CLAW: A Multifunctional Handheld Haptic Controller for Grasping, Touching, and Triggering in Virtual Reality

Inrak Choi[1,2], **Eyal Ofek**[1], **Hrvoje Benko**[1], **Mike Sinclair**[1], **Christian Holz**[1]
[1]Microsoft Research, Redmond, WA, USA
[2]Stanford University, Stanford, CA, USA
irchoi@stanford.edu, {eyalofek, benko, sinclair, cholz}@microsoft.com

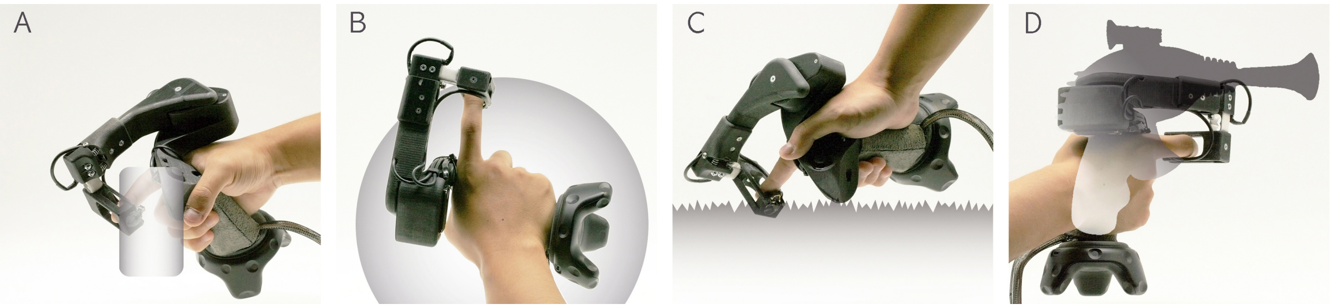

Figure 1. ***CLAW VR controller*** **provides articulated movement and force feedback actuation to the user's index finger which allows for convincing haptic rendering of: (a) grasping, (b) touching, (c) rendering virtual textures, and (d) triggering.**

ABSTRACT

CLAW is a handheld virtual reality controller that augments the typical controller functionality with force feedback and actuated movement to the index finger. Our controller enables three distinct interactions (grasping virtual object, touching virtual surfaces, and triggering) and changes its corresponding haptic rendering by sensing the differences in the user's grasp. A servo motor coupled with a force sensor renders controllable forces to the index finger during grasping and touching. Using position tracking, a voice coil actuator at the index fingertip generates vibrations for various textures synchronized with finger movement. CLAW also supports a haptic force feedback in the trigger mode when the user holds a gun. We describe the design considerations for CLAW and evaluate its performance through two user studies. The first study obtained qualitative user feedback on the naturalness, effectiveness, and comfort when using the device. The second study investigated the ease of the transition between grasping and touching when using our device.

ACM Classification Keywords

H.5.1 [Information Interfaces and Presentation]: Multimedia Information Systems-Artificial, Augmented, and Virtual Realities; H.5.2 [User Interfaces]: Haptic I/O

Author Keywords

Virtual Reality; Haptics; Force Feedback; Controller Design; Grasping; Touching; Texture; Trigger;

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INTRODUCTION

The capabilities of current interaction devices to render meaningful haptics lag far behind their abilities to render highly realistic visual or audio content. In Virtual Reality (VR) and Augmented Reality (AR) scenarios, there is a strong need for haptic devices that let the users feel, touch, push, grab and manipulate virtual objects around them with the similar tactile and force stimulation that the users are familiar with in the real world. To make them effective in a variety of VR/AR scenarios, there is also a need for such devices to allow for free movement in space, i.e., to not have the devices be grounded, but instead be held or worn on the user's body.

To address these challenges, researchers have proposed various types of hand-held or hand-worn haptic devices such as exoskeleton hand gloves for grasping [1], fingertip devices for shear force and weight [27], vibrotactile devices for textures [19], controller type devices for touching [4], and exoskeleton haptic suits for kinesthetic feedback to the entire arms [5]. While potentially effective in rendering specific types of haptic feedback, the main shortcoming of these solutions is that they are mostly single purpose devices, unable to render a range of feedback required for a variety of envisioned VR/AR scenarios. For example, the 3RRS device [9] can render shear and pressure at each fingertip, but is unable to render forces between fingers and is thus unable to effectively simulate grasping soft or hard objects. In contrast, we argue that *creating an effective VR/AR haptic controller device requires the design to be multi-purpose in nature*.

In this paper, we present the design of a novel haptic controller, named CLAW, that augments a typical handheld controller functionality with force feedback and actuated movement to the index finger (Figure 1). The primary design principle of our controller is to provide a multi-purpose controller that contains both the expected functionality of a VR controller (i.e., buttons, 6DOF movement control, thumb joysticks, trigger) and enables a variety of haptic renderings for the most commonly expected hand interactions: grasping, touching, and triggering. Our CLAW controller changes its corresponding haptic rendering by sensing differences in the user's grasp and situational context of the virtual scene. Besides shooting feedback, CLAW can act as an active trigger button. By selecting particular finger force and positions, CLAW can simulate various trigger release points, non-linear responses and haptic behaviors such as a click. The force sensor can also act as an analog input function, e.g., interacting with a slider, changing attributes of a paint brush or pen in a drawing program.

Our paper makes the following three contributions:

1. The design and implementation of a handheld haptic controller capable of rendering three types of haptic feedback in a single multi-purpose device. Three types of haptic feedback include: (a) finger forces when grasping virtual objects, (b) rendering of a virtual object's shapes, stiffness, extent, and textures and (c) realistic trigger feedback while shooting.

2. The idea and the implementation of switching haptic rendering modes based on changes in the user's grip.

3. Two evaluations of the CLAW controller with respect to the overall effectiveness in use and ease of transition between grasping and touching modes.

In the rest of this paper, we first review the state-of-the-art in handheld haptic technologies and commercial VR controllers. We discuss design considerations for a VR haptic controller that integrates both existing controller functions and multiple haptic sensations. We then introduce our CLAW prototype, built in an iterative fashion based on those design requirements.

Finally, we discuss the results of two user studies with our CLAW controller. The first study collected qualitative feedback from participants using our controller to manipulate a variety of virtual objects. Users performed and switched between various interactions, such as picking, squeezing, touching, rubbing, and triggering. The second study explored the effectiveness of our grasp-based method for switching between the pick and place task and pushing a virtual button task. The results from our experiments show that participants were highly effective and confident when manipulating virtual objects with CLAW and that switching between different haptic modes was quick and mostly error-free.

RELATED WORK

We differentiate between two types of haptic devices: *grounded* and *ungrounded* devices [16], where the former are devices fixed to environment (e.g., desk mounted) while the later are attached, held or worn on the human body (e.g., hand). Although grounded devices such as PHANToM [21], HIRO [14], or SPIDAR [23] are effective in rendering external kinesthetic forces to the user's hands in VR, they restrict the user's movement to a small working area which is contrary to our goal of free movement in space. Therefore, we focus our review of related work to ungrounded haptic interfaces only, and, in particular, to wearable and mobile devices that provide haptic feedback to the VR user.

Exoskeleton Haptic Devices

Exoskeleton gloves render kinesthetic feedback when the user holds or touches a virtual object. There have been many efforts to make exoskeleton gloves lightweight, small, and better-performed using various mechanisms. Researchers developed haptic gloves using tendon-driven mechanisms [1], passive actuation mechanisms with magnetorheological fluid for various force feedback [6], simple mechanical brakes for low cost [11, 15], a pneumatic actuator for higher force to weight ratio [7], jamming technologies for variable stiffness control with passive actuation [28, 40]. A gripper style device (force feedback to the thumb and index finger) was also developed for teleoperation [18].

Exoskeleton haptic devices render compelling grasping and touching feedback for every finger of the user's hand. However, they have some limitations in a practical way. They require long time to put on or take off. They are cumbersome and constrain the user's motion. They are expensive because of the number of actuators required. These factors limit their commercial use for VR.

Fingertip Haptic Devices

More recently, researchers examined devices that can be mounted on the user's fingers, stimulating cutaneous haptic feedback to the mechanoreceptors on fingertip skin [17]. Pacchierotti et al. developed a belt mechanism with two motors. By actuating the two motors in same directions or opposite directions, they can render shear force and normal pressure on the fingertip [25]. Minamizawa et al. also used this mechanism to stimulate the sensation of gravity [22]. Tsagarakis et al. developed a device directly contacting between fingertip skin and two motor shafts for the sensation of slipping and shear forces [33]. Solazzi et al. used a voice coil actuator to move a plate for the sensation of contact [29]. Multi-linkage wearable fingertip devices render the slopes of virtual surfaces [9, 27]. Yem et al. combined a mechanical linkage and array of electrodes to generate both shear force and texture [38]. Culbertson et al. attached a voice coil actuator at fingertip to simulate virtual kinesthetic sensation using asymmetric vibration [12].

Fingertip haptic devices are lighter than exoskeletons and render various types of cutaneous feedback. These devices lack of ability to create kinesthetic feedback because they are not connected through mechanical linkages. Also, they need to be placed on the fingertip to receive desired haptic feedback which may take time to put on and off. Applying kinesthetic forces to these actuators may also compromise their effectiveness. These features may not be desirable for general use.

Handheld Haptic Feedback

Handheld devices have gained popularity, in particular, in commercial VR and AR systems. The main reason is that they are easy and convenient to use; A user may hold a controller to interact with a virtual object and quickly lay it aside to interact with real objects, for example a keyboard with bare hands. Also, handheld devices are stable during interaction because users hold them while most wearable devices rely on gloves or straps.

Although most available haptic feedback is limited to simplistic vibrotactile actuation, recent works tries to enrich their haptic rendering capabilities. Researchers developed various handheld haptic devices using a palm stretch mechanism to simulate transient kinesthetic feedback [26], weight-shifting mechanisms to simulate the sensation of holding objects of different mass distributions [31, 39], actuated gimbals for simulating external force [24, 35], and a linearly vibrating mechanism to give perceived heaviness [3]. Most of these devices render haptic feedback to the user's palm or entire hand but they do not apply haptic feedback to fingers so that they are not capable of high fidelity rendering for grasping and touching.

There are handheld haptic controllers interacting with the index finger. MacLean et al. attached a rotating wheel for creating shear force [20]. Benko et al. used tilt-platform and vertically actuated pin array to convey normal surface and textures underneath the user's index fingertip while the user moves the device in space [4].

While previous devices in this category rendered only one kind of haptic feedback such as shear force [20], normal force [4], and textures [4], we integrate multiple haptic feedback into a single multi-purpose device, guided by the user's grip. Song et al. looked at thumb gestures as a guide for prehensile manipulation tasks [30], while CLAW compares thumb gestures for prehensile and non-prehensile manipulation tasks, enabling untrained users to naturally navigate the controller affordances depending on the task.

In this paper, we leverage the mobility and the flexibility offered by today's available handheld controllers. Our proposed device incorporates most of the capabilities of existing commercial controllers yet enabling new functionalities that will increase the haptic realism and allows the user to do hold objects, touch surfaces and manipulate them using natural interaction.

DESIGN AND IMPLEMENTATION OF CLAW

The design goal of our haptic controller is for its seamless use in a virtual environment. It should provide human-scale forces in rendering 3D shapes as well as the sensation of holding a rigid or soft object between the user's fingers. It should generate various textures when users rub virtual surfaces with their index finger. It should also enable a gun trigger sensation. It should provide all the above in a compact and lightweight form factor to facilitate unencumbered mid-air operation.

The main challenge in designing our controller was integrating the default operation provided by current commercial VR systems (e.g., pointing, button selections, user locomotion, trigger) with the haptic output to render virtual shapes and forces experienced from grasping. By maintaining the functionalities of existing controllers in our design, we leverage users' familiarity to facilitate a smooth transition, as well as the ability to plug into existing use-cases and applications.

Design Rules for an ideal VR Haptic Controller

Based on the considerations above, we made a set of design requirements for an ideal VR haptic controller (Table 1). We consider these design rules for our prototype.

	The features expected for an Ideal VR Haptic Controller
1	Handheld for ease of use
2	Input buttons on the controller manipulated by thumb and a trigger manipulated by the index finger for shooting games.
3	6 DOF tracked in space
4	Untethered
5	Ergonomically comfortable
	The features we would like to add
1	Ability to render shapes of virtual objects
2	Ability to render forces from touching or grasping virtual objects such as elastic and inelastic stiffness, damping, inertia, shear force, and weight
3	Ability to render textures of virtual surfaces
4	Realistic haptic effect for triggering
5	Ability to understand some natural manipulation gestures

Table 1. Our design requirements for a VR haptic controller.

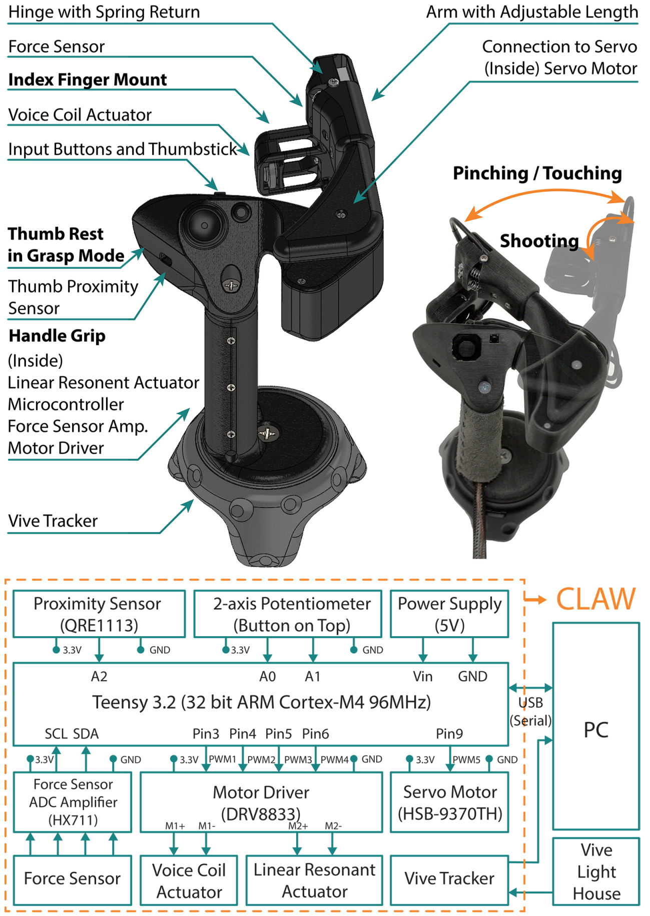

Figure 2. (Top Left) Overall system configuration and components. (Top Right) Actual shape of the controller and its motion range. (Bottom) Mechatronis components block diagram with detailed pinout information.

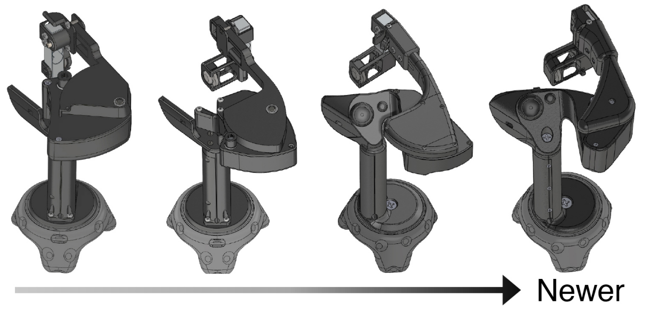

Figure 3. We repeated the prototyping process multiple times for a better ergonomic design and performance. Four CAD models are shown as examples.

Variable	*Value*
Max. Force	Up to 30N
Stiffness range	Up to 10N/deg (5.73N/mm)
Motion range	45°, 0.1° resolution for position control
Force sensing	0 ~ 50N range, 88 Hz sampling rate, 0.023mN resolution, 0.048mN noise (std. dev.)
Force control	Admittance display. 333Hz PD control loop by extrapolating force values.
Hand tracking	Vive tracker
Weight	420g (335g w/o Vive tracker)
Dimensions	90*170*190 mm
Power draw	30mA (idle), 1A (max. force) @ 5V

Table 2. Technical specifications of the controller.

The CLAW VR Controller

Based on our design rules, we designed and built CLAW to extend and integrate the functions of existing VR controllers and multiple haptic feedback modes. Figure 2 (Top) shows the general appearance and the arrangement of mechatronic components. Figure 2 (Bottom) shows the block diagram and general connection information of mechatronic components.

CLAW is handheld where users grab the handle grip with their middle, ring, and little fingers, placing their thumb either at the side on the thumb rest or on top of the controller. The controller features a proximity sensor for detecting thumb positions and several buttons and a thumbstick for explicit user input. Users place their index finger into the opening at the end of the arm, where a voice coil actuator (VCA) under the fingertip renders textures. A force sensor just above the index finger mount senses user input force, including touch, grasping, and triggering. An additional revolute hinge with spring return on the force sensor implements CLAW's trigger mechanism. A servo motor drives the arm, which connects to the main body through another revolute joint.

The handle grip encloses a Teensy 3.2 microcontroller, an HX711 ADC board for sensing force, and a DRV8833 motor driver to power the VCA at the index fingertip and the linear resonant actuator (LRA) in the handle grip. We mounted an HTC Vive tracker at the bottom for 6DOF tracking. Two cables provide power and USB communication with the controller.

The core element of CLAW is the rotating arm as shown in Figure 2 (also see the green part of the controller in Figure 4) to render kinesthetic feedback, i.e., the sensation of force, actuation and displacement of the index finger. CLAW integrates an VCA on the finger mount for cutaneous rendering on the fingertip as shown in Figures 1 and 2. As the user makes contact with virtual objects in the scene, CLAW opens its arm accordingly to move the index finger outward, keeping it on the boundary of the virtual surface in the same 3D position. Refer to Figure 1 (b).

The rotating arm of the controller is mechanically powered by a Hitec HSB-9370TH servo motor. We designed all connecting components using CAD and printed them in PolyJet on an Objet Connex 3 printer. A Teensy 3.2 USB microcontroller PCB is mounted in the controller handle and controls the servo.

To make an ergonomic haptic controller for various hand sizes, we designed an arm with adjustable length. We interated through the designs shown in Figure 3 to optimize ergonomics.

CLAW achieves most of our initial design guides, but three items remain. CLAW is currently not untethered, does not render shear forces to the user's finger, and it does not generate a sense of weight. At this time, we prioritize the other features and these are remaining as future work.

For power consumption, we measured idle current of 30 mA at 7.4v and maximum current of 1A for maximum force exerted. We believe these are within the capability of an untethered, battery operated controller in the future, even with the additional need of powering a 6DOF tracker and radio link.

In essence, CLAW is a combination of a handheld controller base, an index finger exoskeleton, and a fingertip vibro-tactile actuator. Table 3 shows a comparison between CLAW and state-of-art haptic devices for VR. To our knowledge, this is a first handheld controller that integrates this functionality into a single compact design.

Mode Switching Via Thumb Grip Sensing

Our high-level goal is to allow for multi-purpose haptic rendering without requiring a complex method to change between different modes. For touching and rubbing interactions, the user's thumb is usually not on the thumb rest. While pinching or grabbing objects, the thumb is on the thumb rest, aligning with the index finger, to produce a counter-force to the index finger as shown in Figure 4. The counter-motion of both fingers supports simple grasping or pinching tasks (prehensile) while the index finger alone supports touching tasks (non-prehensile) [8, 13]. While the user touches virtual objects using only their index finger, we provide a convenient rest area on the front of the device (where the joysticks and buttons are located), to ensure the thumb is out of the way.

The thumb position and the VR application intent determine the operation mode of the device. To sense the thumb, we integrated an optical proximity sensor (QRE1113) into the controller's thumb rest. The sensor detects when the thumb is on the thumb rest which covers the sensor as shown in Figure 1 (a) and Figure 4 (Top-left). In this mode, the thumb aligns with the index finger as in a pinching or grasping attitude. This switches the controller into 'Grab' mode, during which the controller physically adjusts to the size of the object between

	Easiness of Mounting	*Functions of existing controllers (Trigger, directional joystick etc.)*	*Haptic Feedback*
CLAW	Easy (handheld)	Yes	Kinesthetic feedback for grasping, touching, and triggering. Vibration normal to fingertip for textures.
Vive Controller	Easy (handheld)	Yes	Simple vibrotactile feedback only.
Grabity [10]	Hard (Mounted to two fingertip)	No	Kinesthetic feedback for grasping (binary) and simulating weight. Vibrotactile feedback for touching.
Schorr et al. [28]	Hard (Mounted to two fingertip)	No	Tactile feedback (sensory substitution) for grasping, touching, simulating edges and weight.
Reactive Grip [27]	Easy (handheld)	Yes	Simulating external forces in grip motion only.
CyberGrasp [13]	Hard (Mounted to whole hand)	No	Kinesthetic feedback for grasping and touching.

Table 3. Comparison of CLAW and existing devices. CLAW integrates all functionality found across previous devices into a single, handheld controller by offering multiple interaction modalities and rendering the corresponding haptic feedback.

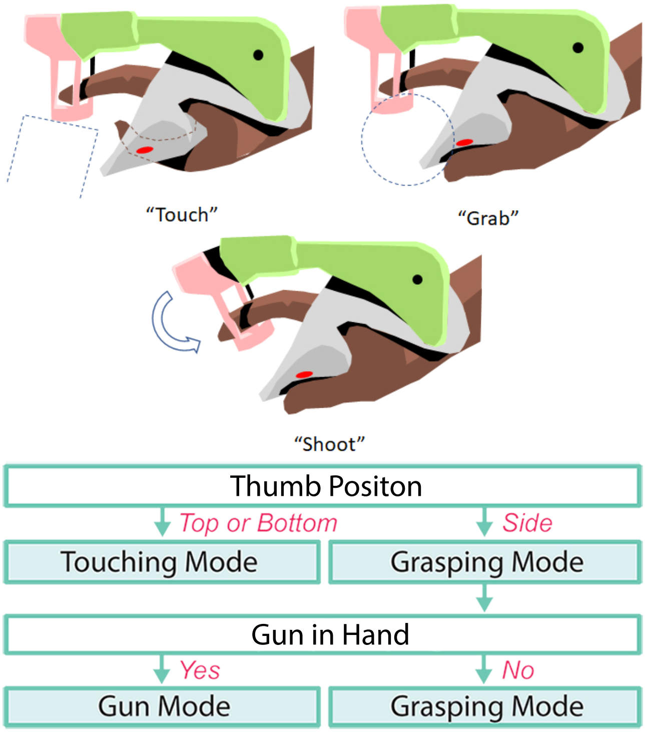

Figure 4. CLAW operates in three haptic modes: (Top-left) When the user tucks away the thumb, off the thumb rest, the controller is in its default 'Touch' mode. (Top-right) The proximity sensor (red) detects when thumb and index finger align, and switches the controller into 'Grab' mode. (Middle) When the user has 'grabbed' a gun, the rotating arm (green) locks in place and mimics a gun, and the finger module (pink) acts as a trigger. (Bottom) The haptic mode is decided based on the user's thumb position and VR scenario.

the index finger and the thumb in the virtual world along with its stiffness in response to squeezing force input. When the thumb is not on the thumb rest (does not align with the index finger), the controller switches back to 'Touch' mode and renders surfaces and textures that lie under the index fingertip as shown in Figure 4 (Top-right).

The block diagram in Figure 4 details how CLAW changes its operation mode. In the initial 'Touch' mode (user's thumb is off the proximity sensor), CLAW resets the arm to a minimum (closed) position, which cannot be altered by the user through force input. Once the controller comes into contact with a virtual object, the arm moves the user's finger according to the amount of object penetration and simultaneously renders normal forces based on the stiffness of the object.

When users are in 'Grasp' mode with their thumb covering the proximity sensor, they can open and close their index finger freely. Once they grasp a virtual object, the servo motor impedes motion at the object's grasp width, rendering grasping forces based on the stiffness of the object. If the object a user has picked up is a gun, the controller enters 'Trigger' mode and locks the arm in a fixed open position. At this point, users may only bend the finger hinge to trigger, which, when above a force of 4N, generates a quick back and forward motion from the servo, simulating an automatic weapon, proximity for haptic trigger feedback in addition to vibration feedback under the index finger. To drop the gun and return to 'Touch' mode, a user moves their thumb off the sensor (i.e., drops a gun).

Force Control

One of the important features of CLAW is that it generates forces in a closed-loop fashion by sensing the forces applied by the user's index finger. Therefore, not only does the controller change the index finger position for rendering the shapes of virtual objects, it also renders various stiffness of grasped objects.

Most existing haptic devices [1, 21] are *impedance* displays that sense positions for input and render force as output. The structure of an impedance display is simple: a closed-loop position control system that does not require a force sensor. However, it should be highly backdrivable with low inertia. The gear ratio is limited so it requires a large and heavy motor to create human-scale force. CLAW is an *admittance* display [2, 34], sensing force as input and rendering position as output (as opposed to mere force). While CLAW needs a force sensor and a force closed loop on top of a position loop, it does not require backdrivability. CLAW can have high inertia with a compact and lightweight geared motor. We thus believe that this admittance display is a better type for a controller form factor haptic device.

The force sensor (strain gauge on a cantilever beam, 0-5kg) measures the force values sampled by the HX711 ADC board. The 24bit ADC board has enough resolution (0.000023N with 0.000048N one standard deviation noise), but it is limited at 88Hz sample rate. To minimize the problem of a low sampling rate compared to the much higher servo position update rate, we derive new force values by using a simple slope extrapolator: calculate the amount of the change from the previous force values but at the higher sampling rate. For the position servo input, we use a simple PD controller operating at 333Hz and tune the gains empirically for quick response with no instability. We use a commercial servo motor (Hitec HSB-9370TH) in which the position loop is run internally closed loop but open loop externally, receiving new position commands at 333Hz. Table 2 shows the detailed specifications of CLAW.

INTEGRATING CLAW INTO A VR ENVIRONMENT

CLAW connects to a PC through USB (serial link) and powered through a separate 5V and 2A power adapter. The baud rate is 2,000,000 bits per second. A HTC Vive headset is used for VR display. Unity 2017 software is used for rendering VR scenes, and our display update rate is 90 Hz.

There are several ways in which our touching and grasping interactions could be implemented in a VR environment (e.g., using collision dynamics, or kinematic control). While CLAW is capable of supporting all such methods, we discuss our implementation below, in addition to discussing the details of the haptic rendering that CLAW enables.

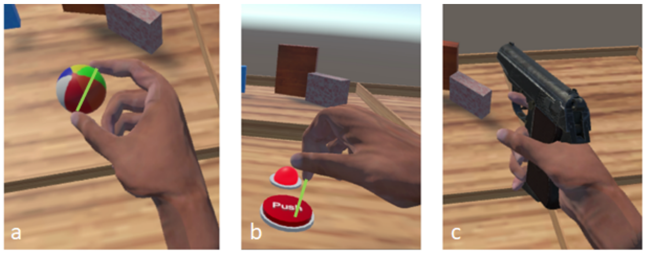

Figure 5. The avatar hand in Unity's VR scene when (a) grabbing, (b) touching, and (c) triggering. Note: the green rays emanating from the fingertips are hidden from the VR user and only visualize directions for determining collisions in VR.

Grasping: Force Between Thumb and Index Finger

For grasping interactions (i.e., when CLAW is in the grasping mode), our VR simulation tests for possible contacts below the thumb and index finger by checking for collisions against a ray originating at each fingertip and pointed towards the opposing finger. If each one of those rays intersects the same virtual object within a small tolerance buffer (1cm) from the fingertip, we consider this virtual object grabbed (Figure 5 (a)), and from that point on, render its position and orientation under kinematic control. While not completely physically correct, this kinematic approach to grasping makes this interaction easier and more controllable, while still giving the user the ability to grip, squeeze and move virtual objects in a natural manner.

When rendering varying elastic stiffness of grasped objects, we use Hooke's Law for spring behavior to compute the amount of visual deformation needed based on the force exerted on the CLAW by the index finger. We also haptically render similar spring behavior on the controller itself.

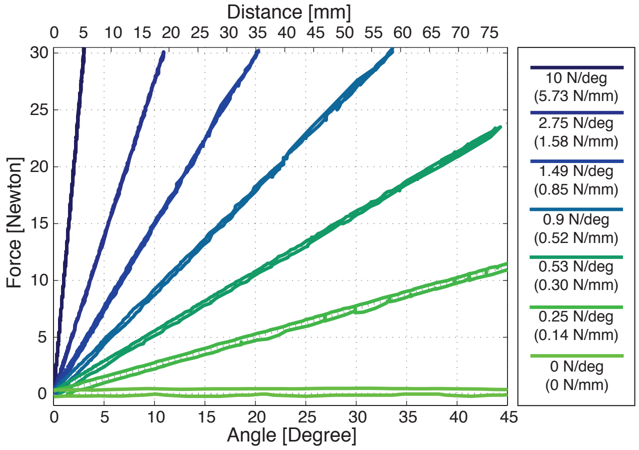

Figure 6. Various stiffness rendering through CLAW.

Under closed-loop force control system, CLAW generates up to 30N of grasping force and up to 10 N/degree (5.73 N/mm) of stiffness. Note that stiffness can be inelastic (like clay) or elastic (like a spring) or a combination. Using this feature, we can simulate various stiffness of different materials like rigid objects (wood, metals) and soft objects (clay, rubber balls, sponges) and even non-linear properties. To evaluate how correctly the controller renders stiffness, we measured forces with different elastic stiffness. Figure 6 shows seven force curves with different levels between the minimum stiffness (0 N/mm) and the maximum stiffness (5.73 N/mm). We generated these curves from actual data sensed by the calibrated strain gauge force sensor and the position input to the servo. We see that the force curves keep consistent stiffness (slopes of force curves) over the entire motion range, although with a small dead band for each curve (0.5N), likely due to static friction, gear slop, hysteresis of the servo encoder, etc. inside the servo motor.

CLAW also senses the force imparted by the index fingertip with a 0.000023 N resolution and 0.000048N noise (one standard deviation) and controls positions with 0.1°(0.17mm) resolution. This actuation capability is generally beyond human perception as shown in previous work: The just noticeable difference (JND) of length discrimination between the thumb and index finger is 1-3mm, the JND of grasping force is 7-10%, and the JND of compliance during squeezing motion is 22% [32, 37]. More rigorous measurements of the perceived stiffness require a future human subject experiment.

From the measurements above, we show that our controller with closed-loop force control renders variable stiffness for rigid and soft materials. However, not every object in the real world has a perfect elastic stiffness like the force curves shown in Figure 6. This hysteresis effect changes the force curves. The pushing forces and recovering forces are not matched. In Figure 7, we simulated three force curves with different hysteresis levels. With elastic stiffness rendered with hysteresis, CLAW generates more realistic grasping forces.

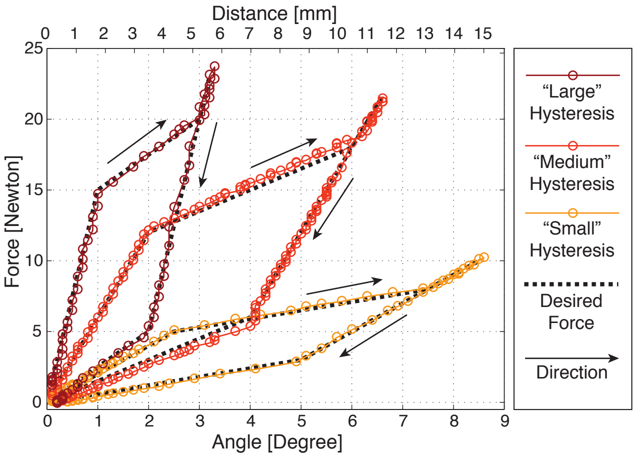

Figure 7. Various hysteresis curve rendering through CLAW.

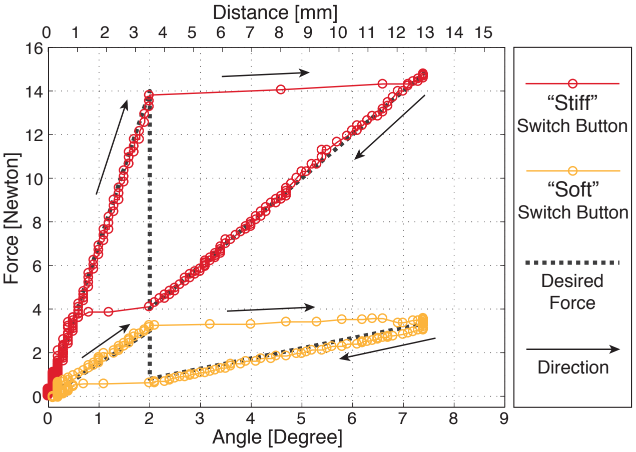

Figure 8. Virtual switch forces rendering.

Surface Rendering: Elevation of the Index Finger

In 'Touch' mode, users feel the shapes of virtual objects through the position change and the forces applied to their index fingertip. In the VR simulation, we build on the height rendering process of NormalTouch [4]: When the user makes contact with virtual objects in the scene, CLAW adjusts the angle of the index finger arm to lift the index finger corresponding to contact with the surface. This causes the user's finger to follow the surface of the virtual object rather than penetrating it upon contact as shown in Figure 5 (b). The actuation mechanism by which CLAW renders normal forces in 'Touch' mode is the same as in 'Grasp' mode.

A variant of this rendering is to simulate a clickable button with sizable hysteresis, i.e., one that produces a 'click' when actuated. We derived two force curves for a "stiff" click and one for a "soft" click as shown in Figure 8. Dotted lines are the desired force curves. Through application of these curves, users feel a stiff elastic force as they push the button. When they reach the hysteresis threshold, they encounter a lower spring force, causing a click sensation as well as a lower return force until they reach the 2nd hysteresis point, at which a higher spring force is encountered.

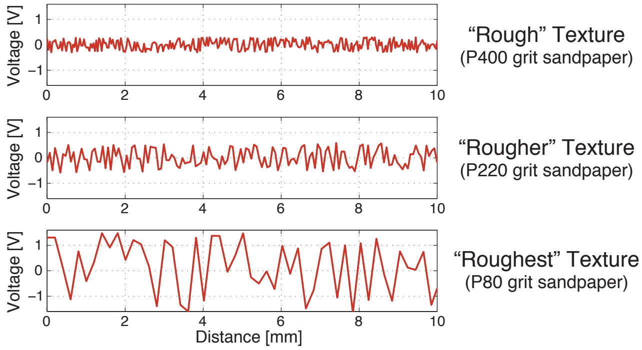

Figure 9. Various roughness rendering using the voice coil actuator under the fingertip mount.

Texture Rendering: Spatial Vibrations of the Index Finger

In 'Touch' mode, CLAW simulates various textures by actuating a voice coil actuator on the fingertip. The microcontroller in CLAW plays back pre-generated haptic patterns. The texture actuator loop runs at 14kHz, and data is played back with speeds corresponding to the user's calculated finger speed and required amplitude information (i.e., grit size of the surface).

The Vive Tracker reports hand (and hence fingertip) positions to the PC at 120 Hz. From Unity, we calculate and report the scalar velocity of the fingertip with respect to the touched surface to CLAW's microcontroller at 90 Hz. As mentioned above, CLAW plays back the corresponding stored haptic pattern to the actuator. CLAW modulates the playback speed proportional to the velocity of the fingertip motion and adjusts the playback amplitude according to other parameters such as overall texture roughness, applied force, etc. This allows users to feel fingertip-normal vibrations simulating various textures when they stroke a virtual surface.

The three graphs shown in Figure 9 are examples of textures CLAW can generate. We simulated different grit size sandpapers (P400, P220, P80). The microcontroller plays back the haptic pattern with 500 random (colored noise) values for the magnitude.

Trigger Mode for Grabbed Objects

Most existing VR controllers rely on a vibration actuator for haptics, when the user pulls the trigger. To generate a realistic trigger feeling with objects that afford this type of interaction, we use the servo motor on the controller arm and the LRA inside the handle grip.

When the user grabs an object that can be triggered (e.g., a water pistol), our VR environment switches CLAW into a dedicated 'Trigger' mode as described above (Figure 5 (c)). The controller from that point on handles the trigger input and reports it back to the VR environment to produce corresponding animations. Similarly, the controller returns to 'Touch' mode when the user switches their thumb accordingly, informing the VR system to reflect this state.

In 'Trigger' mode, the controller arm is locked to a fixed position and users can either pull the trigger or drop the item in this mode. The force sensor at the fingertip measures the trigger force and once the trigger force is higher than a threshold (4N),

Figure 10. Haptic playground in Study 1 contains different objects with different haptic qualities.

CLAW "discharges" the weapon as follows: the servo motor decreases the arm angle quickly with its maximum speed while the LRA simultaneously turns on and vibrates the handle. Because the arm angle decreases fast, the user's trigger force drops below the threshold, resetting the arm to the original position quickly and turning off the LRA. This combination of the servo motor and LRA actuation produces stronger and more realistic trigger haptics than the vibro-tactile feedback sensations produced by traditional controllers.

EVALUATIONS

We performed two experiments to investigate the following core questions regarding our CLAW controller:

1. How effective is the CLAW controller in rendering a variety of different haptic sensations?
2. How easy and reliable is it for users to switch between different haptic modes of the controller?

Participants

To answer these questions, we recruited 12 participants (6 female) with ages ranging from 26 to 61 *(M=32, SD=9.4)*. All our participants were right handed, as our prototype controller was designed for a right-handed user.

Each participant was asked to perform two experiments, after which they filled a questionnaire, and when finished, they were given an $8 gift coupon.

Study 1: Qualitative Feedback for CLAW Interactions

Participants were introduced to the CLAW controller, and were shown a physically simulated virtual playground (Figure 10) containing a range of objects that can be manipulated by grabbing and touching:

- A set of cubes, cylinders and balls that can be grabbed by the user when using the controller in 'Grab' mode, moved and stacked, and pressed on, or pushed by the index finger in 'Touch' mode.
- A set of cubes with different level of softness that the user may grab, stack, and squeeze.
- Several buttons that the user may press, in 'Touch' mode, and turn small lights on and off.

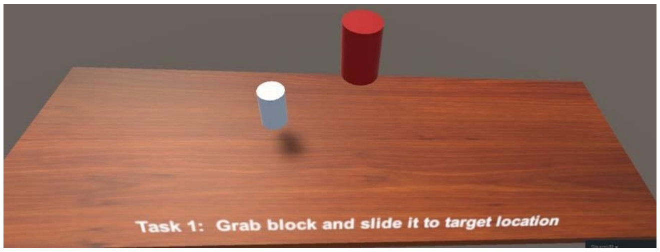

Figure 11. Study 2 Grab Task: A participant needs to grab the white cylinder and align it with the red target.

Figure 12. Study 2 Touch Task: A participant needs to tap the red target.

- A seesaw model that can be used for object stacking, or for pressing in 'Touch' mode.
- A gun that can be grabbed by the user, and then be used to shoot objects in the scene.
- A model of a car that can be touched to explore its shape or be grabbed and stacked.
- Two unmovable gray boxes that exhibit textured haptics of regular spaced grooves when the user's index finger slides along their surface.

To familiarize participants with CLAW's capabilities, the experimenter demonstrated one operation with each of the above objects to each participant. Then, each participant put on a HTC Vive HMD, and used the CLAW controller in the scene for 10 minutes while freely manipulating objects and verbally expressing opinions.

Study 2: Task Switching Evaluation of Grab vs. Touch

Our second experiment was designed to evaluate how reliable and easy is our mode switching technique based on sensing the thumb location. To do so we designed an experiment that required the participant to frequently switch between grabbing and touching modes. Participants performed a series of 50 tasks of two types (described below in detail) with the CLAW controller, while wearing a HTC Vive HMD.

The first task required the participants to use the grab mode of the controller by moving their thumb to lie in front of their index finger, grab a white cylinder, drag it until it aligns with a red target red of same size (Figure 11) and then release it.

The second task requires the participants to move their thumb away from the tip of their index finger to bring the controller to a 'touch' mode, and then push on a red circular button labeled "Push" (Figure 12).

The experiment contained 25 grab tasks and 25 touch tasks in a random order. Completing each task would have immediately presented the participant with the next task, until the experiment is finished. The entire experiment took the participant less than 3 minutes to complete.

After finishing both Study 1 and 2, participants were given a questionnaire consisting of 30 questions related to their experience, each to be ranked on a 1-7 Likert scale. The entire study lasted approximately 30 minutes.

Results and Discussion

Study 1 Results

Table 4 shows the result of the first part of our questionnaire, which directed at participant's experience in Study 1 and used the standard Presence Questionnaire (PQ) by Witmer and Singer [36]. According to the typical scoring of PQ, we report the total and average values, for 5 aggregated categories: "realism", "ability to act", "quality of interface", "ability to examine" and "self-evaluation of performance", as well as the score overall. All average scores were all in the positive range (4-7).

Aggregate categories	*Total*	*Avg. Score*	*Std.Dev.*
Total (All questions)	107.3	5.6	0.6
Realism (Questions 7+8+9+10+11+14+17)	37.8	5.4	0.7
Ability to act (Questions 1+2+8+9)	24.2	6	0.6
Quality of interface (Questions 14+17+18)	12	4	0.7
Ability to examine (Questions 11+12+19)	18.2	6.1	1
Self-evaluation of performance (Questions 15+16)	12.5	6.3	1

Table 4. Study 1 (haptic playground) assessment using Presence Questionnaire [36].

	Question	*Avg. Score*	*Std. Dev.*
1	How well were you able to pick up an object in the VE?	6.3	0.9
2	How well could you explore the VE using touch?	4.5	0.8
3	How well were you able to switch between touching and picking?	5.7	1.1
4	How well were you able to manipulate and fire the gun?	6.2	1.3
5	How realistic was the gun action?	5.6	1.4
6	How well were you able to disambiguate surface texture?	4.3	2
7	How realistic was it to feel different textures?	4.3	1.7

Table 5. Task specific questions from Study 1 and average scores (on a scale 1-7, 7 being best).

Examining the participants comments from Study 1 (playground) and specifically the qualitative results aggregated in Table 5, it is clear that the ability to pick up objects was the most favorite task. Participants gave positive comments, such as *"Best experience at grabbing objects in VR I've tried - better than gloves." "Soft vs. Rigid objects was great!"*.

Touching operation also received positive scores, but lower than grabbing. Several reasons may explain this. First, while holding an object between the user's fingers was a realistic and satisfying experience, the realism of touching a surface is limited by the ungrounding of the controller. CLAW moves the tip of the index finger to avoid solid object penetration, but we cannot stop the user from pushing the controller into the surface, which is when the rendering stops. We thus implemented 'penetration compensation' [4] to render surface shapes during such user behavior, even if the user has pushed the controller inside an object. However, we left this compensation disabled during our user study as it impacts the participant's ability to pick up an object that is close to the surface. Re-enabling this may increase the practical dynamic range of our surface rendering, and thus enhance the user's satisfaction.

Secondly, we detect touch by the index finger by examining a ray originating at the tip of the finger in the direction of the finger (similar to [4]). If this ray hits an object close to the finger, we render a touch event by pushing the index finger back. While in reality the user finger may hit objects along it entire finger, e.g., pushing an object by the side of the finger, this limitation of our current implementation may limit the realism of touching. Although most touch events are indeed performed using the fingertip, we will widen detection of touch events in future versions.

The gun operation was a favorite of the users. The movement of the controller arm along with a vibrotactile rumble generated an impression of recoil not available by current commercial controllers.

CLAW renders texture with limited fidelity in its current implementation due to the latency of our VR setup. CLAW itself is capable of rendering high-fidelity textures at 14kHz, but Unity and the Vive tracker report hand position and motion updates at slow rates only (120Hz and 90Hz, respectively). This is too low for spatial rendering, but could be remedied by using faster haptic software (e.g., CHAI3D) and a better tracking system (e.g., OptiTrack Prime17W). Integrating the 6 DOF tracking system into CLAW would also save the roundtrip through the PC and improve CLAW's current operation.

Study 2 Results

The second experiment looked at the ability of new users to use a multi-modality controller, by requesting the users to execute fast tasks of changing modality. The participants were able to execute 50 tasks with an average of 27 flips between grabbing and touching tasks.

On average, participants executed grabbing task in 5.9 seconds *(SD=2)* while touching a button task, which was a less complicated task, was completed in 2.9 seconds *(SD=1.6)*.

We measured the time that it takes for a user to flip the mode of the controller, by looking at the last frame before the execution of the task, where the user thumb was in the wrong position. This time includes the reaction time of the user, understanding that the mode of the task has changed, the movement of the thumb from pinching position to touching or vice versa, and any mistake done after it. The average time to move from pinching position to a touching position was 1.4 seconds *(SD=0.9)*, while the average for the move from touching position to a pinching mode was 3.6 seconds *(SD=1.5)*. One possible reason for the longer time it takes to move into pinching mode, is that the thumb must move to a specific location in front of the index finger tip, and above the thumb sensor for this transition to register. The other direction, on the other hand, only requires the thumb to move away a bit from the sensor to detect its absence.

When asked to assess their ability to switch between modes, on a 1-7 Likert scale, the participants ranked it very positive at 5.6 *(SD=1.3)*. Overall, no participant reported any issues or confusion about switching between modes and none of them had concerns on the reliability of this method.

In summary, we received overwhelmingly positive feedback on the use of CLAW in a variety of VR manipulation tasks. The feedback from our studies (while mostly qualitative in nature) confirms that CLAW is an effective device for multiple interactions in VR and that our thumb grip mode switching method is a reliable and easy to learn method that follows the user's natural tendencies when interacting with real objects.

LIMITATIONS AND FUTURE WORK

While we have designed CLAW with VR scenarios in mind, it could easily be used in AR. For example, having a fully tracked, handheld, wireless CLAW would permit the user to interact with virtual objects situated in the real world.

However, this future version would require several improvements to our current implementation. For example, our device is not yet wireless. Although all mechatronic components are already embedded inside the controller, the device is tethered because of the communication and power supply. Incorporating Bluetooth wireless communication and integrating a battery would enable fully wireless operation. With a 7.4V 1000mAh li-po battery, the controller would run continuously at least 1 hour or more.

Our current CLAW controller is prototyped only for the right-hand use. While our design could easily be mirrored for the left hand, we have not yet done so due to our limited prototyping time and budget. Once we have two controllers for both hands, we plan to explore two-hand manipulation tasks, such as holding a larger object or shooting an arrow. Although the current controller is not capable of rendering kinesthetic feedback to the user's arms, it would be interesting to explore interactions when performing two handed tasks using two CLAWs.

The size of the user's hand also has an impact on their ability to effectively use CLAW. The current device has a length-adjustable part on the index finger arm designed to accommodate different index finger's lengths. However, our current implementation requires an additional tool (screwdriver) to make an adjustment and the amount of length adjustment is still not enough for everyone, especially children. Future work should improve this mechanism for the length adjustment, making it possible to adjust without extra tools. Furthermore, we should consider designing a smaller version for smaller hands.

Another improvement in the overall quality of the device would be to use different manufacturing and plastics in the device body. While our current prototype consists of 3D printed parts due to its rapid prototyping nature, those parts are too brittle and can break if the device falls or is mishandled (a common problem in VR where the user does not see the device while wearing a headset). We are eager to try ABS material with a FDM printer or injection molding in future iterations.

The CLAW is designed to be a multi-purpose haptic device, but there are still aspects of the haptic interaction with the hand that it does not render. For example, future work should consider adding an extension to create the sensation of slip and friction (similar to the fingertip haptic devices proposed by [9, 33]. We can adapt such a skin stretch mechanism in combination with the voice coil actuator for a more convincing shear force rendering. For rendering kinesthetic sensation to arms, we can also adapt an asymmetric vibration mechanism or actuated gimbals inside the controller as some handheld haptic devices have demonstrated [3, 35]. Another consideration would be to incorporate Peltier elements to render heat/cold sensations at the fingertips or palm.

Finally, CLAW currently depends on a relatively high-cost brushless servo motor ($150), to enable very-quiet, fast, high torque interactions. We are inspired by the recent prototypes [10, 11] that explored the use of active braking in facilitating effective grasping manipulations. Incorporating a brake, instead of a servo, might offer a path towards cheaper, more power efficient implementation which would also make it easier to commercialize the device.

CONCLUSION

In this paper, we present the design of a novel haptic controller, named CLAW, that augments a typical VR handheld controller functionality with force feedback and actuated movement to the index finger. The primary design principle of our controller is to provide a *multi-purpose* controller that contains both the expected functionality of a VR controller (i.e., buttons, 6DOF movement control, thumb joysticks, trigger) and enables a variety of force and tactile renderings for the most commonly expected hand interactions: *grasping*, *touching*, and *triggering*. We also contribute a way to switch between haptic modes, by sensing the differences in the user's grasp as well as the situational context of the virtual scene. Our user evaluations show that CLAW is highly effective in a variety of interactions with participants reporting high scores on realism, control, and manipulation ability, as well as low error rates when switching haptic modes. We hope that our CLAW controller inspires a new generation of VR handheld controllers that provide higher fidelity haptics (beyond vibro-tactile) on a single compact multi-purpose device.

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