HAMSTER: HIERARCHICAL ACTION MODELS FOR OPEN-WORLD ROBOT MANIPULATION

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ABSTRACT

Large models such as VLMs and LLMs have shown strong open-world generalization to complex problems in vision and language, but they have been relatively more difficult to deploy in robotics. One major challenge that has made the deployment of such models challenging in robotics is the lack of scalable robotic training data. Typically, robot datasets must be obtained on hardware, through an expensive on-robot data collection process. For scalable training, it's important that these models are also able to use cheaper, "off-domain" data such as videos, hand-drawn sketches, or data from simulation besides just high-quality, on-robot data. In this work, we posit that hierarchical vision-language-action models can be more effective in utilizing cheap, off-domain data than standard monolithic vision-language-action models, showing considerable cross-domain transfer. In particular, we study a class of hierarchical vision-language-action models, where high-level vision-language models (VLMs) are trained on relatively cheap data sources to produce semantically meaningful intermediate predictions such as 2D paths indicating desired behavior. These predicted 2D paths can then serve as guidance for low-level, 3D aware control policies capable of precise manipulation. Doing so alleviates the high level model from the burden of fine-grained motion prediction, while providing guidance that can significantly improve low-level generalization. In this work, we show that this separation of prediction into semantic high-level predictions, and 3D-aware low-level predictions allows *hierarchical* VLA policies to transfer across significant domain gaps, from simulation to the real world or across scenes with widely varying visual appearance. Doing so allows for the usage of cheap, abundant data sources beyond high-quality on-robot data, thereby enabling broad semantic and visual generalization. We demonstrate how hierarchical architectures trained on such cheap off-domain data can enable robotic manipulation with semantic, visual, and geometric generalization through experiments in simulation and the real world.

1 INTRODUCTION

Developing general robot manipulation policies has been notoriously difficult. With the advent of large vision-language models (VLMs) that display compelling examples of generalization, there is optimism that similar techniques can be helpful for robotic manipulation. A line of prior work (Team et al., 2024; Kim et al., 2024; Gu et al., 2023) builds open-world vision-language-action models (VLAs) by finetuning off-the-shelf, pretrained VLMs. The recipe for training many of these VLA models has been to collect and curate a large-scale robotics-specific dataset, complete with images and corresponding on-robot actions, and then finetune a VLM to directly produce actions (Kim et al., 2024; Brohan et al., 2023a). Such VLAs have shown robustness on simple tasks and controlled environmental variations. However, these models display limited generalization in terms of environment, object, task, and semantic variation. This issue could be attributed to the relative scarcity of diverse, in-domain training data. The data needed to train these models is expensive since it requires end-to-end image-action pairs that must all be collected directly on-robot through an expensive medium

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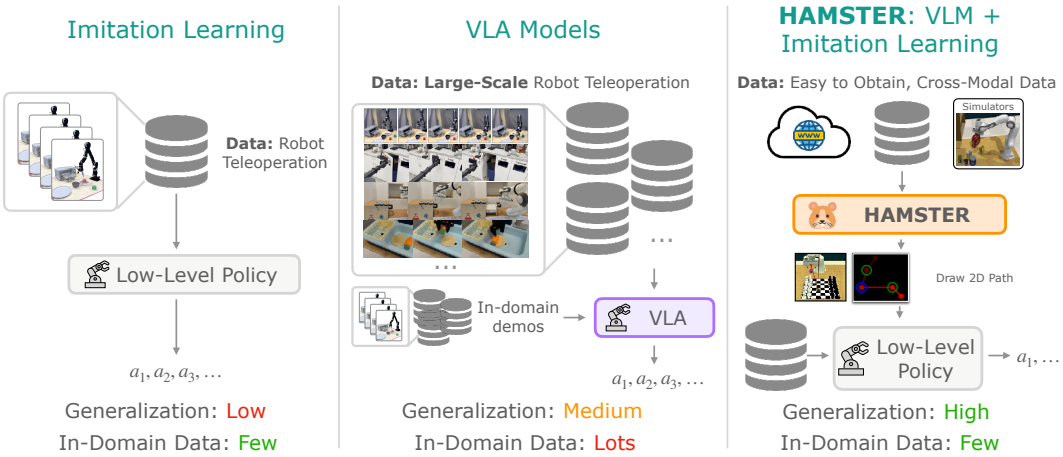

Figure 1: Overview of HAMSTER, VLAs and "smaller" imitation learning methods. HAMSTER's hierarchical design results in better generalization with a small amount of in-domain data. HAMSTER is able to utilize cheap training sources such as videos or simulations for enhanced generalization.

such as teleoperation. A solution for training VLA models must be developed to instead learn from easy-to-collect "cheap" sources of data.

On the other hand, relatively "small" imitation learning models have shown impressive dexterity and geometric robustness. Such models have demonstrated promise across a range of complex tasks involving contact-rich manipulation and 3D reasoning, spanning domains from tabletop manipulation (Shridhar et al., 2023; Goyal et al., 2023) to fine dexterous manipulation (Zhao et al., 2023). Trained on relatively small datasets, these models show local robustness and stable control but typically lack semantic or visual generalization. They are often brittle to changes in the environment, semantic description of the tasks, or changes in the objects being manipulated (Pumacay et al., 2024). Reliable, generalizable robotic learning techniques must marry the generalization benefits of large VLMs, with the efficiency, local robustness and dexterity of small imitation learning policies, all while being able to train from abundant and cheap sources of data. In this work, we ask – can we design VLA models that train on relatively abundant and cheap data sources, showing broad visual and semantic generalization, while retaining the low-level geometric and 3D understanding displayed by small imitation learning models?

We propose that a hierarchical architecture for vision language action models, HAMSTER(**H**ierarchical **A**ction **M**odels with **S**epara**TE**d Path **R**epresentations), can serve as an effective way to learn from abundant and inexpensive off-domain sources of data such as videos or simulation. We study a family of HAMSTERs, where finetuned VLMs are connected to low-level 3D policy learning methods via intermediate 2D path representations. Since these 2D paths can easily be obtained in abundance from data sources such as videos or simulations (either with point tracking, hand-sketching, or proprioceptive projection), these can be used to finetune the larger higher-level VLM in HAMSTER. These 2D paths can then serve as guidance for a low-level policy that operates on rich 3D and proprioceptive inputs, alleviating the burden of long-horizon planning and semantic reasoning, allowing low-level policies to focus on robustly generating precise, spatially-aware actions.

Representations similar to 2D paths has been explored in the robot learning literature (Gu et al., 2023), primarily as a technique for flexible task specification. However, the key hypothesis explored in this paper is distinct – we posit that using cheap data such as videos or simulation to finetune *hierarchical* path generating VLMs can enable a surprising degree of cross-domain transfer as compared to the direct transfer of monolithic vision-language-action models (Brohan et al., 2022; Kim et al., 2024). Here the focus is less on using paths as a scalable technique for task specification, and more on using hierarchy as a mechanism for robust cross-domain transfer across settings with considerable visual and semantic differences. Specifically, we find that VLMs trained to predict 2D path representation can transfer to the real world from simulations that look very different from the real world, or across real-world scenarios with widely varying appearance. Hence, the hierarchical design of HAMSTER provides a way to utilize cheaper, but perceptually varying sources of "off-domain" data (such as simulation or cross-embodiment data) to benefit real-world control policies.

The hierarchical design presented in HAMSTER can also offer additional advantages through the decoupling of VLM training and low-level action prediction. Specifically, since the higher-level VLM is predicting semantically meaningful trajectories from monocular RGB camera inputs, the lower-level control policies can operate from rich 3D and proprioceptive inputs. In doing so, HAMSTER inherits the semantic reasoning benefits of VLMs along with the 3D reasoning and spatial awareness benefits of 3D imitation learning policies (Goyal et al., 2024; Ke et al., 2024). Finally, since HAMSTER is built on both open-source VLMs and low-level policies, it can serve as a fully open-sourced enabler for the community-building vision-language-action models.

2 Related Work

LLMs and VLMs for robotics. Early attempts in leveraging LLMs and VLMs for robotics are through pretrained language (Jang et al., 2022; Shridhar et al., 2023; Singh et al., 2023) and visual (Shah & Kumar, 2021; Parisi et al., 2022; Nair et al., 2023; Ma et al., 2023) models. However, these are not sufficient for complex semantic reasoning and generalization to the open world (Brohan et al., 2022; Zitkovich et al., 2023). Recent research has focused on directly leveraging open world reasoning and generalization capability of LLMs and VLMs, by prompting or fine-tuning them to, e.g., generate plans (Huang et al., 2022; 2023b; Lin et al., 2023; Liang et al., 2023; Singh et al., 2023; Brohan et al., 2023b), construct value (Huang et al., 2023a) and reward functions (Kwon et al., 2023; Sontakke et al., 2023; Yu et al., 2023; Ma et al., 2024; Wang et al., 2024). Our work is more closely related to the literature on VLA models, summarized below.

Monolithic VLA models as language-conditioned robot policies. Monolithic VLA models have been proposed to produce robot actions given task description and image observations directly (Brohan et al., 2022; Jiang et al., 2023; Zitkovich et al., 2023; Team et al., 2024; Kim et al., 2024; Radosavovic et al., 2023). Monolithic VLA models are often constructed from VLMs (Liu et al., 2024b; Bai et al., 2023; Driess et al., 2023; Lin et al., 2024), and are trained on large-scale robot teleoperation data (Brohan et al., 2022; Collaboration et al., 2023; Khazatsky et al., 2024) to predict actions as text or special tokens. However, due to the lack of coverage in existing robotics datasets, they must be finetuned in-domain on expensive teleoperated data. The most relevant monolithic VLA model is LLARVA (Niu et al., 2024), which predicts end-effector trajectories in addition to robot actions. However, LLARVA does not use trajectory prediction to control the robot; rather, it uses it as an auxiliary task to improve action prediction. Therefore, LLARVA still suffers from the limitations of monolithic VLA models. In contrast, our work takes a hierarchical approach, enabling us to use specialist lower-level policies that take in additional inputs the VLMs cannot support, such as 3D pointclouds, to enable better imitation learning. Our predicted paths then enable these lower-level policies to generalize more effectively.

VLMs for predicting intermediate representations. Our work bears connections to prior methods using vision-language models for intermediate prediction. These methods can be categorized by the choice of predicted representation:

Point-based predictions: A common intermediate prediction interface has been keypoint affordances (Stone et al., 2023; Sundaresan et al., 2023; Nasiriany et al., 2024; Yuan et al., 2024). Some examples include using open-vocabulary detectors (Minderer et al., 2022), iterative prompting of VLMs (Nasiriany et al., 2024), or fine-tuning detectors to identify certain parts of an object by semantics (Sundaresan et al., 2023). Perhaps most related, Yuan et al. (2024) finetunes a VLM to predict objects of interest as well as free space for placing an object, and Liu et al. (2024a) propose a mark-based visual prompting procedure to predict keypoint affordances as well as a fixed number of waypoints. As opposed to these, our work finetunes a VLM model to not just predict points but rather entire 2D paths, making it more broadly applicable across robotic tasks.

Trajectory-based predictions: The idea of using trajectory-based task specifications to condition low-level policies was proposed in RT-trajectory (Gu et al., 2023), largely from the perspective of flexible task specification. This work also briefly discusses the possibility of combining RT-Trajectory with trajectory sketches generated from prompting a pre-trained vision language model. Complementary to RT-Trajectory, the focus of this work is less on the use of trajectory sketches for task specification, but rather on the abilities of a hierarchical VLA model to finetune the high-level VLM on cheap and abundant sources. This could include training data such as videos or simulation data, and show transfer to test scenarios of interest with considerable visual and semantic

variation. While RT-trajectory uses human effort or off-the-shelf pre-trained models to generate trajectories, we show that finetuning VLM models on cheap data sources can generate more accurate and generalizable trajectories (see Table. 5). Moreover, our instantiation of this architecture enables the incorporation of rich 3D and proprioceptive information, as compared to monocular 2D policies (Gu et al., 2023).

Leveraging simulation data for training robot policies. There has been extensive work on leveraging simulation for robot learning. Simulation data is popular in reinforcement learning (RL), as RL on real robotic systems is often impractical due to high sample complexity and safety concerns (Lee et al., 2020; Handa et al., 2023; Torne et al., 2024). Recently, simulation has been also exploited to directly generate (Fishman et al., 2022) or bootstrap (Mandlekar et al., 2023) large-scale datasets for imitation learning, to reduce the amount of expensive robot teleoperation data needed. Our work takes a different approach - using simulation data to finetune a VLM, and showing that VLM is able to transfer the knowledge learned from simulation data to real robot systems, despite considerable visual differences. A related observation is recently made by (Yuan et al., 2024), but they use keypoint affordances as the interface between the VLM and the low-level policy as opposed to more general expressive 2D path representations.

3 BACKGROUND

Imitation Learning via Supervised Learning. The goal of imitation learning is to train a probabilistic policy $\pi_\theta(a \mid s, o, z)$ from an expert-provided dataset. This policy π_θ outputs the probability of producing action a conditioned on proprioceptive states s, perceptual observations o, and language instructions z that specify the task. In the typical imitation learning setting, a dataset of expert in-domain trajectories is provided, consisting of observation-action-language tuples $\mathcal{D} = \{(s_i, a_i, o_i, z_i)\}_{i=1}^N$. This dataset can be utilized to learn the parameters of the policy π_θ. While π can take on a variety of architectures with various training objectives (Goyal et al., 2023; Ke et al., 2024; Zhao et al., 2023; Chi et al., 2023), most imitation learning algorithms are trained via supervised learning to maximize the objective: $\mathbb{E}_{(s_i,a_i,o_i,z_i)\sim\mathcal{D}}\left[\log \pi_\theta\left(a_i \mid s_i, o_i, z_i\right)\right]$. This core objective can be modified with rich architectural choices such as 3D policy architectures (Goyal et al., 2023; Ke et al., 2024) or more expressive policy distribution classes (Zhao et al., 2023; Chi et al., 2023), but generalization to out-of-domain to settings with semantic or visual variations is still challenging. We study how vision-language models can be used to aid the generalization of such low-level imitation learning-based policies, discussed in Section 4.1.

Vision Language Models. Typical vision language models (VLMs) (Lin et al., 2024; Liu et al., 2024b) are large transformers (Vaswani et al., 2023) that take vision & text tokens as input and produce text responses. These models are pre-trained on large multimodal datasets (Zhu et al., 2023; Byeon et al., 2022), and then finetuned on targeted high-quality datasets (Shen et al., 2021; Lu et al., 2022). These models tokenize each modality into a shared space to produce a sequence of output tokens corresponding to text or other output modalities. In this work, we assume access to a pre-trained, text and image input VLM (Lin et al., 2024; Liu et al., 2024b), that autoregressively outputs a sequence of text tokens conditioned on an image and previous text tokens. These pretrained VLMs can typically be finetuned using a supervised prediction loss that minimizes the negative log-likelihood of the answer text tokens.

4 HAMSTER: HIERARCHICAL ACTION MODELS FOR ROBOTIC LEARNING

In this work, we examine how VLA models can be trained on relatively abundant data to demonstrate cross-domain transfer capabilities, as opposed to training on expensive image-action data collected on a robot. HAMSTER is a family of hierarchical action models designed for this purpose, exhibiting generalizable and robust manipulation. It consists of two interconnected models: first, a higher-level VLM that is fine-tuned on large-scale, cross-modal data to produce intermediate guidance (detailed in Section 4.1), and second, a low-level policy that produces actions conditioned on the VLM's predicted guidance (detailed in Section 4.2). The finetuned VLM and the low-level policy communicate using a 2D path representation. Figure 2 provides an overview of HAMSTER's design. Crucially, we study the ability of such a hierarchical design to enable training on cheap, abundantly available data such as simulation and videos.

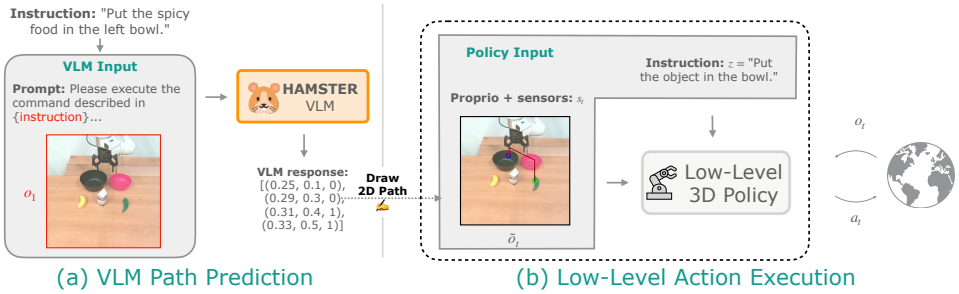

Figure 2: Depiction of HAMSTER's execution. The high-level VLM is called once to generate the 2D path. The low-level policy is conditioned on the 2D path and interacts with the environment sequentially to execute low-level actions. The path predicted by the VLM enhances the low-level policy generalization capability.

Problem Definition. Rather than operating in the pure imitation learning setting as described in Section 3, we study a scenario where cross-domain data is utilized to train VLA models. While the typical imitation learning setting uses a dataset of optimal in-domain, on-robot tuples $\mathcal{D} = \{(s_t, a_t, o_t, z_t)\}_{t=1}^{N}$ to learn a near-optimal policy π_θ, in this setting we additionally assume access to a much larger dataset(s) of "off-domain" approximately optimal data $\mathcal{D}_{\text{off}} = \{(o_i^o, z_i^o)\}_{i=1}^{M}$, where $M \gg N$, such as video or simulation data. This "off-domain" data $\mathcal{D}_{\text{off}}$ is different from in-domain data $\mathcal{D}$ in several important ways: *1)* Off-domain perceptual observations o_i^o may be considerably different than in-domain perceptual observations o_i, even when the underlying physical state of the system is similar. An illustrative example of this is the marked difference between simulation and real-world scene appearance (see Figure 6). *2)* The underlying physical dynamics of the system can be potentially different, i.e., the transition dynamics may be different between off-domain sources such as video or simulation than the test-time deployment setting. While the dynamics may show level differences, we assume the higher-level coarse strategies to solve the task remain invariant. *3)* Off-domain data may not have access directly to actions a or proprioception state s, for instance in video based datasets. This poses challenges to directly applying the standard imitation learning paradigm for these datasets.

The goal is to leverage the combination of a small amount of "expensive" in-domain data $\mathcal{D}$ and a large amount of relatively "cheap" off-domain data $\mathcal{D}_{\text{off}}$ to obtain a generalizable policy π_θ that can be successfully deployed over various initial conditions, task variations, and visual variations in the in-domain robot environment. Without additional assumptions, this problem is arduous due to the lack of alignment between the in-domain and off-domain settings. In this work, we assume access to an intermediate *path-labeler* $p_i = h(o_i, z_i)$ at training time, that accepts an observation o_i and a language instruction z_i from either the off-domain or in-domain datasets, to produce an intermediate path label p_i that indicates *how* to optimally perform the task z_i from the observation o_i. In this work, we choose this intermediate path label p_i to be a sequence of points, a 2D path, on the image that indicates coarse end-effector motion to solve the designated task. This path-labeler at training time can come from different sources – a projection of known proprioception if available, human-drawn trajectory annotations on images, point-tracked end-effector or hand positions from video, and so on. Applying such a path labeler to the off-domain dataset yields $\tilde{\mathcal{D}}_{\text{off}} = \{(o_i^o, z_i^o, p_i^o)\}_{i=1}^{M}$.

4.1 HAMSTER'S VLM FOR PRODUCING 2D PATHS TRAINED FROM OFF-DOMAIN DATA

The first stage of building a HAMSTER VLA model is finetuning a high-level VLM that predicts coarse 2D paths p given a language instruction z and observation o. This path represents the approximate trajectory of the robot end-effector on the input camera image. It also contains information about the gripper state (where to open the gripper and where to close it) as subsequently explained.

Although, conceptually, any VLM can be used to predict such a 2D path by casting an appropriate prompt, we find that standard pre-trained VLMs struggle with predicting such a path in a zero-shot manner (see Table 5). Therefore, we finetune pre-trained VLMs on datasets that ground VLMs to robot scenes and path predictions collected from easier-to-obtain sources, i.e., internet visual-question-answering data, robot data from other modalities, and simulation data. The primary advantages of finetuning such a hierarchical VLM that produces intermediate representations as opposed to directly producing actions a with a monolithic model (Kim et al., 2024; Zitkovich et al., 2023)

are twofold: 1) the lack of actions in certain off-domain datasets (such as videos) makes it impossible to even train monolithic pixel-to-action models, 2) we find empirically that hierarchical VLMs producing intermediate cross-domain predictions generalize more effectively than monolithic VLA models.

Finetuning Objective and Datasets. We use VILA-1.5-13b (Lin et al., 2024), a 13-billion-parameter vision language model trained on interleaved image-text datasets and video captioning data, as our base VLM. We then curate a multi-domain dataset to finetune this model for effective 2D path prediction. Predicting the 2D path of the end-effector requires understanding *what* objects to manipulate in a given task in terms of their pixel positions, but also reasoning about *how* a robot should perform the task. To enable this understanding, we collate a diverse off-domain dataset $\mathcal{D}_{\text{off}}$ from a wide range of modalities, including real-world data, visual question-answering data, and simulation data. Importantly, *none* of this off-domain data used to train the VLM comes from the deployment environment, thereby emphasizing generalizability. However, as outlined in Section 4.2, the predictions of this trained VLM are used to guide a low-level policy at inference time.

We assemble a dataset $\tilde{\mathcal{D}}_{\text{off}} = \{(o_i^o, z_i^o, p_i^o)\}_{i=1}^M$ of image inputs o_i^o, language prompts z_i^o, and path labels p_i^o consisting of three types of data: (1) pixel point prediction tasks (*what*); (2) simulated robotics tasks (*what and how*); (3) a real robot dataset consisting of trajectories (*what and how*). We detail each dataset below; see Figure 7 for visualization of each dataset's prompts and labels.

Pixel Point Prediction. For pixel point prediction, we use the dataset released by RoboPoint (Yuan et al., 2024) with 1.4 million VQA tasks, with most answers represented as a list of 2D points corresponding to locations on the image. A sample consists of a prompt z^o like `Find all instances of cushions`, an input image o^o and labels p^o like $[(0.25, 0.11), (0.22, 0.19), (0.53, 0.23)]$.[1] This dataset consists of data automatically generated in simulation and collected from existing real-world datasets; its diversity and tasks enable the HAMSTER VLM to reason about pixel-object relationships across diverse scenes while retaining its semantic generalization capabilities.

Robot Simulation Data. We additionally generate a dataset of simulated robotics tasks from RLBench (James et al., 2020), a simulator of a Franka robot performing tabletop manipulation for a wide array of both prehensile and non-prehensile tasks. We use the simulator's built-in planning algorithms to automatically generate successful manipulation trajectories and construct ground-truth 2D path labels p^o. Each trajectory contains a sequence of 3D coordinates of the robot's gripper in world space, as well as whether the gripper is open or closed at a given time step. We use known camera intrinsics and extrinsics to project these points on the front image and construct labels $p^o = [(x_{\text{image}}, y_{\text{image}}, \texttt{gripper\_open}), \ldots]$ where $x_{\text{image}}, y_{\text{image}} \in [0, 1]$ are *relative pixel locations* of the end effector's position on the image. The front camera image of the initial state forms the image input o^o and the prompt z^o for the VLM is to provide a sequence of points denoting the trajectory of the robot gripper to achieve the given instruction (see Figure 2) We generate 1000 episodes for each of 79 robot manipulation tasks in RLBench, each episode with $\sim$4 language instructions, for a total of $\sim$300k (o^o, z^o, p^o) tuples for $\tilde{\mathcal{D}}_{\text{off}}$.

Real Robot Data. Using real robot data allows us to ensure the VLM can reason about objects and robot gripper paths when conditioned on scenes, including real robot arms. We use existing, online robot datasets *not from the deployment environment* to enable this VLM ability. We source 10k trajectories from the Bridge dataset (Walke et al., 2023; Collaboration et al., 2023) consisting of a WidowX arm performing manipulation tasks and $\tilde{4}5$k trajectories from DROID (Khazatsky et al., 2024). For both datasets, we use the given end-effector trajectories and given (or estimated) camera matrices to convert robot gripper trajectories to 2D paths p^o. We use a camera image from the first timestep of each robot trajectory as o^o and a similar text prompt z^o as the simulation dataset. Note that we essentially utilize the robot data as video data, where the end effector is tracked over time. In principle, this could be done with any number of point-tracking methods (Doersch et al., 2023) on raw video as well, with no action or proprioceptive labels.

VLM Training. We finetune the HAMSTER VLM on all three datasets by randomly sampling from all samples in the entire dataset with equal weight. One problem with directly training on the path labels p^o is that many paths may be extremely long, e.g., exceeding one hundred points. Since we

[1] Note that this is not a temporally ordered path, but rather simply a set of unordered points of interest in an image. We overload notation here for the sake of notational convenience.

want the HAMSTER VLM to reason at a *high level* instead of on the same scale as the low-level control policy. Therefore, we simplify the paths p^o with the Ramer-Douglas-Peucker algorithm (Ramer, 1972; Douglas & Peucker, 1973) that reduces curves composed of line segments to similar curves composed of fewer points. We train with the standardized supervised prediction loss to maximize the log-likelihood of the language labels p^o: $\mathbb{E}_{(o_i^o, z_i^o, p_i^o)\sim\tilde{\mathcal{D}}_{\text{off}}} \log \text{VLM}\left(p_i^o \mid z_i^o, o_i^o\right)$.

4.2 Path Guided Low-Level Policy Learning

After training the HAMSTER VLM to predict paths, we train a low-level policy to utilize these paths to predict actions. While a low-level control policy *can* learn to solve the task without access to 2D path predictions, providing it with 2D paths can make the task easier. The paths allow the low-level policy to forgo long-horizon and semantic reasoning and focus on local and geometric predictions to produce low-level actions. As we find empirically (see Figure. 3), 2D paths allow for considerably improved visual and semantic generalization of low-level policies. We train low-level policies based on rich 3-D perceptual information, available at test time on a robotic platform with standard depth cameras. Then the question becomes—how do we incorporate 2D path information $\hat{p}$ produced by the VLM in Section 4.1 onto the 3D inputs to enable generalizable robot manipulation?

Conditioning on Paths. We convert 2D paths of the form $p = \{(x_i, y_i, \texttt{gripper\_open})\}_{t=1}^{L}$ into a format that is easy to incorporate into any language (z), proprioception (s), and image (o) conditioned policy $\pi_\theta(a \mid s, o, z)$. While one could concatenate the path with the proprioception or language input, paths are of varied lengths, and this could prevent the integration of such paths into existing policy architectures that cannot take in varied proprioceptive or language inputs. Instead, we directly draw the 2D path points onto the image input to the policy, which is not only generalizable across policy architectures but also may provide easier-to-follow path guidance as the policy does not have to learn how to associate path points with their corresponding image locations (Gu et al., 2023). During training, we use oracle paths constructed by projecting end-effector points to the camera plane as described for simulation and real robot data in Section 4.1.

Formally, we iterate through each trajectory $\tau_i = \{s_i^t, a_i^t, o_i^t, z_i)\}_{t=1}^{T}$ on the in-domain dataset $\mathcal{D}$ to obtain the path p_i. Gu et al. (2023) proposed using colored trajectories to guide a policy's actions, and we largely follow their method of coloring trajectories to indicate gripper status and progression through time. These paths are drawn onto all images in the trajectory $o_i^1 ... o_i^T$ by drawing points at each (x, y) and connecting them with line segments to obtain $\{\tilde{o}_i^t\}_{t=1}^{T}$. We use a color gradient to indicate progression through time (see Figure 2(b) for an example). We plot circles for change in gripper status: e.g., green for closing the gripper and blue for opening. This constructs the final in-domain path-labeled dataset $\mathcal{D}_{\text{path}} = \{(s_i, a_i, \tilde{o}_i, z_i)\}_{i=1}^{N}$.

Imitation Learning. Finally, we train a policy $\pi_\theta(a \mid s, \tilde{o}, z)$ conditioned on proprioception and other sensor information s, path-annotated image observations $\tilde{o}$, and a task language instruction z on $\mathcal{D}_{\text{path}}$. HAMSTER's general path-conditioning framework allows for using arbitrary lower-level control policies as they do not need to condition on the same inputs as the VLM. Therefore, we train 3D low-level policies, such as RVT-2 (Goyal et al., 2024) and 3D-DA (Ke et al., 2024), for low-level control. Here, we assume s includes additional sensor information (i.e., depth), which 3D-DA and RVT-2 utilize to construct point clouds and virtual camera renderings, respectively, for more accurate control and data-efficient imitation learning. We directly train these policies, with no necessary major architectural modifications,with their supervised imitation learning objectives on $\mathcal{D}_{\text{path}}$ to maximize log-likelihoods of the dataset actions: $\mathbb{E}_{(s_t, a_t, \tilde{o}_t, z_t)\sim\mathcal{D}_{\text{path}}} \log \pi_\theta(a \mid s_t, \tilde{o}_t, z_t)$. For further implementation details, see Appendix B.

Online Evaluation. Standard VLA architectures query the VLM for every low-level action (Kim et al., 2024; Brohan et al., 2023a), which can be very expensive with large VLMs—for example, OpenVLA's 7B param VLA only runs at 6Hz on an RTX 4090 (Kim et al., 2024). Instead, HAMSTER's hierarchical design allows us to query the VLM just once at the beginning of the episode to generate a 2D path $\hat{l}$ that we draw onto every subsequent image.[2] Therefore, HAMSTER can be scaled to large VLM backbones without needing end-users to be concerned about inference speed.

[2]HAMSTER is not inherently limited to being queried once per episode, but for simplicity and computational efficiency we query just once per episode in our experiments.

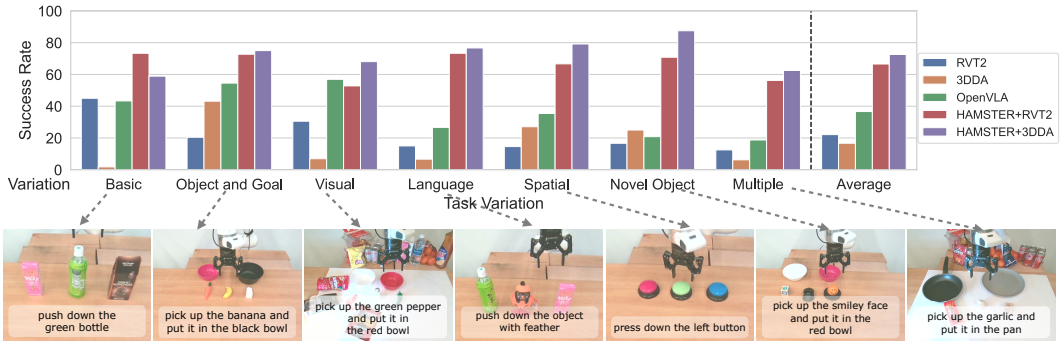

Figure 3: Depiction of quantitative real-world policy execution results on a real-world robot, evaluated across different axes of generalization and across both prehensile and non-prehensile tasks. Across all generalization axes, HAMSTER outperforms monolithic VLAs and the base 3D imitation learning policies.

5 Experimental Evaluation

To test the hypotheses proposed in Section 4, we perform empirical evaluations in both simulation and the real world. The experiments primarily aim to answer the following questions: (1) do hierarchical VLA models enable behavioral generalization to unseen scenarios? (2) do hierarchical VLA models show more effective cross-domain generalization than monolithic VLA models or low-level imitation learning methods? (3) is behavior learned by hierarchical VLA models robust to significant degrees of visual and semantic variations? (4) does including cross-domain data from settings like simulation really help with model generalization? (5) does explicitly finetuning the high-level VLM yield benefits in terms of spatial and semantic reasoning?

5.1 Real World Evaluation on Tabletop Manipulation

Our real-world evaluation experiments aim to test the generalization capability of hierarchical VLA models across significant semantic and visual variations. In particular, we consider a variant of HAMSTER that uses a VLM (VILA-1.5-13b) finetuned on the data mixture in Section 4.1 as the high-level predictor, with two 3D policy architectures - RVT-2 (Goyal et al., 2024) and 3D Diffuser Actor (3D-DA) (Ke et al., 2024) as the choice of low-level policy, as described in Section 4.2. The low-level 3D policies are trained with 320 episodes collected via teleoperation directly on the table-top manipulation setup shown in Fig. 7. Importantly, the high-level VLM in HAMSTER is not finetuned on any in-domain data and is directly transferred only from the cheap data sources described in Section 4.1. This suggests that any generalization that the VLM sees does not result from in-domain training data rather than from cross-domain transfer.

Baseline comparisons. We compare HAMSTER to a state-of-the-art monolithic VLA, OpenVLA (Kim et al., 2024), as well as a non-VLM 3D imitation learning policies. For fair comparison, we finetune OpenVLA on the collected in-domain trajectory data described above since OpenVLA showed poor zero-shot generalization. The 3D imitation learning policy (RVT-2, 3D-DA) baselines are trained with the same teleoperation data used to train the low-level policy in HAMSTER but without the intermediate 2D path representation from HAMSTER's VLM.

Results. Figure 3 summarizes our real-world results. We compile results for multiple task types, including 'pick and place,' and nonprehensile tasks such as 'push buttons' and 'knock down objects.' Similar to prior work (Kim et al., 2024), we test generalization across various axes: *obj and goal:* unseen object-goal combinations; *visual:* visual changes in table texture, lighting, distractor objects; *language:* unseen language instructions (e.g., candy $\rightarrow$ sweet object); *spatial:* unseen spatial object relationships in the instruction; *novel object:* unseen objects; and lastly, *multiple:* a combination of multiple variations. In total, we evaluate each model on 74 tasks for 222 total evaluations.

We find that HAMSTER significantly outperforms monolithic VLA models and 3D imitation learning methods by over **2x** and **3x**, respectively, on average. This is significant because this improved performance is in the face of considerable visual and semantic changes in the test setting, showing the ability of HAMSTER to transfer much more effectively than monolithic VLA models or non-VLM base models. We further group results by task type in Table 6, where we see HAMSTER

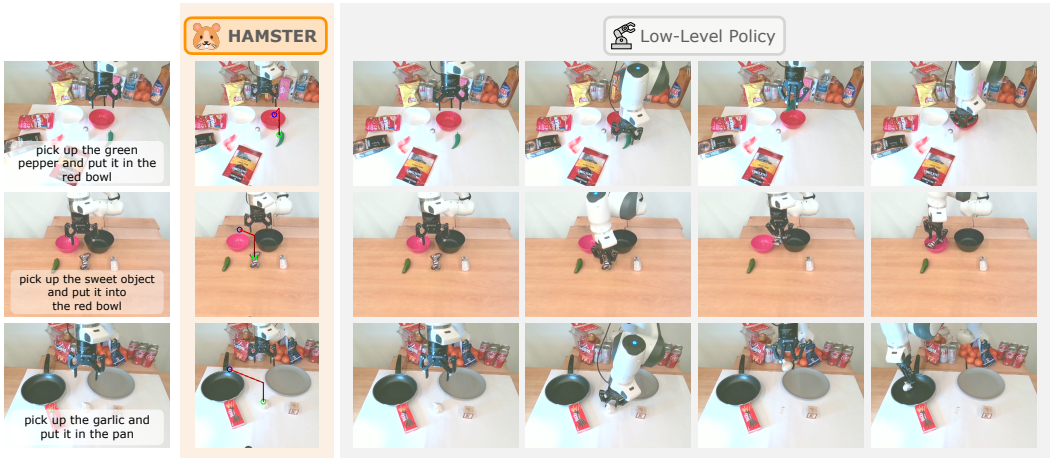

Figure 4: Example real-world HAMSTER rollouts demonstrate its strong performance in novel scenes achieved by leveraging VLMs' generalization capabilities and the robust execution of low-level 3D policies.

	Avg.	no var	bac tex	cam pos	distractor	lig col	man obj col	man obj siz
3D-DA[Ke et al.]	0.35 ± 0.04	0.43 ± 0.06	0.34 ± 0.07	0.35 ± 0.11	0.39 ± 0.11	0.44 ± 0.13	0.41 ± 0.04	0.41 ± 0.11
HAMSTER (w 3D-DA)	**0.46** ± 0.04	**0.57** ± 0.03	**0.48** ± 0.08	**0.39** ± 0.06	**0.41** ± 0.05	**0.59** ± 0.04	**0.57** ± 0.08	**0.51** ± 0.10
	man obj tex	rec obj col	rec obj siz	rec obj tex	rlb and col	rlb var	tab col	tab tex
3D-DA[Ke et al.]	0.27 ± 0.04	0.34 ± 0.10	0.36 ± 0.05	0.36 ± 0.12	0.07 ± 0.03	0.45 ± 0.12	0.42 ± 0.06	0.23 ± 0.04
HAMSTER (w 3D-DA)	**0.48** ± 0.06	**0.48** ± 0.05	**0.40** ± 0.05	**0.56** ± 0.09	**0.11** ± 0.10	**0.58** ± 0.04	**0.56** ± 0.03	**0.35** ± 0.07

Table 1: Simulation evaluation of HAMSTER across different visual variations. We test vanilla 3D Diffuser Actor and HAMSTER across variations in Colosseum (Pumacay et al., 2024) and find that HAMSTER generalizes more effectively than 3D Diffuser Actor. Avg. indicates mean across variations, including no variation.

outperforms OpenVLA across all task types (pick and place, press button, and knock down). See Appendix C for evaluation conditions, a task list, and other experiment details, and Appendix E for failure modes.

5.2 Simulation Evaluation

We also perform controlled experiments in simulation. We use Colosseum (Pumacay et al., 2024) as the benchmark as it displays considerable visual and semantic variations. In simulation, we paired our high-level VLM with 3D Diffuser Actor (Ke et al., 2024) as the low-level policy, since this is one of the state-of-the-art models on RLBench. We compare HAMSTER with a vanilla 3D Diffuser Actor implementation without path guidance. Table 1 summarizes our results in simulation across 5 seeds. HAMSTER significantly outperforms vanilla 3D-DA by 31%. This shows that the 2D paths produced by the VLM in HAMSTER can help low-level policies to generalize better to novel unseen variations. We refer readers to Pumacay et al. (2024) for details on the variations and Appendix F for further simulation experiment details.

5.3 Generalization and Ablation Studies

Finally, we perform additional experiments testing HAMSTER's ability to generalize to novel views, various ways to represent the paths, and finally, the demonstration efficiency of HAMSTER.

View Invariance and Path Representation. We test camera view invariance with a new camera angle, as pictured in Figure 5, by evaluating HAMSTER+RVT2 against OpenVLA on the new camera angle across 10 separate pick and place task trials with 6 training objects and 3 training containers. Additionally, we also compare HAMSTER+RVT2 (Concat), where instead of drawing the path onto the RGB image given as input to RVT2, we modify RVT2 to accept a 6-channel input image consisting of the original RGB image concatenated with a second RGB image that only contains

Figure 5: The camera angle invariance setup: old camera on the right, new camera angle on the left.

Method	Original Camera		Novel Camera	
	Success Score	Full Success	Success Score	Full Success
OpenVLA	6	3	2.25	0
HAMSTER+RVT2	8.25	7	7.25	4
HAMSTER+RVT2 (Concat)	**10**	**10**	**9.75**	**9**

Table 2: Real world results comparing HAMSTER, HAMSTER where paths are concatenated with RGB instead of drawn onto the image, and OpenVLA on a setup with the new camera angle as shown in Figure 5. We report cumulative completion scores out of 10 (10 trials) and total number of fully successful executions. HAMSTER performs better with both path drawing settings.

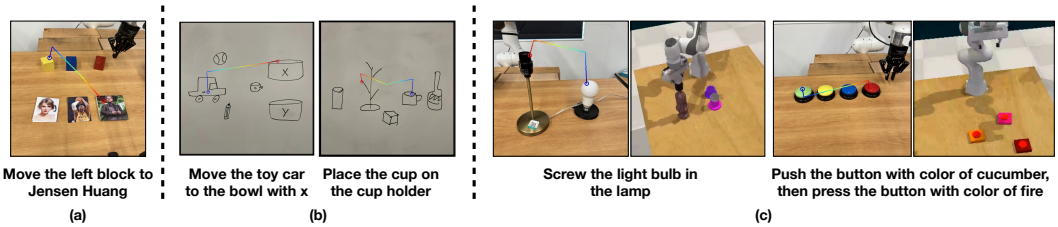

Figure 6: HAMSTER's VLM demonstrates considerable generalization and cross-domain learning to scenarios not encountered in the training set. From left to right: (a) it can effectively utilize world knowledge to generalize to tasks specified by people; (b) it generalizes to highly out-of-domain input images, such as human-drawn sketches; (c) when trained on diverse simulated data it shows transfer to related, but visually distinct tasks in the real world.

the drawn path. This approach is less easily applied to arbitrary imitation learning policies (for example, it cannot be easily applied to 3D-DA as it uses a pre-trained CLIP image encoder expecting 3 input channels), but allows us to represent paths in a different way.

The results in Table 2 demonstrate that HAMSTER far outperforms OpenVLA and is generally robust to a new camera angle. HAMSTERwith concatenated image paths performs the best, which demonstrates this other path representation can work well with RVT2, although it is less general and cannot be easily integrated with 3D-DA.

HAMSTER with Fewer Demonstrations. Finally, we also test HAMSTER's ability to work well with limited demonstrations. We test on a subset of 5 Colosseum tasks, namely, SLIDE_BLOCK_TO_TARGET, PLACE_WINE_AT_RACK_LOCATION, INSERT_ONTO_SQUARE_PEG, STACK_CUPS, SETUP_CHESS. Results in Table 3 demonstrate that HAMSTER+3D-DA with just 50% of the data still achieves 2x the success rate of standard 3D-DA, demonstrating that HAMSTER is demonstration-efficient for the demonstream imitation learning tasks.

Method	Success
3D-DA	0.18 ± 0.10
HAMSTER+3D-DA (50%)	0.36 ± 0.04
HAMSTER+3D-DA	$\mathbf{0.43 \pm 0.05}$

Table 3: Colosseum results demonstrate that HAMSTER is demo-efficient, doubling 3D-DA's success rate even with just 50% of the data.

Finally, we visualize example HAMSTER path drawings in Figure 6, demonstrating HAMSTER effectively generalizes to new tasks. We further investigate design decisions on VLM performance in Appendix D.1, where we find that (1) HAMSTER outperforms zero-shot path generation from closed-source VLMs (Gu et al., 2023; Liang et al., 2023) and (2) that inclusion of simulation data improves HAMSTER's real-world performance. See Appendix D.1 for further details.

6 Conclusion and Limitations

In summary, HAMSTER studies the potential of hierarchical VLA models, achieving robust generalization in robotic manipulation. It consists of a finetuned VLM that accurately predicts 2D paths for robotic manipulation and a low-level policy that learns to generate actions using the 2D paths. This two-step architecture enables visual generalization and semantic reasoning across considerable domain shifts, while enabling data-efficient specialist policies, like ones conditioned on 3D inputs, to perform low-level action execution.

This work represents an initial step towards developing versatile, hierarchical VLA methods, with numerous opportunities for future improvement and expansion. The proposed work only generates

points in 2D space, without making native 3D predictions. This prevents the VLM from having true spatial 3D understanding. Moreover, the interface of just using 2D paths is a bandwidth limited one, which cannot communicate nuances such as force or rotation. In the future, investigating learnable intermediate interfaces is a promising direction. Moreover, training these VLMs directly from large-scale human video datasets would also be promising.

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For extended supplementary details and results, please see `https://sites.google.com/view/hamster-iclr`.

A VLM Finetuning Dataset Details

Pixel Point Pred Data. Our point prediction dataset comes from Robopoint (Yuan et al., 2024). Most data in our point prediction dataset contains labels given as a set of unordered points such as $p^o = [(0.25, 0.11), (0.22, 0.19), (0.53, 0.23)]$. However, data in RoboPoint also contains answers that are instead in natural language for VQA queries such as "what is the person feeding the cat?" We keep these data as is because these VQA queries are likely to benefit a VLM's semantic reasoning an visual generalization capabilities; we fine-tune HAMSTER's VLM on the entire Robopoint dataset as given.

Simulation Data. We selected 81 RLBench tasks out of 103 to generate data by removing the tasks with poor visibility on the `front_cam` view in RLBench. We use the first image in each episode combined with each language instruction. The final dataset contains around 320k trajectories.

Real Robot Data. For the Bridge (Walke et al., 2023) dataset, which only provides RGB images, we extract trajectories by iteratively estimating the extrinsic matrix for each episode. In each scene, we randomly sample a few frames and manually label the center of the gripper fingers. Using the corresponding end-effector poses, we compute the 3D-2D projection matrix with a PnP (Perspective-n-Point) approach. We then apply this projection matrix to the episodes and manually check for any misalignments between the projected gripper and the actual gripper. Episodes exhibiting significant deviations are filtered out, and a new round is started to estimate their extrinsic matrix.

For DROID (Khazatsky et al., 2024), a large portion of the dataset contains noisy camera extrinsics information that do not result in good depth alignment. Therefore, we filter out trajectories with poor-quality extrinsics as measured by the alignment between the projected depth images and the RGB images. This results in ∼45k trajectories (∼22k unique trajectories as trajectories each have 2 different camera viewpoints) which we use for constructing the VLM dataset $\mathcal{D}_{\text{off}}$ as described in Section 4.1.

B Implementation and Architecture Details

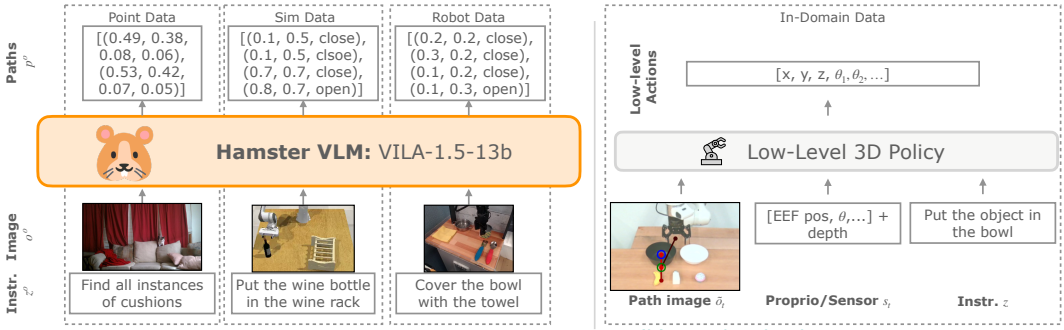

Figure 7: (a): Examples of training data in $\tilde{\mathcal{D}}_{\text{off}}$ used to train HAMSTER's VLM. (b): The data used to train HAMSTER's low-level policies.

B.1 VLM Implementation Details

VLM Prompt. We list the prompt for both fine-tuning on sim and real robot data and evaluation in Figure 8. We condition the model on an image and the prompt, except when training on Pixel Point Prediction data (i.e., from Robopoint (Yuan et al., 2024)) where we used the given prompts from the dataset. Note that we ask the model to output gripper changes as separate language tokens, i.e.,

HAMSTER Prompt

In the image, please execute the command described in ⟨quest⟩{quest}⟨/quest⟩.
Provide a sequence of points denoting the trajectory of a robot gripper to achieve the goal.
Format your answer as a list of tuples enclosed by ⟨ans⟩ and ⟨/ans⟩ tags. For example:
⟨ans⟩`[(0.25, 0.32), (0.32, 0.17), (0.13, 0.24),` ⟨action⟩`Open Gripper`⟨/action⟩`, (0.74, 0.21),` ⟨action⟩`Close Gripper`⟨/action⟩`, ...]`⟨/ans⟩
The tuple denotes the x and y location of the end effector of the gripper in the image. The action tags indicate the gripper action.
The coordinates should be floats ranging between 0 and 1, indicating the relative locations of the points in the image.

Figure 8: The full text prompt we use to train HAMSTER with on simulation and real robot data (Section 4.1). We also use this prompt for inference.

`Open Gripper/Close Gripper`, as opposed to as a numerical value as shown in simplified depictions like Figure 2.

VLM Trajectory Processing. As mentioned in Section 4.1, one problem with directly training on the path labels p^o is that many paths may be extremely long. Therefore, we simplify the paths p^o with the Ramer-Douglas-Peucker algorithm (Ramer, 1972; Douglas & Peucker, 1973) that reduces curves composed of line segments to similar curves composed of fewer points. We run this algorithm on paths produced by simulation and real robot data to generate the labels p^o for $\mathcal{D}_{\text{off}}$. We use tolerance $\epsilon = 0.05$, resulting in paths that are around 2-5 points for each short horizon task.

VLM Training Details. We train our VLM, VILA1.5-13B Lin et al. (2024), on a node equipped with eight NVIDIA A100 GPUs, each utilizing approximately 65 GB of memory. The training process takes about 30 hours to complete. We use an effective batch size of 256 and a learning rate of 1×10^{-5}. During fine-tuning, the entire model—including the vision encoder—is updated.

B.2 Low-level Policy Training Details

We train RVT2 (Goyal et al., 2024) and 3D-DA (Ke et al., 2024) as our lower-level policies. We keep overall architecture and training hyperparameters the same as paper settings. Specific details about how the inputs were modified other than the 2D path projection follow.

For low-level policy training, we train the policies on ground truth paths constructed by projecting trajectory end-effector points to the camera image. In order to also ensure the policies are robust to possible error introduced by HAMSTER VLM predictions during evaluation, we add a small amount of random noise ($N(0, 0.01)$) to the 2D path (x, y) image points during training to obtain slightly noisy path drawings. No noise was added to the gripper opening/closing indicator values.

RVT2 (Goyal et al., 2024). We remove the language instruction for RVT-2 when conditioning on HAMSTER 2D paths.

3D-DA (Ke et al., 2024). In simulated experiments in Colosseum, no changes were needed. In fact, we saw a performance drop for HAMSTER+3D-DA when removing language for Colosseum tasks and a small drop in performance when using simplified language instructions. This is likely due to 3D-DA's visual attention mechanism which cross attends CLIP language token embeddings with CLIP visual features, therefore detailed language instructions are beneficial.

In real-world experiments, we simplify the language instruction in the same way as for RVT2 when conditioning on HAMSTER 2D paths to encourage following the trajectory more closely with limited data. In addition, we reduced the embedding dimension of the transformer to 60 from 120, removed proprioception information from past timesteps, and reduced the number of transformer heads to 6 from 12 in order to prevent overfitting.

RT-Trajectory GPT-4o Prompt

In the image, please execute the command described in '{quest}'.
Provide a sequence of keypoints denoting a trajectory of a robot gripper to achieve the goal. Keep in mind these are keypoints, so you do not need to provide too many points.
Format your answer as a list of tuples enclosed by `<ans>` and `</ans>` tags. For example:
`<ans>[(0.25, 0.32), (0.32, 0.17), (0.13, 0.24), <action>Open Gripper</action>, (0.74, 0.21), <action>Close Gripper</action>, ...]</ans>`
The tuple denotes point x and y location of the end effector of the gripper in the image. The action tags indicate the gripper action.
The coordinates should be floats ranging between 0 and 1, indicating the relative locations of the points in the image.
The current position of the robot gripper is: {current_position}. Do not include this point in your answer.

Figure 9: The full text prompt we use to prompt RT-Trajectory with GPT4-o.

RT-Trajectory Code as Policies Prompt

Task Instruction: {task_instruction}
Robot Constraints:

- The robot arm takes as input 2D poses with gripper open/closing status of the form $(x, y, \text{gripper\_open} == 1)$
- The gripper can open and close with only binary values
- The workspace is a 1×1 square centered at $(0.5, 0.5)$
- The x-axis points rightward and y-axis points downward.

Please write Python code that generates a list of 2D poses and gripper statuses for the robot to follow. Include Python comments explaining each step. Assume you can use `numpy` or standard Python libraries, just make sure to import them.
Enclose the start and end of the code block with `<code>` and `</code>` so that it can be parsed. Make sure that it is a self-contained script such that when executing the code string, there is a variable named `robot_poses` which is a list of poses of the form: `[(x, y, gripper), (x, y, gripper), ...]`.
Scene Description:

```
<code>
{scene_description}
</code>
```

Figure 10: The full text prompt we use for RT-Trajectory with Code-as-Policies on top of GPT4-o. The scene description at the bottom comes from an open-vocabulary object detector describing each detected object and its bounding box in the image based on the task instruction.

C Real World Experiment Details

C.1 Training Tasks and Data Collection

For our real-world experiments, we collected all data using a Franka Panda arm through human teleoperation, following the setup described in Khazatsky et al. (2024). Below, we describe the training tasks:

Pick and place. We collected 220 episodes using 10 toy objects. In most of the training data, 2 bowls were placed closer to the robot base, while 3 objects were positioned nearer to the camera. The language goal for training consistently followed the format: `pick up the {object} and put it in the {container}`.

Knock down objects. We collected 50 episodes with various objects of different sizes. Typically, 3 objects were arranged in a row, and one was knocked down. The language goal for training followed the format: `push down the {object}`.

Press button. We collected 50 episodes with 4 colored buttons. In each episode, the gripper was teleoperated to press one of the buttons. The language goal followed the format: `press the {color} button`.

When training RVT2, which requires keyframes as labels, in addition to labeling frames where the gripper performs the `open gripper` and `close gripper` actions, we also included frames that capture the intermediate motion as the gripper moves toward these keyframes.

C.2 Baseline Training Details

OpenVLA (Kim et al., 2024). Following Kim et al. (2024), we only utilize parameter efficient fine-tuning (LoRA) for all of our experiments, since they showed that it matches full fine-tuning performance while being much more efficient. We follow the recommended default rank of r=32. We opt for the resolution of 360 x 360 to match all of the baseline model's resolutions. We also follow the recommended practice of training the model until it surpasses 95% token accuracy. However, for some fine-tuning datasets, token accuracy converged near 90%. We selected the model checkpoints when we observed that the token accuracy converged, which usually required 3,000 to 10,000 steps using a global batch size of either 16 or 32. Training was conducted with 1 or 2 A6000 gpus (which determined the global batch size of 16 or 32). Emprically, we observed that checkpoints that have converged showed very similar performance in the real world. For example, when we evaluate checkpoint that was trained for 3,000 steps and showed convergence, evaluating on a checkpoint trained for 5,000 steps of the same run resulted in a very similar performance.

RT-Trajectory (Gu et al., 2023). We implement two versions of RT-Trajectory for the comparison in Table 5. The first (0-shot GPT-4o) directly uses GPT-4o to generate 2D paths with a prompt very similar to the one we use for HAMSTER, displayed in Figure 9.

The second version implements RT-Trajectory on top of a Code-as-Policies (Liang et al., 2023), as described in RT-Trajectory. We use OWLv2 (Minderer et al., 2023) to perform open-vocabulary object detection on the image to generate a list of objects as the scene description and then prompt RT-Trajectory with the prompt shown in Figure 10. We also use GPT-4o as the backbone for this method.

C.3 Evaluation Tasks

We evaluate our method on the tasks of `pick and place`, `knock down object`, and `press button` across various generalization challenges, as illustrated in Figure 3. Detailed results are available in Appendix C.3. Following (Kim et al., 2024), we assign points for each successful sub-action. For VLM, human experts are employed to assess the correctness of the predicted trajectories.

D Extended Results

D.1 Impact of Design Decisions on VLM performance

To better understand the transfer and generalization performance of the proposed hierarchical VLA model, we analyze the impact of various decisions involved in training the high-level VLM. We conduct a human evaluation of different variants of a trained high-level VLM on a randomly collected dataset of real-world test images, as shown in Figure 6. We ask each model to generate 2D path traces corresponding to instructions such as "move the block on the right to Taylor Swift" or "screw the light bulb in the lamp" (the full set is in Appendix D.2). We then provide the paths generated by each method to human evaluators who have not previously seen any of the models' predictions. The human evaluators then rank the predictions for each method; we report the average rank across the samples in Table 5.

Category	Task	OpenVLA	RVT2	RVT2+Sketch	3DDA	3DDA+Sketch
Basic	pick up the corn and put it in the black bowl	1	1	1	0	0.25
Basic	pick up the grape and put it in the white bowl	1	0.75	1	0	1
Basic	pick up the milk and put it in the white bowl	0	1	1	0	0.25
Basic	pick up the salt bottle and put it in the white bowl	0.75	0.5	1	0	0
Basic	pick up the shrimp and put it in the red bowl	0.75	0.5	1	0	1
Basic	pick up the cupcake and put it in the red bowl	0	0.5	0.5	0.25	1
Basic	press down the red button	0.5	0	1	0	1
Basic	press down the green button	0	1	0	0	0.25
Basic	press down the yellow button	0	0	1	0	1
Basic	press down the blue button	0.5	0	1	0	0.5
Basic	push down the green bottle	0.5	0	0.5	0	1
Basic	push down the pocky	0	1	1	0	0.5
Basic	push down the red bag	0.5	0.5	0	0	0.5
Basic	push down the bird toy	0	0	0	0	0.5
Basic	push down the yellow box	1	0	1	0	0.5
Object and Goal	pick up the salt bottle and put it in the white bowl	1	1	1	0.5	1
Object and Goal	pick up the banana and put it in the black bowl	0.25	0.25	1	0.5	1
Object and Goal	pick up the grape and put it in the black bowl	1	0.25	0.5	1	1
Object and Goal	pick up the carrot and put it in the red bowl	0.75	0	1	0.5	1
Object and Goal	pick up the milk and put it in the white bowl	0.25	0	1	0	0.25
Object and Goal	pick up the shrimp and put it in the white bowl	0.25	0.75	0.5	0.25	1
Object and Goal	pick up the cupcake and put it in the black bowl	0.25	0	1	0.5	0.75
Object and Goal	pick up the icecream and put it in the black bowl	0.25	0	0.5	0.5	1
Object and Goal	pick up the corn and put it in the red bowl	1	0	1	1	1
Object and Goal	pick up the green pepper and put it in the red bowl	0.75	0	0.5	0	0.25
Object and Goal	pick up the orange and put it in the white bowl	0.25	0	0	0	0
Visual(Table Texture)	pick up the salt bottle and put it in the white bowl	1	1	1	0	1
Visual(Table Texture)	pick up the banana and put it in the black bowl	0.25	0.25	0.75	0.5	0.75
Visual(lighting)	pick up the grape and put it in the black bowl	0.25	0	0.5	0.25	0
Visual(lighting)	pick up the carrot and put it in the red bowl	0.75	0	1	0	0.75
VIsual(clutter)	pick up the milk and put it in the white bowl	0.75	0.25	1	0.25	1
VIsual(clutter)	pick up the shrimp and put it in the red bowl	0.75	0.5	0	0	0.5
Visual(mix)	pick up the green pepper and put it in the red bowl	0.25	0	1	0	0.25
Visual(mix)	pick up the salt bottle and put it in the white bowl	0.25	0	0.25	0.25	1
Visual(appearance change)	pick up the green pepper and put it in the black bowl	1	0	0.5	0	1
Visual(appearance change)	pick up the salt bottle and put it in the black bowl	1	1	1	0	1
Visual(Table Texture)	press down the red button	1	1	0	0	0.5
Visual(lighting)	press down the green button	1	0	0.5	0	0.5
VIsual(clutter)	press down the yellow button	0	0	0.5	0	0.5
Visual(mix)	press down the blue button	0	0	0	0	0.5
Visual(Table Texture)	push down the pocky	0	1	0	0	0
VIsual(clutter)	push down the green bottle	1	0.5	1	0	1
VIsual(clutter)	push down the chocolate box	1	0	0	0	1
Visual(mix)	push down the green bottle	0	0	0.5	0	1
Language	pick up the sweet object and put it in the red bowl	1	1	1	0	1
Language	pick up the spicy object and put it in the red bowl	1	0	1	0	0.75
Language	pick up the salty object and put it in the red bowl	0	0	1	0	1
Language	pick up the object with color of cucumber and put it in the red bowl	0	0	1	0.25	0.75
Language	pick up the object with color of lavender and put it in the black bowl	0	0	1	0	1
Language	pick up the object with the color of sky and and put it in the container with the color of coal	1	0	0	0.25	1
Language	pick up the block with the color of sunflower and put it in the container with the color of enthusiasm	0	0.25	1	0	1
Language	press the button with the color of fire	0.5	0	1	0	0.5
Language	press the button with the color of cucumber	0	0	1	0	0.5
Language	press the button with the color of sky	0	0	0	0.5	1
Language	press the button with the color of banana	0	0	0	0	0.5
Language	push down the object with color of leaf	0	1	1	0	0
Language	push down the box contains cruchy biscuit	0	0	0	0	1
Language	push down the bag with color of fire	0	0	1	0	0.5
Language	push down the object with feather	0.5	0	1	0	1
Spatial	pick up the left object and put it in the left bowl	0	1	1	0.25	1
Spatial	pick up the middle object and put it in the left bowl	0	0	1	0	1
Spatial	pick up the right object and put it in the left bowl	1	0	0.5	0.25	0.5
Spatial	pick up the left object and put it in the right bowl	0.25	0.25	1	0.25	1
Spatial	pick up the middle object and put it in the right bowl	0	0	1	0	1
Spatial	pick up the right object and put it in the right bowl	0.5	0	1	0	1
Spatial	press down the left button	0.5	0	0	0	0.5
Spatial	press down the middle button	0	0	1	1	0.5
Spatial	press down the right button	0	0	1	1	1
Spatial	push down the left object	0.5	0	0	0	0
Spatial	push down the middle object	1	0.5	0	0	1
Spatial	push down the right object	0.5	0	0.5	0.5	1
Novel Object	pick up the "R" and put it in the red bowl	0	0	1	0	1
Novel Object	pick up the boxed juice and put it in the red bowl	0	0.75	0.75	1	1
Novel Object	pick up the cholate bar and put it in the white bowl	0.25	0	0.5	0.5	1
Novel Object	pick up the smile face and put it in the red bowl	1	0	1	0	1
Novel Object	pick up the mouse and put it in the red bowl	0	0.25	1	0	1
Novel Object	pick up the 5 and put it in the white bowl	0	0	0	0	0.25
Multiple	pick up the lays chip and put it in the pan	0.25	0.25	0.75	0	1
Multiple	pick up the garlic and put it in then pan	0.25	0	1	0	0.25
Multiple	pick up the "K" and put it in the pan	0.25	0	0.5	0	1
Multiple	pick up the pocky and put it in the pan	0	0.25	0	0.25	0.25

Table 4: Detailed results of real-world evaluation. The first column indicates the variation category, while the second column presents the language instruction. For the `pick and place` task, 0.25 points are awarded for each successful action: reaching the object, picking it up, moving it to the target container, and placing it inside. For the `knock down` task, 0.5 points are awarded for touching the correct object and successfully knocking it down. For the `press button` task, 0.5 points are awarded for positioning the gripper above the correct button and successfully pressing it.

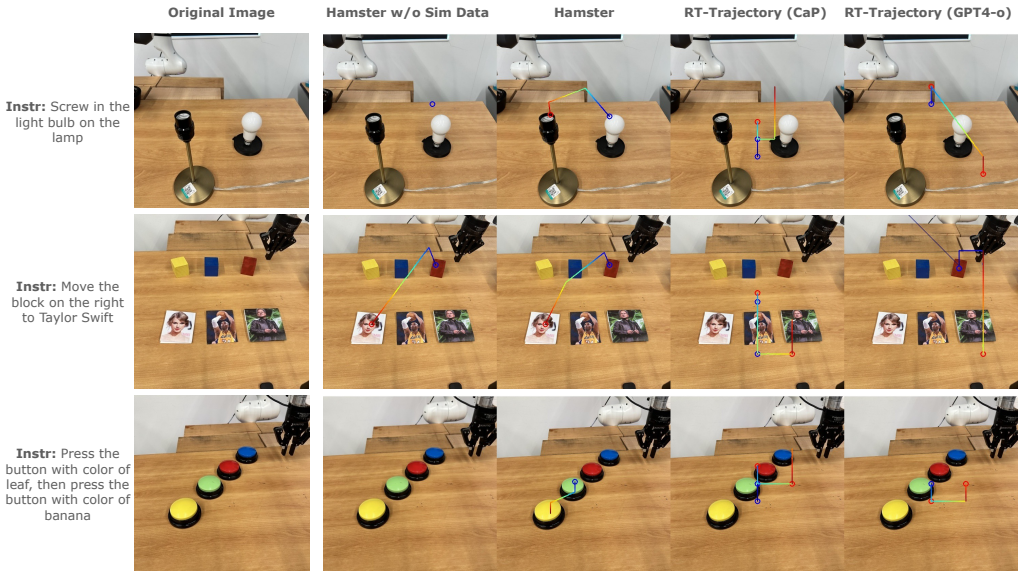

Figure 11: Human VLM evaluation example images and instructions along with corresponding trajectories from HAMSTER without any finetuning on (RLBench) simulation data, HAMSTER finetuned on all the data in Section 4.1, RT-Trajectory (Gu et al., 2023) with Code-as-Policies (Liang et al., 2023) powered by GPT-4o (Achiam et al., 2023), and RT-Trjaectory powered by GPT-4o directly.

We evaluate the following VLM models: (1) zero-shot state-of-the-art closed-source models such as GPT-4o using a similar prompt to ours (shown in Figure 9), (2) zero-shot state-of-the-art closed-source models such as GPT-4o but using Code-as-Policies (Liang et al., 2023) to generate paths as described in Gu et al. (2023) (prompt in Figure 10), (3) finetuned open-source models (VILA-1.5-13b) on the data sources described in Section 4.1, but excluding the simulation trajectories from the RLBench dataset, (4) finetuned open-source models (VILA-1.5-13b) on the data sources described in Section 4.1, including path sketches from the RLBench dataset. The purpose of these evaluations is to first compare with closely related work that generates 2D trajectories using pretrained closed source VLMs Gu et al. (2023) (Comparison (1) and (2)). The comparison between (3) and (4) (our complete method) is meant to isolate the impact of including the simulation path sketches from the RLBench dataset. In doing so, we analyze the ability of the VLM to predict intermediate paths to transfer across significantly varying domains (from RLBench to the real world).

The results suggest that: (1) zero-shot path generation, even from closed-source VLMs Gu et al. (2023) such as GPT-4o with additional help through Code-as-Policies (Liang et al., 2023), underperforms VLMs finetuned on cross-domain data as in HAMSTER; (2) inclusion of significantly different training data such as low-fidelity simulation during finetuning improves the real-world performance of the VLM. This highlights the transferability displayed by HAMSTER across widely varying domains. These results emphasize that the hierarchical VLA approach described in HAMSTER can effectively utilize diverse sources of cheap prior data for 2D path predictions, despite considerable perceptual differences.

D.2 VLM Real World Generalization Study

The full list of task descriptions for this study is below (see Appendix D.1 for the main experiment details). Duplicates indicate different images for the same task. We plot some additional comparison examples in Figure 11. Note that the path drawing convention in images for this experiment differ from what is given to the lower-level policies as described in Section 4.2 as this multi-colored line is easier for human evaluators to see.

1. screw in the light bulb on the lamp

Method	VLM	Finetuning Data	Rank Exc. Real RLB.	Rank Real RLB.	Rank All
RT-Traj.	0-shot GPT-4o	-	3.40	3.63	3.47
RT-Traj.	CaP GPT-4o	-	3.57	3.36	3.41
HAMSTER	VILA	Our Exc. Sim RLB.	1.78	2.39	2.13
HAMSTER	VILA	Our	**1.59**	**1.28**	**1.40**

Table 5: Ranking-based human evaluation of different VLMs, averaged across various real-world evaluation tasks. Results indicate that HAMSTER including simulation data is most effective since it captures both spatial and semantic information across diverse tasks from RLBench. This significantly outperforms zero-shot VLM-based trajectory generation, as described in Gu et al. (2023)

2. screw in the light bulb on the lamp
3. screw in the light bulb on the lamp
4. screw out the light bulb and place it on the holder
5. screw out the light bulb and place it on the holder
6. screw in the light bulb
7. screw in the light bulb on the lamp
8. move the blue block on Taylor Swift
9. pick up the left block and put it on Jensen Huang
10. move the block on the right to Taylor Swift
11. place the yellow block on Kobe
12. pick up the blue block and place it on Jensen Huang
13. move the red block to Kobe
14. press the button on the wall
15. press the button to open the left door
16. press the button to open the right door
17. open the middle drawer
18. open the bottom drawer
19. open the top drawer
20. open the middle drawer
21. open the bottom drawer
22. press the button
23. press the button
24. press the orange button
25. press the orange button with black base
26. press the button
27. pick up the SPAM and put it into the drawer
28. pick up the orange juice and put it behind the red box
29. pick up the tomato soup and put it into the drawer
30. pick up the peach and put it into the drawer
31. move the mayo to the drawer
32. move the dessert to the drawer
33. pick up the object on the left and place it on the left
34. pick up the fruit on the left and put it on the plate
35. pick up the milk and put it on the plate

36. press the button with the color of cucumber, then press the button with color of fire
37. press the button with color of banana
38. press the button with color of leaf
39. press the button with color of leaf, then press the one with color of banana
40. press left button
41. pick up the left block on the bottom and stack it on the middle block on top
42. make I on top of C
43. put number 2 over number 5
44. stack block with lion over block with earth
45. pick up the left block on the bottom and stack it on the middle block on top
46. stack the leftest block on the rightest block
47. stack the block 25 over block L
48. put the left block on first stair

D.3 HUMAN RANKING

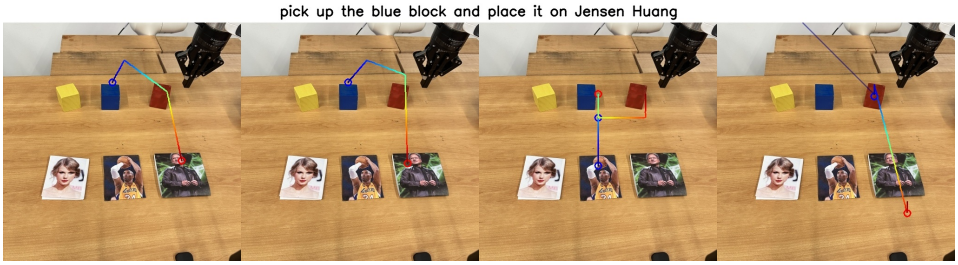

Figure 12: An example of results for human ranking. The trajectory is from blue to red with blue circle and red circle denotes gripper close point and open point respectively. The grader is asked to provide a rank to these trajectory about which trajectory has highest chance to succeed.

Due to the variety of possible trajectories that accomplish the same task, we use human rankings to compare how likely produced trajectories are to solve the task instead of quantitative metrics such as MSE. To do that, we generate trajectories for 48 image-question pairs with HAMSTER w/o RLBench, HAMSTER, Code-as-Policy (Liang et al., 2023), and GPT4o (Achiam et al., 2023). See Figure 12 for an example.

We recruit 5 human evaluators, who are robot learning researchers that have not seen the path outputs of HAMSTER, to grade these 4 VLMs based on the instruction: *"Provide a rank for each method (1 for best and 4 for worst). In your opinion, which robot trajectory is most likely to succeed. Traj goes from blue to red, blue circle means close gripper, red circle means open gripper."* The evaluators are allowed to give multiple trajectories the same score if they believe those trajectories are tied. As they are robot learning researchers, they are familiar with the types of trajectories that are more likely to succeed. Therefore, these rankings act as a meaningful trajectory quality metric.

E FAILURE ANALYSIS

This section outlines the failure modes observed during our experiments and provides a detailed breakdown of the causes. Failures can be attributed to issues in **trajectory prediction**, **trajectory adherence**, and **action execution**.

E.1 DIFFERENT FAILURE MODES

Trajectory Prediction Failures The Vision-Language Model (VLM) may fail to predict the correct trajectory due to several factors:

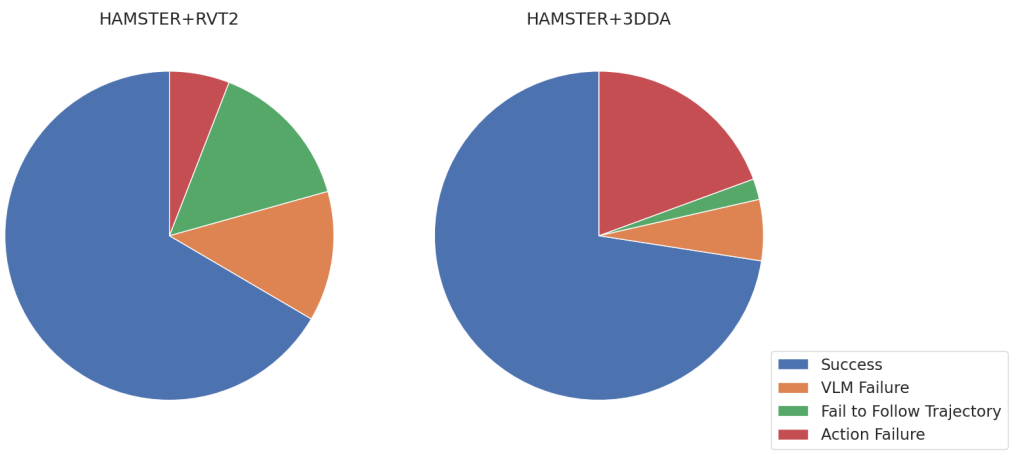

Figure 13: Performance Distribution of RVT2+Sketch and 3DDA+Sketch

- *Failure to understand the language goal:* Although the VLM demonstrates strong capabilities in handling diverse task descriptions, it struggles when the training set lacks similar tasks. This can cause the model to misunderstand the goal and make inaccurate predictions.

- *Incorrect trajectory prediction:* In some cases, the VLM predicts an incorrect trajectory, either by interacting with the wrong objects or misinterpreting the direction of the affordance.

- *Dynamic changes in the environment:* Since trajectories are generated at the beginning of a task, significant environmental changes during execution can lead to failure. The model lacks the ability to dynamically adjust the trajectory or reidentify the object initially referenced.

Trajectory Adherence Failures Failures in adhering to the predicted trajectory arise primarily due to:

- *3D ambiguity:* The use of 2D trajectory predictions introduces ambiguities, such as determining whether a point is positioned above or behind an object, leading to execution errors.

- *Incorrect object interaction:* The low-level action model is not explicitly constrained to strictly follow the predicted trajectory. As a result, it may deviate, interacting with the wrong object and causing task failures.

Action Execution Failures Even when the trajectory is correctly predicted and adhered to, action execution may still fail due to:

- *Execution-specific issues:* Despite training on a diverse set of actions, the model may fail during execution. For example, in grasping tasks, an incorrect grasp angle can cause the object to slip, resulting in a failed grasp.

E.2 Failure Analysis

Our analysis in Figure 13 reveals distinct failure tendencies across methods.

For RVT, 72% of failures stemmed from the low-level model failing to follow the trajectory, while 28% were due to execution failures. In contrast, for 3DDA, only 10% of failures were related to trajectory adherence, with 90% attributed to execution failures.

We hypothesize that this discrepancy arises because RVT incorporates a re-projection step, complicating trajectory adherence. In contrast, 3DDA leverages a vision tower that processes the original 2D image, simplifying trajectory interpretation.

F Simulation Experiment Details

Our simulation experiments are performed on Colosseum (Pumacay et al., 2024), a simulator built upon RLBench (James et al., 2020) containing a large number of visual and task variations to test the generalization performance of robot manipulation policies (see Figure 14 for a visualization of a subset of the variations). We use the `front_camera` and remove all tasks in which the camera does not provide a clear view of the objects in the task, resulting in 14 out of 20 colosseum tasks (we remove `basketball_in_hoop`, `empty_drawer`, `get_ice_from_fridge`, `move_hanger`, `open_drawer`, `turn_oven_on`).

Colosseum contains 100 training episodes for each task, without any visual variations, and evaluates on 25 evaluation episodes for each variation. We follow the same procedure other than using just the `front_camera` instead of multiple cameras. We report results in Table 1 after removing variations with no visual variations (e.g., object friction).

Figure 14: Colosseum benchmark variations. Figure from Pumacay et al. (2024), taken with permission.

Task	openvla	HAMSTER+RVT2	HAMSTER+3DDA
pick and place	0.46	**0.79**	0.78
press button	0.25	0.50	**0.63**
knock down	0.41	0.47	**0.66**

Table 6: Real world average success rates grouped by task type.