

Ag2x2: Robust Agent-Agnostic Visual Representations for Zero-Shot Bimanual Manipulation

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<https://ziyin-xiong.github.io/ag2x2.github.io/>



Fig. 1: **Ag2x2** enables zero-shot acquisition of bimanual manipulation skills without relying on expert demonstrations or engineered rewards. The framework operates in two key stages: (left) learning coordination-aware visual representations directly from human manipulation videos (shown in sequential frames of cooking with highlighted hand) while preserving critical hand position data despite domain differences; and (right) leveraging these representations to acquire diverse bimanual manipulation skills in simulation autonomously, demonstrated through multiple Franka robot arms performing sequential steps of various tasks including cabinet opening (top row), door manipulation (middle row), and rope handling (bottom row).

Abstract—Bimanual manipulation, fundamental to human daily activities, remains a challenging task due to its inherent complexity of coordinated control. Recent advances have enabled zero-shot learning of single-arm manipulation skills through agent-agnostic visual representations derived from human videos; however, these methods overlook crucial agent-specific information necessary for bimanual coordination, such as end-effector positions. We propose **Ag2x2**, a computational framework for bimanual manipulation through coordination-aware visual representations that jointly encode object states and hand motion patterns while maintaining agent-agnosticism. Extensive experiments demonstrate that **Ag2x2** achieves a 73.5% success rate across 13 diverse bimanual tasks from Bi-DexHands and PerAct², including challenging scenarios with deformable objects like ropes. This performance outperforms baseline methods and even surpasses the success rate of policies trained with expert-engineered rewards. Furthermore, we show that representations learned through **Ag2x2** can be effectively leveraged for imitation learning, establishing a scalable pipeline for skill acquisition without expert supervision. By maintaining robust performance across diverse tasks without human

demonstrations or engineered rewards, **Ag2x2** represents a step toward scalable learning of complex bimanual robotic skills.

I. INTRODUCTION

Robotic manipulation today struggles with a fundamental skill that humans take for granted—using our two hands together. While we naturally coordinate our hands to cook, fold laundry, or tie shoelaces, autonomous acquisition of such bimanual manipulation skills remains a major challenge in robotics. This challenge primarily stems from two critical limitations: the dependence on human expertise for supervision and achieving precise bimanual coordination.

Current approaches to bimanual manipulation create a fundamental bottleneck in scaling robotic capabilities due to their reliance on expert input. Reinforcement Learning (RL) methods such as Bi-DexHands [1] demonstrate impressive dexterity but depend on carefully engineered, task-specific rewards that rarely generalize across different tasks or embodiments. Similarly, while imitation learning approaches [2–4] have shown promise when learning from teleoperation [5, 6] and visual demonstrations [7–9], collecting demonstrations for bimanual tasks is exceptionally time-consuming and resource-intensive, limiting scalability.

Recent advances in single-arm manipulation [10–12] offer valuable insights for addressing these challenges by demonstrating that time-contrastive visual representations learned from existing unstructured human videos can effectively guide robotic policy learning. Human videos provide rich task-completion insights that align well with robotic objectives, making them a feasible training source. However, enabling robots to learn directly from human-centric data

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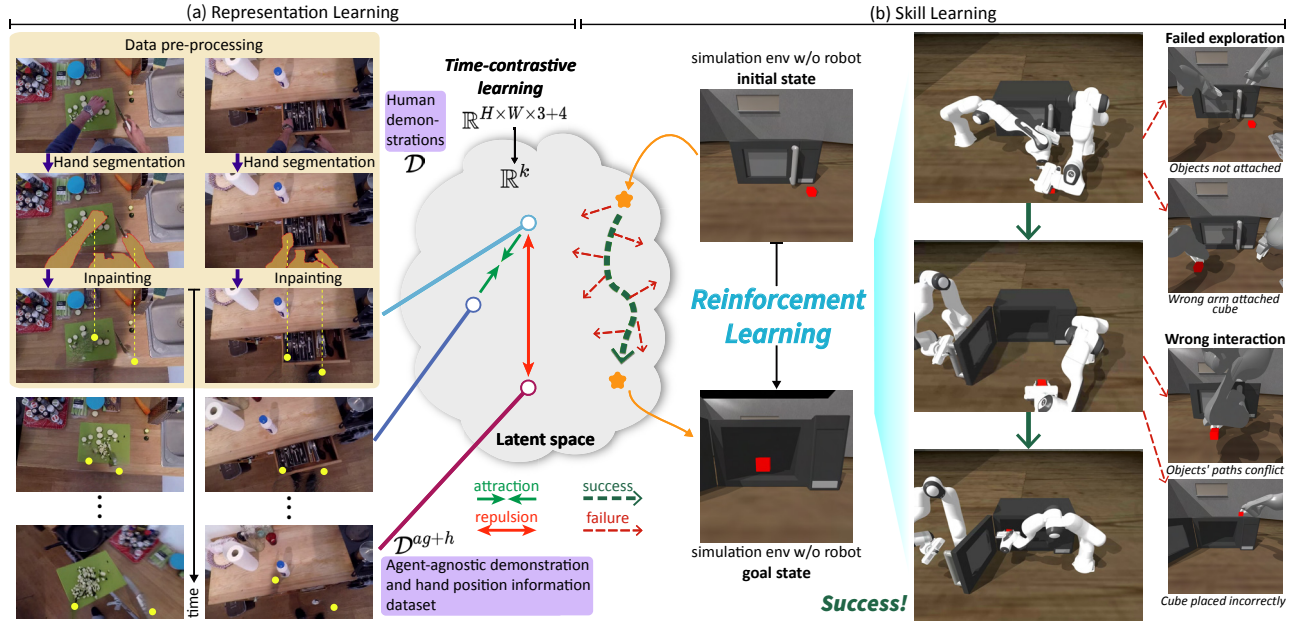


Fig. 2: **Framework of Ag2x2.** Our approach consists of two main components: (a) Representation Learning via time-contrastive learning on agent-agnostic human demonstrations with preserved hand position information, visualized through sequential cooking frames with erased hands but highlighted hand positions; and (b) Skill Learning through RL with agent-agnostic action representations, illustrated by a robot learning to place a cube into a microwave, progressing from failed attempts to successful execution.

requires bridging the domain gap between human and robot embodiments. While some approaches [10, 11] struggle with bias from human kinematic structures, Ag2Manip [12] attempted to solve this by masking regions occupied by humans, focusing exclusively on encoding object movements. This approach, however, eliminates all embodiment information, making it inherently unsuitable for bimanual tasks where spatial and temporal hand coordination is critical—such as transferring objects into initially closed containers. Extending these methods to bimanual manipulation thus necessitates a representation that captures both object progression and the crucial patterns of hand coordination.

To address these limitations, we present Ag2x2, a scalable framework that advances bimanual manipulation skill acquisition through coordination-aware visual representations that jointly encode object states and hand motion patterns while maintaining agent-agnosticism. Through extensive experiments across 13 diverse tasks from Bi-DexHands [1] and PerAct² [13], Ag2x2 achieves a 73.5% success rate, significantly outperforming baseline autonomous methods and even surpassing policies trained with expert-engineered rewards. Particularly noteworthy is Ag2x2’s proficiency in traditionally challenging scenarios for robotics, such as manipulating deformable objects like ropes. Furthermore, we demonstrate that the skills acquired through Ag2x2 can serve as high-quality training data for imitation learning, establishing an efficient pipeline for scalable robotic skill acquisition without expert supervision. By autonomously generating large-scale manipulation data while maintaining robust performance across diverse tasks, Ag2x2 represents a significant step toward reducing reliance on costly human demonstrations and carefully engineered rewards, thus enabling more scalable approaches to robotic learning.

II. RELATED WORKS

Bimanual Manipulation: Bimanual manipulation represents a fundamental leap in complexity beyond single-arm tasks, requiring sophisticated coordination and planning capabilities [9, 14–16]. Current research approaches can be categorized into three distinct paradigms, each with inherent limitations for scalable deployment.

Demonstration-based learning approaches have yielded promising results but face significant scaling barriers. While behavior cloning methods [5, 6] offer framework flexibility across diverse scenarios, and structured representations like those in Bi-KVIL [8] and PerAct² [13] enhance generalization, they all share a common bottleneck: dependence on extensive expert demonstrations. This requirement creates substantial data collection costs that limit real-world applicability. Even systems like 2HandedAfforder [17], which extract bimanual affordances from egocentric human videos, remain constrained to passive extraction without developing coordination-aware policies.

RL approaches [1, 18] circumvent the need for demonstrations but introduce a different yet equally problematic dependency: task-specific reward engineering. These carefully designed rewards require significant expert knowledge to develop and frequently fail to generalize beyond their target scenarios, creating another scalability barrier.

Hybrid methods [19–21] attempt to address limitations of both paradigms but typically remain restricted to narrow task domains (*e.g.*, screw manipulation) or still require substantial expert input. This persistent reliance on human expertise—whether for demonstrations, reward engineering, or task specification—represents the critical obstacle preventing bimanual manipulation from achieving true scalability and generalization across diverse tasks.

Representation Learning for Manipulation: Visual representation learning for robotics has evolved along two complementary trajectories, each with distinct advantages and limitations for bimanual applications.

Task-specific approaches leverage techniques such as contrastive learning [22] and state prediction [23] to extract targeted features. While effective in structured environments with clear objectives, these methods struggle with cross-task generalization and typically demand substantial task-specific training data. Related techniques focusing on policy-representation decoupling [24] or robotic priors [25] enhance performance in narrowly defined tasks but face similar generalization challenges across diverse manipulation scenarios.

General-purpose methods offer broader applicability through pre-trained visual representations [26] and frameworks like RRL [27]. These approaches have demonstrated impressive transferability in single-arm contexts, with recent works [28, 29] validating their effectiveness. Human video-based representations like R3M [11], VIP [10], and Ag2Manip [12] further leverage everyday human activities to learn generalizable manipulation features. However, when applied to bimanual tasks, these methods reveal fundamental limitations: they either focus exclusively on single-arm scenarios, treat hands as independent agents without modeling their coordination, or fail to capture the crucial spatial relationships necessary for effective bimanual manipulation.

Our work addresses this critical gap by introducing a coordination-aware representation framework specifically engineered for bimanual tasks. Unlike existing approaches that either demand task-specific data or neglect coordination information, our method simultaneously captures object state dynamics and hand-hand interactions while maintaining agent-agnosticism. This representation enables autonomous skill acquisition without expert demonstrations or engineered rewards, while preserving the essential spatial and temporal relationships that underpin successful bimanual coordination.

III. METHOD

Our framework, Ag2x2, enables learning of bimanual manipulation skills without expert supervision. As illustrated in Fig. 2, Ag2x2 operates through two core components: (i) a novel representation learning approach that preserves hand coordination information from human videos, and (ii) a reward-shaping mechanism that leverages these representations to guide autonomous skill acquisition through RL.

A. From Single-Arm to Bimanual Representations

Bimanual manipulation fundamentally differs from single-arm tasks by requiring coordinated action between two effectors. While recent work has made progress in learning manipulation from human videos, these approaches face significant limitations when extended to bimanual scenarios.

The agent-agnostic approach introduced in Li *et al.* [12] demonstrated that removing human presence from demonstration videos could facilitate learning transferable manipulation skills. This method processes human demonstration videos $\mathcal{D} = \{v^c := (o_1^c, o_2^c, \dots, o_{n_c}^c)\}_{c=1}^N$ by completely

masking human regions to create agent-agnostic data \mathcal{D}^{ag} . A visual encoder $\mathcal{F}_\phi: \mathbb{R}^{H \times W \times 3} \rightarrow \mathbb{R}^K$ then learns time-contrastive embeddings through:

$$\mathcal{L} = \mathbb{E}_{o_i^c, o_j^c, o_k^c, o_l^c \sim \mathcal{D}^{ag}} \mathcal{L}_{\text{tcn}} + \mathbb{E}_{o \sim \mathcal{D}^{ag}} \mathcal{L}_{\text{reg}}. \quad (1)$$

This objective combines temporal contrastive learning $\mathcal{L}_{\text{tcn}} = -\log \frac{e^{S(z_i^c, z_j^c)}}{e^{S(z_i^c, z_j^c)} + e^{S(z_i^c, z_k^c)} + e^{S(z_i^c, z_l^c)}}$ with regularization $\mathcal{L}_{\text{reg}} = \|\mathcal{F}_\phi(o)\|_1 + \|\mathcal{F}_\phi(o)\|_2$ to learn transferable object-centric features.

However, this approach creates a critical gap for bimanual manipulation: by removing all human presence, it eliminates essential information about spatial relationships between hands—information that is fundamental to coordination tasks like transferring objects between hands or manipulating articulated objects with synchronized movements. While focusing solely on environmental changes was sufficient for single-arm tasks, bimanual manipulation requires understanding both object state progression and the relative positioning of the manipulation agents.

Our key insight is that effective bimanual manipulation requires preserving specific coordination information while still maintaining agent-agnosticism. Rather than completely removing human presence, Ag2x2 selectively retains critical positional information about hand interactions while abstracting away human-specific kinematics and appearance details that would limit transfer to robotic systems.

B. Coordination-Aware Visual Representation

Our visual encoder \mathcal{F}_ϕ extends Ag2Manip’s architecture to jointly encode visual information and hand positions. Specifically, $\mathcal{F}_\phi: \mathbb{R}^{H \times W \times 3+4} \rightarrow \mathbb{R}^K$ maps the concatenation of an RGB image and the 2D coordinates of both hands to a K -dimensional latent embedding, enabling explicit spatial reasoning for bimanual coordination.

The encoder training follows a two-stage approach. First, we fine-tune a ViT-Large model [30] pre-trained on ImageNet-21k [31] using inpainted images as the only input, employing LoRA [32] to maintain pre-trained knowledge while enabling efficient adaptation. Second, we incorporate hand position information by introducing specialized position tokens. We encode each hand’s 2D position through a two-layer MLP with hidden dimensions [16, 32] and ReLU activation, generating position-encoded tokens that are concatenated with the image tokens. For occluded or out-of-frame hands, we utilize hand-specific learnable variables. Both stages optimize the time-contrastive objective defined in Eq. (1), applied to our enhanced dataset \mathcal{D}^{ag+h} .

We derive this hand-aware agent-agnostic dataset \mathcal{D}^{ag+h} from EpicKitchen [33], an extensive collection of ego-centric videos capturing household tasks. Our processing pipeline detects hand poses using the HaMeR model [34] modified with a YOLO-v5 [35] backbone for improved efficiency, projects 3D key points to 2D coordinates using estimated camera poses, computes each hand’s position as the mean of its 21 key points, and generates agent-agnostic frames through ODISE [36] segmentation followed by E²FGVI [37]

inpainting. The resulting dataset comprises frames $o_i^c \in \mathbb{R}^{H \times W \times 3+4}$ that combine processed RGB images with corresponding hand coordinates.

C. Policy Learning and Reward Shaping

We extend agent-agnostic action representation to bimanual manipulation by learning coordinated motions and forces for two free-floating proxy agents, subsequently using inverse kinematics to convert these proxy trajectories into robot joint commands. For effective grasping, we first identify feasible graspable poses for target objects using GraspNet [38]. Each end-effector is represented as an agent-agnostic sphere, with a grasp considered valid when the proxy’s distance from the pose is less than 5cm, indicating successful attachment.

With these graspable regions established, we define our policy learning objective. Given a goal specification $g \in \mathbb{R}^{H \times W \times 3+4}$, comprising both an image of the goal state and 2D projections of desired end-effector positions in camera space, we employ model-free RL to obtain an action policy π that maps proxy states p_t and environment states s_t to actions $a_t = (a_p^t, a_f^t)$. Here, $a_p^t \in \mathbb{R}^6$ specifies target positions for both proxies during exploration, while $a_f^t \in \mathbb{R}^6$ defines their intended forces during interaction. A PD controller translates these target actions into actual proxy movements.

Our reward function is designed to maximize embedding similarity between current state o_t and goal state g while promoting effective exploration. Rather than penalizing deviations from a single optimal trajectory, we introduce a tilted reward formulation:

$$\mathcal{R}(o_t, g; \phi) = \exp((1 + \alpha \cdot \mathbf{1}_{S(z_t, z_g) > \beta}) \frac{S(z_t, z_g) - \beta}{\beta}) - 1, \quad (2)$$

where $\beta = S(z_0, z_g)$ denotes the initial embedding similarity between start and goal states, and $\alpha > 0$ controls reward scaling. This approach improves upon traditional similarity-based rewards by requiring states to exceed the initial condition rather than merely maximizing consecutive improvements, facilitating more effective exploration during early training when policy behavior is predominantly stochastic.

D. Implementation Details

Our implementation consists of two key components: the visual encoder architecture and the policy learning framework. For the visual encoder, we process images resized to $224 \times 224 \times 3$ dimensions and implement LoRA with rank $r = 4$ for the query and value matrices in all self-attention layers. The encoder training proceeds sequentially: first, the visual adaptation phase runs for 40 hours on 4 NVIDIA A100 GPUs using Adam optimization with a learning rate of 10^{-4} , followed by the hand-position integration phase requiring 20 hours on 8 NVIDIA A100 GPUs.

For the RL component, we employ Proximal Policy Optimization (PPO) [39] to train our bimanual manipulation policy. The proxy agents are configured with a sphere collision radius of 2cm and an interactive region radius of 5cm. Based on ablation studies, we set the reward scaling parameter $\alpha = 3.0$. Each manipulation skill requires approximately 3 hours of training on a single NVIDIA 3090 workstation.

IV. EXPERIMENTS

We evaluate Ag2x2’s effectiveness in bimanual manipulation through extensive experiments across diverse manipulation scenarios. Our approach achieves a 73.5% average success rate across 13 challenging tasks requiring coordinated two-handed interaction, significantly outperforming existing autonomous methods and policies trained with expert-designed rewards. This section details our experimental setup (Sec. IV-A), presents quantitative performance results (Sec. IV-B), analyzes key design choices through ablation studies (Sec. IV-C), and provides additional experimental insights (Sec. IV-E).

A. Experimental Setup

Task Selection: We curated 13 diverse bimanual manipulation tasks from two established benchmarks: 6 tasks from Bi-DexHands [1] and 7 from PerAct² [13]. We selected tasks based on two criteria: compatibility with gripper-based manipulation and single-stage structure to ensure well-defined goal specifications. Multi-stage tasks were excluded as they require intermediate goal definitions beyond our current framework.

Implementation: All experiments use two 9-DoF Franka Emika robotic arms with integrated grippers (each with 7 arm joints and 2 gripper fingers), simulated in NVIDIA IsaacGym to leverage its GPU acceleration capabilities for efficient reinforcement learning. For Bi-DexHands tasks, we directly utilized existing object assets. For PerAct² tasks, originally implemented in CoppeliaSim, we converted assets from *.ttm* to *.urdf* and *.dae* formats for IsaacGym compatibility. When direct asset migration was not possible, we substituted comparable alternatives to maintain task integrity.

Evaluation Protocol: Each task begins with the robotic arms in predefined positions, with goals specified by images capturing the target state from one of three camera angles (center, up, down). A task is considered successful when objects reach the goal configuration within an acceptable error margin. To ensure robust evaluation, we test each task under nine different configurations by combining three initialization seeds with three camera perspectives. All evaluated models were trained with 68 parallel environments over 200 episodes per task.

Comparison to Benchmarks: Unlike PerAct², our approach does not require expert-designed waypoints to guide end-effectors through specific intermediate targets, relying only on the final position information. Despite this reduced guidance, Ag2x2 achieves significantly higher success rates on most PerAct² tasks than those reported in the original benchmark [13], demonstrating its superior robustness and adaptability to complex bimanual manipulation scenarios.

B. Experimental Results

Baselines: We benchmark Ag2x2 against leading approaches in zero-shot skill learning, including agent-aware visual representations (R3M [11] and VIP [10]), agent-agnostic representation (Ag2Manip [12]), and LLM-driven autonomous reward generation (Eureka [40]). For Eureka,

we disable human feedback to evaluate solely the method’s intrinsic learning capabilities without task-specific expert knowledge. Our strongest baseline uses expert-designed rewards that directly minimize distances between key object poses and goal states.

Performance Analysis: As shown in Tab. I, Ag2x2 achieves a 73.5% average success rate across all tasks, substantially outperforming Ag2Manip (56.4%) and even expert-designed rewards (63.2%). This improvement is particularly notable given that Ag2x2 requires no manual reward engineering or task-specific demonstrations.

Method performance varies significantly across tasks. Agent-aware representations (R3M, VIP) consistently underperform due to the visual and kinematic gap between humans and robots. Ag2Manip, while effective for single-handed tasks, struggles with bimanual coordination in scenarios like box pushing and tray lifting. Eureka performs well only on tasks with easily describable goal states (closing scissors, pressing buttons) but falters on more complex interactions. Expert-designed rewards show strong performance on most tasks but fail in scenarios requiring temporal coordination between hands and objects, such as (h) *put cubes into drawer*, (j) *lift tray*, and (l) *sweep dirt*.

Ag2x2 demonstrates remarkable consistency across diverse manipulation challenges. It successfully learns 12 of 13 tasks, with only (i) *put cube into microwave* falling below 50% success rate. Most impressively, it masters deformable

TABLE I: Comparison and ablation results. Success rates across 13 bimanual manipulation tasks from two benchmarks. Success counts range from 0-9, representing successful attempts out of 9 evaluation runs. **Methods compared:** R3M, VIP, and Ag2Manip are visual representation approaches; Eureka uses LLM-generated rewards without human feedback; expert reward employs manually-designed reward functions minimizing distance between object poses and goal states; Ag2x2-H is our ablation that excludes hand-related features from reward computation; Ag2x2 is our full model with hand feature integration. **Evaluation protocols:** Our method and its ablation, R3M, VIP, and Ag2Manip were evaluated using 3 seeds \times 3 camera views; Eureka using 3 seeds \times 3 different generated reward functions; and expert reward using 9 different seeds. **Tasks include:** From Bi-DexHands (a-f): close door outward, close door inward, open pen cap, lift pot, swing cup, close scissors; From PerAct² (g-m): push box, put cube into drawer, put cube into microwave, lift tray, press buttons, sweep dirt, straighten rope.

Method	Bi-DexHands							PerAct ²							Overall	
	a	b	c	d	e	f	Avg.	g	h	i	j	k	l	m		Avg.
Eureka [40]	0	0	0	2	1	5	14.8%	0	1	0	0	7	2	0	15.9%	15.4%
R3M [11]	0	0	3	0	1	0	7.4%	2	0	4	2	3	3	0	22.2%	15.4%
VIP [10]	1	3	1	7	2	0	25.9%	0	0	4	5	5	3	0	27.0%	26.5%
Ag2Manip [12]	6	9	7	4	3	7	66.7%	2	3	3	3	9	6	4	47.6%	56.4%
expert reward	8	9	6	6	8	9	85.2%	5	0	6	3	5	3	6	44.4%	63.2%
Ag2x2-H	7	4	7	7	4	9	70.4%	<u>5</u>	4	3	<u>5</u>	<u>8</u>	3	3	46.0%	57.3%
Ag2x2	<u>7</u>	<u>6</u>	9	8	<u>7</u>	9	85.2%	6	5	2	7	9	6	<u>5</u>	63.5%	73.5%

object manipulation ((m) *straighten rope*) without specialized rewards or demonstrations, suggesting broader applicability to complex household tasks like laundry organization. Fig. 3 illustrates successful trajectories from representative tasks.

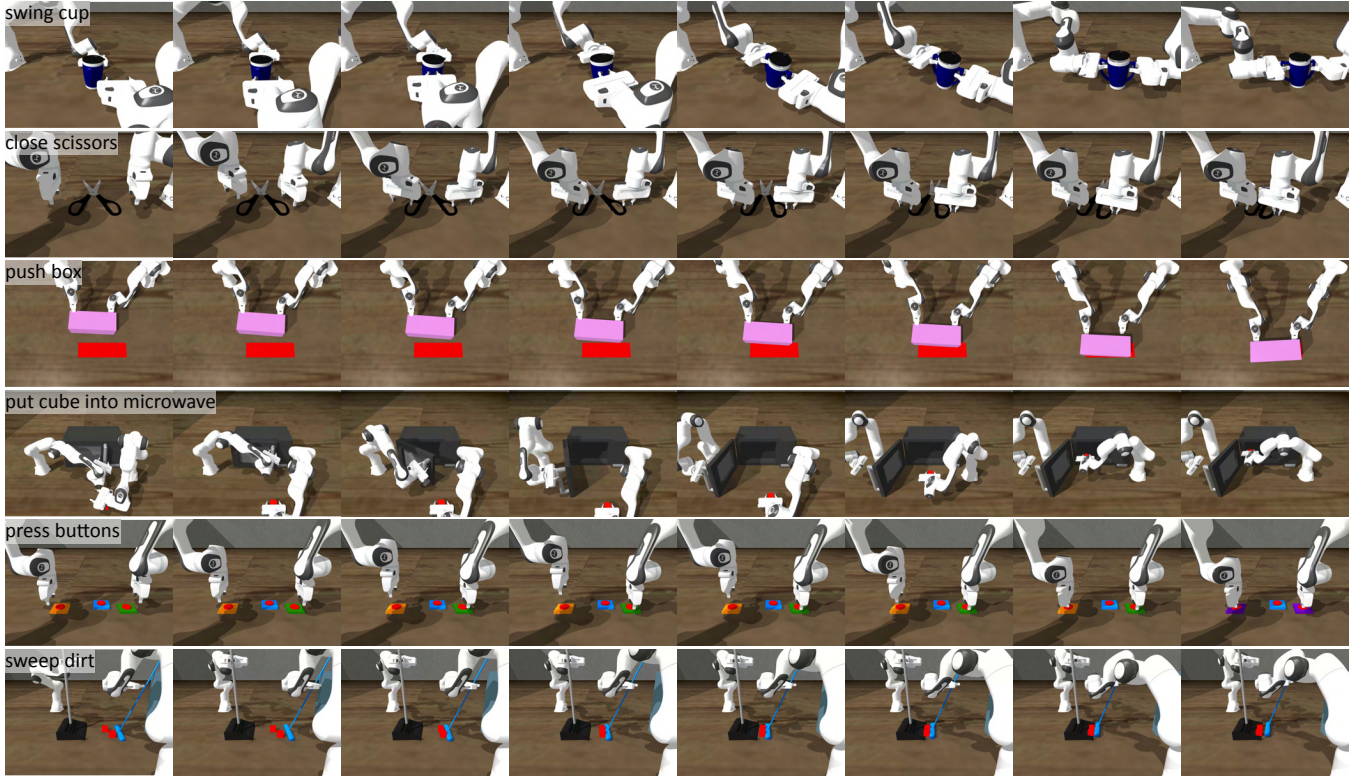


Fig. 3: Qualitative results of bimanual manipulation. Temporal sequences showing successful task execution by our learned policies across six representative tasks: swinging a cup, closing scissors, pushing a box, placing a cube into a microwave, pressing buttons, and sweeping dirt. Each row presents the progression of a single task from left to right. Our method generates coordinated trajectories for both end-effectors, which are converted to joint commands for the two Franka arms through inverse kinematics. Note the synchronized bimanual coordination required across diverse manipulation scenarios, from precise interactions (scissors, buttons) to force-sensitive operations (pushing box, sweeping).

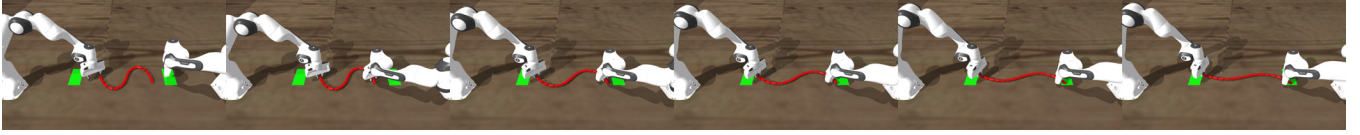


Fig. 4: **Generalization of learned manipulation skills through imitation policy rollout.** This sequence demonstrates an imitation policy successfully straightening a rope from an unseen initial configuration. The policy was trained on just 12 expert trajectories generated by Ag2x2 and successfully transfers to novel states. Images progress from left to right, showing coordinated bimanual manipulation that adapts to the deformable object’s changing state.

TABLE II: **Trajectory smoothness analysis.** Lower values indicate smoother movements with reduced end-effector acceleration throughout task execution. All values represent cumulative acceleration magnitude of both end-effectors across successful task completions only, proportional to m/s^2 by a factor of 36. Dashes (-) indicate methods that failed all evaluation runs for that task. For detailed descriptions of all methods (VIP, Ag2Manip, expert reward, Ag2x2-H, and Ag2x2), refer to Tab. I. Tasks correspond to those listed in Tab. I.

Method	Bi-DexHands						PerAct ²								Avg.
	a	b	c	d	e	f	g	h	i	j	k	l	m		
VIP [10]	2.38	2.11	1.24	1.97	1.85	-	-	-	2.03	1.69	0.56	0.37	-	1.58	
Ag2Manip [12]	1.62	1.62	1.35	1.46	1.60	0.45	1.74	3.98	1.77	1.11	0.48	0.38	0.61	1.36	
expert reward	1.70	1.68	1.15	1.00	1.06	0.70	0.58	-	1.99	1.64	0.49	0.39	0.95	1.11	
Ag2x2-H	1.65	1.79	1.10	1.04	1.66	0.75	0.67	1.37	1.50	1.43	0.59	1.30	1.13	1.23	
Ag2x2	1.62	1.70	1.04	1.53	1.61	0.70	0.48	1.13	2.00	1.24	0.54	0.36	1.04	<u>1.15</u>	

Failure Case Analysis: We identify two primary failure patterns for future improvements. First, object interference significantly impacts performance in container-based tasks like (h) *put cube into drawer* and (i) *put cube into microwave*. In these scenarios, the visual salience of container movements overshadows object placement and hand motion, leading to suboptimal reward and reduced accuracy. Second, imperfect bimanual coordination occasionally emerges in challenging scenarios. In (b) *close door inward*, failures often occur when one hand closes the door prematurely before the other hand positions correctly. Similarly, in (m) *straighten rope*, a common failure pattern involves one hand reaching the target position while the other misses by small margins.

These observations suggest future work should focus on enhancing feature selection mechanisms for bimanual coordination and developing more sophisticated attention frameworks for multi-object interactions.

C. Ablation

To understand the impact of hand position information on bimanual coordination, we conducted an ablation study. In Tab. I, we present “Ag2x2-H” (without hands), which learns directly from videos where human hands have been inpainted without hand position tokens provided to the model.

This ablation reveals three significant findings. First, removing hand position information causes a consistent 16.2% performance drop across our task suite, highlighting this feature’s critical role in facilitating precise bimanual coordination. Second, performance across tasks remains generally consistent with one notable exception: the microwave cube placement task (i) shows improved performance in the ablated model. This counter-intuitive result occurs because the container’s state changes visually dominate this task, overshadowing both hand positioning and object motion signals in reward computation. Third, our ablated model performs similarly to Ag2Manip despite architectural differences, confirming that Ag2x2’s superior performance stems

primarily from the incorporation of hand positioning rather than from switching from ResNet to ViT backbone.

Despite removing hand position information, our ablated model still outperforms most baseline methods and approaches the effectiveness of expert-designed rewards. This suggests our core architectural design remains robust even without explicit hand positioning cues, while still demonstrating that hand positioning substantially enhances performance for complex bimanual tasks.

D. Imitation Learning

Using Ag2x2, we collected 12 demonstration trajectories of rope straightening across various initial configurations. From these demonstrations, we trained an imitation learning policy that successfully generalizes to novel rope configurations. Figure 4 illustrates the learned policy performing on an unseen scenario where the rope’s bending direction is reversed from training examples. This ability to quickly collect high-quality demonstration data and learn generalizable policies highlights Ag2x2’s potential for scaling up bimanual manipulation data collection, addressing a critical bottleneck in robot learning.

E. Additional Analysis

We examine trajectory characteristics, reward quality, and proprioception to provide deeper insights into Ag2x2’s performance advantages.

Trajectory smoothness: We quantify motion efficiency through cumulative end-effector acceleration:

$$\gamma_s = \sum_{t=2}^T \|\alpha_t^L\|_2 + \|\alpha_t^R\|_2, \quad (3)$$

where α_t^L, α_t^R denote the acceleration of left and right end-effectors at time t . Lower γ_s values indicate smoother trajectories with fewer abrupt velocity changes. As shown in Tab. II, Ag2x2 generates trajectories with smoothness comparable to expert-designed rewards and significantly better

TABLE III: **Task progress consistency analysis.** Higher values indicate more direct, monotonic progress toward the goal state. Values represent Spearman Rank Correlation between temporal frame sequence and visual similarity to the final goal state, measuring how consistently the agent progresses toward task completion. Positive values near 1.0 indicate steady progress, while values near 0 or negative suggest inefficient paths with unnecessary motions or regressions. Dashes (-) indicate methods that failed all evaluation runs for that task. For detailed descriptions of all methods and tasks, refer to [Tab. I](#).

Method	Bi-DexHands						PerAct ²								Avg.
	a	b	c	d	e	f	g	h	i	j	k	l	m		
VIP [10]	.724	.900	.021	.136	-.154	-	-	-	.699	-.247	-.249	.056	-	.210	
Ag2Manip [12]	.797	.851	.692	.302	.719	.398	.942	.025	.784	.405	-.244	-.092	.974	.504	
Ag2x2-H	.824	.820	.789	.094	.288	.669	.908	.106	.719	.575	-.223	.136	.981	<u>.514</u>	
Ag2x2	.822	.812	.685	.192	.517	.804	.920	.018	.712	.364	-.185	.077	.963	.516	

TABLE IV: **Impact of proprioception on performance.** Success rates when explicitly incorporating proprioceptive information (end-effector positions) in policy training. Success counts range from 0-9, representing successful attempts out of 9 evaluation runs (3 seeds \times 3 camera views). All three methods use the same visual backbone but differ in their use of proprioceptive signals: Ag2Manip with limited proprioception, Ag2x2-H with partial integration, and Ag2x2 with our complete proprioceptive integration approach. For detailed task descriptions, refer to [Tab. I](#).

Method	Bi-DexHands							PerAct ²								Overall
	a	b	c	d	e	f	Avg.	g	h	i	j	k	l	m	Avg.	
Ag2Manip [12]	6	9	5	4	5	8	68.5%	2	1	2	2	9	5	5	41.3%	53.8%
Ag2x2-H	7	8	5	6	3	9	70.4%	3	0	6	3	8	4	5	46.0%	57.3%
Ag2x2	7	9	9	7	7	9	88.9%	5	2	4	3	9	5	5	52.4%	69.2%

than the highest-performing baseline methods, demonstrating the advantage of coordination-aware representations in generating stable end-effector motions.

Reward Consistency: To evaluate how well our visual representations align with task progress, we use Spearman Rank Correlation [41] to measure the relationship between temporal sequence and goal-state similarity. [Table III](#) shows Ag2x2 achieves superior correlation compared to baselines, indicating more consistent task progression representation.

Our analysis also reveals an important limitation of correlation metrics for certain tasks. For instance, the button-pressing task (*k*) shows a negative correlation despite achieving a 100% success rate. This occurs because discrete state changes (button color transitions) create discontinuities in the visual representation space that don’t align with steady progress measurement.

Proprioception: To determine whether Ag2x2’s gains stem from hand information during pre-training or proprioception (specifically, end-effector positions) during policy learning, we conducted a controlled experiment. We compared three models (Ag2Manip, Ag2x2, and Ag2x2-H), adding a reward term to explicitly include proprioception by encouraging end-effector alignment with target positions. As shown in [Tab. IV](#), the performance differences between models with proprioception remain consistent with our main results in [Tab. I](#). This confirms that Ag2x2’s advantages primarily stem from incorporating hand information during pre-training rather than from proprioceptive signals during policy learning.

V. CONCLUSION

We introduced Ag2x2, a framework addressing zero-shot bimanual manipulation through coordination-aware visual representations. By simultaneously encoding environmental state and hand positions, Ag2x2 achieves a 73.5% success rate across 13 complex bimanual tasks, significantly

outperforming baselines and matching expert-designed policies. Our approach demonstrates particular strength with deformable object manipulation and supports effective imitation learning, establishing a foundation for scalable robotic manipulation.

Limitations: Our method is constrained by its representation of goals as single static images with end-effector positions. Without intermediate trajectory states, Ag2x2 cannot support tasks where intermediate dynamics are essential. For example, when tasked with “throw a ball into a bin” with only the final goal image showing the ball in the bin, the system would attempt to directly place rather than throw the ball. Similarly, tasks with unobservable dynamics (like turning on a microwave without visual feedback on its internal state) remain challenging. While a high-level planner generating intermediate visual and kinematic steps could address some issues, fundamental limitations remain.

Additionally, our current approach only models end-effector positions, limiting applications to simple grippers rather than complex hands with articulated fingers. Extending Ag2x2 to dexterous manipulation would require substantial work in understanding intricate finger coordination beyond our current scope. Nevertheless, we believe our approach of using representations pre-trained on readily available human videos provides a promising foundation for improving learning efficiency even for more complex manipulation tasks.

Implications: Ag2x2 enables autonomous generation of high-quality demonstrations, reducing reliance on human-generated data in robotic training. This creates opportunities for accelerating robotic learning across diverse environments. By enabling autonomous learning of complex bimanual manipulation, our work advances generalizable robot capabilities for sophisticated physical interactions. The demonstrated success suggests coordination-aware visual representations offer a promising direction for robot manipulation.

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