TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction

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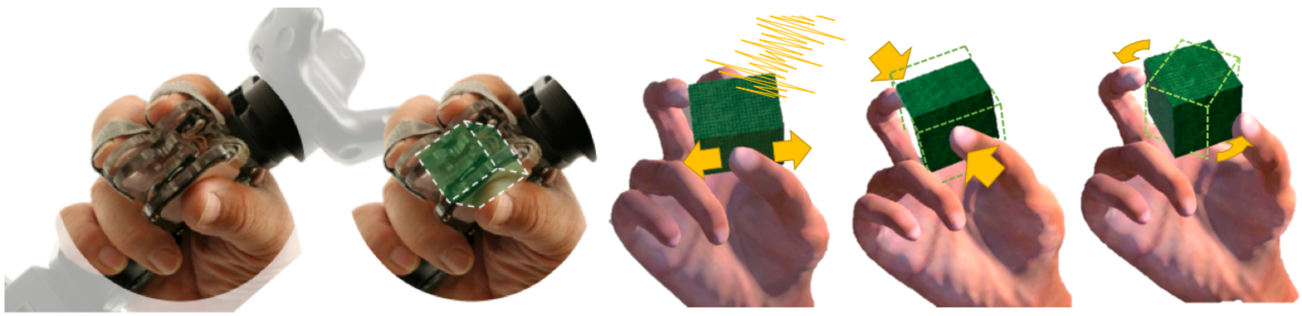

Figure 1: TORC interaction – real vs VR animation rendering.

ABSTRACT

Recent hand-held controllers have explored a variety of haptic feedback sensations for users in virtual reality by producing both kinesthetic and cutaneous feedback from virtual objects. These controllers are grounded to the user's hand and can only manipulate objects through arm and wrist motions, not using the dexterity of their fingers as they would in real life. In this paper, we present TORC, a rigid haptic controller that renders virtual object characteristics and behaviors such as texture and compliance. Users hold and squeeze TORC using their thumb and two fingers and interact with virtual objects by sliding their thumb on TORC's trackpad. During the interaction, vibrotactile motors produce sensations to each finger that represent the haptic feel of squeezing, shearing or turning an object. Our evaluation showed that using TORC, participants could manipulate virtual objects more precisely (e.g., position and rotate objects in 3D) than when using a conventional VR controller.

CCS CONCEPTS

• **Human-centered computing** → **Virtual reality**; **Haptic devices**; **Empirical studies in interaction design**.

KEYWORDS

Haptics; VR object manipulation; Haptic texture; Haptic compliance

ACM Reference Format:
Jaeyeon Lee[1,2], Mike Sinclair[2], Mar Gonzalez-Franco[2], Eyal Ofek[2], and Christian Holz[2]. 2019. TORC: A Virtual Reality Controller for In-Hand High-Dexterity Finger Interaction. In *CHI Conference on Human Factors in Computing Systems Proceedings (CHI 2019), May 4–9, 2019, Glasgow, Scotland UK*. ACM, New York, NY, USA, 13 pages. https://doi.org/10.1145/3290605.3300301

ACM ISBN 978-1-4503-5970-2/19/05…$15.00
https://doi.org/10.1145/3290605.3300301

1 INTRODUCTION

Compared to the visual wonders elicited by recent advances in consumer Head Mounted Displays (HMDs) for virtual reality (VR), haptic sensations on commercial hand-held controllers underwhelm with vibrotactile buzzing [7]. Research has explored many compelling forms of haptic feedback – ranging from exoskeletons [18] to grasping sensations [12], compliance [13], and tactile sensations [5] – but commercial acceptance has proved elusive, in part because of the mechanical complexity of the proposed systems.

Complexity of course drives up cost, but it also reduces reliability – both formidable barriers to advancing rich haptic feedback in consumer products. Devising a less complex controller is no simple matter. To simulate properties of physical objects requires pushing back (or blocking) movement of the hand, in multiple degrees-of-freedom (and hence multiple motors) at human-scale forces. This is a substantial pragmatic problem that calls for new strategies and solutions to deliver consumer-grade haptic feedback.

This type of haptic rigidity is the basis of the power grip that is needed in order to touch a virtual object and feel it is actually present [2, 21, 38]. To better render different types of objects the controller should also account for a level of compliance.

While a power grip happens at the muscular level, the precise control needed for a dexterous experience derives from the cutaneous pressure-sensitive fingertips [3]. In fact, a precision grip is a necessary element for forceful tasks, especially if we need to achieve the optimal minimum force to prevent an object from slipping.

From the motor-perceptual level, we conclude that a complete haptic device must render the full gamut of compliance up to a rigid object, to provide for the muscular, i.e. power, aspects of the experience. And, it must as well deliver cutaneous level stimulation (output) and input at the finger tips, to render enough touch precision [16, 20].

To address this challenge, we contribute TORC (Figure 1), a novel hand-held haptic controller for VR that has a rigid shape and no moving parts, making it a suitable candidate for reliable mass manufacturing. Despite its rigid design, TORC can render a wide range of compelling haptic signals, including compliance of virtual object materials, and the texture of virtual surfaces. Our controller supports a hybrid of both power and precision grasps [42] that enable users to grab virtual objects, hold them, dexterously manipulate them via a precision tripod-type grip with the thumb and two fingers, and finally let go of the virtual object at will.

The design of TORC achieves this through a novel combination of force sensors and vibrotactile actuators that act as multi-sensory substitutions for cutaneous force and rendering. Together these generate the haptic illusion of compliance, texture, grasping and releasing of virtual objects, and dexterous manipulation, all grounded to the palm.

We built a first prototype of TORC to investigate the location of force sensors and vibrotactile actuators for the precision grip, and then built a second prototype with a mobile and rigid form factor to enable both dexterous and compliance applications inside VR. In a user study, we found that participants could rotate and position objects with increased accuracy when using the dexterity and grip of our device.

Taken together, our work contributes the following:

(1) TORC is a haptic VR controller that senses finger movements for manipulating virtual objects and provides haptic feedback to in-hand interaction with virtual objects.
(2) A new design strategy that relies on brain plasticity and multi-sensory integration to produce the illusion of multi-finger compliance, grasping, and manipulation.
(3) TORC achieves all its capabilities in a robust rigid design with no moving parts applying force against the user's muscles, and includes a strong illusion of object compliance.
(4) Through sensing only finger forces and producing proper visual animations, we can provide a kinesthetic perception, including both force and proprioception.

In sum, our work demonstrates that combinations of sensing, low-force actuation, and human perception insights for sensory integration. It can produce reasonably compelling haptics without necessarily resorting to human-scale forces actuated by multiple motors along multiple degrees-of-freedom. This suggests new directions and a pragmatic path forward to deliver rich haptic experiences in consumer-grade hand-held controllers for virtual reality.

2 RELATED WORK

We review haptic interfaces for presenting a realistic sensation of virtual objects. Previous work, as well as the current one, have achieved strong illusions through electromagnetic structures and visuo-haptic interactions.

Wearable and Mobile Haptic Interfaces

We find that previous prototypes have generally tackled the problem from a particular angle, solving to a great extent either need: precise touch or power grasp.

Using wearable and mobile haptic interfaces, researchers could render the various characteristics of precision touch of virtual objects. Finger-worn cutaneous feedback displays have been proposed [10, 31, 43, 46, 55]; in those solutions, a moving mechanical effector was used for force feedback. Recently, Schorr and Okamura [49] presented finger-mounted devices of 3DOF cutaneous force feedback on the fingertip that render weight, friction, and stiffness of a virtual object.

Tactile arrays have been used for wearable and mobile texture presentation [5, 33, 34, 48]. Using thin piezoelectric actuators, Kim et al. [33] presented small and lightweight texture display that has 4×8 linear actuators on the finger tip. Recently, Benko et al. [5] presented hand-held devices that render virtual object's shape and texture using a moving plate and a height-changing actuator array.

Wearable and Mobile haptic interfaces have been used to render the shape of a virtual object in hand.To create kinesthetic force feedback to fingers, those devices were often grounded to the other parts of hand [9, 36, 50]. Because traditional hand-grounded haptic interfaces often had a heavy and complex structure, researchers have been explored a light-weight and efficient structures [11, 12, 24, 27, 28, 58]. Recently, Hinchet et al. [26] proposed a thin glove interface that renders various types of grasp using electrostatic brakes.

Though the finger-worn tactile interfaces and research delivered very realistic cutaneous stimulation at the fingertips, they have limitations for forceful input because they have no ground for pushing against to make force. On the other hand, the grounding makes unwanted force to the body part the device is grounded. In the middle there is the hand-held form factor, which allows for palm level grounding.

Hand-held Haptic Controllers

Recent work on haptic VR feedback has often investigated hand-held interfaces – haptic controllers that can present the haptic sensation of a virtual object and can give an input for manipulating the virtual object. Choi et al. [13] presented CLAW – a haptic controller assembled with a robotic structure that provides kinesthetic and cutaneous haptic feedback of virtual object. Whitmire et al. [54] presented Haptic Revolver that actuates the textured interfaces under the fingertip based on the virtual object under the user's finger in the virtual environment. They used a force input to differentiate the texture exploration mode and the sliding mode of the same movement.

These previous prototypes were very good to deliver textures if the objects were not being held between the fingers. The CLAW [13] supports a partial power grip using only the thumb and index and additionally renders object textures onto the fingertip, but operated either in touch mode or in grasp mode, but not at the same time.

Manipulation of Virtual Objects. In aforementioned devices, the grasping setup of the actual controller also plays an important role as a grounding for force input and output. As a result, manipulation of a virtual object in hand is evoked by the arm movement, not by the fingers in most of haptic controllers. Haptic Links [50] take this to the extreme and enable haptic feedback and manipulation of virtual objects across the user's hands.

These approaches miss an important part of human-object interaction: the dexterity of our fingers that we use every day to manipulate objects in real life. Hence, we believe that the design of a haptic controller should be reconsidered in order to make use of users' capabilities of fine-grained finger motions. We thus set out to devise a haptic interface that can be grasped stably with a power grip, but at the same time allows users to handle and manipulate virtual objects with high precision.

Visual and Haptic Illusions

Here, we describe a series of previous work including pseudo-haptic feedback, haptic illusions and visuo-haptic illusions that have been described to be the basis for delivering strong haptic illusions in VR.

Pseudo-Haptic Feedback. Pseudo-haptic feedback [37, 38] is a method to simulate haptic sensations using vision or sound rather than through a haptic interface. Though the term contains 'haptic', it is more about visual or auditory feedback. Since vision has been considered as a dominant sensory channel [22], various range of haptic sensations including texture [39], friction [40], compliance [4], and weight [19] have been explored using vision-based pseudo-haptic feedback.

Haptic Illusions. Haptic stimulations also have been used to create different types of haptic sensations [41]. Though there are various haptic illusions, we only introduce some of the illusions that might be closely related to in-hand applications. Kildal [30] presented a haptic illusion of compliance using a rigid cube (Kooboh) with pressure sensor and vibrotactile actuator. When a user presses the Kooboh, one feels a series of vibration bursts that simulates the sensation of deformation of the object. This method has been used to present floor compliance [53], virtual buttons [32], and tangential compliance [25]. Rekimoto [47] presented the illusion of pulling force using asymmetric vibrations. This method has been used to guide a finger in VR [31] and to present the sensation of weight in VR [11].

Visuo-Haptic Illusions. While haptic interfaces in pseudo-haptic feedback are typically static rather than changing dynamically or actively presenting haptic illusions. Recent studies have found that perceptual integration of visual feedback and dynamically changing or active haptic feedback creates another type of haptic illusions in VR [6]. Zenner and Krüger [59] presented Shifty, a hand-held haptic device with a shifting mass for presenting visuo-haptic illusion of different size, length, and thickness of a virtual object in hand. Abtahi and Follmer [1] tackle the limitation of the shape display by perceptual integration of visual and haptic feedback. They showed that the visuo-haptic illusions could effectively improve the sparse resolution, small size, and slow actuation speed of the shape display. Yem et al. [56] demonstrated the perception of softness and stickiness of a virtual object using an array of electrotactile displays on the fingertip and pseudo-haptic feedback on a visual display.

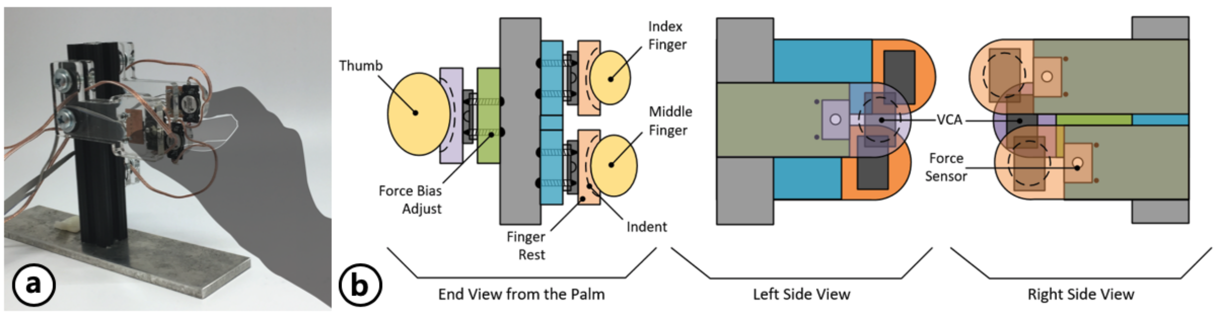

Figure 2: (a) Desk-fixed prototype used in Experiments 1 and 2 (b) diagram of end view, left side view, and right side view.

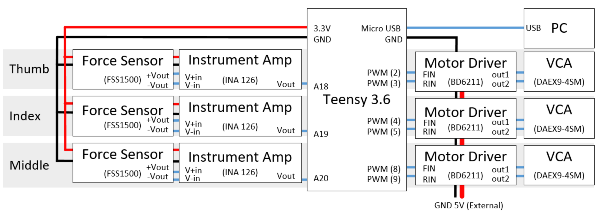

Figure 3: Schematic diagram of desk-fixed prototype.

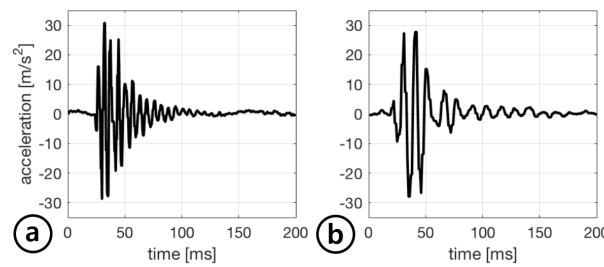

Figure 4: Measured acceleration on index finger rest with vibration from the VCA under the index finger rest. (a) without fingers touching (b) with fingers touching the finger rests.

3 TORC CONTROLLER

TORC was designed to support the precision grip [20] using the thumb and two fingers. As shown in Figure 2, we created a controller form factor that allows the user to move the thumb freely in a plane on a pad, parallel to the rests for the two fingers. This assembly enables users to explore and feel virtual objects through their fingers, and manipulate the object using the thumb. Our design of TORC had several iterations. We describe the basic elements of TORC, the experiments, and the final TORC controller design.

Implementation

We describe the basic elements of TORC that was implemented in the desk-fixed prototype for investigating the number and location of force sensors and vibrotactile actuators.

Hardware. As shown in Figure 2a, we designed the device to be held with thumb and two fingers of the right hand with the remaining fingers gripping the handle. Both finger rests and thumb rest were arranged and fixed to a rigid, non-compliant structure such that there was no perceived motion (proprioception) of the fingers or thumb when squeezing or releasing the device. The force sensors had less than 50 microns of compliance over their full force range.

Sensors and Actuators. Under each finger rest (Figure 2b), we mounted force sensors (Honey-well FSS1500) and voice coil actuators (VCA, Dayton Audio DAEX9-4SM). The force sensors measured the force on a finger or thumb rest with respect to the handle. The VCAs provided a wide-band vibrotactile actuation force with respect to the inertial mass of the VCA. We amplified the output of the force sensor using an instrument amplifier (Motorola INA-126). The amplified force was then routed to the ADC input pin of the Teensy 3.6 microcontroller. The VCA was driven by the PWM output of the microcontroller and amplified using a ROHM BD6211 full bridge with 5V external drive voltage. We used three force sensors and three VCAs on each finger/thumb rest in Experiment 1 and a force sensor and three VCAs in Experiment 2, respectively. Figure 3 depicts the schematic of the desk-fixed prototype.

Compliance Feedback. To render the compliance on a rigid device via the VCAs, we used Kildal's method [29], which presents a vibration burst for certain force changes. We rendered a 6 ms pulse of vibration (170 Hz) to the appropriate VCA for every 0.49 N change in the system force. Because there was no reference that relates the actual and virtual compliance, we set the values to represent the compliance sensation as from the real object we used by changing the force threshold. Using an accelerometer (LIS3DH, ST MicroSystems) with 2 kHz sampling rate, we measured the actual vibration force and its crosstalk on each of the finger rests 20 times. The averaged peak acceleration values (standard deviation) measured on the thumb rest with vibration from the thumb, index, and middle were 26.04 (0.85), 8.64 (1.82), and 4.97 (0.75) m/s^2, respectively. The peak acceleration values measured on the index finger rest with vibration generated on the thumb, index, and middle were 6.79 (1.02), 29.81 (0.93), and 4.30 (0.51) m/s^2, respectively. The peak acceleration values measured on the middle finger rest with vibration from the thumb, index, and middle were 5.38 (0.99), 13.66 (1.94), and 25.84 (2.12) m/s^2, respectively. The vibration was distorted with the presence of visco-elastic fingers as shown in Figure 4.

Experiment 1: Location of Force Sensors

To decide the simplest device that would provide acceptable compliance rendering, we needed to define the number and location of force sensors and VCAs. We surmised that one force sensor would suffice because, based on the opposing geometry of two fingers (index and middle) and a thumb, the adduction force (towards the palm) on the thumb is roughly equal to the sum of flexion forces (toward the palm) of the index and middle fingers when grasping, squeezing and manipulating and object. To verify our assumption, we conducted a simple blind test of two conditions. In Condition A, vibrotactile pulse was delivered to each of the three fingers depending on the change in the force sensor's output, positioned under each finger rests. In Condition B, we rendered identical vibrotactile feedback proportional to the change in the force sensor output on the thumb rest with four participants.

We asked the participants to try it and tell if they felt any difference between the two conditions. They all reported Condition B to be more compliant. To avoid the novelty confounding factor the authors also tried it and they were also not able to tell the difference. Based on these results, we decided to implement a single force sensor under the thumb rest.

Experiment 2: Location of Voice Coil Actuators

To decide the minimum number and the location of VCAs needed to render the haptic sensation of compliance on hand-held controller, we conducted a paired comparison test of 7 combinations of the location of the VCAs: Thumb (T), Index (I), Middle (M), TI, TM, IM, and TIM.

Paired Comparison Test. In the paired comparison test [45, 51], the participant compares all possible pairs of the samples and selects the samples that is more fit for criteria between A and B. The total number of the pairs led by n samples is $n(n-1)/2$. In the experiment, by considering the order effect between two samples, the pairs are presented twice. If the participants' choice is different for the same pairs, the pair is presented once more. Thus, the number of minimum trials is $n(n-1)$ and the maximum $3n(n-1)/2$ depends on the participant's answers. The score of sample A versus sample B is calculated by $(c_A - c_B)/(c_A + c_B)$ where c_A and c_B are the number of times participants chose A and B, respectively. The paired comparison method produces the subjective ranking by the sum of the scores.

We compared all 21 pairs of 7 combinations of VCA positions in the experiment. The number of trials was from 42 to 63 depending on participants' answers. To establish a reference for comparisons of the haptic sensation, we installed a silicone ball on the left side of the participants and asked the participants: which of the rendered sensations A and B was closer to the sensation from the left hand? Based on the participants' answers, we calculated the scores for each of 7 combinations.

Figure 5: Experiment setup. The participant compared two rendered sensations A and B from our device (right hand) to the sensation of an analog object, a ⌀5.08 cm silicone ball made of Eco-flex 00-30 (durometer 27.4 (Shore hardness, scale: OO)) (left hand).

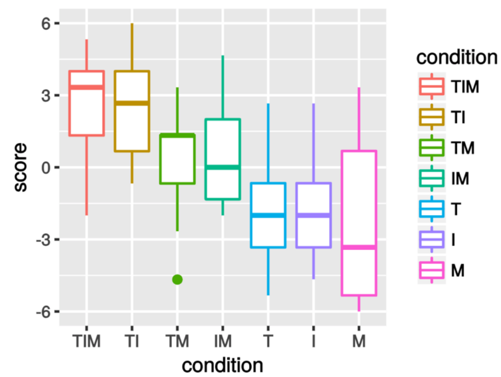

Figure 6: Boxplot representing distribution of the psychophysical preference score between different combinations of the location of VCAs.

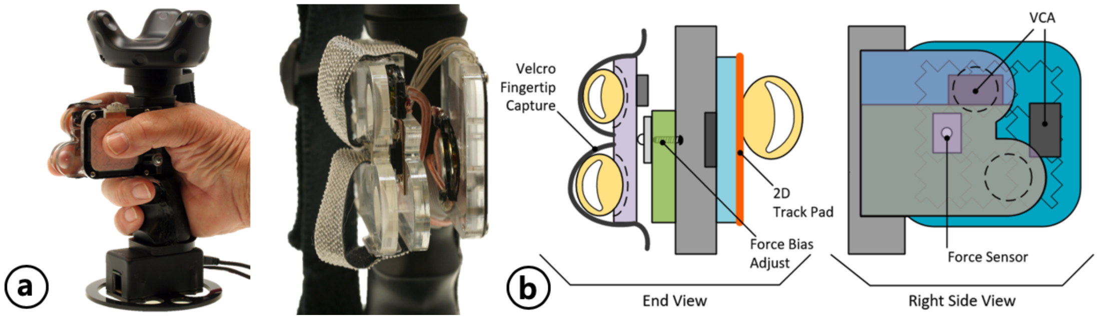

Figure 7: Final TORC controller. (a) photos (b) diagram of end view and right side view.

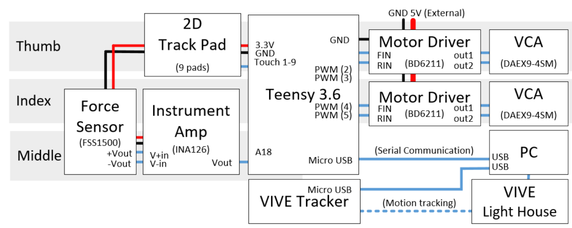

Figure 8: Schematic diagram of TORC controller.

Participants. We recruited 17 right-handed participants (4 female, age from 17 to 58) who had no prior experience in haptic rendering for VR from our institution via e-mail. They received a $15 coupon for completing the 30-min experiment. This user study was approved by an Institutional Review Board.

Experiment Setup. Participants were seated in front of a desk. A laptop was placed at the center, our device on the right side, and silicone balls on the left. Both our device as well as the silicone balls were positioned on the desk so that the participant's arms and wrists could reach the objects with the same pose (Figure 5). The participants provided the paired comparison responses using their left hand via the touchscreen of the laptop.

Task. The participants were asked to select between sensation A and B - which feels closer to the sensation from squeezing the silicone ball in the left hand? Participants were allowed to revisit sensations A and B no more than three times. Because the experiment required repeated forces applied by hand, they could take rest whenever they wanted.

Results. Based on participant answers, we calculated scores for each combination and ranked the scores. Figure 6 shows the distribution of scores for each combination of locations of VCAs. Three-finger condition (TIM: Thumb, Index & Middle fingers) was preferred the best, two-finger conditions (TI, TM, IM) and one-finger conditions (T, I, M) followed.

We performed a one-way within subject ANOVA to the scores. The combination of the location of voice coil actuator showed significant effect on score (F (6,112) = 13.055, p < 0.001). Pairwise t-test with Tukey HSD correction showed that the differences between three-finger condition (TIM) and two-finger conditions (TI, TM, IM) were not significant while the differences between three-finger condition and one finger conditions (T, I, M) were significant (p < 0.001). In addition, the difference between one-finger conditions without thumb (I, M) the two-finger condition with thumb and index (TI) were significant (p < 0.001). We concluded that the presence of vibrotactile feedback on thumb is important while pressing virtual object.

Based on the results, we decided to incorporate two VCAs – one under the thumb and one under the opposing index finger.

Final TORC Controller Design

We modified the desk-fixed version of TORC to build the final TORC controller (Figure 7), which has a considerably lighter form factor. The final prototype shares the basic schematic and electronics with the desk-fixed device (Figure 8). We added a capacitance-based 2D trackpad under the thumb and a restraint apparatus to keep the middle and index finger tips always in contact with the finger rests. A thin sheet of acetal was added to the top of the trackpad to minimize friction with the thumb. The index and middle finger rests were built as one piece with a single VCA providing vibrotactile sensations to both fingers.

Trackpad. We built the 2D trackpad [8] using printed 3 × 3 copper pads. We wired the 9 pads to 9 touch pins of the Teensy 3.6 board to measure the individual capacitances of the squares to the thumb. Incorporating real-time processing, the center of mass for all capacitance-to-ground measurements was calculated to determine input locations. TORC's 2D trackpad has enough accuracy to detect approximately 130 × 130 different locations.

Negative Force. The force sensor under the finger rest was mechanically biased with a setscrew to place the force sensor about 10% into its force sensing range with no pressure applied. In this way, a negative force on the finger rest (restrained fingers forcing the rigid finger rests outwards with respect to the handle) indicated to the system the user's release or outward extension of the fingers proportional to the sensor's reported negative force value. This resulted in a visual rendering animation of the fingers and thumb moving outward. Note that an outward or negative force on the restrained fingers is with respect to the handle only (naturally gripped by the last two fingers) and does not include the thumb rest. The thumb is not restrained as it needed to be able to slide on the trackpad easily and be able to "clutch" if required. In a similar technique, a positive inward force of the thumb towards the fingers would cause a visual animation of the virtual fingers closing in on each other (possibly modified by the presence of an interposing virtual object).

This last inclusion, a method to tie the fingers to the finger rests, was not used during any of the user evaluations. We added them to exploit the versatility of TORC and how proprioception could be perceived with correct visuals and kinesthetic forces, without the user's fingers moving.

4 TORC INTERACTION SCENARIOS

TORC can sense the movement and pressure of the user's thumb to simulate a sensation of compliance and texture. When used as a controller in VR, the hand is rendered to convey its look accordingly. Using inverse kinematics, all of the hand fingers are moving as sensed in a dexterous way.

We rendered VR scenes in Unity 2018 at a display rate of 90 Hz inside the head-mounted display (HMD). Inside VR, object interactions may be visually implemented in different ways (e.g., using collision dynamics, or kinematic control). TORC is capable of supporting all such methods. We discuss our implementation of TORC interaction scenarios below as well as the details of the haptic rendering that TORC enables.

Grasping and Releasing a Virtual Object

When a user holds a virtual object, the thumb, index and middle finger tips are positioned to be touching the surface of the virtual object. The contact point between a finger and an object is found by originating a ray at each fingertip in a direction orthogonal to the finger pad, and looking for an intersection with an object. The positions of the fingers' other joints are estimated using inverse kinematics (Figure 9 (left)).

Acquisition of an object can be declared, following Choi et. al. [13] when at all rays emanating from the fingers intersect the same virtual object within a small distance tolerance (e.g. 1 cm). Grabbed objects follow the hand motion using kinematic control. While it is not completely physically correct, kinematic control allows the user to lift the thumb from the controller without releasing the grabbed objects and allows the user the ability to manipulate, move and squeeze the virtual object in a natural manner as discussed below. Releasing the object is done by trying to lift the index and middle fingers off their pads. We used retainers around those fingers, such that a small outward force can be sensed and used as a reliable trigger for object release (Figure 9 (middle & right)).

Figure 9: Fingers are holding the object, with joint position estimated by inverse kinematics (left). Applying a little pressure outward by opening the index & middle fingers releases the grabbed object (middle & right).

Another option using the hand orientation may release the object when the thumb is raised above the controller surface. To enable sensing this thumb raising for other gestures such as clutching (see the next subsection), we can limit the release of the object only when the hand is pointing down and there is no finger (ring finger or the pinky) that may prevent gravity from pulling it down (Figure 10).

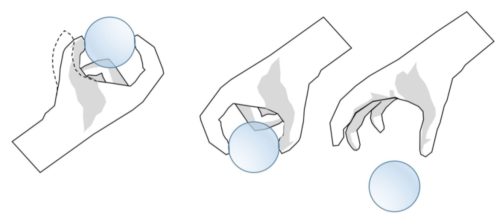

Figure 10: Context-based release. When holding the hand up, the thumb may be lifted without releasing the held object (left). In contrast, doing the same while the hand points down will release and drop the object (right).

In-hand Exploration: Compliance

When holding an elastic object, the user may apply force between the thumb and the opposing fingers to squeeze the virtual object. We used a spring behavior according to Hooke's law to estimate the amount of the object's deformation and update the position of the rendered finger tips. Although the user's physical fingers do not move, the combination of the visual stimuli accompanied with the rendered haptic sensation combines to a compelling experience (Figure 11).

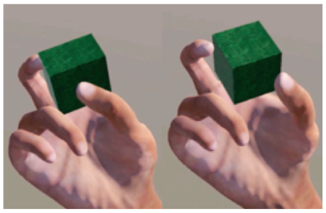

Figure 11: Applying force on the controller allows users to squeeze virtual objects. A simulated haptic sensation rendered on TORC completes the visual simulation.

In-hand Exploration: Texture

Our current implementation of TORC is sensing the 2D movement of the thumb tip as well as the force towards the fingers that is applied by it. When holding a virtual object in hand, the position of the thumb tip on the surface of the controller controls the visual orientation of the object around a point centered between the fingers.

When a user starts moving one's thumb on the 2D trackpad, the thumb movement is rendered in VR and TORC plays a texture feedback depending on the thumb movement [14, 57]. The amplitude of texture feedback increases proportional to the speed and becomes zero when the user stops the thumb motion on the trackpad.

Precise Object Manipulation

Object manipulation with a movement of the finger tips is a natural ability of the human hand. It allows fine movement of an object relative to the hand coordinate system, while the hand itself may be supported and static.

When a user starts moving the thumb on the trackpad with force, it changes the orientation of the virtual object. The index and middle fingers do not move in reality, but in the virtual image of the hand, they are rendered rotated in the opposite direction of the thumb to the pose as if the object is rotated (Figure 12).

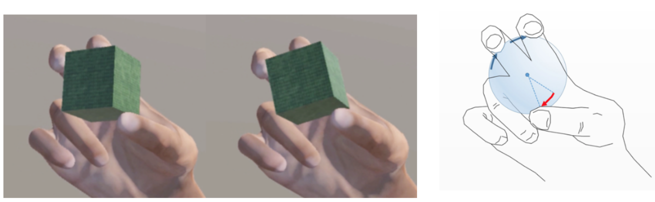

Figure 12: TORC allows precise manipulation of a held objects rotation by sensing finger motion (left). Rotation is around the center of rotation between the fingers and it is controlled by the thumb motion. The index and middle fingers rotate in the opposite direction (middle & right).

The semantics of the motion may change according to the context of the application. For example, when holding an object such as a screwdriver or a key, its rotation may be bounded to 1D rotation around a given axis, or in the case of a slippery object, the actual angle of rotation may be dependent on the force applied by the thumb.

As the object is attached to the hand using kinematic control, it is possible to lift the thumb off the controller surface, positioned correctly with respect to gravity, without having the object drop out of the hand. The lifted thumb may be used as a clutch gesture, moving the thumb to a new location on the surface of the controller and continue rotating the object.

Continuous Exploration and Manipulation

Because TORC supports in-hand manipulation and exploration based on different force levels and thumb movements, the interactions above can be integrated at the same time instead of splitting them into separate input modes [13]. Hence, a user can explore the texture and the compliance of a virtual object and manipulate it continuously as we do normally in the real world [35, 44]. Likewise, compliant objects can be squeezed while they are being rotated.

5 USER STUDY

Among TORC's interaction scenarios, we were interested in quantifying the effectiveness of the in-hand, finger-based manipulation in compared to the conventional, wrist- and arm-based manipulation. To evaluate the performance of precise manipulation, we conducted a user study with two-level docking task, comparing TORC to the original HTC VIVE controller.

Participants

We recruited 16 right-handed participants (ages 26 to 61, 5 female) from our institution via e-mail. One participant had no experience with VR. The rest had some previous experience. There were two conditions: TORC and VIVE. The order of the conditions were counterbalanced. For each condition, we conducted one experimental session that contained 20 trials. The whole experiment took approximately 45 minutes and there was no prior training session. All participants received a $15 coupon. This user study was approved by an Institutional Review Board.

Experiment Setup

We asked the participants to seat on a chair placed at the center of approximately $2 \times 2\ m^2$ free space. The participants wore HTC Vive VR Headset and held the trigger (original Vive controller) in the left hand and the experimental controller in the right hand (either the original Vive controller or TORC). We did not use noise-canceling headset since we expected that the auditive cue plays a role in the VR experience in contrast to the haptic experiments.

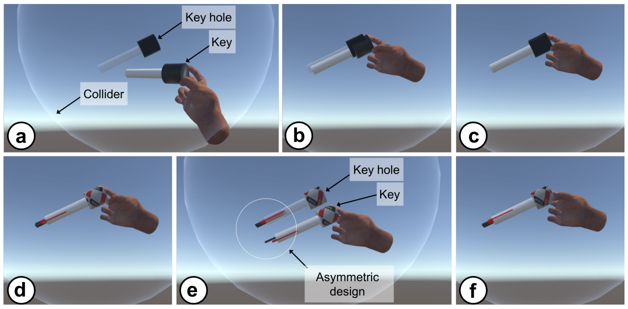

Figure 13: Two-level docking task. Participants had to match the key they were holding with the controller to a target key hole. The first docking task (a, b, c) only aimed at positional docking (*Locating*), therefore the key hole and the key did not display any superficial pattern. In the second docking task (d, e, f), the key hole displayed a particular pattern that participants were asked to match. In essence that meant they needed to rotate their hand and key (*Rotating*).

Task

The manipulation consisted of a two-level docking task (Figure 13): *Locating* (Figure 13a–c) and *Rotating* (Figure 13d–f). In each trial, a key hole appeared in front of the participant (always at a constant distance of 0.75 m, within arm reach). Seating in the free space, when the participant pressed the trigger in the left hand, the experiment software set a new trial. In VR, there was a key hole (transparency: 50%) positioned in random orientation but still ergonomically reachable to place the key with the right hand (range: x-axis from 180 to 360 degrees, y-axis from 0 to 30 degrees, z- axis from -60 to 60 degrees) and an opaque key in the participant's right hand (Figure 13a). The first docking task was to locate the key to the keyhole (*Locating* task, Figure 13b). When the participant thinks that the key and keyhole are aligned accurately (Figure 13c), she presses the trigger in the left hand. The software then changes the key and key hole into asymmetric design for the second docking task (Figure 13d). The second docking task was to align the key and key hole by rotating the key (*Rotating* task). Figure 13e shows the angular difference of the key and the key hole. When the participant thinks that the key and key hole are aligned accurately, she presses the trigger in the left hand (Figure 13f). The next trial is then started. In the *Rotating* task, haptic feedback of a pulse of vibration (6 ms) was given every 5 degree of turning in either controllers. Participants were asked to perform the task as quickly and accurately as possible throughout the experiment. We calculated the task completion time using a timer being activated only while the user's virtual hand is in the semi-transparent spherical collider (Figure 13a–f). The participants were allowed to take a break whenever they wanted by moving their arms out of the collider.

	Hand Ownership:
Q1	I felt as if the virtual hand I saw was my hand.
Q17	I felt as if my (real) hand was turning into an 'avatar' hand.
Q19	At some point, it felt that the virtual hand resembled my own (real) hand, in terms of shape, skin tone or other visual features.
	Touch Proxy:
Q10	It seemed as if I felt the touch of the key in the location where I saw the virtual fingers touched.
Q13	It seemed as if my hand was touching the key.
Q22	I felt a sensation in my hand when I saw key turning.
	Ergonomics:
Q14	I felt as if my hand was located where I saw the virtual hand.
	Preference:
Q26	I preferred the original HTC Vive controller for the task.

Table 1: Questionnaire.

Questionnaire

After finishing each session with a condition, participants completed a questionnaire for each condition. We delivered the full embodiment questionnaire [23] for both conditions. Furthermore, we added questions to further explore the qualitative details of our device asking preference (Q26) and asked the question at the end of the experiment. Table 1 shows the questions that showed significant differences between conditions.

Analysis

We logged the position and orientation of the controllers, timestamps, and the participants' input using trigger through the experiment. We calculated the distance error in *Locating* task, the distance and angular error in *Rotating* task, the task completion time for both tasks. We collected a total of 640 data points (16 participants × 2 conditions × 20 trials) for *Locating* task and 640 data points for *Rotating* task. All participants answered two sets of embodiment questionnaire and provided preference (Q26). All the responses were analyzed using non-parametric methods (Wilcoxon rank paired-test).

Results

Questionnaire. Analyzing the questionnaire responses (Figure 14), we found that people preferred TORC over VIVE (Q26). Participants thought TORC has a better touch proxy

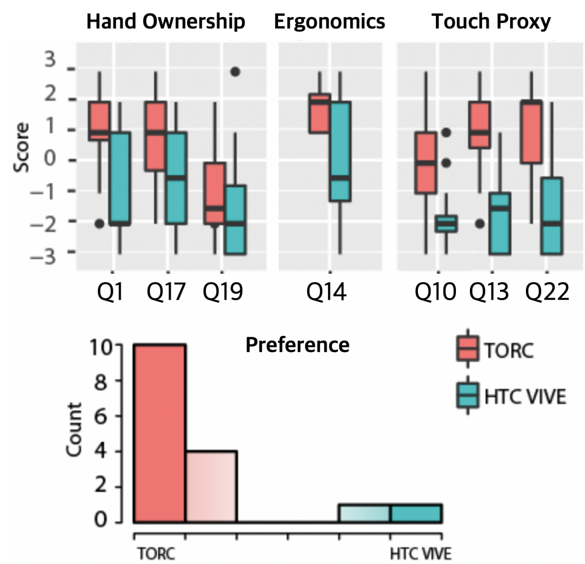

Figure 14: Questionnaire Responses. (top) Boxplots of the scores, only showing questions with significant difference between conditions. (bottom) Histogram of preference between two methods (response to Q26).

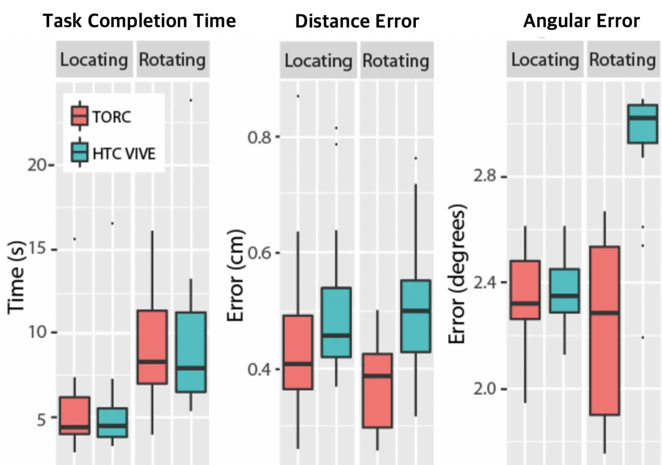

Figure 15: Task Performance. Boxplots of the task completion time, distance error and angular error during the different parts of the experiment (*Locating* task and *Rotating* task), for the two controllers: TORC and VIVE.

than the VIVE controller (Q10, Q13, Q22, $V > 91$, $p < 0.007$, C.I. 95% = [1, 4]). Overall, they concluded that TORC was more ergonomic (Q14, $V = 73$, $p = 0.007$, C.I. 95% = [1.5, 4]). Additionally, participants reported a significantly higher ownership of the virtual hand represented in Virtual Reality when using TORC (Q1, Q17, and Q19, $V = 61$, $p = 0.014$, C.I. 95% = [1, 4.5]).

Task Performance. Figure 15 (middle) shows the distance error from VIVE and TORC in the *Locating* task. The error was 0.5 ± 0.02 cm for VIVE and 0.4 ± 0.02 cm for TORC. After analyzing the results, we found that it was significantly greater error in the VIVE condition than in the TORC condition ($V = 108$, $p = 0.04$, 95% C.I = [0.003, 0.11]). This was true for both tasks, and the effect was even greater during the *Rotating* task, when the distance error for TORC dropped even further to 0.37 ± 0.02 cm but the error for the VIVE remained high.

Figure 15 (right) shows the angular error (calculated as intrinsic geodesic distance between q0 and q1. Where q0 and q1 are the quaternions of the key and the key hole) from VIVE and TORC controllers in the *Rotating* task. The error was 2.92 ± 0.06 degrees for VIVE and 2.24 ± 0.09 degrees for TORC. The error was significantly higher in the VIVE condition ($V = 135$, $p = 0.0005$, 95% C.I. = [0.44, 0.88]).

Note that as participants tried to fit the rotation in the TORC and they decreased the distance error, but the opposite was true in the VIVE condition ($V = 491$, $p = 0.0002$), this might mean that with more level of detail TORC outperforms in the precision positioning.

No significant differences were found on the task completion time between two controllers (Figure 15 (left)).

6 DISCUSSION

The final TORC prototype consists of two vibrotactile actuators, one force sensor, and a custom 2D trackpad. This simple configuration has advantage in several aspects during task operation, as seen by the results in our experiment (lessening the angular and distance errors) while providing good ergonomics, hand ownership and touch proxy.

Ergonomics and Hand Owenership

The ergonomic and hand ownership effects that TORC provides are also very relevant for future haptic controllers. Studies on tool vs. hand operation show that despite humans use tools to extend their physical capabilities, and explore surrounding objects, the interactions are very different than when using the hands [52]. In particular, tools require familiarity; they introduce difficulties that depend of the characteristics of the tool and its relationship to the body. And in VR, this is very important, because controllers can be used to control a second tool: for example, a fork, from a first-person perspective. If the controller feels just like a hand proxy, then the illusion is such that the virtual tool (e.g. the fork) is directly at their hand. In that regard, the great ergonomics and hand ownership that TORC provides will only enhance the grasping illusion in VR and we believe that will allow also better VR tool operation.

Visuo-Haptic Illusions for In-hand Objects

Part of the reason why TORC creates such a compelling experience is that we exploit multisensory illusions that combine visuo-haptic feedback. Recent studies have shown precisely how these two modalities can interact and enhance or hinder the haptic experience [6, 7]. Here we discuss the potential design spaces that TORC opens up by combining pseudo-haptic feedback and haptic illusions.

Grasping and Releasing. By adding a negative force bias with appropriate finger animation in VR, we were able to fool the perception of proprioception through visual feedback and kinesthetic forces given along the normal axis.

Compliance. Despite the rigidity of TORC, we were able to present a compelling illusion of compliance by combining pseudo-haptic feedback and haptic illusions [30]. We first set the haptic illusion parameters so that the force changes on the device were felt as similar as possible with an analog object (Experiments 1 and 2). Then we set the pseudo-haptic feedback parameters in VR so that the overall perception was felt as realistic as possible. Future work is needed to investigate the effect of individual parameters to author various sensations of compliance in VR.

Surface Information. We demonstrated the exploration of texture using the thumb and proportionally mapping the amplitude of the signal and the speed of the thumb using white noise or periodic signals. Since conventional texture rendering techniques [14, 15, 57] focus on tool-mediated texture rendering (holding a pen/probe in hand) or texture rendering for index finger, we could not directly apply these results to TORC interaction. In TORC, participants hold the objects in-hand and explore using the thumb hence our texture exploration approach. However, more work is needed to fully understand haptic rendering of texture for thumb-based exploration of in-hand objects.

In fact, it would be possible to combine pseudo-haptic feedback and haptic illusions for surface informations, such as texture [39], compliance[4, 25], and friction[40], while exploring the surface of the virtual object using thumb.

Shape and Size. TORC presents haptic feedback of texture and compliance. However, we depend on visual feedback for the different shapes and size of the virtual object. One of the participants in the user study mentioned that TORC's flat touch surface for the thumb does not feel like the curved key. Discrepancy between the virtual and real objects can break the presence [7, 38]. Future work is needed to understand the acceptable curvature of a virtual object and how to mitigate larger ones.

Weight. Though we have focus on rendering external properties of the virtual object, internal properties such as weight, can also be presented in VR using TORC [49]. Besides the pseudo-haptic feedback to alter the perception of mass using C/D gain [19], the vibrotactile actuators can be used to haptic illusion of pulling force [11, 47] and illusory motion among an array of vibrotactile actuators [41].

TORC Hardware

TORC was designed to be simple and robust, with no actuators working against the user's force, and could be easily incorporated in durable commercial controllers. Additionally, given its design it is particularly inexpensive compared to devices that use electromagnetic motors. The overall circuit price is less than $90 including the most expensive part (FSS1500, $40) and the second most expensive part (Teensy 3.6 board, $30). The design also allows for fast responses. In compared to the electromagnetic motors that make torque, the VCAs immediately react to the control signal. Finally, it consumes less power. Most of the power is consumed by the VCAs. In that regard, despite we described TORC as a whole VR controller, it can be an addition to the conventional hand-held devices that have moving parts (e.g. CLAW [13]).

We surmised that a force sensor between the thumb and two fingers was enough for our interaction scenarios: capturing hand opening, closing, and kinesthetic force feedback. However, it is known that the distribution of force on different fingers contain user intentions [17] on the object. Multiple force sensors on each fingertip can be used to manipulate virtual objects in other ways (e.g. see-sawing pencil using two fingers and the thumb).

7 CONCLUSION

We presented TORC, a rigid controller that enables a user to perform dexterous finger-based interaction and exploration of a virtual object. We designed the device based on a precision grasp using the thumb and two fingers, to give the fingers on virtual objects more degrees of freedom between forceful and light touch, and between normal and tangential movement. The results of our user study confirmed TORC's was a great proxy for precise manipulation for virtual objects, all while maintaining a high level of hand ownership and ergonomics. We hope that this paper motivates the community to pursue future work on the design of VR controllers that act and feel more like our own hands.

ACKNOWLEDGMENTS

We would like to thank Ken Hinckley for helpful feedback.

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