DexUMI: Using Human Hand as the Universal Manipulation Interface for Dexterous Manipulation

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***Abstract*—We present DexUMI - a data collection and policy learning framework that uses the human hand as the natural interface to transfer dexterous manipulation skills to various robot hands. DexUMI includes hardware and software adaptations to minimize the embodiment gap between the human hand and various robot hands. The hardware adaptation bridges the kinematics gap using a wearable hand exoskeleton. It allows direct haptic feedback in manipulation data collection and adapts human motion to feasible robot hand motion. The software adaptation bridges the visual gap by replacing the human hand in video data with high-fidelity robot hand inpainting. We demonstrate DexUMI's capabilities through comprehensive real-world experiments on two different dexterous robot hand hardware platforms, achieving an average task success rate of 86%.**

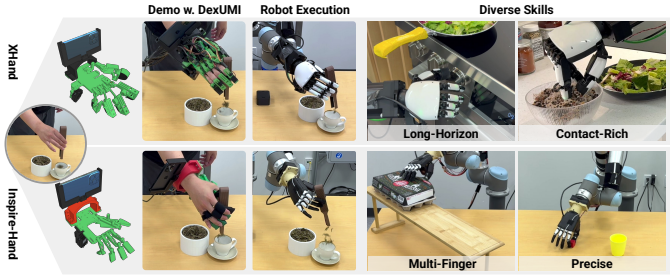

Fig. 1: **DexUMI** transfer dexterous human manipulation skills to various robot hand by using wearable exoskeletons and a data processing framework. We demonstrate DexUMI's capability and effectiveness on both underactuated (e.g., Inspire) and fully-actuated (e.g., XHand) robot hand for a wide variety of manipulation tasks.

I. Introduction

Human hands are incredibly dexterous in a wide range of tasks. Dexterous robot hands are designed with the hope of replicating this capability. However, it remains a significant challenge to transfer skills from human hands to robotic counterparts due to their substantial *embodiment gap*. This gap manifests in various forms, such as differences in kinematic structures, contact surface shape, available tactile information, and visual appearance.

What further complicates this challenge is the diversity of dexterous hand hardware designs available today. Each robotic hand presents different engineering trade-offs in degrees of freedom, motor ranges, actuation mechanisms, and overall dimensions. The solution for reducing the embodiment gap must handle the vast hardware design space. Teleoperation has become a popular manipulation interface for dexterous hands. However, teleoperation can be difficult due to the spatial observation mismatch and the lack of direct haptic feedback. These problems do not exist when human hand can perform the manipulation task directly. In other words, human hand itself is a better manipulation interface. In this paper, we ask the following question: How can we minimize the embodiment gap, so that we can use the human hand as the universal manipulation interface for diverse robot hands? To answer this question, we propose **DexUMI**, a framework with hardware and software adaptation components that is designed to minimize the action and observation gaps.

The **hardware adaptation** takes the form of a wearable hand exoskeleton. A user can directly collect manipulation data while wearing it. The exoskeleton is designed for each target robot hand through *a hardware optimization framework* that refines exoskeleton parameters (e.g., link lengths) to closely match the robot finger trajectories while maintaining wearability for the human hand. The hardware adaption provides the following benefits:

- **Intuitive demonstration with direct haptic feedback:** Unlike teleoperation systems, the wearable exoskeleton has no spatial mismatch and allows users to directly contact objects during manipulation, making the demonstration intuitive and doable without a robot.
- **Records feasible motion for the robot hand:** The exoskeleton constrains human hand motions to match the kinematics of the target hand, ensuring the recorded motion is transferable.
- **Capturing precise joint action:** Unlike retargeting methods, our exoskeleton reads precise joint angles directly from encoders, eliminating inaccuracies due to visual fingertip tracking.
- **Matching tactile information for learning:** Most handheld grippers for data collection [10, 42, 55] do not record the tactile information. Our design includes additional tactile sensors on the fingertip to record the same tactile info as what the robot hand would record.

Our **software adaptation** takes the form of a data processing pipeline that bridges the visual observation gap between human demonstration and robot deployment. This processing pipeline first removes the human hand and exoskeleton from the demonstration video using video segmentation, then

inpaints the video with the corresponding robot hand and environment backgrounds that match the target action. This adaptation ensures visual input consistency between training and robot deployment, despite visual differences between human and robotic hands.

With both hardware and software adaptation layers, DexUMI allows us to collect data on various tasks with minimal kinematic and visual gaps then transfer skills to robots. Comprehensive real-world experiments demonstrate DexUMI's capability on two different dexterous hand types: a 6-DoF Inspire hand [16] and a 12-DoF XHand [17]. Our approach achieves 3.2 times greater data collection efficiency compared to teleoperation and an average success rate of 86% across four tasks , including long-horizon and complex tasks requiring multi-finger contacts.

II. Related Work

Although extensive work has studied how to enable learning in simulated environments [3, 33, 61, 57, 39, 65, 22, 1, 24, 68, 30, 27, 45, 58, 38], we focus on reviewing real world data collection methods.

Teleoperation: Teleoperation is a popular interface for dexterous manipulation. Hand control is achieved with motion capture gloves [72, 56, 35, 53, 69], virtual-reality devices [26, 12, 9], or camera-based tracking [28, 66, 48, 21, 5, 23, 46]. Most approaches employ optimization-based retargeting to map human fingertips to robot hand. While being adaptable to different robot platforms, retargeting struggles with fundamental morphological differences between human and robot hands, especially the thumb flexibility [4]. Recent work by Zhou et al. [73] introduced a hand exoskeleton for direct joint mapping, but the mechanical structural differences limit the mapping accuracy. Additionally, teleoperation or kinesthetic teaching [25] require the robot hardware to be present, limiting the flexibility of data collection. In contrast, DexUMI collects manipulation data without physical robots.

Human hand video: Learning manipulation skills from human hand video is an attractive direction. Prior works have explored learning affordance [29, 40, 63, 15] or extracting human and object pose [43, 8, 41, 67, 47] from video. Though showing promising results, many of these works either require additional real-world robot data or need to learn the policy in simulation and depend on privileged information, such as object pose, to deploy the policy in the real world.

Wearable devices: Another line of work focuses on designing wearable devices for data collection, such as portable handheld grippers [59, 10, 20, 70, 13, 44, 52, 54, 42, 55, 32, 34, 37]. These approaches have demonstrated promising results in scaling real-robot manipulation skills. However, these systems primarily target simple parallel/pinch grippers and cannot be easily adapted to multi-fingered systems. Alternatively, Dexcap [60] uses motion capture gloves for in-contact data collection. However, it still relies on retargeting methods and human-correction data through teleportation. In contrast, our method eliminates these requirement, enabling direct policy deployment with data collected through DexUMI. Recently,

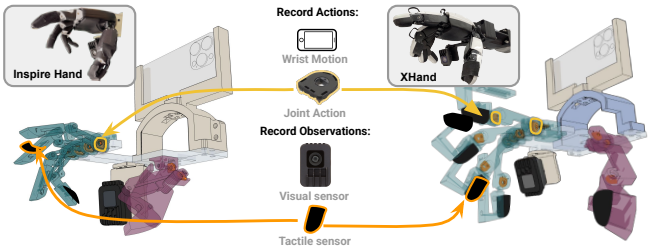

Fig. 2: **Exoskeleton Design.** The optimized exoskeleton design shares the same joint-to-fingertip position mapping as the target robot hand while maintaining the wearability. The exoskeletons utilizes the encoder to precisely capture the joint action and 150° DFoV camera to record the information-rich visual observation. An iPhone is rigidly mounted to track the wrist pose through the ARKit.

Wei and Xu [62] and Fang et al. [14] proposed hand-over-hand systems for dexterous hands. These works require the actual robot hand to be available and lifted by the human hand.

III. Hardware Adaptation to Bridge the Embodiment Gap

This section introduces our hardware adaptation, which is a wearable exoskeleton design that adapts human motion to feasible robot actions. While the final exoskeleton design is robot-specific, the principles of the design framework can be shared. We introduce the design framework in two parts: mechanism design optimization (§III-A) and sensor integration (§III-B).

A. Exoskeleton Mechanism Design

Modern robot hands often closely mimic human hands anatomically, meaning that a hand exoskeleton would compete for space with the human hand wearing it. The biggest challenge is for the thumb, whose pronation–supination movement can sweep a large volume and cause significant collision between the human thumb and a naively designed exoskeleton. Our exoskeleton design has two goals to achieve:

1) *Shared joint-action mapping:* The exoskeleton and the target robot hand must share the same joint-to-fingertip position mapping, including their limits, so the action can transfer.
2) *Wearability:* The exoskeleton must allow sufficient natural movements of the user's hand.

While the first goal can be mathematically defined, the wearability goal is hard to write down concretely. Our solution is to parameterize the exoskeleton design and formulate the wearability requirements as constraints on the design parameters, then find a solution that accommodates wearability while preserving kinematic relationships by solving an optimization. To make the optimization feasible, we prioritize the exact kinematics of fingertip links, while allowing greater flexibility in the kinematics of links less likely to contact objects.

E.1 Design initialization: We initialize the design with parameterized robot hand models based on URDF files (See Fig. 3). When such detailed designs are unavailable (e.g., the Inspire-Hand's finger mechanisms), we substitute them with equivalent general linkage designs with the same DoFs (e.g.,

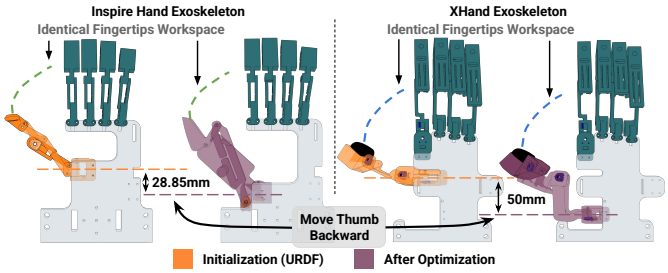

Fig. 3: **Mechanism Optimization.** To avoid thumb collision between human hand and exoskeleton, the hardware optimization step allows us to move the exoskeleton thumb backward while still preserving the original fingertip and joint mapping in SE(3) space.

a four-bar linkage) and allow optimization to find parameters that best match the observed kinematic behavior. Please see Appendix for details.

E.2 Bi-level optimization objective: Our optimization objective maximizes the following similarity: $\max_{\mathbf{p}} \mathcal{S}(\mathcal{W}^{\text{tip}}_{\text{exo}}(\mathbf{p}), \mathcal{W}^{\text{tip}}_{\text{robot}})$, where $\mathcal{W}^{\text{tip}}_{\text{exo}}$ and $\mathcal{W}^{\text{tip}}_{\text{robot}}$ represent the fingertip workspaces (set of all possible fingertip pose in SE(3)) for the exoskeleton and robot hand, respectively. $\mathbf{p} = \{j_1, ..., j_n, l_1, ..., l_m\}$ is the exoskeleton design parameters including joint positions $j_i \in \mathbb{R}^3$ in the wrist coordinate (i.e., flange) and linkage lengths l_j. The function $\mathcal{S}(\cdot, \cdot)$ represents a similarity metric between the two workspaces, which quantifies how closely the exoskeleton's fingertip pose distribution matches that of the robot hand. In practice, the $\mathcal{S}(\cdot, \cdot)$ is implemented as minimization by sampling configurations from both workspaces. Given a set of K robot hand configurations $\theta_{\text{robot},k}$ and N exoskeleton configurations $\theta_{\text{exo},n}$:

$$\begin{aligned}
&\mathcal{S}(\mathcal{W}^{\text{tip}}_{\text{exo}}(\mathbf{p}), \mathcal{W}^{\text{tip}}_{\text{robot}}) = \\
&\quad - \Bigg(\sum_{k=1}^{K} \min_{\boldsymbol{\theta}_{\text{exo}}} \|\mathcal{F}^{\text{tip}}_{\text{exo}}(\mathbf{p}, \boldsymbol{\theta}_{\text{exo}}) - \mathcal{F}^{\text{tip}}_{\text{robot}}(\boldsymbol{\theta}_{\text{robot},k})\|^2 \\
&\quad + \sum_{n=1}^{N} \min_{\boldsymbol{\theta}_{\text{robot}}} \|\mathcal{F}^{\text{tip}}_{\text{exo}}(\mathbf{p}, \boldsymbol{\theta}_{\text{exo},n}) - \mathcal{F}^{\text{tip}}_{\text{robot}}(\boldsymbol{\theta}_{\text{robot}})\|^2 \Bigg) \qquad (1)
\end{aligned}$$

where $\mathcal{F}^{\text{tip}}_{\text{exo}}$ and $\mathcal{F}^{\text{tip}}_{\text{robot}}$ are the forward kinematics for the exoskeleton and robot hand respectively. Optimizing the first term encourages the exoskeleton to cover the robot hand's workspace by finding exoskeleton configurations closest to the sampled robot hand configurations. The second term requires $\mathcal{W}^{\text{tip}}_{\text{exo}}(\mathbf{p}) \subseteq \mathcal{W}^{\text{tip}}_{\text{robot}}$, ensuring the exoskeleton's fingertip workspace remains within the robot hand's capabilities, preventing generation of unreachable poses outside the robot hand's workspace.

E.3 Constraints: We apply bound constraints $j_i \in \mathcal{C}_i$ and $l_j^{\min} \leq l_j \leq l_j^{\max}$, which are empirically selected to ensure that the exoskeleton can be comfortably worn. For example, we want to move the thumb swing joint closer to the wrist along the x-axis under MANO [51] convention to avoid collision between the human thumb's pronation–supination movement and that of the exoskeleton.

B. Sensor Integration

Sensors on the exoskeleton need to satisfy the following design objectives:

1) *Capture sufficient information:* the sensors need to capture ALL the information necessary for policy learning, which includes: robot action such as joint angle (*S.1*) and wrist motion (*S.2*), as well as observations in both vision (*S.3*) and tactile (*S.4*).
2) *Minimize embodiment gap:* the sensory information should have minimal distribution shift between human demonstration and robot deployment.

S.1 Joint capture & mapping. To precisely capture joint actions, our exoskeleton integrates joint encoders at every *actuated* joint – using resistive position encoders for both the XHand and Inspire-hand. We choose the `Alps` encoder [2] for its size and precision. Due to the joint friction and motor backlash, the mapping between exoskeleton joint encoder θ^i_{exo} and robot hand motor $\mathcal{M}^i_{\text{robot}}$ values is often non-linear, therefore, we train a simple regression model for each joint to obtain this mapping. To calibrate the regression model, we collect a set of paired data by uniformly sampling K motor values on the physical robot for each finger and then find the corresponding exoskeleton joint value by overlaying the visual observation between the robot hand and exoskeleton. This process creates a paired dataset for us to train the regression model.

S.2 Wrist pose tracking. We use iPhone ARKit to capture the 6DoF wrist pose, as smartphones represent the most accessible devices capable of providing precise spatial tracking. This tracking device is only needed for data collection, not for robot deployment.

S.3 Visual observation. We mounted a 150° diagonal field of view (DFoV) wide-angle camera `OAK-1` [19] under the wrist for both the exoskeleton and the target robot dexterous hand. This positioning was chosen to effectively capture hand-object interactions. Critically, the camera poses in the wrist frame were identical for the exoskeleton and the robot hand, which maintains visual consistency between training and deployment.

S.4 Tactile sensing. The wearable exoskeleton allows users to directly contact objects and receive haptic feedback. However, this human haptic feedback cannot be directly transferred to the robotic dexterous hand. Therefore, we install tactile sensors on the exoskeleton to capture and translate these tactile interactions. To ensure consistent sensor readings, we install the same type of tactile sensors on the exoskeleton as those used on the target robot hand. For XHand, we use the electro-magnetic tactile sensor that comes with the hand. For the Inspire-Hand, we install the same resistive tactile sensor `Force Sensitive Resistor` [18] for both the exoskeleton and the robot hand.

IV. Software Adaptation to Bridge the Visual Gap

Fig. 4 shows the visual gap between human demonstration (a) and robot deployment (h). To bridge this visual gap, we developed a data processing pipeline to adapt the demonstration image into what the robot will see as if the robot hand was collecting data. This adaptation uses off-the-shelf pretrained

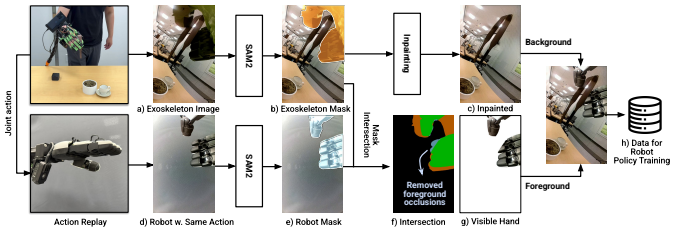

Fig. 4: **Bridging the Visual Gap.** To convert the visual observation into policy training data, we first segment the exoskeleton using SAM2 (b) and inpaint the missing background (c). The corresponding joint action (a) is replayed on the dexterous hand to obtain the robot hand image (d). SAM2 is applied to obtain the robot mask (e). The intersection (f) of the exoskeleton mask (b) and robot mask (e) identifies the visible part of the hand during interaction. Finally, we replace pixels in the inpainted background (c) with the visible robot hand (g).

models to ensure generalizability. The adaptation takes four steps:

V.1 Segment human hand and exoskeleton. Firstly, we segment (Fig. 4b) the human hand and exoskeleton on observation videos using SAM2 [49]. Since SAM2 requires initial prompt points, we established a protocol where the human operator always begins with the same hand gesture, allowing us to reuse the same prompt points for all demonstrations.

V.2 Inpaint environment background. With segmentation, we remove the human hand and the exoskeleton pixels from the image data. Then we use ProPainter [74], a flow-based inpainting method, to fully refill (Fig. 4c) the missing areas [6, 31, 7].

V.3 Record corresponding robot hand video. Next, to render robot hand properly into the video, we replay the recorded joint action on the robot hand and record another video with only the robot hand (Fig. 4d). This step does not involve the robot arm. We then used SAM2 again to extract the robot hand pixels (Fig. 4e) and discard the background. Notice, it is possible to train an image generation model to output the robot hand image based on the actions, but it requires additional model training.

V.4 Compose robot demonstrations. The last step is to merge the inpainted-background-only video with robot-hand-only video. It is crucial to maintain proper occlusion relationships: the robot hand does not always appear on top. We developed an occlusion-aware compositing approach leveraging: (1) our consistent under-wrist camera setup, and (2) the kinematic and shape similarity between the exoskeleton and robot hand. We compute a visible mask (Fig. 4f) by intersecting the exoskeleton mask and robot hand mask. Rather than naively overwriting pixels, we selectively replace pixels in the inpainted observation with robot hand pixels only if those pixels are present in the visible mask. This preserved natural occlusion relationships between the hand and objects when viewed from our under-wrist camera perspective. This approach generated visually coherent robot manipulation demonstrations that maintained proper spatial relationships.

Imitation learning. Our imitation learning policy $p(\mathbf{a_t}|o_t, f_t)$ takes processed visual observation o_t and tactile sensing f_t as input. The output is a sequence of actions $\{a_t, \ldots, a_{t+L}\}$ of length L, starting from the current time t, denoted as $\mathbf{a_t}$. The robot action a_t includes a 6-DOF end-effector action and N-DOF hand action where N depends on the specific robot hand hardware.

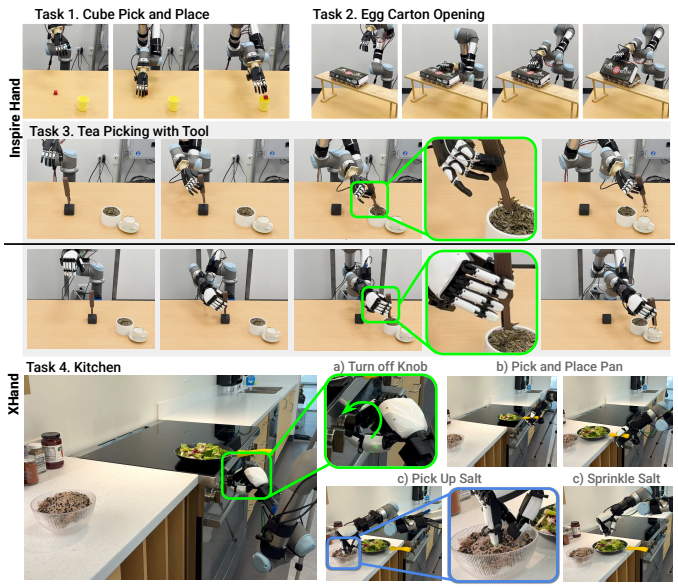

Fig. 5: **Policy Rollout:** We evaluate DexUMI's capabilities across challenging real-world tasks. The **Cube** task tests basic picking precision. The **Egg Carton** task evaluates multi-finger coordination. The **Tea Picking** task assesses performance on contact-rich manipulation requiring millimeter-level fine-grained fingertip actions. Finally, the **Kitchen** task tests capabilities on long-horizon high-precision actions to manipulate a knob, move a pan using both the side of thumb and index finger (beyond just fingertips), and utilize tactile sensing for visually challenging salt picking tasks.

V. Evaluation

Target robot hands: We evaluate DexUMI across two different robot hands:

- *Inspire Hand (IHand):* A twelve-DoF (six active DoFs) underactuated hand. The thumb has two active and two passive DoFs, while each remaining finger has one active and one passive DoF.
- *XHand:* A fully-actuated hand with twelve active DoFs. The thumb contains three DoFs, the index finger has three DoFs, and each of the remaining fingers has two DoFs.

Tasks: We evaluate DexUMI across four different real-world tasks:

- **Cube** [IHand]: Pick up a 2.5cm wide cube from a table and place it into a cup. This evaluates the basic capabilities and precision of the DexUMI system.
- **Egg Carton** [IHand]: Open an egg carton with multiple fingers: the hand needs the index, middle, ring, and little fingers to apply downward pressure on the carton's top while simultaneously using the thumb to lift the front latch.
- **Tea** [IHand & XHand]: Grasp tweezers from the table and use them to transfer tea leaves from a teapot to a cup. The main challenge is to stably operate the deformable tweezers with multi-finger contacts.

Method			Inspire Hand			
Action	Tactile	Visual	Cube	Carton	Tea tool	Tea leaf
Rel	Yes	Inpaint	**1.00**	0.85	**1.00**	0.85
Abs	Yes	Inpaint	0.10	0.35	0.80	0.00
Rel	No	Inpaint	0.95	**0.90**	**1.00**	**0.90**
Abs	No	Inpaint	0.90	0.85	0.90	0.60
Rel	No	Mask	0.60	0.10	0.90	0.50
Rel	No	Raw	0.20	0.05	0.85	0.05

TABLE I: **Evaluation Results (Inspire Hand).** Stage-wise accumulated success rates for different combinations of finger action representation (Absolute vs Relative), tactile feedback (Yes vs No), and visual rendering approaches (Inpaint vs Mask/Raw).

Method			XHand				
Action	Tactile	Visual	Tea tool	Tea leaf	Kitchen knob	Kitchen pan	Kitchen salt
Rel	Yes	Inpaint	**1.00**	**0.85**	**0.95**	**0.95**	**0.75**
Abs	Yes	Inpaint	**1.00**	0.25	0.50	0.45	0.00
Rel	No	Inpaint	0.95	0.80	**0.95**	**0.95**	0.15
Abs	No	Inpaint	**1.00**	0.75	0.60	0.60	0.0
Rel	No	Mask	/	/	/	/	/
Rel	No	Raw	/	/	/	/	/

TABLE II: **Evaluation Results (XHand).** Stage-wise accumulated success rates. The Mask and Raw visual approaches were not tested on XHand (indicated by /).

- **Kitchen** [XHand]: The task involves four sequential steps: turn off the stove knob; transfer the pan from the stove top to the counter; pick up salt from a container; and lastly, sprinkle it over the food in the pan. The task tests DexUMI's capability over long-horizon tasks with precise actions, tactile sensing and skills beyond using fingertips.

Comparison: We evaluate the impact of policy action space choices, tactile sensing, and software adaptation on system performance.

- *Relative vs. Absolute finger action:* We compare the form of finger action trajectory: absolute position or relative trajectory proposed by [10]. We always use relative position for wrist action.
- *With vs. Without tactile sensing:* We trained policies with and without tactile sensor input.
- *With vs. Without software adaptation:* We examine two variants without software adaptation: (1) Mask, which replaces pixels occupied by the exoskeleton (during training) or robot hand (during inference) with a green color mask, and (2) Raw, which simply passes unmodified images containing the exoskeleton as policy input.

Evaluation protocol: For each evaluation episode, the test objects are randomly placed on the table at initialization. We conduct 20 evaluation episodes per task, maintaining consistent initial object configurations across our method and all baselines. For long horizon tasks, we report stage-wise accumulated success rate in Tab. I and Tab. II.

A. Key Findings

DexUMI framework enables efficient dexterous policy learning: As shown in Tab. I and Tab. II, the DexUMI system achieves high success rates across all four tasks on two robot hands. The system handles precise manipulation, long-horizon tasks, and coordinated multi-finger contact, while effectively generalizing across diverse manipulation scenarios.

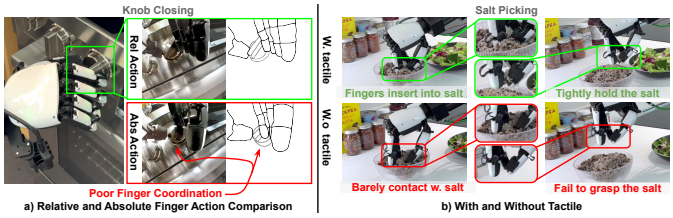

Fig. 6: **Comparisons.** a) The policy outputs relative hand actions yield more precise action and demonstrate better multi-finger coordination. Note, we draw a sketch for the knob closing for better visualization. b) Even with noisy tactile sensor reading, the tactile significantly improve tasks which is visually challenging.

Relative finger trajectories are more robust to noise and hardware imperfections: Tab. I and Tab. II show relative finger trajectory consistently achieves better success across all tasks. Fig. 6 shows more insights: relative trajectory can make critical contact events more reliable. We hypothesize two reasons for this difference: 1. Relative action has a simpler distribution than absolute and is thus easier to learn; 2. Relative action learns a reactive behavior where the delta action keeps accumulating until a key event is reached (e.g. fingers close on contact). However, the absolute action learns a static mapping and would stall if the mapping has errors.

Only relative finger trajectories can benefit from the noisy tactile feedback: An interesting observation in Tab. I and Tab. II is how having tactile affects the results differently. The tactile sensor on the XHand can drift and become inconsistent after experiencing high pressure. Therefore, in most cases, having tactile makes the results worse. We observed that only with relative trajectory can the policy benefit from having such tactile sensing. For the Inspire hand, the tactile sensors we manually installed are even more noisy (See section §III-B for details), then all methods become worse after adding tactile sensor as input. However, policies with relative trajectory still suffer less performance drop compared with the ones with absolute trajectory.

Tactile feedback improves performance on tasks with clean force profiles: We try to understand what kind of task would benefit from having tactile sensing. We focused on the XHand as its tactile sensors provide cleaner readings. We observed that tactile feedback significantly improved performance on picking up salt. This task highlights the effect of tactile because 1) The tactile sensors give a clear, large reading when the fingers touch the bowl of salt. 2) There is little useful visual information close to grasping as the camera view is mostly blocked by the bowl. In this case, we found that tactile feedback completely changes policy behavior. With tactile sensors, the fingers always insert into the salt first then close the fingers. Without tactile feedback, the fingers attempt to grasp the salt sometimes in the air. On the contrary, tactile info does not help in tweezer manipulation, which lacks strong correlation between hand motion and force feedback. Holding

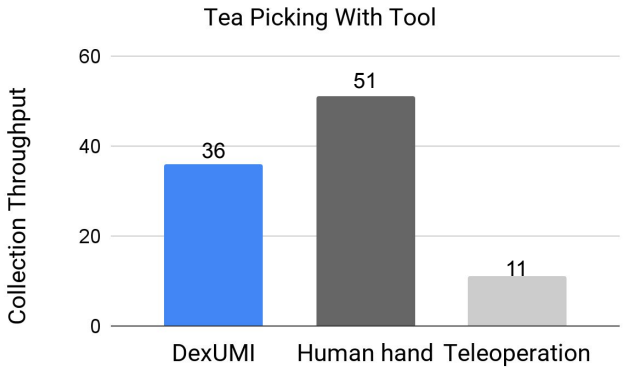

Fig. 7: **Efficiency:** Collection throughput (CT) within 15-minute. Though DexUMI still slower than bare hand, it achieves significant higher efficiency than teleportation.

a tweezer only triggers minimal tactile sensor readings.

DexUMI framework enables efficient dexterous hand data collection: We compared data collection efficiency across three ways: DexUMI, bare human hand, and teleoperation on the tea-picking-with-tool task. The same human operator collected data using each approach within 15-minute sessions. We computed the collection throughput (CT) based on the number of successful demonstrations acquired. As illustrated in Fig. 7, while DexUMI remains slower than direct human hand manipulation, it achieves 3.2 times greater efficiency than traditional teleoperation methods, significantly reducing the time required for dexterous manipulation data collection.

VI. Conclusion

We present DexUMI, a scalable and efficient data collection and policy learning framework that uses the human hand as an interface to transfer human hand motion to precise robot hand actions while providing natural haptic feedback. Through extensive challenging real-world experiments, we demonstrate DexUMI's capability in learning dexterous manipulation policies for precise, contact-rich, and long-horizon tasks. Our work establishes a new approach to collecting real-world dexterous hand data efficiently and at scale beyond traditional teleoperation.

VII. Limitation and Future Work

We would like to discuss DexUMI's limitations from three different aspects: hardware adaptation, software adaptation, and existing robot hand hardware.

Hardware Adaptation:

- *Per robot hand exoskeleton design:* Although DexUMI demonstrates generalizability across underactuated and fully-actuated hands, our optimization framework still requires hardware-specific tuning, especially for wearability. One future work direction is fully automated optimization formulation given robot hand model and some description of the human hand. Further, our hardware optimization framework can potentially leverage generative models [64] to increase efficiency and accuracy when design space grows.
- *Fingertips Matching:* Our current formulation focuses only on matching the fingertip workspace between the designed exoskeleton and target robot hand. It would be interesting for future work to also model remaining potential contact geometries such as the palm.
- *Wearability:* The hardware optimization pipeline makes the exoskeleton wearable and allows humans to operate it relatively easily for extended periods. However, wearability could be further improved by integrating soft materials, such as TPU for parts that contact the human hand. Additionally, constrained by both the design of the target hand and 3D printing material strength, users might still experience limitations in fully stretching certain fingers.
- *Reliability of Tactile Sensors:* Throughout our experiments, we found that reliable tactile sensors are key to maintaining consistent tactile observation between the exoskeleton and corresponding robot hand, thereby reducing the embodiment gap. In our implementation, the resistive tactile sensors added to the Inspire hand and its exoskeleton proved sensitive to their attachment way on fingers. Meanwhile, the electromagnetic tactile sensors on the XHand and its exoskeleton showed a tendency to drift after exposure to high pressure. Since the human hand generates more force than the robot hand, tactile sensor readings frequently drift when humans operate the exoskeleton. Future work can also incorporate other types of tactile sensors, such as vision-based tactile sensors [71, 50, 36] and capacitive F/T sensors [11].
- *Material Limitations:* Our experiments demonstrate that DexUMI is able to capture fine-grained fingertip actions such as closing tweezers. However, we sometimes found that encoders cannot precisely capture human motion due to 3D printing material strength limitations; occasionally, the human hand slightly distorts the exoskeleton linkage when manipulating objects. In such cases, encoders are unable to capture this distortion.

Software Adaptation:

- *Robot Hand Image:* Currently, we still require real-world robot hardware to obtain robot hand images. However, this requirement could be eliminated by implementing an image generation model that receives motor values as input and produces corresponding hand pose images as output.
- *Inpainting Quality:* Throughout our experiments, we found that the current software adaptation pipeline can already yield high-fidelity robot hand images. Nevertheless, we observed that illumination effects on the robot hand cannot be fully reproduced, and some areas in the image appear blurred due to limitations in the inpainting process.
- *Camera Location:* DexUMI currently requires the camera to be rigidly attached to the robot hand/exoskeleton and does not support a moving camera. However, it would be feasible to collect a dataset and train an image generation model that receives the relative pose between the camera and hand, along with hand pose information, to generate

the corresponding hand pose image from any given camera position.

Existing Robot Hand Hardware:

- *Precision:* Throughout our experiments, we found that both the Inspire Hand and XHand lack sufficient precision due to backlash and friction. For example, the fingertip location of the Inspire Hand differs when moving from 1000 to 500 motor units compared to moving from 0 to 500 motor units. Although the desired motor value is the same in both cases, the final fingertip position varies. We observed this phenomenon in both robot hands. Consequently, when fitting regression models between encoder and hand motor values, we can typically ensure precision in only "one direction"—either when closing the hand or opening it. This inevitably causes minor discrepancies in the inpainting and action mapping processes. Further, we found that the XHand mapping between motor command and fingertip location slightly differs across time shifts or after each reboot.
- *Size Discrepancy:* The size difference between the robot hand and the human hand may cause wearability issues. For example, if the robot hand is twice as large as the human hand, it becomes difficult for both the human hand and the exoskeleton to reach the joint configurations required by the robot hand.
- *Co-design:* Many of these wearability issues arise from design constraints in existing commercial hardware. An interesting direction would be to explore a reverse design paradigm: first designing an exoskeleton that is comfortable and fully operable for humans, and then using that exoskeleton as the foundation for designing the robot hand.

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