Beyond Visuals: Investigating Force Feedback in Extended Reality for Robot Data Collection

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***Abstract*— This work explores how force feedback affects various aspects of robot data collection within the Extended Reality (XR) setting. Force feedback has been proved to enhance the user experience in Extended Reality (XR) by providing contact-rich information. However, its impact on robot data collection has not received much attention in the robotics community. This paper addresses this shortcoming by conducting an extensive user study on the effects of force feedback during data collection in XR. We extended two XR-based robot control interfaces, Kinesthetic Teaching and Motion Controllers, with haptic feedback features. The user study is conducted using manipulation tasks ranging from simple pick-place to complex peg assemble, requiring precise operations. The evaluations show that force feedback enhances task performance and user experience, particularly in tasks requiring high-precision manipulation. These improvements vary depending on the robot control interface and task complexity. This paper provides new insights into how different factors influence the impact of force feedback.**

I. INTRODUCTION

Robot data collection plays a crucial role in advancing robotics by enabling robots to acquire complex skills through human guidance [1]. For effective learning, robots require large volumes of high-quality data, as the success of data-driven methods heavily depends on the quality and diversity of the training demonstrations [2].

Extended Reality (XR) has emerged as a promising tool to facilitate the collection of such demonstrations. XR provides an immersive interface, allowing users to control robots in an intuitive manner. This technology further reduces setup time, making it an effective means for generating demonstrations. Despite its benefits, conventional XR-based robot data collection primarily relies on visual feedback, which may be insufficient for tasks demanding high precision.

Beyond visual information, haptic feedback is a promising complement to robot data collection. To facilitate tasks that demand high precision, force feedback has been introduced as an additional sensory channel, enriching teleoperation by providing tactile information. Force feedback refers to the use of actuators to generate resistive or assistive forces, allowing users to feel physical interactions with the virtual or remote environment [3].

However, the impact of force feedback in robot teleoperation and data collection remains underexplored. The effectiveness of force feedback across different control paradigms is not yet fully understood, and its influence on task performance has not been systematically evaluated. To

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Fig. 1: Kinesthetic Teaching (KT) for data collection with force feedback. The virtual and real robots are aligned, ensuring that all movements of the real robot are accurately projected onto the virtual counterpart.

address this shortcoming, this study investigates the role of force feedback in an XR-based teleoperation setup through the following hypotheses:

Hypothesis 1 (H1): Force feedback enhances the efficiency, effectiveness, and user experience of data collection.

Hypothesis 2 (H2): The influence of force feedback varies across different interfaces.

Hypothesis 3 (H3): The impact of force feedback on efficiency, effectiveness, and user experience varies across different task types.

To test these hypotheses, we conducted a systematic user study where participants controlled a virtual robot in simulation using different XR-based interfaces. The study focused on four interfaces, including two primary ones: Kinesthetic Teaching and Motion Controller, both with and without force feedback. The combination of an XR environment with force feedback enabled Kinesthetic Teaching is novel to the best of our knowledge. A total of 31 participants completed a series of tasks, providing demonstration data while interacting with each interface. Performance was evaluated using both objective metrics (task success rate and completion time) and subjective metrics (questionnaire assessing user experience).

The results of the study indicate that force feedback with Kinesthetic Teaching in XR is a powerful and intuitive approach for collecting demonstrations with high performance and good user experience. Interfaces incorporating force feedback demonstrated improved precision and stability, especially in tasks requiring fine motor control. Furthermore, the impact of force feedback varied across different control modalities and tasks, suggesting that its benefits are context-dependent.

In summary, this work makes two key contributions. First, it presents a comprehensive user study that systematically evaluates the impact of force feedback on robot teleoperation and data collection. Second, it introduces a force feedback-based Kinesthetic Teaching interface, which outperforms its non-feedback counterpart in terms of performance and user experience. These insights contribute to the development of more effective robot teleoperation systems and may inform future applications in real-world robotic control and teleoperation.

II. Related Work

A. Force Feedback in Human-Robot Interaction

Force perception is fundamental to how humans interact with the world, enabling us not only to engage with our environment but also to perceive these interactions simultaneously [4]. Force feedback has been shown to enhance position control, improve navigation and precision tasks, and reduce reliance on visual and auditory modalities [5]. It also improves temporal accuracy [6] and enhances overall user comfort [7]. Recently, integrating force feedback into robot teleoperation interfaces has gained increasing attention [8]–[10]. While physical interactions with real robots allow operators to experience reaction forces, this feedback is absent in virtual environments and teleoperation settings. To address this limitation, different force feedback modalities have been introduced to improve interaction fidelity. Some approaches use twin controllers with the same parameters and sensors as the robot to provide direct force feedback to the operator's hand and wrist [11] or industrial force feedback devices designed for robotics applications [12]. Others employ force-feedback gloves with motor vibrations [13] or integrate bimanual robot avatars with upper-body controllers to enhance immersion through haptic feedback [14].

In XR environments, vibration-based force feedback from controllers has been shown to enhance immersion, increase perceived performance, and reduce task difficulty [15]. This approach is particularly beneficial for tasks requiring delicate manipulation, such as handling fragile objects [16] or deformable materials [13].

Despite these advances, the impact of different force feedback modalities in human-robot interaction remains underexplored. By incorporating force feedback, interaction systems can become more intuitive and efficient, improving performance and user satisfaction across various applications. However, few studies have explored the influence of different force feedback modalities on tasks performance and user experience in HRI systems.

B. XR in Robot Data Collection

Extended Reality (XR), including Virtual Reality (VR), Augmented Reality (AR), and Mixed Reality (MR), combines real objects with virtual environments to enhance Human-Robot Interaction [17]. In recent years, XR has been widely applied in robotics, promoting the development of more intuitive and efficient control methods and interfaces [18]. In robot teleoperation, XR enables operators to manipulate robots within virtual environments, thereby improving operational efficiency and reducing workload [19]. XR can intuitively convey visual information to operators and even provide multiple views, offering users an immersive experience [20].

Numerous studies have demonstrated that XR devices can be used to control or interact with real robots [21], [22]. XR provides depth perception and intuitive visual feedback, allowing users to perceive spatial relationships more accurately, thereby significantly improving operational efficiency [23]. Many studies also show that AR interfaces reduce task completion time, enhance operator performance, and are generally preferred over traditional interfaces [24]. Compared to other display devices, VR headsets enable users to perform manipulation tasks faster, with lower perceived workload and higher usability [19]. Furthermore, research indicates that in XR environments, virtual robots can be as accurate and efficient as physical robots—or even more so [25]. This opens possibilities for teleoperation and simulation without the need for physical robot hardware, reducing research costs and increasing accessibility.

Previous studies have shown that using kinesthetic teaching (KT) interfaces and VR motion controller (MC) interfaces to control virtual robots in XR devices results in higher efficiency and effectiveness compared to other control interfaces [26]. The kinesthetic teaching interface allows operators to interact directly with the physical entity of the virtual robot, while the VR motion controller guides the virtual robot's end-effector through manual control.

To collect demonstration data in virtual environments using XR interfaces, these two interfaces (KT and MC) are adopted as the primary methods for controlling virtual robots. Leveraging the IRIS framework [27], XR devices are integrated to provide intuitive visual feedback and incorporate different forms of force feedback.

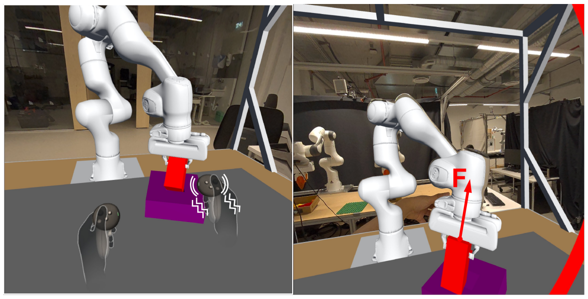
III. Experiment

A. System Design

1) XR Platform and Physics Simulator: Our XR framework is based on [27] and utilizes the Meta Quest 3 as the XR headset. This framework projects scenes from the simulation into the XR headset. The simulation runs on a PC, with the headset connected via a Wi-Fi router. The XR framework transmits the entire scene, including all objects, meshes, materials, and textures, to the headset, generating an identical Unity scene. To ensure synchronization, the simulation continuously updates the headset with scene modifications, including the position and rotation of each object.

The simulation scene is highly adjustable, offering greater flexibility than real-world environments. This work uses

Mujoco [28] as simulatior, and data loggers are implemented to record the state information of the virtual robot and objects, such as position, velocity, acceleration, and orientation.



(a) MCV (b) KTF

Fig. 2: Two types of robot control interfaces with force feedback. The force can be perceived either through the vibration of the motion controller or the applied force from the real robot. These images are captured from the perspective of XR headsets.

2) Robot Control Interface: In data collection tasks, robot control interfaces are used to operate the robot in both simulated and real-world environments. Kinesthetic Teaching (KT) and Motion Controllers (MC) are among the most commonly used interfaces, as they provide intuitive and effective control. KT is an intuitive interface that enables users to control robots by physically guiding their movements. In contrast, MC employ inverse kinematics to manipulate robots in Cartesian space, where the robot's end effector is controlled via the controller's trigger. This study focuses on these two interfaces to investigate the impact of force feedback on their performance.

3) Motion Controller with Vibration Feedback (MCV): Building on the initial MC interface, force feedback is provided through vibration from the Touch Plus controllers under specific conditions. In the simulation, contact forces between the gripper's fingertips and objects, as well as collisions with the environment, are detected. If the gripper touches an object without closing, continuous vibration is applied. A short vibration cue is given when the gripper grasps an object, with no further feedback while holding it.

4) Kinesthetic Teaching with Force Feedback (KTF): Building on the initial KT interface, force feedback is introduced by transmitting the forces experienced by the virtual robot's joints to the physical robot's joints in real time. In the simulation, external forces on the virtual robot's joint torque sensors are scaled and applied to corresponding joints of the physical robot. This process enhances users' perception of physical forces while maintaining a safe environment, making manipulation more intuitive and responsive.

B. User Study

A user study was designed to compare the force feedback interface with the original one, assessing their impact on data collection efficiency, effectiveness, and user experience across various tasks and identifying significant differences.

1) Task Design: As shown in Fig. 3, four demonstration tasks were chosen for the user study: *Push Cube*, *Pick and Place*, *Assemble Peg*, and *Open Drawer*.

Push Cube. Participants push a cube into a target area, The task is considered complete when the cube is within the target area and the colored face is correctly aligned.

Pick and Place. Participants pick up a box and place it on a target platform without overlapping the edges. This task and Push Cube are two common manipulation tasks designed to evaluate the fundamental manipulation skills of a robot control interface.

Assemble Peg. Participants insert a 60 mm × 60 mm square peg into a 64 mm × 64 mm square hole. The task is complete when the peg is securely inserted with no misalignment. If the peg is dropped, the task fails. This task requires highly accurate movement from operators, which is used to assess the responsiveness and precision of robot control interfaces.

Open Drawer. Participants align and grip the drawer handle, pulling it out smoothly. The task is complete when the drawer is open but not fully extended. This task, involving compound movements, evaluates the comprehensive manipulation capabilities of the robot control interface.

These tasks, ranging from basic to complex, are common in robot manipulation tasks and involve both simple and precise manipulations.

2) Objective Metrics Design: To comprehensively assess each interface objectively, *Task success* and *Task completion time* were employed as objective metrics. The *task success* indicates whether a task was completed as required, recorded as 0 (failure) or 1 (success). *Task completion time* represents the duration taken to finish a task, with the maximum allowed time recorded if the participant failed or exceeded the time limit. If the task was not completed within the time limit, the task success was recorded as 0. Task time limits were determined based on a pilot study, ensuring sufficient time for task completion without extending the overall duration of the user study. In this study, the time limit for all tasks is set to 60 seconds.

3) Subjective Metrics Design: In addition to the objective metrics, it is also important to asses how the user experiences each interface. Hence, for subjective metrics, two types of questionnaires are used to test hypotheses: overall subjective metrics and task-wise subjective metrics. The overall subjective questionnaire evaluates the overall performance of the four interfaces by *User Experience Questionnaire Short Version (UEQ-S)* [29]. UEQ-S measures interface quality across two dimensions: pragmatic quality and hedonic quality, each with four items, with the scale from -3 to +3. The task-wise subjective questionnaire was designed to evaluate user experience for each individual task. Four task-specific metrics—accuracy, stability, efficiency, and usability—were assessed using a 5-point Likert scale to capture participants' perceptions of the interfaces. Accuracy measures the effectiveness of the interface and the user's understanding of the system. Stability evaluates the reliability of the interface, which directly influences user trust. Efficiency quantifies the time and effort required to complete tasks,