PHABS: A Handheld Haptic Device for Force-Annotated Bimanual Demonstration Data

***Abstract*— Human video and simulation are increasingly used to sidestep the bottlenecks of teleoperated data collection. Yet, none of these sources, video, simulation, or existing handheld teleoperation, reliably captures the contact forces that define skilled manipulation. We argue that small, force-rich teleoperation data can serve as a force-anchoring modality that complements larger, force-blind video and simulation corpora. We present an in-development device, PHABS (Portable Haptic Assisted Bimanual System). This handheld bimanual device captures synchronized position and pinching-force data during two-handed manipulation while rendering haptic feedback to the operator via capstan-driven actuators. The design targets two-handed manipulation of the same or related objects with fine pinching-force control on each hand, a class underrepresented in existing datasets because it is difficult to capture either from third-person video or from force-blind teleop. A pilot study (n=3) on stiffness discrimination and bimanual pick-and-place indicates that closed-loop force feedback improves task success and operator confidence relative to a position-only baseline. We position PHABS as an in-progress hardware infrastructure intended for collecting a force-annotated anchor dataset, and we report both a working pinching subsystem and lessons from a lateral-force subsystem still under revision.**

I. INTRODUCTION

The push toward learning manipulation from human video [1], [2], [3] and large-scale simulation has reframed the role of teleoperation. Teleoperated demonstrations are slow to collect, lossy in degrees of freedom, and bound to a particular embodiment [4], [5], but they remain the cleanest source of paired sensor-action data aligned with a robot's physical interface. A productive view is that these sources are complementary: human video offers scale and diversity, simulation offers contact-rich dynamics, and teleoperation offers small, high-quality demonstrations that can anchor the noisier sources.

Our work focuses on a dimension of manipulation data that is underrepresented across all three sources: contact force. Human video provides no direct force signal; pose and object deformation give only indirect cues. Simulators compute contact forces internally but have no reference against which to calibrate those forces for human-like manipulation. And most existing handheld teleoperation systems capture only hand pose [4], [6]. Recent work has begun integrating visuotactile sensing into handheld grippers [7], [8], but these systems sense tactile signals as policy observations without rendering forces back to the demonstrator the human operator still cannot *feel* the forces they apply during data collection. This is where the field of haptics has a contribution to make. Skilled human manipulation depends on a closed sensorimotor loop in which felt contact forces continuously shape motor commands; when that loop is broken, operators compensate visually and over-grip, producing demonstrations whose force profiles reflect the interface rather than the task. Policies trained on any of these sources must therefore infer force implicitly from geometry or from passive tactile logs, which is especially brittle for tasks where grip precision matters: handling fragile objects and opening sealed packaging.

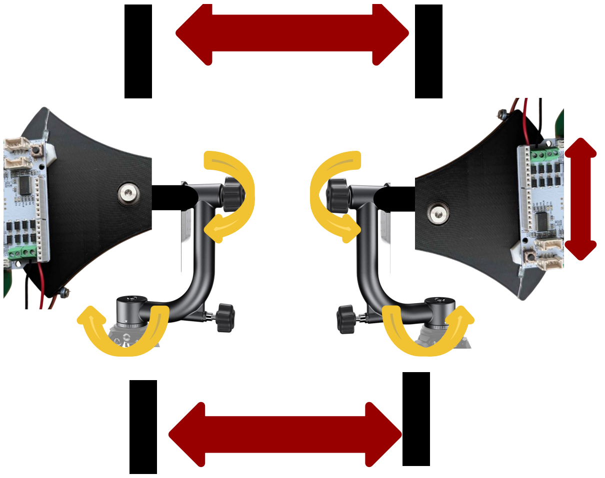

Fig. 1. Conceptual design of the PHABS device, with red indicating actuated degrees of freedom that provide haptic force feedback and yellow indicating passive degrees of freedom used for position sensing only. The design targets two-handed pinching manipulation of shared or related objects manipulation tasks to improve teleoperation performance and the quality of demonstration data collected for robot learning.

We present PHABS (Portable Haptic Assisted Bimanual System), an in-progress handheld bimanual device that captures synchronized position and pinching-force data while rendering force feedback to the operator. By closing the sensorimotor loop during data collection, PHABS targets two-handed manipulation of the same or related objects with fine pinching-force control on each hand a class of tasks that is difficult to capture from third-person video or force-blind teleoperation alike, and produces a small, force-rich anchor dataset intended to complement larger force-blind sources.

This paper contributes:

- A handheld bimanual haptic teleoperation device for two-handed pinching manipulation, with synchronized position and pinching-force capture.
- A pilot user study (n=3) evaluating the effect of closed-loop haptic feedback on bimanual manipulation task performance.

II. RELATED WORKS

A. Learning from Human Video and Portable Data Collection

A major line of recent work learns manipulation directly from human video, either via pretrained visual representations [2], [1] or, more recently, large-scale egocentric datasets with paired 3D hand pose [3]. These sources offer scale and strategic diversity that teleoperation cannot match, but provide no direct contact-force signal. A complementary line bridges the embodiment gap by building portable, handheld devices that mimic robot end-effectors: UMI [4] uses a handheld parallel-jaw gripper with a wrist-mounted camera for in-the-wild data collection, and DexCap [6] provides a portable mocap system for dexterous hand pose. Neither captures contact force at the interface. Recent work has begun to close this gap by integrating visuotactile sensors into handheld grippers [7], [8], but these systems sense tactile signals for policy input without rendering force back to the demonstrator. PHABS complements these efforts by closing the sensorimotor loop: operators feel the forces they apply during data collection, which we hypothesize produces force profiles more consistent with natural human manipulation.

B. Haptic Feedback in Teleoperation

Haptic feedback has been repeatedly shown to improve operator performance in teleoperation. Purushottam et al. [9] demonstrate haptic teleoperation of a wheeled humanoid performing heavy lifting, showing that user preferences for feedback vary by task phase. Lenz and Behnke [10] present a bimanual exoskeleton with force-torque sensing at the robot's end-effectors and an oscillation observer for stability. Griffin et al. [11] show that appropriate tactile, force, and motion feedback significantly improves shared-control telemanipulation, and Milstein et al. [12] find that haptic properties of a gripper, not visual feedback, govern the forces users apply during interaction with deformable objects. In contrast to exoskeleton-based systems [10], PHABS prioritizes portability and cross-embodiment compatibility; in contrast to prior handheld haptic devices and force-blind data collection systems [4], [6], [7], it targets two-handed pinching manipulation with synchronized position and closed-loop force capture for downstream learning.

III. MECHANICAL DESIGN

The device was designed to provide two modalities of haptic force feedback: lateral force feedback for tasks where both hands press inward on a shared object (e.g., stabilizing a fragile package from both sides while opening it), and pinching force feedback between the thumb and index finger, as shown in Fig. 2. Each pincher assembly was mounted onto a two-axis gimbal with a pan axis (rotation about the vertical axis of the housing) and a roll axis (rotation about the longitudinal axis of the housing).

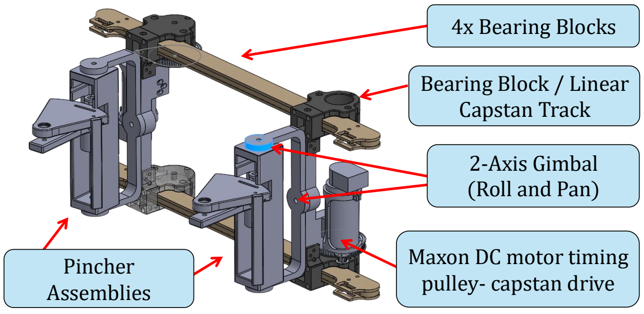

Fig. 2. Full mechanical assembly of the PHABS device, showing the two pincher assemblies mounted on bearing block carriages that translate along parallel wooden rails. The central column houses the Maxon DC motor and capstan drive for lateral force feedback, with two-axis gimbals connecting each pincher to its respective carriage.

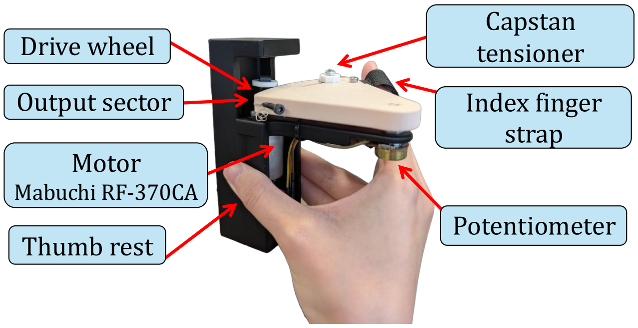

Fig. 3. Pinch feedback mechanism in right-handed configuration. The Mabuchi RF-370CA motor drives the output sector via a direct-drive capstan. The user's thumb rests on the housing while the index finger is strapped to the sector, with the potentiometer serving as both the sector pivot and angle sensor.

A. Pincher

The pinching force feedback mechanism was designed based on the Force Dimension omega.7 end-effector [13] to fit the natural shape and range of motion of the hand while grasping, providing force feedback between the thumb and index finger, as shown in Fig. 3.

The mechanism is actuated via a direct-drive capstan, in which a Mabuchi RF-370CA motor rotates a drive wheel that winds a cable around the output sector. The sector rotates about a potentiometer, which serves as both the pivot point and the angle sensor. A capstan tension adjustment screw maintains cable preload to minimize backlash. During operation, the user rests their thumb on the thumb rest on the housing, while their index finger is strapped to a handle on the output sector, allowing active force feedback during both opening and closing of the hand. The remaining fingers grasp the housing to provide stability. The housing has mirrored configurations for the left and right hands.

The output pinching force is given by:

$$F_{pinch} = \frac{r_s}{r_h r_d} \tau_{motor} \tag{1}$$

With $\tau_{motor} = 2.48$ mN·m, $r_s = 75$ mm, $r_h = 60$ mm, and $r_d = 4.75$ mm, the maximum expected output force is $F_{pinch} = 0.65$ N.

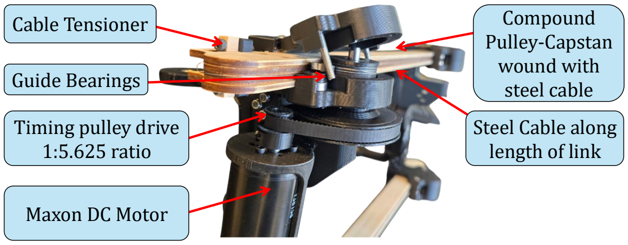

Fig. 4. Linear capstan drive assembly for lateral force feedback, showing the Maxon DC motor, 1:5.625 timing pulley stage, compound pulley-capstan wound with steel cable, guide bearings, and cable tensioner. The steel cable transmits motor torque along the length of the output link to the bearing block carriage.

The pincher assembly is mounted to the lateral mechanism via a two-axis gimbal (roll + pan), allowing the device to passively align with arbitrarily oriented objects before grasping. The passive alignment also supports coordinated two-handed manipulation of a shared object, e.g., pinching both sides of a package while rotating it.

B. Lateral Force Feedback

The lateral-force subsystem uses a linear capstan drive [14] with two bearing-block carriages translating along parallel rails. One carriage is actuated by a Maxon DC motor; the other is fixed, providing a static reaction surface. Each carriage mounts a gimbal and pincher assembly, so squeezing the hands together produces programmable resistive force. In practice, this subsystem bound excessively under load and was not used in the pilot user study.

IV. HARDWARE

The system is controlled by an Arduino Mega communicating with the simulation computer over serial at 38,400 baud. Potentiometer (pincher angle) and encoder (slider displacement) signals are calibrated, low-pass filtered, and transmitted alongside force commands returning from the simulator. The system logs synchronized pose (from Vive trackers) and pinching force (from potentiometer-derived grip aperture) as CSV/JSON streams.

V. SOFTWARE

To provide haptic feedback during pinching interactions, objects in the virtual environment were modeled with stiffness and damping coefficients. We use a god-object proxy model: on first contact, the commanded finger position is snapshotted as the surface, and rendered force is computed as $F = kx + b\dot{q}$ on the penetration depth x, where $\dot{q}$ is the filtered finger closing velocity, with the output clamped at $F_{\max}$.

The virtual environment was rendered in PyBullet, with two URDF grippers driven kinematically by HTC Vive trackers and a shared-frame calibration tracker.

VI. METHODS

A pilot user study was conducted to evaluate the effect of haptic feedback on operator performance during two-handed virtual object manipulation. Participants were seated in front of a monitor displaying the PyBullet simulation environment, holding one pincher device in each hand as seen in Fig. 6. HTC Vive trackers were attached to each hand to provide 6-DOF position and orientation tracking, with four base stations positioned around the participant to ensure full coverage and minimize occlusion.

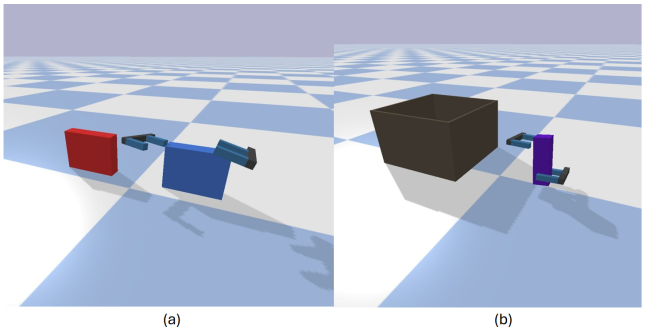

Fig. 5. (a) Virtual environment for the stiffness comparison task. (b) Virtual environment for the block movement task.

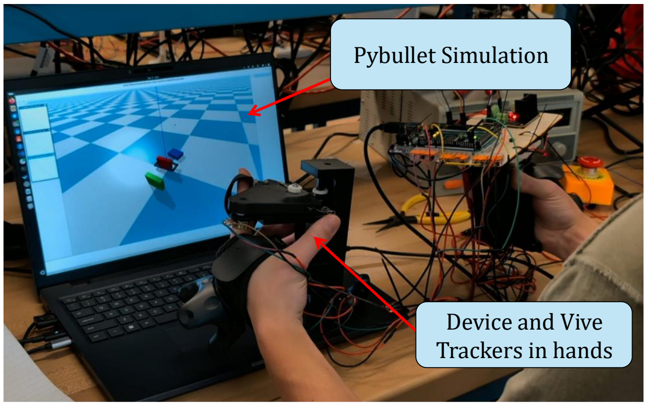

Fig. 6. PHABS in operation during a bimanual virtual object manipulation task. The operator holds one pincher device in each hand, with HTC Vive trackers providing 6-DOF pose to the PyBullet simulation. Capstan-driven force feedback is rendered to both hands in response to virtual contact forces, closing the sensorimotor loop during teleoperation.

Each participant completed two tasks. In the first task, participants were presented with two virtual blocks of differing stiffness and asked to identify the stiffer block by pinching each one. In the second task, participants were asked to pick up a target block with one hand, transfer it to the other hand, and place it into a target box. Each task was performed twice: once with haptic feedback disabled and once with it enabled, allowing within-subject comparison of performance. A trial was considered successful if the participant correctly identified the stiffer block in the first task, or completed the full pickup, handoff, and placement sequence without dropping the object in the second. Following the trials, participants were asked to provide qualitative feedback on the perceived usefulness of the haptic feedback and the comfort of the device.

VII. RESULTS

A total of 3 participants completed the pilot user study. In the stiffness discrimination task, 3 of 3 participants correctly identified the stiffer block when haptic feedback was enabled. In the manipulation task, 3 of 3 participants completed the full pickup, handoff, and placement sequence with haptic feedback enabled, compared to 1 of 3 without feedback. These results are preliminary; a larger study is needed to establish statistical significance and to characterize effects across tasks and user populations.

TABLE I

PILOT STUDY RESULTS

Task	Condition	Successful Participants	Total Participants
Stiffness Discrimination	With Haptics	3	3
Manipulation Task	With Haptics	3	3
	Without Haptics	1	3

Qualitative feedback was consistent with the quantitative results. Participants reported that without haptic feedback, it was difficult to determine when contact had been made with a virtual object, leading to hesitant and repeated grasping attempts. With feedback enabled, participants reported greater confidence during grasping and transfer interactions, noting that the force cues allowed them to gauge grip strength in real time. Two of three participants rated the haptic feedback as useful or very useful on a post-trial questionnaire.

VIII. DISCUSSION

Unlike recent visuotactile handheld grippers [7], [8], which log contact signals passively, PHABS renders forces back to the operator during demonstration. Decades of haptics research have shown that closed-loop force feedback improves operator performance, grip-force control, and task success across a range of teleoperation settings [11], [12], [10]; we expect the same mechanism to produce cleaner, more deliberate force profiles during data collection. Whether this improvement in demonstration quality translates to improved downstream policies is the central empirical question our future work aims to answer.

IX. ONGOING WORK

PHABS is an actively developing platform, and the results presented here reflect an early prototype rather than a finished system. Work is in progress along three threads: hardware iteration, dataset collection, and evaluation.

Lateral-force subsystem. The immediate hardware priority is making the lateral-force subsystem viable. The initial prototype bound under load: the adjustable preload screws introduced a fundamental tradeoff in which tight settings allowed 3D-printed surfaces to contact the wooden rails, while loose settings admitted moments from the pincher assemblies that caused binding. The gimbal configuration compounded this; when both roll axes aligned, the system reached a singularity and could not support its own weight. We are replacing the wooden rails with circular rods running on linear bearings, which eliminates the preload-vs-binding tradeoff in the original design. The motor is also being placed closer to the capstan drive to reduce the moment applied. Component testing is ongoing.

Pinch subsystem and full integration. On the pinch side, the press-fit between the output sector and the potentiometer is not robust to out-of-plane forces; decoupling the rotation shaft from the sensor will reduce friction and improve force transmission. The housing was sized to the team's hand dimensions, which proved unrepresentative. We are currently redesigning to be more comfortable for a larger array of hand sizes. We are also characterizing the motors empirically to handle stiction and back-EMF nonlinearities, adding current limiting to prevent motor burnout, and replacing cables with shielded lines for better signal integrity. Ultimately, we aim for a lighter, fully self-contained enclosure with onboard power and wireless communication, removing the current tether to the simulation computer, so that an operator can pick up the device and begin collecting demonstrations without surrounding infrastructure beyond a host laptop.

Dataset plan. We are preparing a force-annotated bimanual demonstration dataset targeting two task families underrepresented in existing corpora: fragile-object handling (e.g., picking and placing deformable produce) and sealed-packaging manipulation (e.g., opening bags by pulling the tab). Each demonstration will log 6-DOF hand pose from both hands alongside continuous pinching-force traces, time-synchronized in post-processing. The intent is to release a small, high-quality dataset as a force-annotated anchor alongside larger pose-only datasets such as UMI [4] and EgoDex [3], to support downstream work on force-conditioned policy learning.

Evaluation plan. The central empirical question raised above, whether closed-loop haptic feedback during collection produces measurably better demonstrations, will be tested directly. We plan a within-subject study in which operators collect matched demonstrations on the same task with haptics enabled and disabled, followed by training identical policies on each condition and comparing success rates on fragile-object and packaging benchmarks. Scaling the pilot study to a larger participant pool is a prerequisite for this evaluation and is our next user-study milestone.

X. CONCLUSIONS

We introduced PHABS, an in-development handheld bimanual haptic teleoperation device for two-handed pinching manipulation of shared or related objects. The pinching subsystem demonstrated working force feedback during virtual object interaction, supporting stiffness discrimination and improving bimanual manipulation performance in a pilot study; the lateral-force subsystem was fabricated and is being revised following binding and singularity issues identified during assembly. The pilot study, though small, supports the core premise that closed-loop haptic feedback improves teleoperation performance on tasks requiring fine force control, and by extension, the quality of the force-rich demonstration data that such devices can collect. With the ongoing hardware, dataset, and evaluation work described above, we aim to turn PHABS into a practical tool for generating force-annotated anchor data to complement the larger human-video and simulation corpora driving current robot learning.

References

[1] K. Grauman, A. Westbury, E. Byrne, Z. Chavis, A. Furnari, R. Girdhar, J. Hamburger, H. Jiang, M. Liu, X. Liu, M. Martin, T. Nagarajan, I. Radosavovic, S. K. Ramakrishnan, F. Ryan, J. Sharma, M. Wray, M. Xu, E. Z. Xu, C. Zhao, *et al.*, "Ego4D: Around the world in 3,000 hours of egocentric video," in *Proceedings of the IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, 2022.

[2] S. Nair, A. Rajeswaran, V. Kumar, C. Finn, and A. Gupta, "R3M: A universal visual representation for robot manipulation," in *Proceedings of the 6th Conference on Robot Learning (CoRL)*, 2022.

[3] R. Hoque, P. Huang, D. J. Yoon, M. Sivapurapu, and J. Zhang, "EgoDex: Learning dexterous manipulation from large-scale egocentric video," *arXiv preprint arXiv:2505.11709*, 2025.

[4] C. Chi, Z. Xu, C. Pan, E. Cousineau, B. Burchfiel, S. Feng, R. Tedrake, and S. Song, "Universal manipulation interface: In-the-wild robot teaching without in-the-wild robots," in *Proceedings of Robotics: Science and Systems (RSS)*, 2024.

[5] Z. Fu, T. Z. Zhao, and C. Finn, "Mobile ALOHA: Learning dexterous whole-body control from intervention," in *arXiv preprint arXiv:2401.02117*, 2024.

[6] C. Wang, H. Shi, W. Wang, R. Zhang, L. Fei-Fei, and C. K. Liu, "DexCap: Scalable and portable mocap data collection system for dexterous manipulation," in *Proceedings of Robotics: Science and Systems (RSS)*, 2024.

[7] X. Zhu, B. Huang, and Y. Li, "Touch in the wild: Learning fine-grained manipulation with a portable visuo-tactile gripper," *arXiv preprint arXiv:2507.15062*, 2025.

[8] E. Helmut, N. Funk, T. Schneider, C. de Farias, and J. Peters, "Tactile-conditioned diffusion policy for force-aware robotic manipulation," *arXiv preprint arXiv:2510.13324*, 2025.

[9] A. Purushottam, J. Yan, C. Xu, and J. Ramos, "Heavy lifting tasks via haptic teleoperation of a wheeled humanoid," in *2025 IEEE-RAS 24th International Conference on Humanoid Robots (Humanoids)*, (Seoul, Korea), pp. 345–350, 2025.

[10] C. Lenz and S. Behnke, "Bimanual telemanipulation with force and haptic feedback through an anthropomorphic avatar system," *Robotics and Autonomous Systems*, vol. 161, p. 104338, 2023.

[11] W. B. Griffin, W. R. Provancher, and M. R. Cutkosky, "Feedback strategies for shared control in dexterous telemanipulation," in *Proceedings 2003 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, (Las Vegas, NV, USA), pp. 2791–2796, 2003.

[12] A. Milstein, L. Alyagon, and I. Nisky, "Grip force control during virtual interaction with deformable and rigid objects via a haptic gripper," *IEEE Transactions on Haptics*, vol. 14, no. 3, pp. 564–576, 2021.

[13] Force Dimension, Nyon, Switzerland, *omega.7 Haptic Device: Force Feedback Interface*, 2026. `https://www.forcedimension.com/products`.

[14] W. Harris, L. Yager, S. Sylvester, E. Peiros, and M. C. Yip, "An investigation into dynamically extensible and retractable robotic leg linkages for multi-task execution in search and rescue scenarios," *arXiv preprint arXiv:2511.10816*, 2025.