47.3
Instruction	Motion Blur	59.3	66.1	80.9
	Lexical Transform	57.7	55.2	58.7
	Syntactic Transform	59.1	69.5	76.1
Environment	Adversarial Prompts	49.3	62.6	64.5
	Irrelevant Objects	72.3	72.7	77.0
	Lighting Variation	64.4	67.4	64.9
	External Force	15.0	14.6	18.2
	Average	34.4	37.2	47.6

Observation Uncertainty. The baseline frequently misjudges task states under obscure inputs. For example, due to visual interference, it often fails to recognize task completion and repeatedly attempts to grasp the target. Although BYOVLA helped reduce distraction from irrelevant objects or background clutter, it remains insufficient for reliable state estimation. RobustVLA, however, accurately infers execution states under degraded observations, which is critical for task success.

Environment Uncertainty. The baseline often encountered OOD situations under environmental changes such as distractor objects and varying illumination, leading to degraded tracking of targets, misjudgment of self-states, or even catastrophic failures (e.g., descending directly toward the table). Our approach maintains strong target-tracking and state-estimation capabilities under diverse environmental factors.

Instruction uncertainty. Variations in object references, actions, or prepositions—through synonym substitution, word-order changes, or irrelevant content—often cause the baseline to misinterpret instructions, leading to failures in object tracking, spatial reasoning, and instruction following. RobustVLA, in contrast, consistently extracts key information from diverse instructions and executes them reliably.

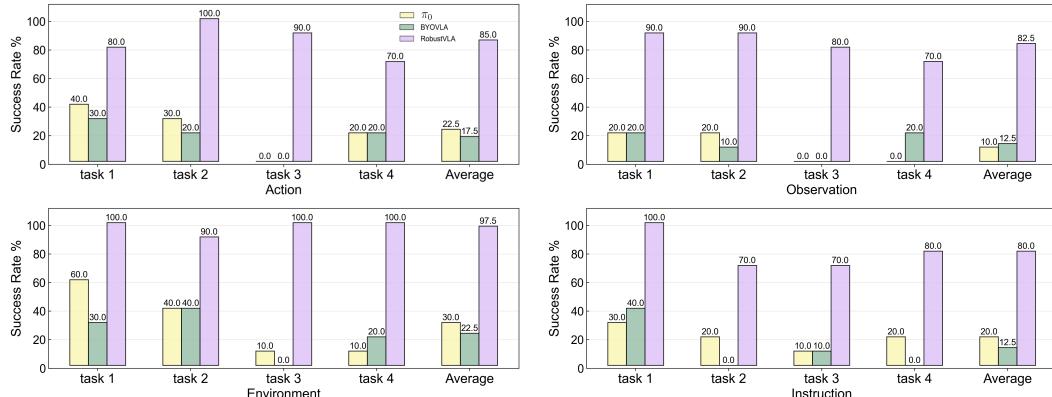


Figure 6: Details of Real-World Experimental Results

D PSEUDO CODE OF ROBUSTVLA

We present the pseudocode of our RobustVLA implemented on π_0 backbone in Algorithm. 1. Comparing with π_0 , our RobustVLA gains robustness with minimal loss in clean performance by incorporating robustness against VLA input and output. In robustness against VLA input, we additionally use UCB algorithm to select the best perturbation. Both robustness against VLA input

and output are trained using adversarial training with TRADES objective (Zhang et al., 2019), which optimally balance clean performance and robustness.

Algorithm 1 Pseudo Code of RobustVLA Training on π_0

Input: Model θ , dataset \mathcal{D} , augmentation set Ω
Output: Trained model θ^*

Initialize UCB balancer for Ω
Initialize optimizer
for step = 1 to T **do**
 Sample batch $\{(\mathbf{o}_t, A_t^1)\} \sim \mathcal{D}$
 // UCB Step
 Select augmentation i^* using UCB
 $\omega^i(\mathbf{o}_t) \leftarrow \text{augment}(\mathbf{o}_t, i^*)$
 // Flow matching setup
 Sample $A_t^0 \sim \mathcal{N}(0, \mathbf{I})$, $\tau \sim \text{Beta}(1.5, 1)$
 $A_t^\tau \leftarrow \tau A_t^1 + (1 - \tau) A_t^0$
 $u \leftarrow A_t^0 - A_t^1$
 // Clean loss
 $v_\theta \leftarrow v_\theta(\mathbf{o}_t, A_t^\tau, \tau)$
 $\mathcal{L}_{\text{clean}} \leftarrow \|v_\theta - u\|^2$
 $\mathcal{L}_{\text{total}} \leftarrow \mathcal{L}_{\text{clean}}$
 // Robust Against VLA Output
 $\delta \leftarrow \text{random_perturbation}$
 for $i = 1$ to action_pgd_steps **do**
 $\mathcal{L}_{\text{out}} \leftarrow \max_{\|\delta\|_\infty \leq \epsilon_{\text{action}}} \mathbb{E}_{t, \epsilon} \left[\|v_\theta(o_t, A_t^{\text{adv}}(\delta), t) - u_t^{\text{adv}}(\delta)\|^2 \right]$
 $\delta \leftarrow \text{PGD_update}(\delta, \nabla_\delta \mathcal{L}_{\text{out}})$
 end for
 $\mathcal{L}_{\text{total}} \leftarrow \mathcal{L}_{\text{total}} + \mathcal{L}_{\text{out}}$
 // Robust Against VLA Input
 $\{\eta\} \leftarrow \text{random_perturbation}$
 for $j = 1$ to $\text{observation_pgd_steps}$ **do**
 $\mathcal{L}_{\text{in}} \leftarrow \max_{\|\{\eta\}\|_\infty \leq \epsilon_{\text{obs}}} \mathbb{E}_{t, \epsilon} \left[\|v_\theta(\omega^i(\mathbf{o}_t)^{\text{adv}}, x_t, t) - u_t\|^2 \right]$
 $\{\eta\} \leftarrow \text{PGD_update}(\{\eta\}, \nabla_{\{\eta\}} \mathcal{L}_{\text{in}})$
 end for
 $\mathcal{L}_{\text{total}} \leftarrow \mathcal{L}_{\text{total}} + \mathcal{L}_{\text{in}}$
 Update θ with $\nabla_\theta \mathcal{L}_{\text{total}}$
 // UCB update
 Update UCB statistics with $-\mathcal{L}_{\text{in}}$
end for
Return: $\theta^* = \theta$
