Prometheus: Universal, Open-Source Mocap-Based Teleoperation System with Force Feedback for Dataset Collection in Robot Learning

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Abstract— **This paper presents a novel teleoperation system with force feedback, utilizing consumer-grade HTC Vive Trackers 2.0. The system integrates a custom-built controller, a UR3 robotic arm, and a Robotiq gripper equipped with custom-designed fingers to ensure uniform pressure distribution on an embedded force sensor. Real-time compression force data is transmitted to the controller, enabling operators to perceive the gripping force applied to objects. Experimental results demonstrate that the system enhances task success rates and provides a low-cost solution for large-scale imitation learning data collection without compromising affordability.**

All hardware designs, software, and implementation details—including fabrication guidelines, PCB specifications, and deployment instructions—are released as open-source at https://github.com/Eterwait/Prometheus.

Keywords: ***Teleoperation, Force feedback, Bimanual Manipulation, Imitation Learning, Robotic Manipulation, Real-Time Control, Haptic Devices, Robotic Manipulation, UR3 Robot, Foundation Models, Robot Learning, Embodied AI***

I. Introduction

Robotics has undergone significant advancements in recent years, particularly in demonstration-based learning using neural networks with transformer architectures. These methods show remarkable potential for automating both industrial and everyday tasks. However, the performance of such models heavily depends on the quantity and quality of the training data.

A common data collection approach involves teleoperation with motion capture systems, where human motions are transferred to a robot via inverse kinematics. While effective, this method has a critical limitation: the lack of force feedback during object manipulation. Without accurate force perception, both the operator and the neural network may apply excessive gripping forces, leading to object deformation or damage.

To address this issue, we propose a low-cost, open-source teleoperation system with integrated force feedback (Fig. 1). Our solution leverages 3D-printed and commercially available mechanical components, combined with custom-designed PCBs for electronics. The entire system—including hardware designs, firmware, and software—is released as open-source to ensure reproducibility and further research development.

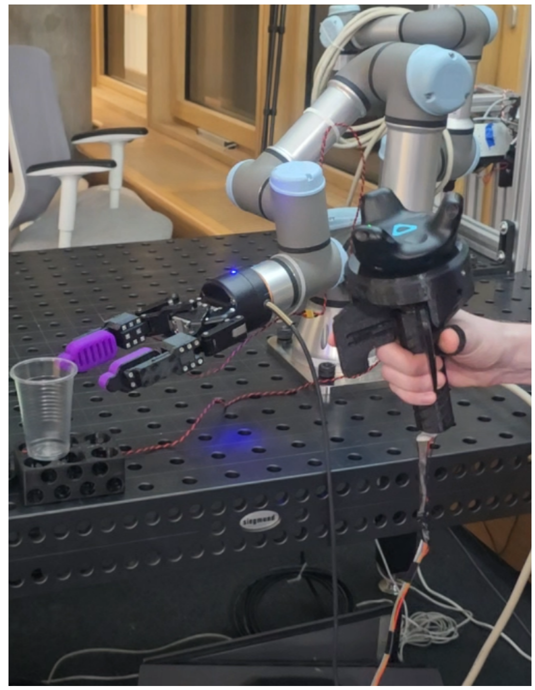

Fig. 1: Main view of the system

All hardware and software components will be made available as open-source resources, including detailed instructions for fabrication, assembly, PCB ordering, and system deployment.

II. Related Work

A. Teleoperation

Modern approaches to teleoperation can generally be divided into two categories.

The first approach is robot-specific and relies on building a kinematic copy of the robot. By knowing the robot's joint positions, the system uses forward kinematics to replicate the robot's behavior. This method provides a natural, intuitive way of controlling the robot by directly mirroring its structure and movement. Examples of this approach can be seen in systems like Echo [1], GELLO [1], ALOHA [2], Mobile ALOHA [3], AirExo [4], and Aloha 2 [5].

The main advantage of this approach is its intuitiveness, as operators can directly interact with a system that mirrors the robot's structure, requiring minimal learning. Furthermore, it

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offers high precision in tasks demanding fine motor skills, such as surgical operations or delicate industrial processes. However, the robot-specific nature of this approach limits its adaptability; each system must be custom-built for the robot it controls. Additionally, the need for a physical kinematic copy increases costs and technical complexity, making this approach less practical for more generalized applications.

The second approach is more versatile and can be used across a variety of robotic systems. It employs inverse kinematics to reproduce the end-effector's position, bypassing the need for a direct kinematic copy. The position of the end-effector can be determined using VR controllers [6]–[17], glove-based systems [17]–[22], vision-based tracking [21], [23]–[29], or IMU sensors [30], [31]. This method is particularly useful in scenarios where greater flexibility and system compatibility are required.

Unlike the first approach, this method shines in its adaptability and applicability to a wide range of robots. Input devices like VR controllers or gloves provide flexibility, enabling operators to control different robotic systems without the need for custom hardware. However, it comes with certain drawbacks. The reliance on inverse kinematics introduces computational complexity, which may lead to delays or inaccuracies in real-time scenarios. Additionally, while versatile, this approach can feel less intuitive to operators and may require training to achieve precise control.

B. Haptic feedback

Haptic feedback systems enhance teleoperation by providing force and tactile sensations to the operator, improving precision and immersion. Several approaches exist for integrating haptic feedback with bimanual manipulators, utilizing different control devices, each with its own set of limitations.

One notable approach uses controllers equipped with repurposed prosthetic hands, as demonstrated in [6]. These systems leverage touch sensors embedded in prosthetic hands to provide tactile feedback. While effective for simulating touch, this method is often constrained by the limited range of force sensations it can replicate, which may reduce the realism of interactions.

Another common implementation involves VR controllers, as seen in [14], where the vibration mechanism in controllers serves as haptic feedback. This approach is cost-effective and widely accessible but offers only basic feedback through vibrations, lacking the nuanced force sensations needed for more complex tasks.

Glove-based systems, such as those used in [22], [32], [33] represent a more immersive option. These systems provide a combination of tactile and force feedback by mimicking the hand's natural movements. However, gloves often suffer from limited precision and can be cumbersome for extended use, particularly in tasks requiring fine motor skills.

Specialized haptic devices, highlighted in works like [34], [35], offer the most precise and responsive feedback. These devices excel in delivering a high-fidelity force-feedback experience, making them ideal for critical applications such as medical simulations. However, their high cost and complexity limit their adoption in broader applications.

Fig. 2: External view of the controller

III. System Architecture

Our system consists of a custom-built controller with HTC VIVE Tracker 2.0, a UR3 robot, and a Robotiq 2F-85 gripper equipped with custom robotic fingers for uniform pressure distribution on the internal force sensor. Operator uses HD Pro Webcam C920 USB, mounted on the gripper for visual feedback, and the controller for force feedback.

A. Controller

To receive force feedback and ensure comfortable control of the robot and gripper, we developed a specialized haptic device (Fig. 2). It consists of a frame connected to a handle and a cover with an attached HTC Vive tracker. Two actuation sticks rotate on bearings mounted on the frame. One stick is connected to the motor's frame, while the other is connected to the motor's shaft.

The working principle of this controller is as follows (Fig. 3): when the motor is mounted on a bearing and a lever is attached to its shaft, a torque is generated when the motor starts. According to Newton's Third Law, the motor's body experiences an equal and opposite reaction torque. Since the motor is not fixed to an external support, it begins to rotate in the opposite direction. As a result, the lever and the motor body rotate in opposite directions.

The controller serves as a mounting point for the HTC Tracker 2.0, which is used to track the coordinates of the human hands. Using the approach described in [7], we transform the position and orientation of the hand from the operator's frame to that of the manipulator. The RTDE library [36] is used to calculate the inverse kinematics of

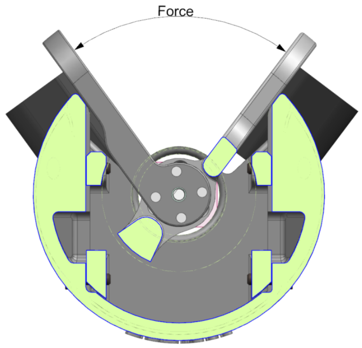


Fig. 3: Principle of work

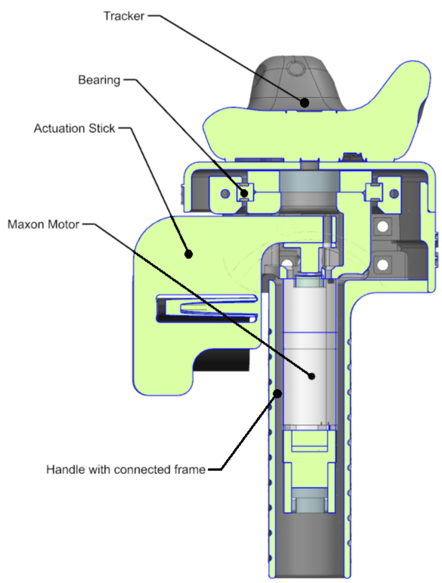


Fig. 4: Internal schematic of the controller

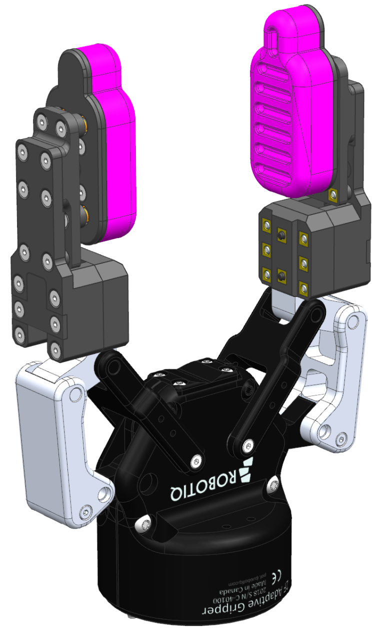


Fig. 5: Gripper with a force-feedback robotic finger

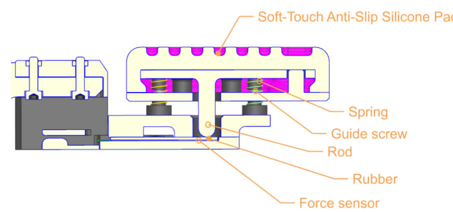


Fig. 6: Schematic of the robotic finger mechanism

the UR3 and transmit the corresponding joint angles to the manipulator.

B. Robotic finger

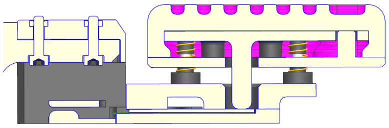
For gripping operations and receiving force feedback, we placed a force sensor in the gripper finger (Fig. 5). We used the Robotiq 2F-85 as the gripper and the RP-C7.6-LT as the force sensor. The main challenge in integrating a force sensor into robotic gripper end effectors lies in determining an optimal placement. Directly gluing the force sensor onto the gripper's end [37] is not an ideal solution, as it limits force feedback to a small sensing area and increases the risk of sensor damage.

One possible solution is the development of a custom sensor [38] based on a spring and potentiometer integrated into the gripper's structure. In our work, we designed a unique gripper finger that provides force feedback from the entire surface of the end effector while enhancing adaptability and protecting the force sensor (Fig. 6).

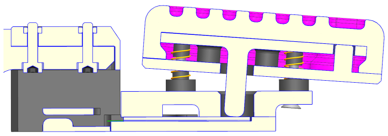
The working principle of our mechanism involves pushing a rod, which is part of the pad structure, onto the force sensor through a rubber sheet (Fig. 7). Springs return the pad to its original position after the force is removed, while guide screws secure the pad to the structure. The Soft-Touch Anti-Slip Silicone Pad was cast from two-component silicone into a plastic mold. This pad prevents slipping, ensures more uniform force distribution, and enables soft gripping of objects.

C. Electronics

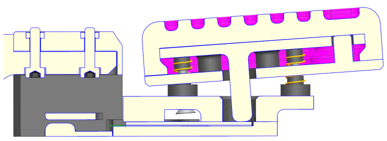
The system (Fig. 8) consists of two printed circuit boards (PCBs): the Force Sensor Board (Fig. 9) and the Motor Control Board (Fig. 10). The Force Sensor Board measures the force exerted by the gripper, linearizes the signal, and transmits it to the Motor Control Board. The Motor Control Board then computes the control force required for the motor, processes encoder position data, and transmits all relevant information to a computer. The Motor Control Board is based on an STM32F401RET6TR MCU, which manages all system operations. The board is equipped with reverse polarity and overcurrent protection. It communicates with the computer via a galvanically isolated USB interface and exchanges data with the Force Sensor Board using the RS-485 protocol.



(a) Initial position



(b) Force applied to the end of the pad



(c) Force applied to the beginning of the pad

Fig. 7: Operation of the mechanism under applied force

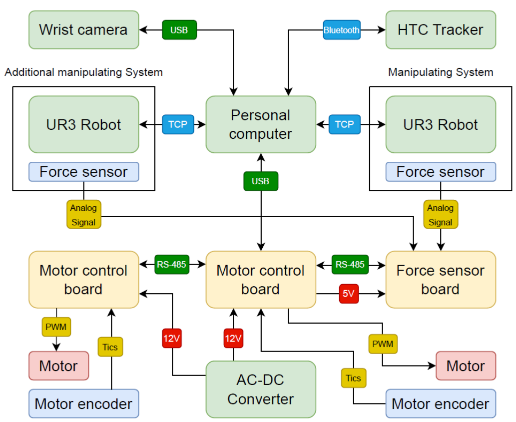


Fig. 8: System architecture

The Force Sensor Board based on an STM32F303CBT6 MCU. It receives power and control commands from the Motor Control Board, acquires data from the force sensor, linearizes the signal using an operational amplifier with a bipolar power supply, and transmits the processed data back to the Motor Control Board.

1) Force Sensor Linearization System: The employed force sensors operate based on the principle of decreasing electrical resistance under applied pressure. However, the resulting voltage response is nonlinear and requires linearization. This is achieved using an operational amplifier with a bipolar power supply. The force sensor serves as the input to a current-to-voltage converter, whose output is governed by the following equation:

$$V_{\text{OUT}} = V_{\text{REF}} \times \left(-\frac{R_G}{R_{\text{FS}}} \right) \tag{1}$$

where:

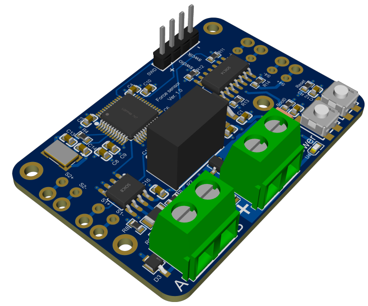


Fig. 9: Force Sensor Board

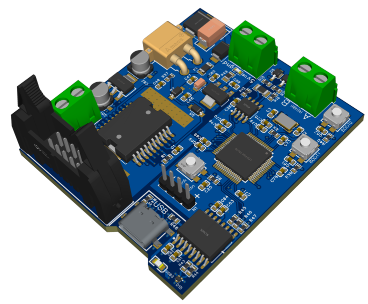


Fig. 10: Motor Control Board

- $V_{\text{REF}} = 3.3$ V is the reference voltage applied to the operational amplifier.
- R_G is the feedback resistor in the operational amplifier, which determines the gain of the circuit.
- R_{FS} is the resistance of the force sensor in its fully compressed state.

Using this equation, you can select resistors for force sensors with different force feedback characteristics.

IV. User Study

A. Experimental Setup

A series of experiments were carried out to compare the amount of force necessary for pick-and-place tasks while using the proposed system Prometheus (Fig. 11). Users were asked to perform a pick-and-place task with an egg in two scenarios: (1) with force feedback and (2) without force feedback.

Participants: Fifteen participants, six females and nine males, capable of performing the experiment, aged 24.1±4.3 years, volunteered to participate in the experiments.

B. Experimental Results

The results indicate that, on average, users applied 35.77% less force in the first scenario compared to the second when grasping and manipulating the object (Fig. 12). This finding demonstrates that force feedback enables users to apply only the necessary amount of force for object handling, which is particularly important when working with fragile items.

Fig. 11: Eggs experiment

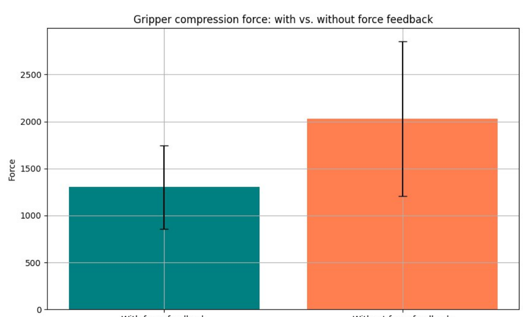


Fig. 12: Gripper compression force: with vs. without force feedback

V. Conclusion

In this paper, we introduce Prometheus, a motion capture-based teleoperation system designed for data collection to facilitate the training of neural networks. The system enables precise and efficient real-time control of a robot, including both unilateral and bimanual manipulation. It utilizes the HTC Vive virtual reality platform to track the operator's movements and incorporates a custom-designed force feedback mechanism. This haptic feedback enhances control accuracy and provides a more immersive user experience.

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