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LeVR: A Dynamic Active Haptic Proxy to Render Weight in Virtual Reality

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I. INTRODUCTION

Virtual Reality (VR) training has gained popularity in recent years due to its versatility and safety in applications such as industrial education and rehabilitation. The addition of haptic information [1] during VR training, e.g., on the physical properties of a virtual object like mass and inertial forces, has been shown to enhance motor learning [2] and increase movement economy and precision [3]. However, rendering these dynamic forces remains a challenge, particularly for ungrounded haptic devices. While ungrounded devices allow for a large free workspace, they often face limitations such as high cost, latency, and side effects through noise, vibrations, or airflow [4]. To address these limitations, we present the first design and evaluation of *LeVR*, a low-cost, portable haptic proxy (see Fig. 1). *LeVR* aims to provide information about virtual objects' weight by rendering the vertical forces experienced when lifting objects. It achieves this by dynamically accelerating a motorized sled along a linear rail upon interaction with the virtual object, allowing users to perceive differences in object weight through a simple and portable design.

II. METHODS

A. LeVR Working Principle and Mechanical Design

LeVR creates the illusion of a virtual object's weight by accelerating a motorized sled along a linear rail to recreate the dynamic forces, $F = m \cdot a$, experienced upon lifting an object with mass m. For this, the acceleration a when lifting the device, and thus the virtual object in the simulation, is measured by a 6-axis accelerometer (MPU6050, InvenSense, USA). We used a cable-driven capstan transmission to accelerate the sled while reducing backlash and the device's weight. We aimed to render weights from the industrial context, such as wrenches and screwdrivers, ranging from $17\,\mathrm{g}$ to $227\,\mathrm{g}$. Therefore, we chose a moving mass of $315\,\mathrm{g}$ to maximize the rendered forces while we kept the overall device weight to $691\,\mathrm{g}$ to avoid fatigue. Following the research conducted by [5], we aspired to provide a stimulus for the first $100\,\mathrm{ms}$ of the interaction with the virtual object and account for maximum physiological accelerations of the wrist during lifting movements of $6.45\,\mathrm{m/s^2}$ [6]. The minimum rail length of $9.3\,\mathrm{cm}$ was calculated so it would allow for a maximum generated force of $m_{\text{max}} \cdot a_{\text{max}} = 0.227\,\mathrm{kg} \cdot 6.45\,\mathrm{m/s^2}$ to be applied over $100\,\mathrm{ms}$, followed by a deceleration phase at one-third of the acceleration. The final rail length was set to $15\,\mathrm{cm}$ to account for future adjustments and provide a buffer for testing.

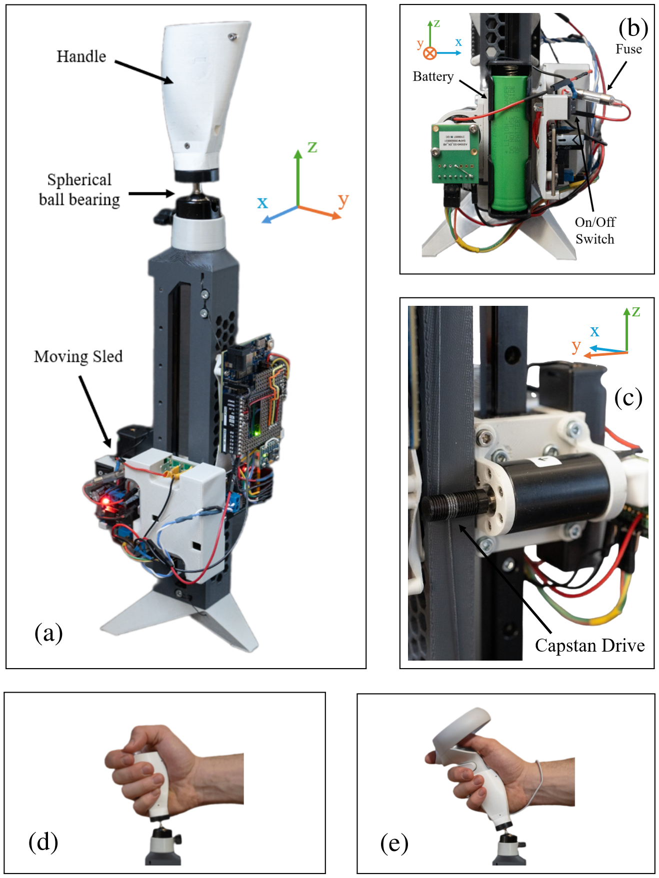

Fig. 1. Overview of *LeVR*: (a) The sled with the attached motor (2342048CR, Faulhaber, Germany), battery, voltage regulator, and motor driver (SOLO PICO, SOLO Motor Controllers, Italy) moves along the vertical axis. (b) The battery and voltage regulator provide a portable power supply. (c) The linear Capstan drive transmission. (d) *LeVR* is held by the handle only when used stand-alone. (e) A VR controller can be inserted into the handle when used with a VR game.

The device features an ergonomic grip with a spherical bearing in the handle to accommodate different wrist angles. *LeVR* can be powered by connecting a DC power supply to the motor driver, which powers all other electric components, or by using a battery, enabling a completely wireless setup. The total cost of the device amounts to 365 €.

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B. Control

We run an impedance control scheme on the microcontroller (Arduino R4 Wifi, Italy) to calculate the motor's required torque to render the desired virtual mass m, either set stand-alone on the device or received from a VR game via Wi-Fi. This entails the calculation of gravitational and inertial forces to render the virtual mass, compensate for gravitational and inertial forces acting on the motorized sled, keep it in a central position on the linear rail, and protect it from running into the rail limits. The device operates with an update frequency of $500\,\mathrm{Hz}$ when running stand-alone and $150\,\mathrm{Hz}$ with the VR game.

C. Experimental Evaluation

We conducted a device characterization using a series of step responses, with reference forces of $0.11\,\mathrm{N}$, $0.29\,\mathrm{N}$, $0.64\,\mathrm{N}$, $0.99\,\mathrm{N}$ and $1.46\,\mathrm{N}$, ten steps each, and step durations of $0.2\,\mathrm{s}$. Further, we evaluated the device's frequency response using a linear chirp signal sweeping from $0\,\mathrm{Hz}$ to $20\,\mathrm{Hz}$, with an amplitude of $2.92\,\mathrm{N}$ over $10\,\mathrm{s}$. To measure the output, *LeVR* was mounted in a tripod with a 6-axis force/torque sensor (Mini45, ATI, USA).

We also ran a pilot study with three participants (1 female, 2 male, ages 30–34 years) to evaluate whether *LeVR*'s haptic feedback enabled weight discrimination in a VR environment (2022.3.25f1, Unity Technologies, USA). The participants wore a VR headset and held *LeVR* in their right hand with the embedded VR controller (Quest 2, Meta, USA) (Fig. 1e). They were asked to lift and sort five identical-looking virtual cubes with masses $17\,\mathrm{g}$, $45\,\mathrm{g}$, $99\,\mathrm{g}$, $145\,\mathrm{g}$ and $227\,\mathrm{g}$ into sockets labeled "very light" through "very heavy" (see Fig. 2). During the lifting movements, *LeVR* rendered the mass of each cube based on the measured device acceleration as previously described. Six rounds were conducted per participant, with masses reshuffled between trials.

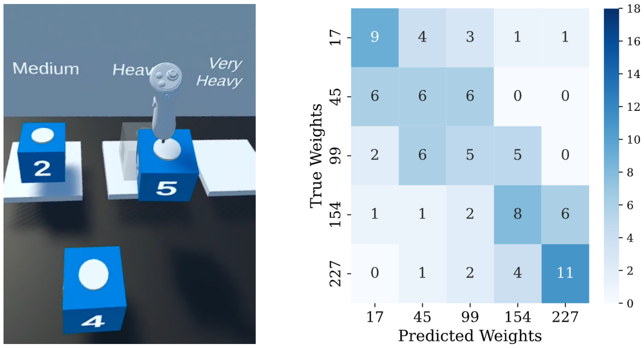

Fig. 2. Left: A user interacting with a virtual object in the VR environment in Unity. Right: The aggregated confusion matrix of all three participants.

III. RESULTS

Latencies between interaction with the virtual object and torques produced by the motor were $3.9\,\mathrm{ms}$ running stand-alone and $11.3\,\mathrm{ms}$ with the VR game, staying below a noticeable threshold of $25\,\mathrm{ms}$ [7]. The step response tests revealed that the device rendered stimuli with durations dependent on the exerted force: $5\,\mathrm{ms}$ for $0.29\,\mathrm{N}$, $20\,\mathrm{ms}$ for $0.64\,\mathrm{N}$, $50\,\mathrm{ms}$ for $0.99\,\mathrm{N}$, and $70\,\mathrm{ms}$ for $1.46\,\mathrm{N}$. We also observed that undesired lateral forces, caused by the motor block's asymmetric mass distribution relative to the device's center of gravity, reached up to $18.07\,\%$ of the intended vertical forces. For the lowest force input of $0.11\,\mathrm{N}$, no measurable stimulus was generated. We measured increasing overshoot with larger reference forces, peaking at $148\,\%$ for $1.46\,\mathrm{N}$, resulting in a maximum force of $3.62\,\mathrm{N}$. The averaged onset delay and rise time were $1.6\,\mathrm{ms}$ and $0.7\,\mathrm{ms}$, respectively. The frequency response test revealed a phase crossover frequency at $11\,\mathrm{Hz}$.

The outcomes from the pilot study suggest that the participants could generally differentiate the lightest (17 g) and heaviest (227 g) masses, as visualized in the confusion matrix (Fig. 2). However, lighter objects (17–99 g) were frequently confused, and performance varied greatly between participants. Further, all users reported fatigue from the device's weight, and lateral movements induced noticeable swinging.

IV. DISCUSSION AND CONCLUSION

We presented *LeVR*, a low-cost, ungrounded haptic proxy that creates the illusion of weight in VR by partially simulating the dynamic forces resulting from the interaction with virtual objects. *LeVR* preserves a free range of motion and can generate low-latency feedback, making it particularly suitable for dynamic interactions. The results from the device characterization and pilot user study suggest that *LeVR* can generate distinguishable stimuli that may be perceived as different weights. However, force rendering inaccuracies and side effects, such as swinging of the device, still limit its current suitability for slow or static interactions. Future work should improve the device's design, e.g., to minimize overshoot, mitigate swinging, and reduce its weight. We hope our work provides a stepping stone in research on haptic weight rendering in VR, ultimately benefiting industrial training and rehabilitation outcomes.

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