RDT-1B: A DIFFUSION FOUNDATION MODEL FOR BIMANUAL MANIPULATION

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ABSTRACT

Bimanual manipulation is essential in robotics, yet developing foundation models is extremely challenging due to the inherent complexity of coordinating two robot arms (leading to multi-modal action distributions) and the scarcity of training data. In this paper, we present the Robotics Diffusion Transformer (RDT), a pioneering diffusion foundation model for bimanual manipulation. RDT builds on diffusion models to effectively represent multi-modality, with innovative designs of a scalable Transformer to deal with the heterogeneity of multi-modal inputs and to capture the nonlinearity and high frequency of robotic data. To address data scarcity, we further introduce a Physically Interpretable Unified Action Space, which can unify the action representations of various robots while preserving the physical meanings of original actions, facilitating learning transferrable physical knowledge. With these designs, we managed to pre-train RDT on the largest collection of multi-robot datasets to date and scaled it up to 1.2B parameters, which is the largest diffusion-based foundation model for robotic manipulation. We finally fine-tuned RDT on a self-created multi-task bimanual dataset with over 6K+ episodes to refine its manipulation capabilities. Experiments on real robots demonstrate that RDT significantly outperforms existing methods. It exhibits zero-shot generalization to unseen objects and scenes, understands and follows language instructions, learns new skills with just 1$\sim$5 demonstrations, and effectively handles complex, dexterous tasks. We refer to the project page for the code and videos.

1 INTRODUCTION

Bimanual manipulation is essential for robots to accomplish real-world tasks (Edsinger & Kemp, 2007). For practical applications, a useful manipulation policy should be able to generalize to unseen scenarios, such as unseen objects and scenes. However, current approaches either depend on task-specific primitives (Mirrazavi Salehian et al., 2017; Rakita et al., 2019; Grannen et al., 2023a) or are limited to small-scale model, data and simple tasks (Krebs et al., 2021; Franzese et al., 2023; Grannen et al., 2023b; Zhao et al., 2023; Grotz et al., 2024; Liu et al., 2024), thereby exhibiting only narrow generalization and failing in complex tasks. Following the success in natural language processing (Achiam et al., 2023; Touvron et al., 2023) and computer vision (Radford et al., 2021; Kirillov et al., 2023), one promising direction to enable generalizable behaviors is to develop a foundation model through imitation learning on large-scale datasets.

Developing bimanual manipulation foundation models confronts the dual challenges of data scarcity and architectural limitations. The prohibitive costs of dual-arm systems create severe data scarcity (Sharma et al., 2018; Collaboration et al., 2023), fundamentally conflicting with the data-hungry nature of foundation models. Inspired by recent attempts in unimanual manipulation (Brohan et al., 2023; Kim et al., 2024), we mitigate this through cross-robot pretraining: leveraging multi-robot datasets for pre-training followed by target-robot fine-tuning, amplifying data volume by three orders of magnitude to extract transferable physical priors. However, two interconnected technical barriers emerge. First, the doubled action space induces multi-modal action distributions (Li, 2006; Jia et al.,

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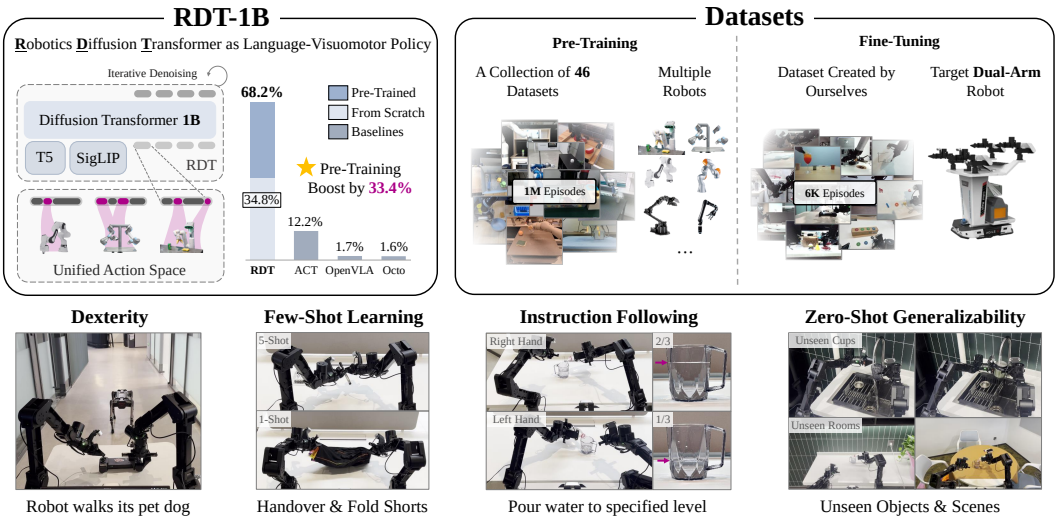
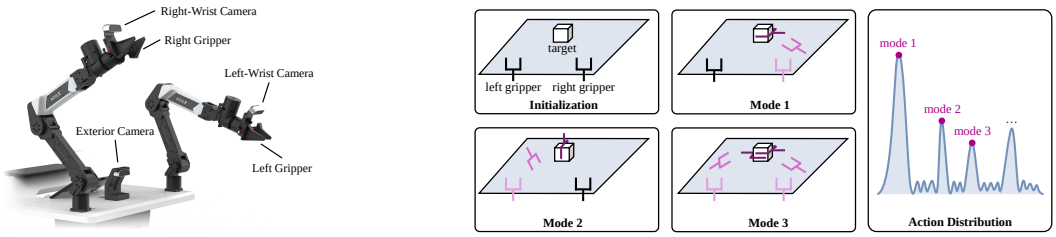


Figure 1: **Overview of Robotics Diffusion Transformer with 1B-Parameters (RDT-1B)**, a language-conditioned visuomotor policy for bimanual manipulation,with state-of-the-art generalizability to unseen scenarios (See App. H for metric calculation details).

2024) (see Fig. 2b for an illustrative example) that demand *expressiveness* capability beyond current methods (Zhao et al., 2023; Brohan et al., 2023; Kim et al., 2024), while simultaneously requiring *scalabilty* for stable large-scale training on multimodal data (text, vision, actions). Beyond architectural constraints, physical and action space variations across robots introduce data heterogeneity that risks negative transfer (Pan & Yang, 2009). Existing solutions either discard robots with structural inconsistencies or retain only cross-robot invariant features (Brohan et al., 2023; Ghosh et al., 2023; Shah et al., 2023a), sacrificing valuable data diversity essential for generalization.

In this paper, we introduce the *Robotics Diffusion Transformer (RDT)*, the largest bimanual manipulation foundation model with strong generalizability. RDT employs diffusion transformer (DiT) as its scalable backbone (Peebles & Xie, 2023), with special designs for language-conditioned bimanual manipulation. For expressiveness, RDT excels in capturing the full modalities of bimanual actions from massive data by using the capacity of diffusion models to represent complex distributions (Sohn et al., 2015; Ho et al., 2020). For scalability, we harness the Transformer backbone and carefully design the multi-modal encoding to eliminate the heterogeneity of various modalities. Moreover, robotic data is differed significantly from images and videos with temporal and spatial continuity (Chen et al., 2019; Liang et al., 2022). To characterize its inherent nonlinear dynamics (de Wit et al., 2012), high-frequency changes (Ghosh et al., 2023), and the unstable numerical range, we make important modifications to the original DiT structure, including MLP decoding, improved normalization, and alternate injection of conditions (see Fig. 4 for their importance). To further enable training RDT on heterogeneous data, we propose the *Physically Interpretable Unified Action Space*, a unified action format for various robots with gripper arms. This innovative format mitigates potential conflicts between different robots while retaining the physical meanings of the original actions, which can promote the model to learn generalizable physical knowledge across diverse robotic datasets.

With the above designs, we managed to pre-train the RDT model on the largest collection of multi-robot datasets to date (Collaboration et al., 2023; Walke et al., 2023; Fang et al., 2023; Kumar et al., 2024) and scale it up to 1.2B parameters, which is the largest diffusion-based pre-trained model for robotic manipulation. To further enhance its bimanual manipulation capabilities, we fine-tuned the RDT on a self-collected multi-task bimanual dataset comprising over 6K+ trajectories, which is one of the most extensive bimanual datasets. In our experiments, we have comprehensively evaluated RDT against strong baselines in both bimanual manipulation and robotic foundation models. Results show that RDT achieves state-of-the-art performance, outperforming baselines by achieving an improvement of 56% in success rates across a wide spectrum of challenging tasks. In particular, RDT has exceptional zero-shot and few-shot ($1 \sim 5$ shots) generalizability to unseen objects, scenes, instructions, and even skills. RDT is also capable of accomplishing tasks requiring fine-grained operations, such as controlling a robot dog with a joystick. Finally, ablation studies show that diffusion modeling, large model size, and large data size all contribute to superior performance.



(a) Target dual-arm robot

(b) Illustration of multi-modality

Figure 2: **(a)** Schematic diagram of the ALOHA dual-arm robot. **(b)** A toy example of grasping a cube. Compared with unimanual manipulation, bimanual manipulation has more possible action modes, leading to stronger multi-modality. Colors from light to dark indicate that time goes forward.

2 Related Work

Learning-based Bimanual Manipulation. One substantial challenge in learning a bimanual manipulation policy is the high dimensionality of the action space, which exacerbates the data scarcity (Zollner et al., 2004; Smith et al., 2012; Lioutikov et al., 2016; Stepputtis et al., 2022) and the multi-modal behavior (Colomé & Torras, 2018; 2020; Figueroa & Billard, 2017; Sharma et al., 2018; Xie et al., 2020; Franzese et al., 2023). Some works have developed more cost-effective interfaces for data collection (Zhao et al., 2023; Aldaco et al., 2024), but they are limited to specific hardware configurations and still insufficient to bridge the data gap for a generalizable policy. Others attempt to reduce data requirements by introducing inductive biases, such as distinguishing two arms for stabilization and functionality (Grannen et al., 2023b), parameterizing movement primitives (Batinica et al., 2017; Amadio et al., 2019; Chitnis et al., 2020; Franzese et al., 2023), or using voxel representations (Grotz et al., 2024; Liu et al., 2024). These methods use strong priors or simplified modeling, which successfully reduce the action space, but at the cost of a reduced scope of application and inability to express the multi-modality of bimanual behaviors (Pearce et al., 2023).

Foundation Models for Robotics. Foundation models have shown immense promise in enabling generalizable behaviors by training multi-task "generalist" models (Brohan et al., 2022; 2023; Ghosh et al., 2023; Kim et al., 2024) on large multi-task robot datasets (Collaboration et al., 2023; Brohan et al., 2022; Fang et al., 2023). Most studies adapt large vision-language models to directly predict action (Brohan et al., 2022; Driess et al., 2023; Brohan et al., 2023; Collaboration et al., 2023; Kim et al., 2024). While demonstrating generalization to new objects and tasks, they face issues with quantization errors and uncoordinated behaviors (Pearce et al., 2023) when applied to bimanual manipulation. It's largely due to their discretization of action spaces. To enhance precision, diffusion models have been used for continuous control (Ho et al., 2020; Chi et al., 2023; Pearce et al., 2023; Ghosh et al., 2023). Ghosh et al. (2023) pre-train a Transformer-based diffusion policy on a subset of Open X-Embodiment (Collaboration et al., 2023) dataset (25 datasets), with up to 93M parameters.

3 Problem Formulation and Challenges

We start by formulating the task and elaborating on the challenges. To evaluate the model on the hardware, we choose the ALOHA dual-arm robot as our target robot since it is one of the most representative dual-arm robots and is suitable for collecting human demonstration data via teleoperation (Zhao et al., 2023; Fu et al., 2024; Aldaco et al., 2024). Fig. 2a shows a schematic diagram of the target robot, which consists of two arms with grippers and three cameras. Note that our setting and foundation model are generic to any dual-arm gripper robot.

We consider the concrete task of language-conditioned bimanual manipulation with vision, which is fundamental in robotics and has great value in real-world scenarios such as household (Stepputtis et al., 2020; Brohan et al., 2022; Zhao et al., 2023). Formally, given a language instruction ℓ, the policy is presented with an observation $\boldsymbol{o}_t$ at time $t \in \mathbb{N}^+$; and then it produces an action $\boldsymbol{a}_t$ to control *two robot arms* to achieve the goal specified by ℓ. The observation is represented as a triple $\boldsymbol{o}_t := (\boldsymbol{X}_{t-T_{\text{img}}+1:t+1}, \boldsymbol{z}_t, c)$, where $\boldsymbol{X}_{t-T_{\text{img}}+1:t+1} := (\boldsymbol{X}_{t-T_{\text{img}}+1}, \ldots, \boldsymbol{X}_t)$ is the RGB observation history of size T_{img}, $\boldsymbol{z}_t$ is the low-dimensional proprioception of the robot, and c is the control frequency. The action $\boldsymbol{a}_t$ is usually a subset of the desired proprioception $\boldsymbol{z}_{t+1}$[1].

[1]E.g., $\boldsymbol{z}_t$ may include the gripper position at time t, and $\boldsymbol{a}_t$ can be the target gripper position at step $t+1$.

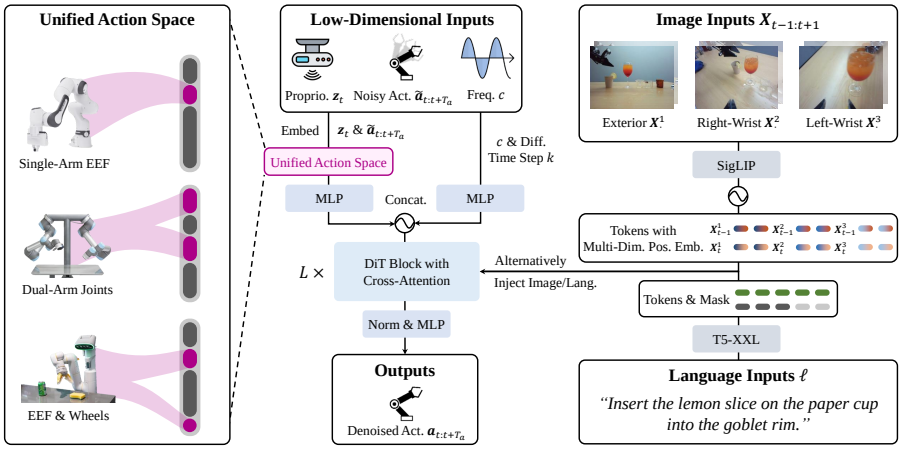


Figure 3: **RDT framework.** Heterogeneous action spaces of various robots are embedded into a unified action space for multi-robot training. **Inputs:** proprioception $\boldsymbol{z}_t$, noisy action chunk $\tilde{\boldsymbol{a}}_{t:t+T_a}$, control frequency c, and diffusion time step k, acting as denoising inputs; image inputs ($T_{\text{img}} = 2$ and $\boldsymbol{X}_\cdot = \{\boldsymbol{X}_\cdot^1, \boldsymbol{X}_\cdot^2, \boldsymbol{X}_\cdot^3\}$ denotes a set of images from exterior, right-wrist, and left wrist cameras) and language inputs, acting as conditions. **Outputs:** denoised action chunk $\boldsymbol{a}_{t:t+T_a}$.

A specific task in bimanual manipulation typically consists of multiple elements: a *skill* (e.g., verbs like "pick", "wipe", or "open"), an *object* (e.g., nouns like "bottle", "table", or "door"), a *scene* (i.e. the environment in which the task takes place), and a *modality* describing how the skill is performed (e.g., adverbials like "pick the bottle with the left hand"). When encountering a new task, a practical policy is required to generalize to unseen[2] elements in the task, which is particularly challenging for previous rule-based methods (Mirrazavi Salehian et al., 2017; Rakita et al., 2019; Grannen et al., 2023a) as well as learning-based methods that are limited to either small models and data or simple tasks, as discussed in Sec. 2.

We aim to train a foundation model policy via imitation learning to achieve generalizability. However, the available data for a specific dual-arm robot is particularly scarce ($<$ 10K trajectories) due to high hardware costs, far from the common requirement to train a foundation model. To address this, we propose to employ a pre-training and fine-tuning pipeline (Radford et al., 2018) to take advantage of data from multiple robots by drawing inspiration from recent advances in unimanual manipulation (Ghosh et al., 2023; Collaboration et al., 2023; Kim et al., 2024). In this manner, we would expand the data size by three orders of magnitude. Specifically, we first pre-train the model on a large-scale multi-robot dataset $\mathcal{D}_{\text{pre}}$ (mostly single-arm) and then fine-tune on a dataset of the target robot $\mathcal{D}_{\text{ft}}$. We denote the dataset by $\mathcal{D}_\cdot = \{(\ell^{(i)}, \boldsymbol{o}_t^{(i)}, \boldsymbol{a}_t^{(i)}) \mid 0 \le t < T^{(i)}, 1 \le i \le N\}$, where $T^{(i)}$ is the length of the i-th trajectory and N is the number of trajectories. Moreover, it is worth emphasizing that our goal is to use multi-robot data to enhance the model's generalizability in bimanual manipulation *rather than* developing a cross-embodiment model for various robots. There are two main challenges to developing such a foundation model with multi-robot data:

Challenge 1: How to design a powerful architecture? A generalizable foundation model necessitates a powerful architecture. This requirement encompasses two primary aspects. Firstly, the architecture must possess sufficient *expressiveness* to capture the multi-modality in the action distribution. Fig. 2b illustrates a toy example where the robot attempts to grasp a cube. We can see that there are many modes to finish this task, in contrast to unimanual manipulation, where only one robot arm is controlled. When collecting demonstrations, the human operator may randomly pick one of them, leading to multi-modality in the collected action data. Secondly, *scalability* is necessary for such an architecture. As a foundation model, it should effectively process heterogeneous inputs from various modalities (text, images, actions, etc.) while being scalable to train stably on large datasets.

Challenge 2: How to train on heterogeneous data? Training on multi-robot data presents a unique challenge of data heterogeneity. The physical structure and the action space can vary greatly across different robots. Previous attempts either restrict themselves to a subset of robots with similar action spaces (Yang et al., 2023; Ghosh et al., 2023; Kim et al., 2024) or only retain a subset of inputs

[2] *unseen* means that a certain element has not appeared in the training data.

sharing the same structure (Collaboration et al., 2023; Yang et al., 2024), at the cost of losing a lot of information. It remains largely under-addressed on how to train models on such heterogeneous data.

4 Robotics Diffusion Transformer

We now present Robotics Diffusion Transformer (RDT), as illustrated in Fig. 3. In Sec. 4.1, we present the diffusion model and the corresponding architecture to address Challenge 1. In Sec. 4.2, we resolve Challenge 2 by proposing a physically interpretable unified action space to unify various robot action spaces and enable multi-robot pre-training. We also collect a comprehensive multi-task bimanual dataset for fine-tuning to improve the bimanual manipulation capabilities of RDT.

4.1 RDT Model

Diffusion Modeling. Due to multi-modality, given the language instruction ℓ and observation $\boldsymbol{o}_t$, there may be many possible actions $\boldsymbol{a}_t$ to proceed with the task. The policy will learn the "average" of action modes if we model it as a deterministic mapping $(\ell, \boldsymbol{o}_t) \mapsto \boldsymbol{a}_t$ and regress the tuples of $(\ell, \boldsymbol{o}_t, \boldsymbol{a}_t)$ in the training data. This may result in out-of-distribution actions, such as the arithmetic mean of multiple modes, which can be completely infeasible (Pearce et al., 2023). Instead, we choose to model the continuous conditional distribution $p(\boldsymbol{a}_t|\ell, \boldsymbol{o}_t)$. As discussed in Sec. 2, among various approaches, diffusion models excel in both expressiveness and sampling quality, but can be slow to sample high-dimensional data (e.g., images). Luckily, for our settings, the drawback is minor since that $\boldsymbol{a}_t$ has a much lower dimension than images, which requires only minimal sampling overhead. This has made diffusion models an ideal choice for policy as in Chi et al. (2023).

Nevertheless, employing diffusion models for robotic tasks faces unique challenges since the inherent properties of robotic physics quantities (i.e., the action and proprioception) are different from image/video data. Image and video data, while high-dimensional, often exhibit a degree of temporal and spatial continuity (Chen et al., 2019; Liang et al., 2022), with changes between frames typically being incremental. In contrast, robotic physics quantities are characterized by its *nonlinear dynamics* (de Wit et al., 2012) and the potential for *high-frequency changes* stemming from the physical interactions, such as collision, constraints, and material properties like damping. Moreover, the quantities also feature an *unstable numerical range*, probably due to extreme values caused by unreliable sensors. This underscores the necessity of adapting current diffusion models to effectively capture the instability and nonlinearity of robot data. Next, we will first elaborate on diffusion formulation and then introduce our design of architecture to resolve these challenges.

When making a decision with diffusion policies, we first sample a totally noisy action $\boldsymbol{a}_t^K \sim \mathcal{N}(\mathbf{0}, \boldsymbol{I})$ and then perform $K \in \mathbb{N}^+$ denoising steps to denoise it to a clean action sample $\boldsymbol{a}_t^0$ from $p(\boldsymbol{a}_t|\ell, \boldsymbol{o}_t)$:

$$\boldsymbol{a}_t^{k-1} = \frac{\sqrt{\bar{\alpha}^{k-1}}\beta^k}{1-\bar{\alpha}^k}\boldsymbol{a}_t^0 + \frac{\sqrt{\alpha^k}(1-\bar{\alpha}^{k-1})}{1-\bar{\alpha}^k}\boldsymbol{a}_t^k + \sigma^k \boldsymbol{z}, \quad k = K, \dots, 1, \tag{1}$$

where $\{\alpha^k\}_{k=1}^K, \{\sigma^k\}_{k=1}^K$ are scalar coefficients pre-defined by a noise schedule (Nichol & Dhariwal, 2021). Here, $\beta^k := 1 - \alpha^k$, and $\bar{\alpha}^{k-1} := \prod_{i=1}^{k-1} \alpha^i$, $\boldsymbol{z} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{I})$ if $k > 1$, else $\bar{\alpha}^{k-1} = 1, \boldsymbol{z} = \mathbf{0}$. However, $\boldsymbol{a}_t^0$ is intractable before sampling is finished. We opt to use a learnable denoising network $f_{\boldsymbol{\theta}}$ with parameters $\boldsymbol{\theta}$ to estimate the clean sample from a noisy one: $\boldsymbol{a}_t^0 \leftarrow f_{\boldsymbol{\theta}}(\ell, \boldsymbol{o}_t, \boldsymbol{a}_t^k, k)$. To train such a network, we will minimize the following mean-squared error (MSE) of denoising:

$$\mathcal{L}(\boldsymbol{\theta}) := \text{MSE}\left(\boldsymbol{a}_t, f_{\boldsymbol{\theta}}(\ell, \boldsymbol{o}_t, \sqrt{\bar{\alpha}^k}\boldsymbol{a}_t + \sqrt{1-\bar{\alpha}^k}\boldsymbol{\epsilon}, k)\right), \tag{2}$$

where $k \sim \text{Uniform}(\{1, \dots, K\})$, $\boldsymbol{\epsilon} \sim \mathcal{N}(\mathbf{0}, \boldsymbol{I})$, and $(\ell, \boldsymbol{o}_t, \boldsymbol{a}_t)$ is sampled from our training dataset. Later in this paper, we will denote noisy action inputs by $\tilde{\boldsymbol{a}}_t := \sqrt{\bar{\alpha}^k}\boldsymbol{a}_t + \sqrt{1-\bar{\alpha}^k}\boldsymbol{\epsilon}$, in which the superscript of k is dropped for simplicity. Besides, in practice, we prefer to predict a sequence of actions, i.e., an action chunk, in one shot to encourage temporal consistency (Chi et al., 2023) and to alleviate error accumulation over time by reducing number of decisions in a task (Zhao et al., 2023). Specifically, we model $p(\boldsymbol{a}_{t:t+T_a}|\ell, \boldsymbol{o}_t)$, where $\boldsymbol{a}_{t:t+T_a} := (\boldsymbol{a}_t, \dots, \boldsymbol{a}_{t+T_a-1})$ is an action chunk and T_a denotes the chunk size (Zhao et al., 2023). We provide a detailed discussion in App. A.

We now present the design of the architecture, including the encoding of multi-modal inputs and the network structure of $f_{\boldsymbol{\theta}}$, while details are deferred to App. B.

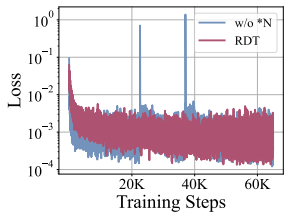
Encoding of Heterogeneous Multi-Modal Inputs. The heterogeneity of multi-modal inputs is reflected in the structure; that is, the format and number of dimensions of each modality are significantly different. This has posed challenges for mult-modal training. To address this, we encode these diverse modalities into a unified latent space. Below are the encoding methods:

- **Low-Dimensional Inputs** are low-dimensional vectors that represent physical quantities of the robot, including the proprioception, the action chunk, and the control frequency. To encode them, we use MLPs (with Fourier features (Tancik et al., 2020)), which can effectively capture the *high-frequency changes* in low-dimensional spaces.
- **Image Inputs** are high-dimensional and contain rich spatial and semantic information. To extract compact representations, we use an image-text-aligned pre-trained vision encoder, SigLIP (Zhai et al., 2023). We fix its weights during training to save GPU memory.
- **Language Inputs** are of varying length and highly abstract, posing integration challenges due to their complexity and ambiguity. To encode them, we use a pre-trained Transformer-based language model, T5-XXL (Raffel et al., 2020). We also fix its weights during training to save GPU memory.

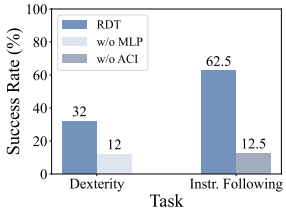
Besides, heterogeneity also manifests in both cross-modal and intra-modal information density. First, modalities differ inherently in information capacity (e.g., visual inputs typically yield more tokens than text). Second, substantial variance exists within modalities, as seen in robotic perception where exterior cameras capture broader scenes versus the limited views from wrist cameras (Fig. 3). This discrepancy risks shortcut learning: focusing on exterior views while neglecting details from wrist cameras. To promote balanced multimodal integration, we implement stochastic independent masking across modalities during encoding, preventing overreliance on specific inputs.

Network Structure of f_{θ}. We choose Transformer as the scalable backbone network (Bao et al., 2023; Peebles & Xie, 2023) and make the following three key modifications from Diffusion Transfomer (DiT) by considering the characteristics of our robotic problem:

- **QKNorm & RMSNorm.** The *unstable numerical range* of the inputting robotic physical quantities can lead to problems such as gradient instability and numerical overflow, especially when training large foundation models. To solve this problem, we add QKNorm (Henry et al., 2020) to avoid numerical instability when calculating attention. Besides, we also note that our problem can be considered as a time series forecasting task, and the centering operation in the original DiTs' LayerNorm could cause *token shift* and *attention shift*, thus destroying the symmetry of the time series (Huang et al., 2024). Therefore, we replace LayerNorm with RMSNorm (Zhang & Sennrich, 2019) without a centering operation. Fig. 4a shows that large-scale pre-training tends to be very unstable or even explode without this modification.
- **MLP Decoder.** To improve the approximation capability for *nonlinear* robot actions, we replace the final linear decoder with a nonlinear MLP decoder as a projection from the latent space back to the physical space. As empirically shown in Fig. 4b, without this design, RDT cannot effectively capture nonlinear dynamics and thus loses the ability to accomplish dexterous tasks that require delicate operations.
- **Alternating Condition Injection (ACI).** In our model, image and language inputs serve as conditions, which are high-dimensional and variable in length, contrasting with the class label conditions in traditional DiTs (Peebles & Xie, 2023). These informative conditions are challenging to compress into a single token, making the original adaptive layer norm approach unsuitable. Therefore, we employ cross-attention to accommodate conditions of varying lengths avoiding the information loss in further compression. Besides, we further analyze that, given that image tokens are usually much more than text tokens, simultaneous injection of both modalities tends to overshadow text-related information, thus impairing the capability of the instruction following (see Fig. 4b for quantitative results). To



(a) Loss w/o QKN & RMSN



(b) Task w/o MLP or ACI

Figure 4: **(a)** Unstable loss curve during training without QKNorm & RMSNorm. **(b)** Success rates of RDT (w/o MLP Decoder or w/o ACI) in tasks of *Robot Dog* (walk straight sub-task) and *Pour Water-L-1/3* (correct amount sub-task). See Fig. 5 for task definitions. All the models are without pre-training in this experiment due to resource constraints.

mitigate this issue, we strategically alternate between injecting image and text tokens in successive layers' cross-attention rather than injecting both in every layer.

4.2 DATA

Training on Heterogeneous Multi-Robot Data. To enable training on heterogeneous multi-robot data, we need a unified action space shared among various robots to provide a unified format for multi-robot actions. The mapping from the original action space of a robot to the unified action space should be physically interpretable, and each dimension of the space should have a clear physical meaning. This can encourage the model to learn shared physical laws from different robot data, thereby improving the efficiency of learning from data of different robots (Shah et al., 2023a).

The design of the space consists of two steps. Firstly, for each robot, we can use a single space to accommodate both its proprioception $\boldsymbol{z}_t$ and action $\boldsymbol{a}_t$. This is because $\boldsymbol{a}_t$ is usually a subset of the desired $\boldsymbol{z}_{t+1}$ (de Wit et al., 2012; Kouvaritakis & Cannon, 2016), and thus the space of $\boldsymbol{z}_t$ naturally contains the space of $\boldsymbol{a}_t$. Secondly, we design a unified space that encompasses all the main physical quantities of most robots with gripper arms. As illustrated in the left side of Fig. 3, we embed the action space of a robot into this unified space by filling each element of the original action vector into the corresponding position of the unified action space vector according to its physical meaning, with the remaining positions being padded. The specific definition of the space is given in App. C.

With this unified space, we are able to pre-train RDT on data from almost all modern robots with gripper arms, and greatly expand the data scale towards the requirement for a foundation model. Specifically, our collection of pre-training datasets includes 46 datasets of various robots, with a total size of 1M+ trajectories and 21TB. More details and preprocessing are deferred to App. D.

Collecting a Comprehensive Multi-Task Bimanual Dataset. Though having been pre-trained on large-scale datasets, RDT could still need help to zero-shot generalize to the target dual-arm robot due to the embodiment gap. To bridge the gap, we need to collect a multi-task bimanual dataset on the target robot for fine-tuning. Recent advances in large language models (Ziegler et al., 2019; Brown et al., 2020; Touvron et al., 2023) have shown that high-quality fine-tuning datasets are crucial for model performance. We ensure the high quality of our dataset from three aspects: **(1)** Regarding quantity, we have collected 6K+ trajectories, making our dataset one of the largest bimanual datasets nowadays; **(2)** Regarding comprehensiveness, we consider 300+ challenging tasks, covering most manipulation task types, from pick-and-place to plugging cables, even including writing math equations; **(3)** Regarding diversity, we prepare 100+ objects with rigid and non-rigid bodies of various sizes and textures and 15+ different rooms with different lighting conditions. Besides, we further utilize GPT-4-Turbo (Achiam et al., 2023) to rewrite human-annotated instructions to increase text diversity. For more information, we refer to Fig. 6 and App. E.

5 EXPERIMENTS

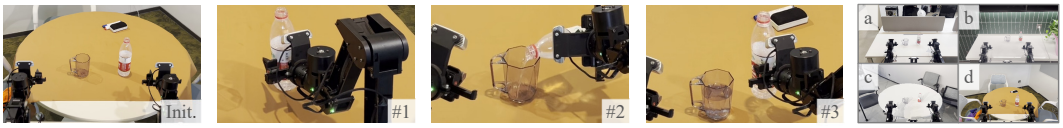
We aim to answer the following questions through real-robot experiments: $\mathcal{Q}$**1**: Can RDT zero-shot generalize to unseen objects and scenes? $\mathcal{Q}$**2**: How effective is RDT's zero-shot instruction-following capability for unseen modalities? $\mathcal{Q}$**3**: Can RDT facilitate few-shot learning for previously unseen skills? $\mathcal{Q}$**4**: Is RDT capable of completing tasks that require delicate operations? and $\mathcal{Q}$**5**: Are large model sizes, extensive data, and diffusion modeling helpful for RDT's performance?

5.1 EXPERIMENT SETUPS

Tasks. We select 7 challenging tasks to evaluate the generalizability and capabilities of RDT from different dimensions, including complex scenarios that the model may encounter in real-world tasks, such as various unseen elements and dexterous manipulation. An illustration of the dimension of each task is given in Table 1 while detailed definitions and visualizations are provided in Fig. 5.

Data. We use the pre-training and fine-tuning datasets in Sec. 4.2. We now list the number of demos related to each task in our fine-tuning dataset. *Wash Cup*: 133 demos for seen cups combined and 0 demos for unseen cups; *Pour Water*: 350 demos for seen rooms combined and 0 demos for unseen

Wash Cup: *"Fill the mug with water from the faucet and pour it into the sink."* The mug is randomized up to 10cm. The robot needs to Pick Up Cup (#1), Turn On Faucet (#2), Get Water (#3, to ensure that the water falls into the cup), Pour Out Water (#4), and Place Back Up (#5). The last image shows seen and unseen cups (from left to right).



Pour Water: *"Pour water from the bottle into the mug."* The bottle and mug are randomized up to 6cm. The robot needs to Pick Up Bottle (#1), Pour Water (#2), and Place Back Bottle (#3). The last image shows one seen room (a) and three unseen rooms (b-d).

Pour Water-L-1/3 (-R-2/3): *"Pour water from the bottle into the mug until about one-third (two-thirds) with the left (right) hand."* In the left-hand task, the bottle is initially placed to the left of the mug, and vice versa. The bottle and mug are randomized up to 6cm.

Handover: *"Pick up the black marker on the right and put it into the packaging box on the left."* The marker pen and box are randomized up to 3cm. The robot needs to Pick Up Pen (#1), Switch Hand (#2), Drop Pen (#3), and ensure it can Fall into Box (#4).

Fold Shorts: *"Fold the basketball shorts into a rectangle."* The shorts are randomized up to 3cm and wrinkles are also randomized.

Robot Dog: *"Push the left joystick forward to make the robot dog walk straight forward."* The remote control is randomized up to 4cm and the robot dog is up to 50cm. The robot needs to Grab Remote (#1) and Push Joystick (#2) as straight as possible to make the robot dog walk in a straight line as shown in the last two images.

Figure 5: **Task definitions and visualizations.** For 7 challenging tasks, we describe their language instruction, randomization, and definitions of each sub-task. For *Pour Water-L-1/3* and *Pour Water-R-2/3*, we show the resulting water levels in two images.

rooms; *Pour Water-L-1/3* & *Pour Water-R-2/3*: 18 demos for the water level of little, 19 demos for half, and 19 demos for full; *Handover*: 5 demos; *Fold Shorts*: 1 demo; *Robot Dog*: 68 demos.

Model Training and Inference. We scale the size of RDT up to 1.2B parameters, establishing it as the currently largest diffusion-based robotic foundation model. The model is pre-trained on 48 H100 80GB GPUs for a month, giving a total of 1M training iteration steps. It takes three days to fine-tune this model using the same GPUs for 130K steps. We defer further details to App. F, including the running platform, design choices, and data augmentation techniques. For real-time inference, we adopt DPM-Solver++ (Lu et al., 2022), a recent sampling accelerator of diffusion models. It can reduce the diffusion steps required to sample an action chunk from 100 steps to 5 steps, achieving an action chunk inference frequency of 6 Hz (action chunks per second) and an average action inference frequency of 381 Hz (actions per second) on the target robot's onboard RTX 4090 24GB GPU.

Baselines. To comprehensively evaluate RDT, we consider the most advanced baselines in robotic foundation models and bimanual manipulation, including Action Chunking with Transformers

Table 1: **Dimensions when designing tasks.** For *Pour Water-L-1/3* and *Pour Water-R-2/3*, only the water levels of *little*, *half* (i.e., 1/2), and *full* are seen in training instructions. For *Handover* and *Fold Shorts*, the dataset only contains 5 demos and 1 demo of the skill, respectively. For *Robot Dog*, it requires delicate operations, as a slight angle when pushing joysticks can make the robot dog deviate.

TASK NAME	DIMENSION	EXPLANATION
Wash Cup	Unseen Object ($\mathcal{Q}$**1**)	To wash one seen and two unseen cups with the faucet
Pour Water	Unseen Scene ($\mathcal{Q}$**1**)	To pour water into the cup in three unseen rooms
Pour Water-L-1/3	Instruction Following ($\mathcal{Q}$**2**)	To pour water into the cup with the **left hand** until **one-third** full
Pour Water-R-2/3	Instruction Following ($\mathcal{Q}$**2**)	To pour water into the cup with the **right hand** until **two-thirds** full
Handover	5-Shot Learning ($\mathcal{Q}$**3**)	To move the marker to the box, where handover is needed due to far distance
Fold Shorts	1-Shot Learning ($\mathcal{Q}$**3**)	To fold the shorts in half horizontally
Robot Dog	Dexterity ($\mathcal{Q}$**4**)	To push the joystick straight to control the robot dog to walk in a straight line

(ACT) (Zhao et al., 2023), OpenVLA (Kim et al., 2024), and Octo (Ghosh et al., 2023). ACT is a state-of-the-art method in bimanual manipulation, which uses VAE to model the action distribution. OpenVLA is the largest open-source foundation model (7B), employing the discretization modeling. Octo is a diffusion-based foundation model, and its largest version has only 93M parameters.

Metric and Hardware. We employ the success rate as our main metric, which is calculated by dividing successful trials by total trials. *Wash Cup* is tested with 8 trials for each cup (one seen cup, two unseen cups, 24 trials in total). *Pour Water* is tested with 8 trials for each room (three unseen rooms, 24 trials in total). *Pour Water-L-1/3* and *Pour Water-R-2/3* are tested with 8 trials each. *Handover*, *Fold Shorts*, and *Robot Dog* are tested with 25 trials each. All the tests are performed on the ALOHA dual-arm robot (see App. G for hardware configurations). Experimental details, such as the implementation and hyper-parameters, are elaborated in App. H.

Ablation Study. Answering $\mathcal{Q}$**5**, we have conducted ablation studies on the model size, pre-training, and the modeling method to understand their importance. We consider the variants of: *RDT (ours):* the original RDT. *RDT (regress):* RDT without diffusion modeling. It models the deterministic mapping $(\ell, \boldsymbol{o}_t) \mapsto \boldsymbol{a}_t$. *RDT (small):* RDT without large parameters. It has only 166M parameters. *RDT (scratch):* RDT without pre-training. It is trained from scratch during fine-tuning. In Table 2, we evaluate these variants in terms of three dimensions of generalizability. Table 7 provides a comparison of different variants of RDT as well as baselines.

Table 2: **Ablation study results.** Here are the success rates (%) of the original RDT and its three variants in tasks of *Wash Cup* (unseen cup 2, total success rate), *Pour Water* (unseen room 3, total success rate), and *Pour Water-L-1/3* (correct amount sub-task). All the models except *RDT (scratch)* are pre-trained before fine-tuning.

VARIANT NAME	UNSEEN OBJECT	UNSEEN SCENE	INSTRUCTION FOLLOWING
RDT (regress)	12.5	50	12.5
RDT (small)	37.5	**62.5**	25
RDT (scratch)	0	25	62.5
RDT (**ours**)	**50**	**62.5**	**100**

5.2 Results Analysis

From the results in Table 3, we can see that RDT consistently outperforms other baselines. This is because RDT employs diffusion with a powerful network architecture to model the distribution of multi-modal actions accurately, while discretization and VAE lack accuracy and expressiveness, respectively. Besides, the large number of parameters after large-scale pre-training provides a lot of prior knowledge, which significantly improves the generalizability. Here is a detailed analysis:

- $\mathcal{Q}$**1 &** $\mathcal{Q}$**2:** RDT can zero-shot generalize to unseen objects, scenes, and modalities. In *Wash Cup* and *Pour Water*, RDT can still achieve a high success rate on unseen scenarios, and its performance is not much different from that on seen ones. In contrast, the other baselines cannot even complete the entire task. In *Pour Water-L-1/3* and *Pour Water-R-2/3*, from the third row of Fig. 5 or Fig. 10 (zoomed-in version), we can find that RDT understands precisely which hand to manipulate and how much water to pour and closely follows the instruction through its actions, even though it has never seen words like "one-third" or "two-thirds". It is precisely because of large-scale pre-training that RDT has seen a large number of diverse objects, scenes, and instructions, leading to such strong zero-shot generalization.

Table 3: **Quantitative results.** We report success rates (%) of ACT, OpenVLA, RDT (from scratch, no pre-trained), and RDT (ours, pre-trained) for 7 tasks. Sub-columns in each sub-task cell represent different elements (objects, instructions, scenes). ACT is not language-conditioned and thus unavailable for instruction following. RDT (**ours**) consistently outperforms others.

Wash Cup: seen cup 1 | unseen cup 1 | unseen cup 2 (**Unseen Object**)																		
	Pick Up Cup			Turn On Faucet			Get Water			Pour Out Water			Place Back Cup			Total		
ACT	50	12.5	37.5	0	0	0	0	0	0	0	0	0	37.5	0	0	0	0	0
OpenVLA	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
Octo	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
RDT (scratch)	37.5	12.5	0	0	12.5	12.5	0	0	0	37.5	12.5	0	25	0	0	0	0	0
RDT (**ours**)	87.5	87.5	50	62.5	75	50	50	75	50	87.5	75	50	87.5	62.5	50	**50**	**75**	**50**

Pour Water-L-1/3 | Pour Water-R-2/3 (**Instruction Following**)												
	Pick Up Bottle		Pour Water		Place Back Bottle		Total		Correct Hand		Correct Amount	
OpenVLA	50	0	0	0	0	0	0	0	50	0	0	0
Octo	0	0	0	0	0	0	0	0	0	0	0	0
RDT (scratch)	100	75	75	25	62.5	25	62.5	25	100	75	62.5	12.5
RDT (**ours**)	100	87.5	100	87.5	100	87.5	**100**	**87.5**	**100**	**87.5**	**100**	**75**

Pour Water: unseen room 1 | unseen room 2 | unseen room 3 (**Unseen Scene**)													Fold Shorts (**1-Shot**)
	Pick Up Bottle			Pour Water			Place Back Bottle			Total			-	Total
ACT	25	87.5	25	0	50	12.5	0	37.5	12.5	0	37.5	12.5	-	0
OpenVLA	0	0	0	0	0	0	0	0	0	0	0	0	-	0
Octo	50	0	12.5	12.5	0	0	12.5	0	0	12.5	0	0	-	4
RDT (scratch)	62.5	100	62.5	25	87.5	37.5	25	75	25	25	75	25	-	40
RDT (**ours**)	62.5	100	62.5	62.5	100	62.5	62.5	100	62.5	**62.5**	**100**	**62.5**	-	**68**

	Handover (**5-Shot**)					Robot Dog (**Dexterity**)			
	Pick Up Pen	Switch Hand	Drop Pen	Fall into Box	Total	Grab Remote	Push Joystick	Total	Walk Straight
ACT	44	0	0	0	0	88	32	32	32
OpenVLA	0	0	0	0	0	84	0	0	0
Octo	12	0	0	0	0	100	4	4	0
RDT (scratch)	88	32	24	16	16	100	64	64	32
RDT (**ours**)	100	56	56	40	**40**	100	76	**76**	**48**

- *Q***3:** RDT can learn new skills using only a few shots. In *Handover* and *Fold Shorts*, RDT has learned new and complex skills of handover and folding through few-shot learning, whose action patterns are very different from known skills, while the success rate of others is almost zero. Such improvement is also due to large-scale pre-training. Few-shot learning can help RDT quickly adapt to new working environments, which is of great significance for practical applications.
- *Q***4:** RDT can handle dexterous tasks. In *Robot Dog*, RDT accurately controls the angle when pushing the joystick, while others have caused the robot dog to deviate. This is because diffusion, with our powerful network architecture, can model the distribution of multi-modal and nonlinear actions so that the action precision can meet the requirements of dexterous tasks. We also note that the joystick and the remote control are both black, making the joystick not visually apparent. It probably makes ACT prone to failure. In contrast, large-scale pre-training has made RDT learn a better vision-language representation of the joystick concept, improving the recognition capability.
- *Q***5:** Large model size, extensive data, and diffusion are all essential factors for our excellence. In Table 2, there is a serious performance drop without any of these factors, demonstrating the necessity of our contributions. In particular, *RDT (scratch)* performs poorly on unseen objects and scenes, indicating that the knowledge from pre-training is critical for generalization.

6 Conclusion

In this paper, we tackled the challenges of data scarcity and increased manipulation complexity in generalizable bimanual manipulation by developing the Robotics Diffusion Transformer (RDT), a diffusion-based foundation model for language-conditioned visuomotor imitation learning. Our model was pre-trained on an extensive multi-robot dataset and fine-tuned on a self-collected bimanual dataset. We further introduce a Physically Interpretable Unified Action Space to unify action representations across different robots, enhancing robustness and transferability. Outperforming existing methods, RDT not only demonstrates significant improvements in dexterous bimanual capability and instruction following but also achieves remarkable performance in few-shot learning and zero-shot generalization to unseen objects and scenes.

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ETHICS STATEMENT

All the data used in this research comes from open-source and well-documented datasets, and we strictly follow all applicable licensing and usage guidelines. Our finetuning dataset is collected by the authors of this paper along with some volunteers.

While RDT is a model trained for scalable, language-conditioned visuomotor policy learning and tested on the ALOHA dual-arm robot, we emphasize that any harmful use of our model is neither intended nor encouraged, and we encourage responsible deployment on real-world robots.

REPRODUCIBILITY STATEMENT

To reproduce our pre-training and fine-tuning processes, we have provided the code in the repository. We also include instructions for downloading the dataset, how to use the training code, and a guide for deploying on a real machine in the README file. We have fully open-sourced all our code, model weights, and fine-tuning datasets. We refer to the project page for more information.

Please refer to App. D for pre-training dataset details, App. E for fine-tuning dataset details, App. F for RDT training details, App. G for hardware details, and App. H for experimental details and implementation of baselines.

REFERENCES

TensorFlow Datasets, a collection of ready-to-use datasets. https://tensorflow.google.cn/datasets. 23

Martín Abadi, Ashish Agarwal, Paul Barham, Eugene Brevdo, Zhifeng Chen, Craig Citro, Greg S. Corrado, Andy Davis, Jeffrey Dean, Matthieu Devin, Sanjay Ghemawat, Ian Goodfellow, Andrew Harp, Geoffrey Irving, Michael Isard, Yangqing Jia, Rafal Jozefowicz, Lukasz Kaiser, Manjunath Kudlur, Josh Levenberg, Dandelion Mané, Rajat Monga, Sherry Moore, Derek Murray, Chris Olah, Mike Schuster, Jonathon Shlens, Benoit Steiner, Ilya Sutskever, Kunal Talwar, Paul Tucker, Vincent Vanhoucke, Vijay Vasudevan, Fernanda Viégas, Oriol Vinyals, Pete Warden, Martin Wattenberg, Martin Wicke, Yuan Yu, and Xiaoqiang Zheng. TensorFlow: Large-scale machine learning on heterogeneous systems, 2015. URL https://www.tensorflow.org/. Software available from tensorflow.org. 23

Josh Achiam, Steven Adler, Sandhini Agarwal, Lama Ahmad, Ilge Akkaya, Florencia Leoni Aleman, Diogo Almeida, Janko Altenschmidt, Sam Altman, Shyamal Anadkat, et al. Gpt-4 technical report. *arXiv preprint arXiv:2303.08774*, 2023. 1, 7, 21

Stavros P Adam, Stamatios-Aggelos N Alexandropoulos, Panos M Pardalos, and Michael N Vrahatis. No free lunch theorem: A review. *Approximation and optimization: Algorithms, complexity and applications*, pp. 57–82, 2019. 25

Jorge Aldaco, Travis Armstrong, Robert Baruch, Jeff Bingham, Sanky Chan, Kenneth Draper, Debidatta Dwibedi, Chelsea Finn, Pete Florence, Spencer Goodrich, et al. Aloha 2: An enhanced low-cost hardware for bimanual teleoperation. *arXiv preprint arXiv:2405.02292*, 2024. 3

Fabio Amadio, Adrià Colomé, and Carme Torras. Exploiting symmetries in reinforcement learning of bimanual robotic tasks. *IEEE Robotics and Automation Letters*, 4(2):1838–1845, 2019. 3

Fan Bao, Shen Nie, Kaiwen Xue, Yue Cao, Chongxuan Li, Hang Su, and Jun Zhu. All are worth words: A vit backbone for diffusion models. In *Proceedings of the IEEE/CVF conference on computer vision and pattern recognition*, pp. 22669–22679, 2023. 6, 19

Aleksandar Batinica, Bojan Nemec, Aleš Ude, Mirko Raković, and Andrej Gams. Compliant movement primitives in a bimanual setting. In *2017 IEEE-RAS 17th International Conference on Humanoid Robotics (Humanoids)*, pp. 365–371. IEEE, 2017. 3

Suneel Belkhale, Yuchen Cui, and Dorsa Sadigh. Hydra: Hybrid robot actions for imitation learning. *arxiv*, 2023. 22

Anthony Brohan, Noah Brown, Justice Carbajal, Yevgen Chebotar, Joseph Dabis, Chelsea Finn, Keerthana Gopalakrishnan, Karol Hausman, Alex Herzog, Jasmine Hsu, et al. Rt-1: Robotics transformer for real-world control at scale. *arXiv preprint arXiv:2212.06817*, 2022. 3, 19, 20, 22

Anthony Brohan, Noah Brown, Justice Carbajal, Yevgen Chebotar, Xi Chen, Krzysztof Choromanski, Tianli Ding, Danny Driess, Avinava Dubey, Chelsea Finn, et al. Rt-2: Vision-language-action models transfer web knowledge to robotic control. *arXiv preprint arXiv:2307.15818*, 2023. 1, 2, 3, 19

Tom Brown, Benjamin Mann, Nick Ryder, Melanie Subbiah, Jared D Kaplan, Prafulla Dhariwal, Arvind Neelakantan, Pranav Shyam, Girish Sastry, Amanda Askell, et al. Language models are few-shot learners. *Advances in neural information processing systems*, 33:1877–1901, 2020. 7

Lawrence Yunliang Chen, Simeon Adebola, and Ken Goldberg. Berkeley UR5 demonstration dataset. https://sites.google.com/view/berkeley-ur5/home. 22

Lili Chen, Shikhar Bahl, and Deepak Pathak. Playfusion: Skill acquisition via diffusion from language-annotated play. In *CoRL*, 2023. 22

Xin Chen, Aming Wu, and Yahong Han. Capturing the spatio-temporal continuity for video semantic segmentation. *IET Image Processing*, 13(14):2813–2820, 2019. 2, 5

Cheng Chi, Siyuan Feng, Yilun Du, Zhenjia Xu, Eric Cousineau, Benjamin Burchfiel, and Shuran Song. Diffusion policy: Visuomotor policy learning via action diffusion. In *Proceedings of Robotics: Science and Systems (RSS)*, 2023. 3, 5, 19, 21, 22

Rohan Chitnis, Shubham Tulsiani, Saurabh Gupta, and Abhinav Gupta. Efficient bimanual manipulation using learned task schemas. In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 1149–1155. IEEE, 2020. 3

Open X-Embodiment Collaboration, Abby O'Neill, Abdul Rehman, Abhiram Maddukuri, Abhishek Gupta, Abhishek Padalkar, Abraham Lee, Acorn Pooley, Agrim Gupta, Ajay Mandlekar, Ajinkya Jain, Albert Tung, Alex Bewley, Alex Herzog, Alex Irpan, Alexander Khazatsky, Anant Rai, Anchit Gupta, Andrew Wang, Andrey Kolobov, Anikait Singh, Animesh Garg, Aniruddha Kembhavi, Annie Xie, Anthony Brohan, Antonin Raffin, Archit Sharma, Arefeh Yavary, Arhan Jain, Ashwin Balakrishna, Ayzaan Wahid, Ben Burgess-Limerick, Beomjoon Kim, Bernhard Schölkopf, Blake Wulfe, Brian Ichter, Cewu Lu, Charles Xu, Charlotte Le, Chelsea Finn, Chen Wang, Chenfeng Xu, Cheng Chi, Chenguang Huang, Christine Chan, Christopher Agia, Chuer Pan, Chuyuan Fu, Coline Devin, Danfei Xu, Daniel Morton, Danny Driess, Daphne Chen, Deepak Pathak, Dhruv Shah, Dieter Büchler, Dinesh Jayaraman, Dmitry Kalashnikov, Dorsa Sadigh, Edward Johns, Ethan Foster, Fangchen Liu, Federico Ceola, Fei Xia, Feiyu Zhao, Felipe Vieira Frujeri, Freek Stulp, Gaoyue Zhou, Gaurav S. Sukhatme, Gautam Salhotra, Ge Yan, Gilbert Feng, Giulio Schiavi, Glen Berseth, Gregory Kahn, Guangwen Yang, Guanzhi Wang, Hao Su, Hao-Shu Fang, Haochen Shi, Henghui Bao, Heni Ben Amor, Henrik I Christensen, Hiroki Furuta, Homer Walke, Hongjie Fang, Huy Ha, Igor Mordatch, Ilija Radosavovic, Isabel Leal, Jacky Liang, Jad Abou-Chakra, Jaehyung Kim, Jaimyn Drake, Jan Peters, Jan Schneider, Jasmine Hsu, Jeannette Bohg, Jeffrey Bingham, Jeffrey Wu, Jensen Gao, Jiaheng Hu, Jiajun Wu, Jialin Wu, Jiankai Sun, Jianlan Luo, Jiayuan Gu, Jie Tan, Jihoon Oh, Jimmy Wu, Jingpei Lu, Jingyun Yang, Jitendra Malik, João Silvério, Joey Hejna, Jonathan Booher, Jonathan Tompson, Jonathan Yang, Jordi Salvador, Joseph J. Lim, Junhyek Han, Kaiyuan Wang, Kanishka Rao, Karl Pertsch, Karol Hausman, Keegan Go, Keerthana Gopalakrishnan, Ken Goldberg, Kendra Byrne, Kenneth Oslund, Kento Kawaharazuka, Kevin Black, Kevin Lin, Kevin Zhang, Kiana Ehsani, Kiran Lekkala, Kirsty Ellis, Krishan Rana, Krishnan Srinivasan, Kuan Fang, Kunal Pratap Singh, Kuo-Hao Zeng, Kyle Hatch, Kyle Hsu, Laurent Itti, Lawrence Yunliang Chen, Lerrel Pinto, Li Fei-Fei, Liam Tan, Linxi "Jim" Fan, Lionel Ott, Lisa Lee, Luca Weihs, Magnum Chen, Marion Lepert, Marius Memmel, Masayoshi Tomizuka, Masha Itkina,

Mateo Guaman Castro, Max Spero, Maximilian Du, Michael Ahn, Michael C. Yip, Mingtong Zhang, Mingyu Ding, Minho Heo, Mohan Kumar Srirama, Mohit Sharma, Moo Jin Kim, Naoaki Kanazawa, Nicklas Hansen, Nicolas Heess, Nikhil J Joshi, Niko Suenderhauf, Ning Liu, Norman Di Palo, Nur Muhammad Mahi Shafiullah, Oier Mees, Oliver Kroemer, Osbert Bastani, Pannag R Sanketi, Patrick "Tree" Miller, Patrick Yin, Paul Wohlhart, Peng Xu, Peter David Fagan, Peter Mitrano, Pierre Sermanet, Pieter Abbeel, Priya Sundaresan, Qiuyu Chen, Quan Vuong, Rafael Rafailov, Ran Tian, Ria Doshi, Roberto Mart'in-Mart'in, Rohan Baijal, Rosario Scalise, Rose Hendrix, Roy Lin, Runjia Qian, Ruohan Zhang, Russell Mendonca, Rutav Shah, Ryan Hoque, Ryan Julian, Samuel Bustamante, Sean Kirmani, Sergey Levine, Shan Lin, Sherry Moore, Shikhar Bahl, Shivin Dass, Shubham Sonawani, Shuran Song, Sichun Xu, Siddhant Haldar, Siddharth Karamcheti, Simeon Adebola, Simon Guist, Soroush Nasiriany, Stefan Schaal, Stefan Welker, Stephen Tian, Subramanian Ramamoorthy, Sudeep Dasari, Suneel Belkhale, Sungjae Park, Suraj Nair, Suvir Mirchandani, Takayuki Osa, Tanmay Gupta, Tatsuya Harada, Tatsuya Matsushima, Ted Xiao, Thomas Kollar, Tianhe Yu, Tianli Ding, Todor Davchev, Tony Z. Zhao, Travis Armstrong, Trevor Darrell, Trinity Chung, Vidhi Jain, Vincent Vanhoucke, Wei Zhan, Wenxuan Zhou, Wolfram Burgard, Xi Chen, Xiangyu Chen, Xiaolong Wang, Xinghao Zhu, Xinyang Geng, Xiyuan Liu, Xu Liangwei, Xuanlin Li, Yansong Pang, Yao Lu, Yecheng Jason Ma, Yejin Kim, Yevgen Chebotar, Yifan Zhou, Yifeng Zhu, Yilin Wu, Ying Xu, Yixuan Wang, Yonatan Bisk, Yongqiang Dou, Yoonyoung Cho, Youngwoon Lee, Yuchen Cui, Yue Cao, Yueh-Hua Wu, Yujin Tang, Yuke Zhu, Yunchu Zhang, Yunfan Jiang, Yunshuang Li, Yunzhu Li, Yusuke Iwasawa, Yutaka Matsuo, Zehan Ma, Zhuo Xu, Zichen Jeff Cui, Zichen Zhang, Zipeng Fu, and Zipeng Lin. Open X-Embodiment: Robotic learning datasets and RT-X models. https://arxiv.org/abs/2310.08864, 2023. 1, 2, 3, 4, 5, 21, 23

Adria Colomé and Carme Torras. Dimensionality reduction for dynamic movement primitives and application to bimanual manipulation of clothes. *IEEE Transactions on Robotics*, 34(3):602–615, 2018. 3

Adrià Colomé and Carme Torras. *Reinforcement learning of bimanual robot skills*. Springer, 2020. 3

Shivin Dass, Jullian Yapeter, Jesse Zhang, Jiahui Zhang, Karl Pertsch, Stefanos Nikolaidis, and Joseph J. Lim. Clvr jaco play dataset, 2023. URL https://github.com/clvrai/clvr_jaco_play_dataset. 22

Carlos Canudas de Wit, Bruno Siciliano, and Georges Bastin. *Theory of robot control*. Springer Science & Business Media, 2012. 2, 5, 7

Danny Driess, Fei Xia, Mehdi SM Sajjadi, Corey Lynch, Aakanksha Chowdhery, Brian Ichter, Ayzaan Wahid, Jonathan Tompson, Quan Vuong, Tianhe Yu, et al. Palm-e: An embodied multimodal language model. *arXiv preprint arXiv:2303.03378*, 2023. 3

Aaron Edsinger and Charles C Kemp. Two arms are better than one: A behavior based control system for assistive bimanual manipulation. In *Recent Progress in Robotics: Viable Robotic Service to Human: An Edition of the Selected Papers from the 13th International Conference on Advanced Robotics*, pp. 345–355. Springer, 2007. 1

Hao-Shu Fang, Hongjie Fang, Zhenyu Tang, Jirong Liu, Junbo Wang, Haoyi Zhu, and Cewu Lu. Rh20t: A robotic dataset for learning diverse skills in one-shot. In *RSS 2023 Workshop on Learning for Task and Motion Planning*, 2023. 2, 3, 20, 21, 22

Niko Sünderhauf Federico Ceola, Krishan Rana. Lhmanip: A dataset for long horizon manipulation tasks., 2023. 22

Yunhai Feng, Nicklas Hansen, Ziyan Xiong, Chandramouli Rajagopalan, and Xiaolong Wang. Finetuning offline world models in the real world. *arXiv preprint arXiv:2310.16029*, 2023. 22

Nadia Figueroa and Aude Billard. Learning complex manipulation tasks from heterogeneous and unstructured demonstrations. In *Proceedings of Workshop on Synergies between Learning and Interaction*, 2017. 3

Giovanni Franzese, Leandro de Souza Rosa, Tim Verburg, Luka Peternel, and Jens Kober. Interactive imitation learning of bimanual movement primitives. *IEEE/ASME Transactions on Mechatronics*, 2023. 1, 3

Zipeng Fu, Tony Z Zhao, and Chelsea Finn. Mobile aloha: Learning bimanual mobile manipulation with low-cost whole-body teleoperation. *arXiv preprint arXiv:2401.02117*, 2024. 3, 21, 22, 24, 25

Dibya Ghosh, Homer Walke, Karl Pertsch, Kevin Black, Oier Mees, Sudeep Dasari, Joey Hejna, Charles Xu, Jianlan Luo, et al. Octo: An open-source generalist robot policy, 2023. 2, 3, 4, 9, 21, 25

Jennifer Grannen, Yilin Wu, Suneel Belkhale, and Dorsa Sadigh. Learning bimanual scooping policies for food acquisition. In *Conference on Robot Learning*, pp. 1510–1519. PMLR, 2023a. 1, 4

Jennifer Grannen, Yilin Wu, Brandon Vu, and Dorsa Sadigh. Stabilize to act: Learning to coordinate for bimanual manipulation. In *Conference on Robot Learning*, pp. 563–576. PMLR, 2023b. 1, 3

Markus Grotz, Mohit Shridhar, Tamim Asfour, and Dieter Fox. Peract2: A perceiver actor framework for bimanual manipulation tasks. *arXiv preprint arXiv:2407.00278*, 2024. 1, 3

Jiayuan Gu, Fanbo Xiang, Xuanlin Li, Zhan Ling, Xiqiang Liu, Tongzhou Mu, Yihe Tang, Stone Tao, Xinyue Wei, Yunchao Yao, Xiaodi Yuan, Pengwei Xie, Zhiao Huang, Rui Chen, and Hao Su. Maniskill2: A unified benchmark for generalizable manipulation skills. In *International Conference on Learning Representations*, 2023. 22

Dan Hendrycks and Kevin Gimpel. Gaussian error linear units (gelus). *arXiv preprint arXiv:1606.08415*, 2016. 25

Alex Henry, Prudhvi Raj Dachapally, Shubham Pawar, and Yuxuan Chen. Query-key normalization for transformers. *arXiv preprint arXiv:2010.04245*, 2020. 6, 19

Minho Heo, Youngwoon Lee, Doohyun Lee, and Joseph J. Lim. Furniturebench: Reproducible real-world benchmark for long-horizon complex manipulation. In *Robotics: Science and Systems*, 2023. 22

Jonathan Ho, Ajay Jain, and Pieter Abbeel. Denoising diffusion probabilistic models. *Advances in neural information processing systems*, 33:6840–6851, 2020. 2, 3

Edward J Hu, Yelong Shen, Phillip Wallis, Zeyuan Allen-Zhu, Yuanzhi Li, Shean Wang, Lu Wang, and Weizhu Chen. Lora: Low-rank adaptation of large language models. *arXiv preprint arXiv:2106.09685*, 2021. 26

Nan Huang, Christian Kümmerle, and Xiang Zhang. Unitnorm: Rethinking normalization for transformers in time series. *arXiv preprint arXiv:2405.15903*, 2024. 6

Eric Jang, Alex Irpan, Mohi Khansari, Daniel Kappler, Frederik Ebert, Corey Lynch, Sergey Levine, and Chelsea Finn. BC-z: Zero-shot task generalization with robotic imitation learning. In *5th Annual Conference on Robot Learning*, 2021. URL https://openreview.net/forum?id=8kbp23tSGYv. 22

Xiaogang Jia, Denis Blessing, Xinkai Jiang, Moritz Reuss, Atalay Donat, Rudolf Lioutikov, and Gerhard Neumann. Towards diverse behaviors: A benchmark for imitation learning with human demonstrations. *arXiv preprint arXiv:2402.14606*, 2024. 1

Dmitry Kalashnikov, Alex Irpan, Peter Pastor, Julian Ibarz, Alexander Herzog, Eric Jang, Deirdre Quillen, Ethan Holly, Mrinal Kalakrishnan, Vincent Vanhoucke, et al. Qt-opt: Scalable deep reinforcement learning for vision-based robotic manipulation. *arXiv preprint arXiv:1806.10293*, 2018. 22

Alexander Khazatsky, Karl Pertsch, Suraj Nair, Ashwin Balakrishna, Sudeep Dasari, Siddharth Karamcheti, Soroush Nasiriany, Mohan Kumar Srirama, Lawrence Yunliang Chen, Kirsty Ellis, et al. Droid: A large-scale in-the-wild robot manipulation dataset. *arXiv preprint arXiv:2403.12945*, 2024. 20, 22

Minchan Kim, Junhyek Han, Jaehyung Kim, and Beomjoon Kim. Pre-and post-contact policy decomposition for non-prehensile manipulation with zero-shot sim-to-real transfer. 2023. 22

Moo Jin Kim, Karl Pertsch, Siddharth Karamcheti, Ted Xiao, Ashwin Balakrishna, Suraj Nair, Rafael Rafailov, Ethan Foster, Grace Lam, Pannag Sanketi, et al. Openvla: An open-source vision-language-action model. *arXiv preprint arXiv:2406.09246*, 2024. 1, 2, 3, 4, 9, 19, 25, 26

Alexander Kirillov, Eric Mintun, Nikhila Ravi, Hanzi Mao, Chloe Rolland, Laura Gustafson, Tete Xiao, Spencer Whitehead, Alexander C Berg, Wan-Yen Lo, et al. Segment anything. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pp. 4015–4026, 2023. 1

Basil Kouvaritakis and Mark Cannon. Model predictive control. *Switzerland: Springer International Publishing*, 38:13–56, 2016. 7

Franziska Krebs, Andre Meixner, Isabel Patzer, and Tamim Asfour. The kit bimanual manipulation dataset. In *2020 IEEE-RAS 20th International Conference on Humanoid Robots (Humanoids)*, pp. 499–506. IEEE, 2021. 1

Vikash Kumar, Rutav Shah, Gaoyue Zhou, Vincent Moens, Vittorio Caggiano, Abhishek Gupta, and Aravind Rajeswaran. Robohive: A unified framework for robot learning. *Advances in Neural Information Processing Systems*, 36, 2024. 2, 21, 22

Michelle A Lee, Yuke Zhu, Krishnan Srinivasan, Parth Shah, Silvio Savarese, Li Fei-Fei, Animesh Garg, and Jeannette Bohg. Making sense of vision and touch: Self-supervised learning of multimodal representations for contact-rich tasks. In *2019 IEEE International Conference on Robotics and Automation (ICRA)*, 2019. URL https://arxiv.org/abs/1810.10191. 22

Weiwei Li. *Optimal control for biological movement systems*. University of California, San Diego, 2006. 1

Hanwen Liang, Niamul Quader, Zhixiang Chi, Lizhe Chen, Peng Dai, Juwei Lu, and Yang Wang. Self-supervised spatiotemporal representation learning by exploiting video continuity. In *Proceedings of the AAAI Conference on Artificial Intelligence*, volume 36, pp. 1564–1573, 2022. 2, 5

Rudolf Lioutikov, Oliver Kroemer, Guilherme Maeda, and Jan Peters. Learning manipulation by sequencing motor primitives with a two-armed robot. In *Intelligent Autonomous Systems 13: Proceedings of the 13th International Conference IAS-13*, pp. 1601–1611. Springer, 2016. 3

Huihan Liu, Soroush Nasiriany, Lance Zhang, Zhiyao Bao, and Yuke Zhu. Robot learning on the job: Human-in-the-loop autonomy and learning during deployment. In *Robotics: Science and Systems (RSS)*, 2023. 22

I Liu, Chun Arthur, Sicheng He, Daniel Seita, and Gaurav Sukhatme. Voxact-b: Voxel-based acting and stabilizing policy for bimanual manipulation. *arXiv preprint arXiv:2407.04152*, 2024. 1, 3

Yingfei Liu, Tiancai Wang, Xiangyu Zhang, and Jian Sun. Petr: Position embedding transformation for multi-view 3d object detection. In *European Conference on Computer Vision*, pp. 531–548. Springer, 2022. 19

Cheng Lu, Yuhao Zhou, Fan Bao, Jianfei Chen, Chongxuan Li, and Jun Zhu. Dpm-solver++: Fast solver for guided sampling of diffusion probabilistic models. *arXiv preprint arXiv:2211.01095*, 2022. 8, 25

Jianlan Luo, Charles Xu, Xinyang Geng, Gilbert Feng, Kuan Fang, Liam Tan, Stefan Schaal, and Sergey Levine. Multi-stage cable routing through hierarchical imitation learning. *arXiv pre-print*, 2023. URL https://arxiv.org/abs/2307.08927. 22

Jianlan Luo, Charles Xu, Fangchen Liu, Liam Tan, Zipeng Lin, Jeffrey Wu, Pieter Abbeel, and Sergey Levine. Fmb: a functional manipulation benchmark for generalizable robotic learning, 2024. URL https://arxiv.org/abs/2401.08553. 22

Corey Lynch, Ayzaan Wahid, Jonathan Tompson, Tianli Ding, James Betker, Robert Baruch, Travis Armstrong, and Pete Florence. Interactive language: Talking to robots in real time, 2022. URL https://arxiv.org/abs/2210.06407. 22

Tatsuya Matsushima, Hiroki Furuta, Yusuke Iwasawa, and Yutaka Matsuo. Weblab xarm dataset, 2023. 22

Oier Mees, Lukas Hermann, Erick Rosete-Beas, and Wolfram Burgard. Calvin: A benchmark for language-conditioned policy learning for long-horizon robot manipulation tasks. *IEEE Robotics and Automation Letters (RA-L)*, 7(3):7327–7334, 2022. 22

Seyed Sina Mirrazavi Salehian, Nadia Barbara Figueroa Fernandez, and Aude Billard. Dynamical system-based motion planning for multi-arm systems: Reaching for moving objects. In *IJCAI'17: Proceedings of the 26th International Joint Conference on Artificial Intelligence*, pp. 4914–4918, 2017. 1, 4

Soroush Nasiriany, Tian Gao, Ajay Mandlekar, and Yuke Zhu. Learning and retrieval from prior data for skill-based imitation learning. In *Conference on Robot Learning (CoRL)*, 2022. 22

Alexander Quinn Nichol and Prafulla Dhariwal. Improved denoising diffusion probabilistic models. In *International conference on machine learning*, pp. 8162–8171. PMLR, 2021. 5

Jihoon Oh, Naoaki Kanazawa, and Kento Kawaharazuka. X-embodiment u-tokyo pr2 datasets, 2023. URL https://github.com/ojh6404/rlds_dataset_builder. 22

Takayuki Osa. Motion planning by learning the solution manifold in trajectory optimization. *The International Journal of Robotics Research*, 41(3):291–311, 2022. 22

Abhishek Padalkar, Gabriel Quere, Antonin Raffin, João Silvério, and Freek Stulp. A guided reinforcement learning approach using shared control templates for learning manipulation skills in the real world. *Research square preprint rs-3289569/v1*, 2023. 22

Sinno Jialin Pan and Qiang Yang. A survey on transfer learning. *IEEE Transactions on knowledge and data engineering*, 22(10):1345–1359, 2009. 2

Jyothish Pari, Nur Muhammad Shafiullah, Sridhar Pandian Arunachalam, and Lerrel Pinto. The surprising effectiveness of representation learning for visual imitation, 2021. 22

Adam Paszke, Sam Gross, Francisco Massa, Adam Lerer, James Bradbury, Gregory Chanan, Trevor Killeen, Zeming Lin, Natalia Gimelshein, Luca Antiga, et al. Pytorch: An imperative style, high-performance deep learning library. *Advances in neural information processing systems*, 32, 2019. 23

Tim Pearce, Tabish Rashid, Anssi Kanervisto, Dave Bignell, Mingfei Sun, Raluca Georgescu, Sergio Valcarcel Macua, Shan Zheng Tan, Ida Momennejad, Katja Hofmann, and Sam Devlin. Imitating human behaviour with diffusion models. In *The Eleventh International Conference on Learning Representations*, 2023. 3, 5

William Peebles and Saining Xie. Scalable diffusion models with transformers. In *Proceedings of the IEEE/CVF International Conference on Computer Vision*, pp. 4195–4205, 2023. 2, 6, 19

Alec Radford, Karthik Narasimhan, Tim Salimans, Ilya Sutskever, et al. Improving language understanding by generative pre-training. 2018. 4

Alec Radford, Jong Wook Kim, Chris Hallacy, Aditya Ramesh, Gabriel Goh, Sandhini Agarwal, Girish Sastry, Amanda Askell, Pamela Mishkin, Jack Clark, et al. Learning transferable visual models from natural language supervision. In *International conference on machine learning*, pp. 8748–8763. PMLR, 2021. 1

Ilija Radosavovic, Tete Xiao, Stephen James, Pieter Abbeel, Jitendra Malik, and Trevor Darrell. Real-world robot learning with masked visual pre-training. In *CoRL*, 2022. 22

Colin Raffel, Noam Shazeer, Adam Roberts, Katherine Lee, Sharan Narang, Michael Matena, Yanqi Zhou, Wei Li, and Peter J. Liu. Exploring the limits of transfer learning with a unified text-to-text transformer. *Journal of Machine Learning Research*, 21(140):1–67, 2020. URL http://jmlr.org/papers/v21/20-074.html. 6, 19, 25

Daniel Rakita, Bilge Mutlu, Michael Gleicher, and Laura M Hiatt. Shared control–based bimanual robot manipulation. *Science Robotics*, 4(30):eaaw0955, 2019. 1, 4

Jeff Rasley, Samyam Rajbhandari, Olatunji Ruwase, and Yuxiong He. Deepspeed: System optimizations enable training deep learning models with over 100 billion parameters. In *Proceedings of the 26th ACM SIGKDD International Conference on Knowledge Discovery & Data Mining*, pp. 3505–3506, 2020. 23

RethinkRobotics. Sawyer performing table top manipulation. https://github.com/RethinkRobotics/sawyer_robot. 22

Erick Rosete-Beas, Oier Mees, Gabriel Kalweit, Joschka Boedecker, and Wolfram Burgard. Latent plans for task agnostic offline reinforcement learning. 2022. 22

Stéphane Ross, Geoffrey Gordon, and Drew Bagnell. A reduction of imitation learning and structured prediction to no-regret online learning. In *Proceedings of the fourteenth international conference on artificial intelligence and statistics*, pp. 627–635. JMLR Workshop and Conference Proceedings, 2011. 19

Saumya Saxena, Mohit Sharma, and Oliver Kroemer. Multi-resolution sensing for real-time control with vision-language models. In *7th Annual Conference on Robot Learning*, 2023. URL https://openreview.net/forum?id=WuBv9-IGDUA. 22

Nur Muhammad Mahi Shafiullah, Anant Rai, Haritheja Etukuru, Yiqian Liu, Ishan Misra, Soumith Chintala, and Lerrel Pinto. On bringing robots home. *arXiv preprint arXiv:2311.16098*, 2023. 22

Dhruv Shah, Ajay Sridhar, Arjun Bhorkar, Noriaki Hirose, and Sergey Levine. Gnm: A general navigation model to drive any robot. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*, pp. 7226–7233. IEEE, 2023a. 2, 7

Rutav Shah, Roberto Martín-Martín, and Yuke Zhu. MUTEX: Learning unified policies from multimodal task specifications. In *7th Annual Conference on Robot Learning*, 2023b. URL https://openreview.net/forum?id=PwqiqaaEzJ. 22

Pratyusha Sharma, Lekha Mohan, Lerrel Pinto, and Abhinav Gupta. Multiple interactions made easy (mime): Large scale demonstrations data for imitation. In *Conference on robot learning*, pp. 906–915. PMLR, 2018. 1, 3

Haochen Shi, Huazhe Xu, Samuel Clarke, Yunzhu Li, and Jiajun Wu. Robocook: Long-horizon elasto-plastic object manipulation with diverse tools. *arXiv preprint arXiv:2306.14447*, 2023. 22

Christian Smith, Yiannis Karayiannidis, Lazaros Nalpantidis, Xavi Gratal, Peng Qi, Dimos V Dimarogonas, and Danica Kragic. Dual arm manipulation—a survey. *Robotics and Autonomous systems*, 60(10):1340–1353, 2012. 3

Kihyuk Sohn, Honglak Lee, and Xinchen Yan. Learning structured output representation using deep conditional generative models. *Advances in neural information processing systems*, 28, 2015. 2

Simon Stepputtis, Joseph Campbell, Mariano Phielipp, Stefan Lee, Chitta Baral, and Heni Ben Amor. Language-conditioned imitation learning for robot manipulation tasks. *Advances in Neural Information Processing Systems*, 33:13139–13150, 2020. 3

Simon Stepputtis, Maryam Bandari, Stefan Schaal, and Heni Ben Amor. A system for imitation learning of contact-rich bimanual manipulation policies. In *2022 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pp. 11810–11817. IEEE, 2022. 3

Matthew Tancik, Pratul Srinivasan, Ben Mildenhall, Sara Fridovich-Keil, Nithin Raghavan, Utkarsh Singhal, Ravi Ramamoorthi, Jonathan Barron, and Ren Ng. Fourier features let networks learn high frequency functions in low dimensional domains. *Advances in neural information processing systems*, 33:7537–7547, 2020. 6

Hugo Touvron, Thibaut Lavril, Gautier Izacard, Xavier Martinet, Marie-Anne Lachaux, Timothée Lacroix, Baptiste Rozière, Naman Goyal, Eric Hambro, Faisal Azhar, et al. Llama: Open and efficient foundation language models. *arXiv preprint arXiv:2302.13971*, 2023. 1, 7

Homer Walke, Kevin Black, Abraham Lee, Moo Jin Kim, Max Du, Chongyi Zheng, Tony Zhao, Philippe Hansen-Estruch, Quan Vuong, Andre He, Vivek Myers, Kuan Fang, Chelsea Finn, and Sergey Levine. Bridgedata v2: A dataset for robot learning at scale. In *Conference on Robot Learning (CoRL)*, 2023. 2, 21, 22

Zhiqiang Wang, Hao Zheng, Yunshuang Nie, Wenjun Xu, Qingwei Wang, Hua Ye, Zhe Li, Kaidong Zhang, Xuewen Cheng, Wanxi Dong, et al. All robots in one: A new standard and unified dataset for versatile, general-purpose embodied agents. *arXiv preprint arXiv:2408.10899*, 2024. 21

Lingxuan Wu, Xiao Yang, Yinpeng Dong, Liuwei Xie, Hang Su, and Jun Zhu. Embodied active defense: Leveraging recurrent feedback to counter adversarial patches. *arXiv preprint arXiv:2404.00540*, 2024. 21

Fan Xie, Alexander Chowdhury, M De Paolis Kaluza, Linfeng Zhao, Lawson Wong, and Rose Yu. Deep imitation learning for bimanual robotic manipulation. *Advances in neural information processing systems*, 33:2327–2337, 2020. 3

Ge Yan, Kris Wu, and Xiaolong Wang. ucsd kitchens Dataset. August 2023. 22

Jonathan Yang, Dorsa Sadigh, and Chelsea Finn. Polybot: Training one policy across robots while embracing variability. *arXiv preprint arXiv:2307.03719*, 2023. 4

Jonathan Yang, Catherine Glossop, Arjun Bhorkar, Dhruv Shah, Quan Vuong, Chelsea Finn, Dorsa Sadigh, and Sergey Levine. Pushing the limits of cross-embodiment learning for manipulation and navigation. *arXiv preprint arXiv:2402.19432*, 2024. 5

Xiaohua Zhai, Basil Mustafa, Alexander Kolesnikov, and Lucas Beyer. Sigmoid loss for language image pre-training, 2023. 6, 19, 25

Biao Zhang and Rico Sennrich. Root mean square layer normalization. *Advances in Neural Information Processing Systems*, 32, 2019. 6, 19

Tony Z Zhao, Vikash Kumar, Sergey Levine, and Chelsea Finn. Learning fine-grained bimanual manipulation with low-cost hardware. *arXiv preprint arXiv:2304.13705*, 2023. 1, 2, 3, 5, 9, 19, 21, 22, 25

Gaoyue Zhou, Victoria Dean, Mohan Kumar Srirama, Aravind Rajeswaran, Jyothish Pari, Kyle Hatch, Aryan Jain, Tianhe Yu, Pieter Abbeel, Lerrel Pinto, Chelsea Finn, and Abhinav Gupta. Train offline, test online: A real robot learning benchmark. In *2023 IEEE International Conference on Robotics and Automation (ICRA)*, 2023. 22

Yi Zhou, Connelly Barnes, Jingwan Lu, Jimei Yang, and Hao Li. On the continuity of rotation representations in neural networks. In *2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, pp. 5738–5746, 2019. doi: 10.1109/CVPR.2019.00589. 21

Xinghao Zhu, Ran Tian, Chenfeng Xu, Mingyu Ding, Wei Zhan, and Masayoshi Tomizuka. Fanuc manipulation: A dataset for learning-based manipulation with fanuc mate 200id robot. 2023. 22

Yifeng Zhu, Abhishek Joshi, Peter Stone, and Yuke Zhu. Viola: Imitation learning for vision-based manipulation with object proposal priors. *6th Annual Conference on Robot Learning (CoRL)*, 2022a. 22

Yifeng Zhu, Peter Stone, and Yuke Zhu. Bottom-up skill discovery from unsegmented demonstrations for long-horizon robot manipulation. *IEEE Robotics and Automation Letters*, 7(2):4126–4133, 2022b. 22

Daniel M Ziegler, Nisan Stiennon, Jeffrey Wu, Tom B Brown, Alec Radford, Dario Amodei, Paul Christiano, and Geoffrey Irving. Fine-tuning language models from human preferences. *arXiv preprint arXiv:1909.08593*, 2019. 7

R Zollner, Tamim Asfour, and Rüdiger Dillmann. Programming by demonstration: dual-arm manipulation tasks for humanoid robots. In *2004 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)(IEEE Cat. No. 04CH37566)*, volume 1, pp. 479–484. IEEE, 2004. 3