Embracer: A Wearable Encountered-Type Haptic Controller for 3 DoF Input and Feedback

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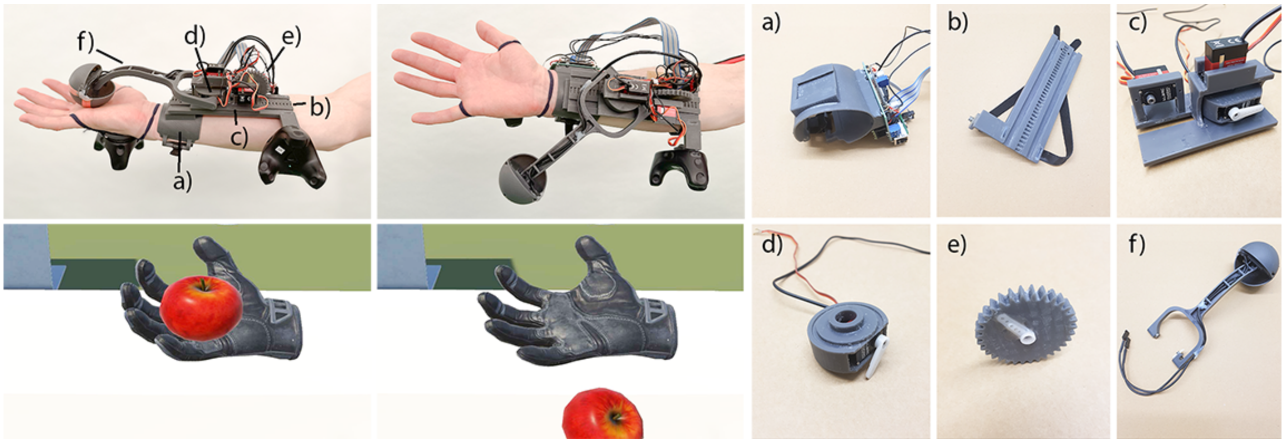

Figure 1: We present Embracer, a 3 DoF wearable encountered-type haptic controller. It has 3 actuated axes of motion to allow the end effector to freely target arbitrary positions on the user's palm. Through lateral actuation, it can create stretching sensations in the user's hand. It can also sense manipulation along the same 3 DoF and grasping of the end effector. Embracer consists of: a) the bracelet with the microcontroller and the power regulator, b) the rail with a tracker mount and Velcro straps, c) the carriage with the three servo motors, d) housing of the pivot axis, e) the gear for the linear axis and f) the lever.

Abstract

The lack of haptic sensations beyond very simple vibration feedback diminishes the feeling of presence in Virtual Reality. Research suggested various approaches to deliver haptic sensations to the user's palm. However, these approaches are typically limited in the number of actuation directions and only focus on enhancing the system's output, ignoring haptic input. We present Embracer, a wrist-mounted encountered-type haptic controller that addresses these gaps by rendering forces along three axes through a sphere-shaped end effector within the user's palm. Using modified servo motors, we sense user-performed manipulations of the end effector as an input modality. In this paper, we contribute the design and implementation of Embracer together with a preliminary technical evaluation. By providing a more comprehensive haptic feedback system, Embracer enhances the realism and immersion of haptic feedback and user control.

CCS Concepts

• **Human-centered computing → Haptic devices**; **Pointing devices**; *Virtual reality*.

Keywords

virtual reality, haptics, input device, force feedback

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1 Introduction

From education [12] and training [2] to therapy [7] and rehabilitation [14], Virtual Reality (VR) has found rapid adoption. This proliferation of VR experiences is rooted in continuous improvements in the visual and auditory experiences, which offers users a stronger feeling of immersion and presence [18]. Although these developments bring us closer to Sutherland's ultimate display [19], commercial VR systems still largely ignore the haptic aspects of the experience such as (passive) touch, pressure, or stretch [15].

In recent years, research proposed a variety of systems that provide passive touch [3], stretch [1, 22] and active force feedback [17] through the use of handheld controllers [5, 23], exoskeletons [8, 9] or finger-mounted [4, 20] wearable devices. However, such devices typically permanently occupy the palm of the user's hand [21], limiting other uses of the hand. More recently, research started to explore wrist-mounted folding mechanisms [16]. Such systems typically employ a spherical end effector that is actuated into the user's palm, allowing it to exert various counterforces. When not in use, the end effector can fold away. While practical and useful, the latest embodiments of this approach, such as Haptic PIVOT by Kovacs et al. [13], WeATaViX by de Tinguy et al. [6] or WriMouCon by Jo et al. [11] share some limitations: First, they do not allow lateral movement and thus can not create the sensation of movement on the skin as is perceived, for example, when pulling on a rope. Second, while increasing the realism of output, the input (i.e., the interaction with virtual elements) continues to be centered around buttons and triggers, diminishing the immersive potential.

In this paper, we add to the stream of research on wrist-mounted devices providing encountered-type haptic feedback and go beyond the state of the art by addressing these two gaps in the literature. We present Embracer, a wearable encountered-type haptic controller for three degrees of freedom (3 DoF) input and feedback. Building on the insights and proven designs of such devices presented by prior work, we add two additional actuated axes of motion to allow free movement of the end effector towards and within the palm of the hand. Through lateral actuation, while being in contact with the user's palm, Embracer enables it to render complex tactile sensations such as stretching and pressure directly within the hand. To further address the mismatch between input and output, we modified the built-in motors of Embracer to read the internal potentiometer values directly, enabling more direct and natural input by manipulating the end effector. Thereby, scenarios such as pulling an apple from a tree in multiple directions, simulating the friction of a rolling ball in the user's palm, enhancing the realism of object interaction within a virtual environment are possible.

Additionally, the device can replicate the recoil of an opened champagne bottle, providing dynamic feedback corresponding to the virtual activity. These applications not only showcase the Embracer's ability to deliver nuanced haptic sensations that correspond to complex virtual interactions but also highlight its potential in training simulations and entertainment applications, where realistic tactile feedback significantly enhances the user experience.

We contribute the design and implementation of Embracer, a wrist-mounted on-demand encountered type controller that can act as input and output devices.

2 Embracer: Design and Prototype

When reviewing the body of related work, we found no wrist-mounted haptic controllers that can simultaneously offer:

(1) force-feedback in arbitrary directions at any location and
(2) more natural input modalities beyond buttons or touch.

To address these gaps, we designed Embracer: a wearable, encountered-type haptic controller that provides omnidirectional feedback and allows for natural input. The system provides three controllable axes, and the position of the motors is directly monitored using built-in potentiometers, enabling precise positioning of the end effector. Two independently working touch surfaces on the end effector can sense different types of grasps.

2.1 Mechanical Structure and Movement

The Axes. Motion along the **linear axis** is facilitated by a 170 mm rail (see fig. 1 b)) mounted along the forearm, starting below the wrist and attached to a bracelet. Three servos mounted on a carriage slide along this rail to allow the end effector to move along the palm of the user's hand. This setup translates the servo motor's movement to a gear, enabling 60 mm longitudinal motion. The **swing axis** is located at the front of the carriage. We aligned the servo vertically to the open hand to provide lateral rotations of the end effector. The swing motion covers a range of +/-34° to both sides of the linear axis. The **pivot axis** controls the distance between the end effector and the user's palm. The servo motor for this axis is positioned below the swing axis and above a bearing, facilitating its movement. The pivot servo generates rotational movement, using a 180 mm Y-shaped lever to swing up to 100° into the palm. One arm connects to the servo, while the other attaches to a bearing inside the housing, allowing stable low-friction movement.

End Effector. Similar to de Tinguy et al. [6], we use a spherical end effector with a 65 mm diameter that can be easily replaced by unscrewing three screws, allowing for different shaped end effectors for various use cases.

Wristband and Tracking. We designed an ergonomic wristband to hold all hardware that should remain stationary when the carriage reacts to a command. All construction parts were printed using a *Formlabs 3* printer with Tough 2000 Resin material. Finally, we attached a Vive Tracker 3.0 to the side of the rail to track the entire device in the VR space. Figure 1 provides more details on the individual parts developed while creating Embracer.

2.2 Hardware and Sensing

The Embracer is driven by a teensy 4.1 (600MHz) and connected via ethernet/UDP to the PC. The microcontroller receives control values from the VR scene and controls the servo motors. We decided to use mini servos with metal gears (3x ALZRC DS452MG) to keep the controller as light and sturdy as possible but still provide the necessary speed and force. We modified the servos to receive absolute position readings by soldering a cable directly to the motor's potentiometer pin. Further, we added capacitive sensors, similar to Kovacs et al. [13] and de Tinguy et al. [6]. However, we improved on their design and incorporated two stripes of copper foil at the end effector, connected to our HW-763 sensors, allowing us

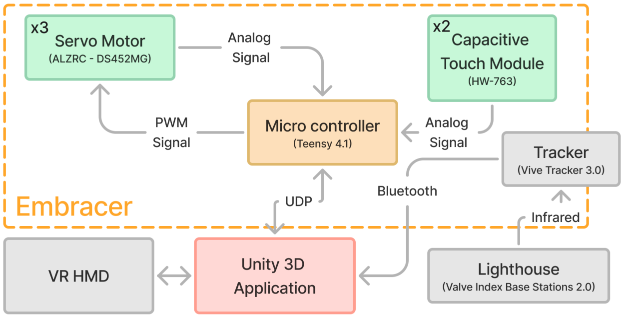

Figure 2: Schematic of the main system components.

to distinguish between light contact and intentional grip. The total weight of the Embracer is 421g, including the mechanics of the controller, the servos, the electronics and the microcontroller, but excluding the Vive Tracker 3.0 (an additional 75g).

2.3 Motor Control and Simulation

To operate the hardware components smoothly, considerable effort went into the motor control and simulation environment.

Motor Control and Communication. When used as an input controller, the servo motors are turned off, and the position and orientation values along the three axes are read directly from the potentiometers. For actuation, motions use ease-in and ease-out schemes to avoid unwanted spikes in acceleration and protect servo mechanics from damage. Servo values and capacitive sensor values are sent to the VR PC, and control values for the three axes are received via UDP at a constant sampling rate of 60Hz.

We considered the control reference frame to be centered in the standby position of the controller (All angle rotations at 0 degrees and linear axis in the farthest position in the direction of the shoulder) and the linear axis as the x coordinate, with positive values toward the wrist, while the y axis is the normal vector arising from the controller. We modelled the forward kinematics of the controller on the basis of the convention described above.

Simulation in VR. We implemented a simplified mechanical simulation in Unity 2020.3). The controller is modelled 1:1 in VR, including its motion profiles. Whenever another VR object comes close to it, the object motions are projected onto the controller axes, and the corresponding motions and forces are derived and sent to the controller. Only the closest one is tracked when several objects are in range, constituting a reasonable simplification. When a capacitive sensor detects a signal, the currently tracked object is fixed to the controller's position. If no such signal is detected, it will continue its motion and correctly bounce or deflect. This behavior allows the user to realistically hit, catch, drop and throw objects in the VR scene (See Figure 2 for the complete system workflow).

3 Technical Evaluation

Forces. To evaluate forces at the motors' maximum voltage of 7.8V, we used a load cell sensor connected to an Arduino board, calibrating the system with a 50g weight and conducting a series of 100 impact and constant pressure tests for each axis. With our lever (180mm), we achieved a motor torque of 46N*cm. With this, we are able to provide a haptic perception of 0.26 kg. However, our controller is also capable of withstanding an initial impact force of 8.68N, enabling rapid object collisions with almost 900g impact.

Speed. We conducted a speed analysis using the potentiometers, calculating speed per cm (linear axis) and per degree (other axes). For the swing axis, we measured the time it took to move from -34° to +34° with the lever in a horizontal position. We also tested the pivot axis by moving the lever up and down by 90°, resulting in a speed of 211ms rising, and 193ms falling (average over 5 trials). The speed measurements ranged from 3.125 cm/sec to 466 deg/sec.

Latency. Embracer exhibits no noticeable latency between visual output and haptic feedback. We measured the round-trip time of the UDP connection and found an average speed of 4 ms. Additionally, the teensy 4.1 controls and processes commands for the motors faster than what our application can visually render at 60Hz, which is already sufficient for humans to perceive the scene as latency-free (See Appendix for the complete set of measurements).

4 Limitation & Future Work

Weight and the Gorilla Arm. We acknowledge that the controller may cause fatigue with prolonged use, amplifying the gorilla arm problem [10]. We plan to address this by removing the wired connection, using lighter materials and lighter tracking.

Simultaneous Use as Input and Output device. To the best of our knowledge, Embracer is the first wearable encountered-type haptic device to use the same end effector for both input and output. We plan to overcome the current limitation to a single simultaneous function by using external potentiometers to reliably detect the movement of the end effector during actuation.

Evaluation. We deliberately evaluated Embracer at a technical level to provide a solid foundation for future research. While we are confident that this is a strong contribution to the field, future work should investigate how end users perceive these novel forces. Potential user evaluation scenarios include assessing user comfort and interaction perception in virtual reality applications, such as the feeling of "recoil," "pull," and "passive" forces.

5 Conclusion

In this paper, we presented Embracer: a wearable encountered-type haptic controller that can generate omni-directional haptic feedback in the palm of the user's hand while also providing input. We are convinced that this paper contributes valuable insights to designing and implementing wearable encountered-type haptic input and output interfaces. However, the prototype and methods have limitations and raise questions for future work.

6 Open Science

We encourage readers to reproduce and extend our work. The CAD data are open-sourced and made available on GitHub[1].

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[1] https://github.com/mimuc/embracer

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Appendix: Technical Evaluation

Axes	Peak-Force (Impact)	Steady-State Force	Angular/Linear Speed	Acceleration
Pivot Axis (Falling)	8.68N	2.58N	465 deg/sec	2.41 deg/sec^2
Pivot Axis (Rising)			426 deg/sec	2.02 deg/sec^2
Swing axis	5.77N	2.84N	466 deg/sec	2.79 deg/sec^2
Linear axis	25.49N	18.16N	3.125 cm/sec	0.016 cm/sec^2

Table 1: Measured forces, speeds and accelerations in the technical evaluation.