Haptic PIVOT: On-Demand Handhelds in VR

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ABSTRACT

We present PIVOT, a wrist-worn haptic device that renders virtual objects into the user's hand on demand. Its simple design comprises a single actuated joint that pivots a haptic handle into and out of the user's hand, rendering the haptic sensations of grasping, catching, or throwing an object – anywhere in space. Unlike existing hand-held haptic devices and haptic gloves, PIVOT leaves the user's palm free when not in use, allowing users to make unencumbered use of their hand. PIVOT also enables rendering forces acting on the held virtual objects, such as gravity, inertia, or air-drag, by actively driving its motor while the user is firmly holding the handle. When wearing a PIVOT device on both hands, they can add haptic feedback to bimanual interaction, such as lifting larger objects. In our user study, participants (n=12) evaluated the realism of grabbing and releasing objects of different shape and size with mean score 5.19 on a scale from 1 to 7, rated the ability to catch and throw balls in different directions with different velocities (mean=5.5), and verified the ability to render the comparative weight of held objects with 87% accuracy for ~100g increments.

Author Keywords

Virtual Reality; Haptic Feedback; VR Controller; Haptic Proxy.

CSS Concepts

• **Human-centered computing~Human computer interaction (HCI)**; *Haptic devices*;

INTRODUCTION

Haptic VR controllers are essential devices for interacting with virtual content. They exist in a variety of shapes and functions, ranging from common handheld controllers [52] to haptic gloves [29][42]. While most commercial devices provide only vibrotactile feedback, researchers have demonstrated a wide variety of hand-held controllers rendering texture [54], shape [4], grasp [10] and squeeze feedback [36], shifting weight [55], and haptic behavior for two-handed use [49]. The general downside of these devices is that they are in continuous contact with the user's hand, thereby possibly undermining the sensation of free-hand interactions, and that they need to be put aside occasionally for using the hand in the physical world.

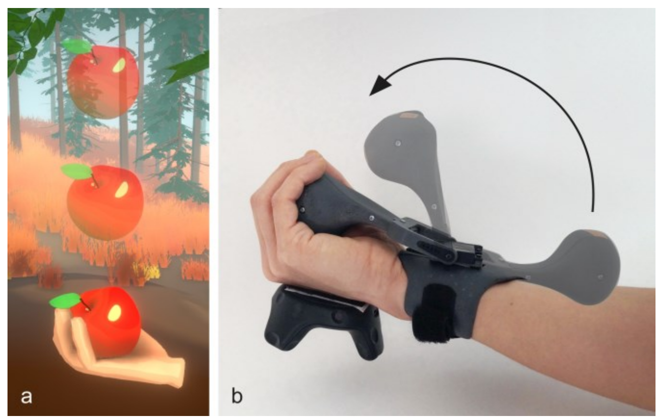

Figure 1. PIVOT is a wrist-worn haptic device with a pivoting handle that appears in the user's hand on demand, rendering grasping, catching, and throwing hand held objects in virtual reality.

Another approach for creating haptic sensation for virtual environments is by using physical proxies that are positioned in the real space where they would be found in VR, aka. encounter type haptics. However, this approach is either limited to scripted experiences or requires expensive and large machinery to position these proxies dynamically, such as robotic arms [2], moving platforms [18], or involves multiple human helpers [7]. While the fidelity of the provided haptic sensation is high, the most common limitations of this approach are the limited workspace and speed of actuation.

To combine the benefits of both approaches, i.e., the versatility of the handheld haptic devices and the high realism of physical proxies, we propose PIVOT, a *wrist-worn* haptic device that enables grasping virtual objects anywhere in space by *pivoting* a generic haptic proxy into the user's hand, as shown in Figure 1. This greatly reduces the user's effort to engage, disengage, and re-engage

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with virtual objects; and frees the user's hand when the device is not in use. PIVOT positions its handle depending on the proximity of the virtual object, providing the natural affordance of grasping and rendering matching object-hand collisions. Holding this physical proxy, combined with the quick actuation mechanism, enables agile manipulations, like catching and throwing. PIVOT also enables rendering dynamic forces acting on the grabbed virtual object by actively driving the handle while it's firmly held by the user.

Figure 2 shows PIVOT, a haptic VR controller that:

(1) Renders the haptic sensation of grasping and releasing static objects;
(2) Enables catching and throwing flying objects;
(3) Simulates dynamic forces provided by the grabbed object such as weight, inertia, or drag; and
(4) Allows for free use of the hands when necessary.

Figure 2. PIVOT's key design element is the actuated pivoting handle that is grounded to the user's forearm.

PIVOT's handle acts as a generic proxy while additionally offering similar ergonomics and functionality as conventional VR controllers, including touch sensing, a trigger button, and vibrotactile feedback. The device design includes a back-drivable motorized hinge for the flexing wrist movement and an additional passive radioulnar hinge that enables the hand to move sideways (here: up-down) while holding the handle.

In our user study, participants evaluated three tasks: (1) grasping objects of different shapes and sizes, (2) catching and throwing a ball in different directions and velocity, and the (3) effectiveness of weight rendering. We found that PIVOT's generically-shaped handle can render objects with different shape and size effectively within the range of 5±2cm. The device performed well when simulating catching and throwing objects moving at high speeds up to 25 m/s. Participants were also able to estimate the weight of different objects and compare them with significant accuracy.

RELATED WORK

The work in this paper builds upon the large body of research in the field of haptics and VR controllers. These haptic devices are ranging from world grounded stationary devices, through haptic proxies, handheld controllers, and wearable haptic gloves. PIVOT shares similarities with many of these devices.

World-grounded haptic devices and proxies

Grounded haptic devices have the potential to provide haptic feedback with realistic force sensation, matching the user's input force and stopping or impeding their motion in place. Examples of grounded force-feedback devices include the Novint Falcon [44], PHANTOM [38], HIRO [22], or SPIDAR [40].

Grounded force feedback devices can act as encounter-type devices that are capable of rendering realistic transitions between free space and haptic contact with virtual objects. These devices collide with fingers and display interaction forces only if a contact occurs in the virtual environment. Examples include TouchMover [16], H-Wall [12], RoomShift [18], Snake Charmer [2], and Haptic-go-round [33]. The haptic proxies mounted on these devices can have certain shape and size discrepancies from the virtual counterpart, as studied by Tinguy et al. [21]. Furthermore, haptic retargeting techniques can reduce the spatial mismatch, like in [3][8]. On the whole, haptic proxies combined with robotic devices render realistic haptic experiences, but require a large, stationary setup and limit the interaction to the operational space of the device.

Handheld haptic controllers

Handheld controllers typically provide haptic force feedback grounded to the user's palm, or by weight shifting and gyroscopic effects at the finger level. The main benefit of these is that they can be carried around without the limitations of large, stationary machinery. Recently, numerous haptic VR controllers have been developed that render expressive haptic sensations. Their downside is however, that they occupy the hand at all time during use. If a user places them down while in VR, such controllers need to be tracked in the environment, so they can be found later.

Exceeding the limited tactile sensations of vibrotactile motors, researchers have instrumented controllers to render kinesthetic effects to simulate holding virtual objects. Depending on object interaction, some controllers move internal weights to physically shift the center of gravity [45][50][55]. A similar effect has been demonstrated by moving multiple internal masses at different rates to create the impression of varying weight [1]. There are several attempts for reproducing the sensation of external forces. Examples include using external gimbals [41][53], air moving propellers [30][34], or by changing the air-drag of the device [56].

Another class of haptic controllers produces tactile and kinesthetic effects on the user's finger while holding and moving the controllers. For example, Haptic Revolver [54] spins a wheel under the finger to render shear forces with varying materials. NormalTouch, TextureTouch [4] and

CLAW [10] are controllers that create the sensation of touching virtual shapes using a tilt and extrusion platform.

Finally, several haptic controllers were designed to support grasping virtual objects. TORC [36] is a controller without moving parts that senses applied force and simulates grasps by individually vibrating the finger-pad surfaces when applying pressure during grasping. CLAW [10], CapstanCrunch [17] and PaCaPa [46] are haptic controllers with movable arms that can produce touch sensation, grasp force feedback, and object textures through vibration under the user's finger. Haptic Links [49] dynamically locks and unlocks two controllers with variable stiffness to support bimanual tasks in VR.

Compared to existing prototypes, PIVOT's form factor can incorporate some of their benefits, such as providing the sense of compliance using a force sensor and voice coil actuator [36], while preserving the ability to use the hands freely without the need for removing the device.

Wearable haptic devices

Wearable haptic devices typically come in the form of gloves or exoskeletons that either fully or partially cover the user's hands. They can render touch and grasp effects during interaction, simulating convincing haptic sensations.

In their smallest form factor, wearable haptic devices are finger-mounted actuators that can render texture [25] and shear [43] force sensation on the user's fingertip. These effects can also be used to render the contact when grasping an object and simulate the object's weight by deforming the finger pad [39].

Exoskeleton devices typically redirect the grounding force reaction to another part of the body. They are developed in many flavors, resembling the human body, like external tendons [37], flexible metal strips [31], or finger phalanx replicas [28] along the outside of the hand which allows room for interaction and grasping while rendering feedback. Others employ an in-hand design and are thus grounded within the user's palm matching each finger with an actuator [6] or come in the form of a mitten [48]. Resistive versions can produce large resistance force during grasping by jamming brakes [58] or by locking sliders, such as in Wolverine [9]. TouchVR [51] is a hand mounted haptic device that produces touch sensation on the middle of the palm using a small deltoid robot. Leigh and Maes [13][14] developed body-integrated robotic joint interfaces that augment the human hand with extra fingers that can also act as a an on-demand joystick or trigger button. Other researchers have explored inflatable devices that render virtual graspable objects by inflating air-pockets in the middle of the palm [11][20]. In particular PuPop [20] offers rendering various shapes and sizes by a multitude of integrated air-pockets, however its pneumatic actuation mechanism is only suitable for slow interaction scenarios.

In some examples, exoskeleton type haptic devices are grounded to more distant body parts. Wireality [23] connects the fingers of the hand to the shoulder of the user by string-brakes, while Siu et al. [19] and Zhao et al. [57] proposed a torso grounded device for exploring virtual environments for the blind. PIVOT is related to these as it grounds the device to the user's forearm while providing haptic sensation to the hand. Finally, Level-Ups [15] are quickly actuated motorized feet extensions that simulate virtual stair steps just in time, similarly to PIVOT's quick actuation mechanism.

While the haptic sensations produced by haptic gloves and exoskeletons can be of high fidelity, their main overhead for use is their weight and embodiment around the wearer's hand, that often limits the full range of motion and dexterity. PIVOT shares similarities to these devices in the sense that it is also body worn, however, its end-effector is not in constant contact with the user, but when its required. These qualities may classify PIVOT as a *wearable-encounter-type* haptic device.

PIVOT'S USE IN VR

PIVOT's central element is the pivoting handle that is fastened to the user's forearm and actuated by a servo motor. This simple design is the key enabler for several haptic effects and interaction techniques we describe in this section. In all the cases, user's hand position is tracked using a 6DoF VIVE [52] tracker stack onto the back of the palm of the user.

Touching and grasping virtual objects

PIVOT's main capability is rendering haptic sensations for acquiring, grasping and releasing virtual objects. As shown in Figure 3, when the user reaches for an object, PIVOT moves its handle towards the user's hand proportionally with the distance to the virtual object. As a result, PIVOT's handle touches the user's hand in synchrony with the virtual object.

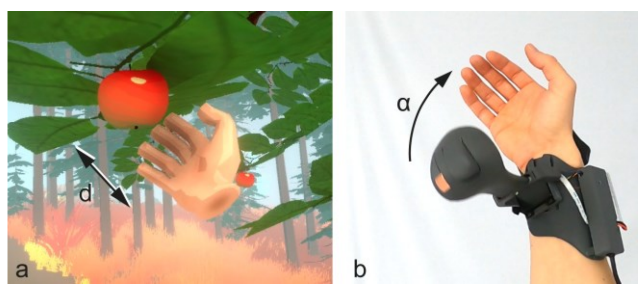

Figure 3. (a) When reaching out for a virtual object, (b) PIVOT rotates its handle towards the user's hand inverse-proportionally with the distance to the virtual object.

The moment that the user grasps the handle, PIVOT switches off its motor, giving the user the possibility to move the handle passively. In addition to this, the passive radioulnar hinge allows lateral wrist motion in a free and natural way. Therefore, grasping and holding a virtual object does not lock the hand to the forearm, but has the appearance that the object "really" is held in the hand. The analog coupling between grasping a virtual object and holding PIVOT's handle physically creates a compelling sensation of acquiring an object in a direct and natural way.

Catching and throwing

Using its quick actuation mechanisms, PIVOT can naturally render haptic feedback in response to throwing and catching virtual objects. The main difference to grasping stationary objects is in PIVOT's process loop that predicts the contact with the flying object. When a potential object is flying towards the hand, PIVOT starts moving the handle in advance, accounting for the latency of the system and placing it in the user's hand at the time the user expects the object to make contact.

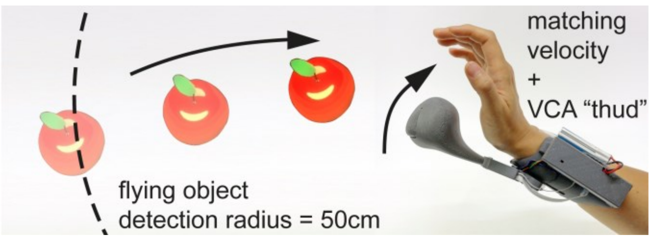

Figure 4. When an object is detected approaching the user's hand with a higher velocity than 0.5m/s, PIVOT predicts the moment of contact and starts moving its handle early on to produce a haptic collision sensation at the right moment.

For throwing an object, PIVOT only needs to detect when the user lets go of the handle using the touch-sensitive areas on the handle's surface. When the fingers are lifted, PIVOT engages the motor to drive the handle out of the hand and simultaneously detaches the virtual object from the virtual hand model with the throwing velocity. Due to the latency of the release signal, the throwing velocity vector is determined as the highest velocity before the hand started to slow down.

Force rendering

In addition to touch feedback, PIVOT can produce a sensation of dynamic forces acting on the handheld virtual object, like gravity, springiness, inertia or drag. It does this by continuously actuating its handle motor, while it is firmly grasped by the user.

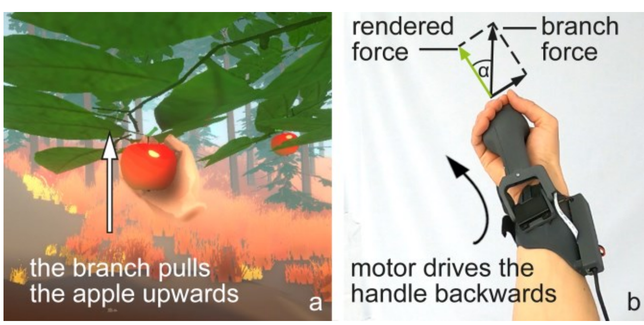

Figure 5. PIVOT renders the normal component of the springy force of the branch by actively driving it's handle while being grasped.

As illustrated in Figure 5, on the example of plucking an apple, PIVOT renders the springy force of the branch by actively driving the handle out of the user's hand. The intensity of the force is scaled with the deformation of the branch (see supplemental video). Since PIVOT's handle has only one active degree of freedom, it renders the perpendicular component of the force to the palm, as shown in Figure 5b. This way user can feel the intensity of the force when the palm is facing upwards, and would not be able to feel the force if the palm is parallel to the direction of the force. Despite this limitation, PIVOT still renders a compelling sensation of force (see the *User study* section).

At the moment when the apple is plucked, the force vector switches to gravity and starts pulling the apple downwards. Conformingly, PIVOT's handle motor reverses directions and starts pushing into the hand to simulate gravity in a similar manner. To increase the perceived realism of tearing off the apple, the built-in voice coil actuator (VCA) in the handle plays a haptic "thud" sensation. When throwing the apple, the inertia vector is also calculated and added to the rendered force, so that user perceives the sensation of an accelerating mass. In a similar manner, forces pointing into any direction can be rendered by projecting their intensity onto the axis perpendicular to the palm's plane (e.g., for rendering air-drag or viscose friction).

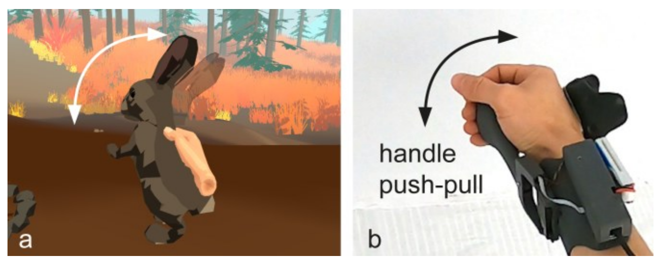

Figure 6. The user feels the inertia of the wiggling bunny through PIVOT's handle being actuated back and forth.

Figure 6 shows an example for rendering force feedback for dynamic animated objects, such as a wiggling bunny. User perceives the inertia of the wiggling bunny through quickly actuating PIVOT's handle back and forth.

PIVOT also supports two-handed operation to render haptic feedback in response to larger and heavier virtual objects. Because the device cannot physically constrain the two hands to each other, it renders large objects as compliant and applies coupled force feedback on both hands.

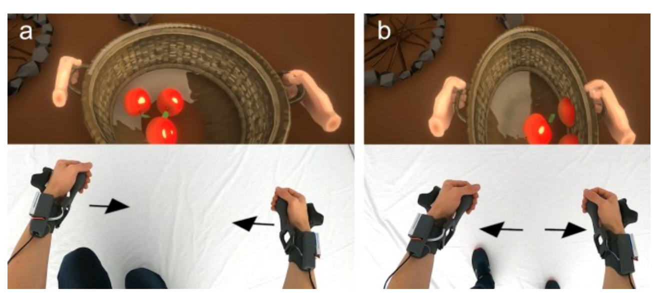

Figure 7. Wearing PIVOT on both arms enables haptic feedback for bimanual interactions. Here, the user is stretching and compressing a basket, which is rendered as synchronized push-pull forces on both hands.

Figure 7 shows a user lifting a basket in VR wearing a PIVOT device on each hand. Each PIVOT individually renders the corresponding forces on the respective hand, which creates the impression that both hands are physically connected by the held object. As shown in Figure 7a, when the user stretches the basket, both devices pull the hands inwards with the same intensity and proportional to the stretch level. Similarly, pressing the handles closer together will produce the sensation of pushing outwards (Figure 7b).

Free-hand use and summoning on-demand

One of PIVOT's key benefits is that it lets users use their hands freely. As shown in Figure 8a, the folded idle state affords free-hand interaction, such as resting the hand on the table, operating tangible objects, such as a keyboard and mouse, or placing up the headphones (Figure 8b – image from the user study).

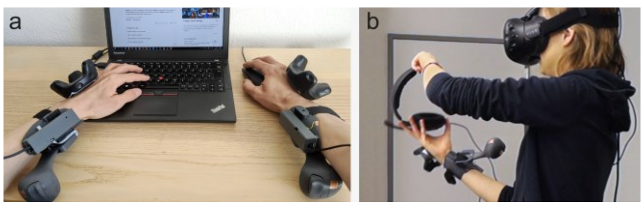

Figure 8. PIVOT's design affords natural use of the hands in the real world, e.g., operating a computer or placing up headphones.

Users can summon PIVOT's handle at any time in VR by performing a gesture similar to catching a yo-yo. PIVOT's internal accelerometer detects this motion and actively drives the handle into the user's hand. The handle can be dismissed anytime in a similar manner, simply by performing a drop motion, which is again detected in the accelerometer and pivots the handle out of the palm. This gesture may be used to acquire an arbitrary invisible object in VR, like the flashlight example in the supplementary video, or to use PIVOT's handle acting as a VR controller to interact with virtual content. The benefit of this is that the controller is always at hand when its needed without the need to search for it in the room and pick it up, and still leaves the hand free when it is not in use.

This functionality is envisioned to be especially useful in AR scenarios, where many tasks involve physical and virtual aspects and where users switch their attention between touchable real-world affordances (e.g., an appliance for repair) and overlay virtual content. While interacting with the real world requires free hands as physical objects provide natural haptic feedback, PIVOT can complement the otherwise missing haptic cues for virtual overlays.

PIVOT'S HARDWARE IMPLEMENTATION

PIVOT's implementation comprises a mechanical system, custom electronics, control firmware and front-end software elements in VR. Figure 9 shows an overview of the main hardware components of PIVOT. The device is self-contained except for the USB connection to the PC, which could potentially also be wireless.

The device is equipped with a 32 bit, 180 MHz Teensy 3.6 microcontroller that controls the servo motor, gathers the sensory information and communicates with the PC. Figure 10 shows the block diagram of the entire system.

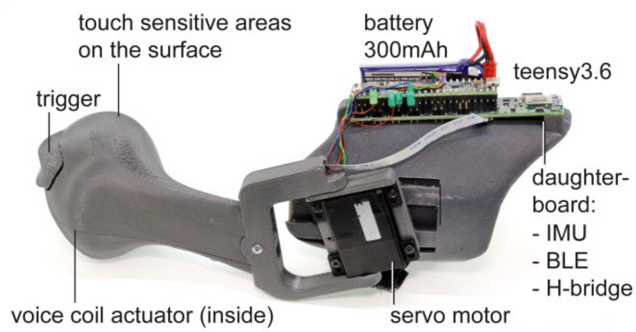

Figure 9. PIVOT's functional elements: touch sensors, voice coil actuator (VCA), Teensy microcontroller with H-bridge daughterboard, and a retrofitted RC servo motor.

For tracking the user's hand, we use a commercial VIVE [52] tracker. To leave the user's palm entirely free for grasping, the tracker is attached to the back of the hand using a double-sided adhesive (reused from skin safe EMS electrodes). Alternatively, an elastic band around the palm can serve this purpose too.

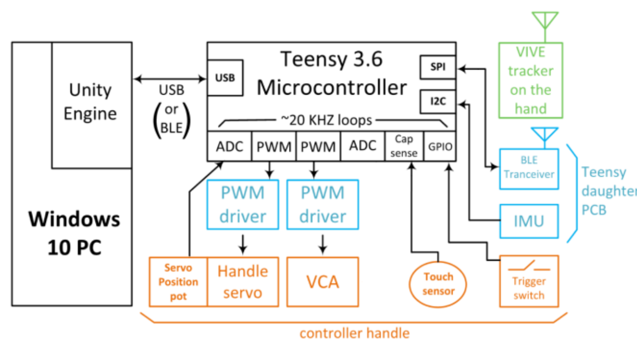

Figure 10. PIVOT's system diagram

PIVOT uses a serial communication interface over USB to the PC. This allows for low latency (<1 ms) polling, which is crucial for real time haptic experiences. Even though the daughterboard is also equipped with a BLE5 communication module, we found that the resulting latency (15–25 ms) was deteriorating the haptic experience.

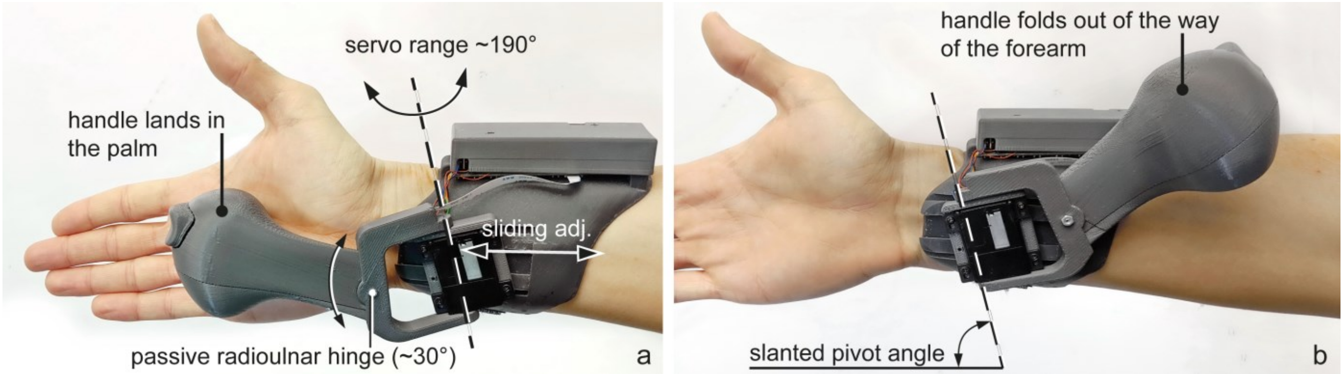

Figure 11. PIVOT's mechanical design: the servo actively pivots the handle around the slanted vertical axis, while the handle affords passive radioulnar motion to accommodate natural hand tilting. A sliding rail mount on the hand-cuff enables adjustment to individual hand sizes.

Mechanical design

PIVOT's key element is the single-servo pivoting handle. The main function of this design decision is to move the handle into the user's palm when needed, and to move it out of the way when it is not in use. The choice of the angle and axis of rotation for the handle is deliberate. As shown in Figure 11, the handle's rotation axis is not exactly perpendicular to the hand, but it is slightly slanted. This is important as it allows the handle to not interfere with the thumb while pivoting it into the palm, and to idle at a location next to the user's arm where it least interferes with the hand during interaction with real-world objects or while resting on a table (Figure 8a). The horizontal sliding adjustment allows users to adjust the size of the device, so the cuff can be placed close to the wrist joint, while the handle still hits the middle of the palm. This makes sure the forearm's torsion is least affecting the device rotation in respect to the hand.

Figure 12 illustrates the additional passive radioulnar hinge at the base of the handle that enables free hand motion up to ± 30° during engagement (rotational in the plane of the palm). This passive joint is a friction fit and adjusts when the user firmly grasps the handle.

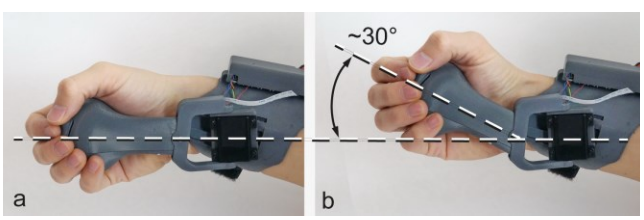

Figure 12. The passive, friction based radioulnar hinge enables the hand to move when holding the handle (here: up-down).

PIVOT's hand cuff is 3D printed from a flexible material (Form2 Flexible) to accommodate different arm diameters and shapes. Upon putting on the controller, the spring-like behavior of the cuff hugs the user's arm and gives it a comfortable but firm hold. An elastic Velcro strap secures the cuff to the forearm. All other parts of the controller are 3D printed from rigid ABS material.

The equipped device weights 188g, including a 350mAh battery. In addition, the VIVE tracker mounted to the back of the hand weights 89g. The key objective in designing PIVOT was to keep the pivoting handle as lightweight as possible to reduce the inertial forces during acceleration. As shown in Figure 13, PIVOT's housing is a thin (1mm) wall structure and its handle contains only the essential parts, keeping the weight of the handle down to 45g.

Actuation and motor control

To drive PIVOT's handle, we modified an off-the-shelf RC servo motor (Hitech HS-7115TH) to gain control over: (1) torque and speed, (2) back-drivability, and (3) real-time position feedback. With this custom functionality, we control PIVOT's handle in a way that it gets to the user's hand with the right speed, exerts the desired force, and can be switched off anytime to enable passive rotation of the handle.

To achieve this, we removed the servo motor's original control circuit and replaced it with our custom driver electronics and software running on the Teensy controller. The implemented PID loop allows high peak currents to achieve higher speed, enables toque control, and it also implements a time-based protection mechanism to protect the motor in case it comes to overpowering.

To measure the force that the device can deliver, we attached a newton-meter at the end of the 120mm long handle lever. At full motor power we measured 3.5N force, that equals in 42N/cm motor torque (slightly higher than the datasheet value of the servo motor (39N/cm), due to the custom electronics). This practically means that the device is capable of rendering about 350g weight on the palm. The actuation time required for the handle to travel from one end position to the other (~190°) at maximum speed is about 340ms.

Electronics and input sensing

PIVOT's control board is built on a Teensy 3.6 [47] microcontroller that interfaces with a custom I/O daughter-board. This daughterboard contains the motor driver, VCA PWM circuits, an inertial sensor to detect hand motions, a BLE5 chip (Nordic nrf52832) for wireless communication (only used experimentally), and operational amplifiers to process the analog signal from the servo's potentiometer encoder. Directly reading the absolute position of the potentiometer enables the frontend software to be always aware or the current handle position, even when the motor is turned off.

Figure 13 shows the inside of the handle containing the trigger, capacitive sensing, and the VCA. We use the Teensy's built-in active loading [26] capacitive sensing functionality to detect touch on the copper-based patches placed on the inside of the handle at four distinct locations. The handle also contains a VCA to render vibrotactile feedback as well as a trigger button as commonly found in VR controllers.

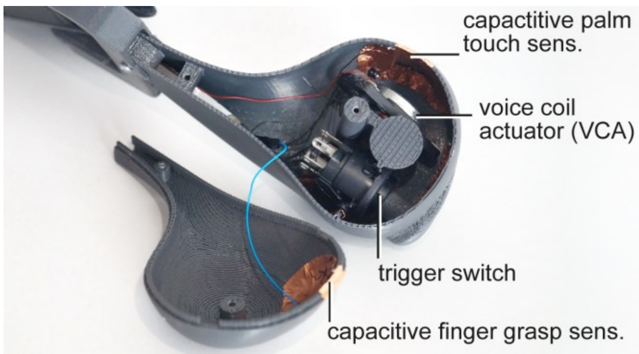

Figure 13. The inside of the handle contains: a trigger switch, capacitive touch sensing copper tapes, and a VCA.

The four touch-sensitive patches are located to distinguish different grasps, and to help PIVOT to predict users' intentions for grasping or releasing. The first capacitive sensing area faces the palm, which comes makes contact first when grasping, indicating that the handle reached the palm. For detecting a firm grasp, a capacitive sensing area is placed roughly under the middle and ring finger's fingertips. In addition, there are two patches dedicated for detecting the thumb location for a rough position input for the VR controller use case.

Software implementation

We use the Unity 2019 game engine as our software platform, running on an Alienware 15 R3 laptop, equipped with a VIVE Pro VR system. Unity maintains the representation of all the virtual objects in the interaction space at 90 frames per second, as well as the location and orientation of the user's head and the tracker attached to user's palm.

As shown in Figure 14, PIVOT continuously checks a spherical 'trigger volume' around the user's hand. When an object is found within the 30 cm vicinity (i.e., within the range of PIVOT's preparation radius), the handle moves to the preparation position with moderate speed. This reduces the latency of later physical contact in case the user reaches out quickly to pick up a virtual object. Even when in the preparation position, the handle does not interfere with the user's palm and thus remains unnoticeable. When the distance becomes less than 10 cm (Figure 14 proportional radius), the handle starts to dynamically adopt its angle proportional to the distance of the target object. When the handle is grasped by the user, the virtual object is set to follow the hand motion, as long as the touch is detected on the handle. When the hand opens, the object is released from the hand object in Unity, and physics forces are enabled, so the object continues to fly. The kinetic energy of the released object is set by assigning it the velocity of the hand at the moment of release. To account for the signal latency of the touch detection (~1-2ms), we assign the highest velocity to the object, measured within a small temporal window prior to the object release (~0.5 seconds).

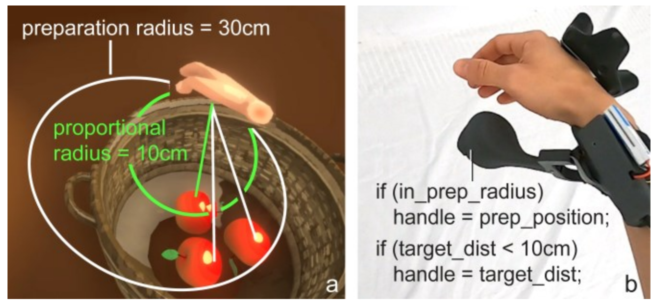

Figure 14. When reaching out to pick up an object, PIVOT checks the distances to the surrounding objects. If an object is in the 30cm radius, the handle moves to the preparation position with moderate speed. When the target distance becomes closer than 10cm, the handle starts to move continuously closer to the hand with the decreasing distance.

To visualize realistic grabbing of objects, we animate the fingers of the virtual hand model by projecting a ray from each fingertip to the center of the grabbed object. The intersection point of each ray with the surface of the object is the grasp location of the fingertips. The joints of the fingers are animated using FinalIK's [24] inverse kinematic engine.

USER STUDY

We conducted a user study to evaluate PIVOT's ability to simulate: (1) grasping sensation for a variety of objects, (2) catching & throwing of objects at different speeds and directions, and (3) perceptual illusion of weight of an object. We recruited twelve participants (ages 19-26, mean=22). Each participant performed a series of tasks inside VR using PIVOT. After each task, participants also completed an offline questionnaire.

Task 1: Grasping objects of various shape and size

In the first task, we measured PIVOT's ability to render a grasping sensation. We asked participants to reach towards, grab, move and release virtual objects of different size (Figure 15, 1-4) and shape (5-9). Note the size range includes the diameter of the handle of the wrench and the handle of the cup, but not the full object.

Results

Participants rated their experience in response to the question "How realistic does the grab & hold haptic experience feel?"

on a 1 (not real at all) to 5 (very realistic) Likert scale directly inside the HMD.

Participants found it realistic (average score 3.9) to hold spheres of 5 cm (the most similar shape to PIVOT's handle, o3) and within a tolerance of ±2cm in diameter (o2). Objects beyond this range (o1 and o4) were not perceived as realistic ($V = 66$, $p < 0.01$). This indicates that users accept slight discrepancies between the visual and actual size of objects.

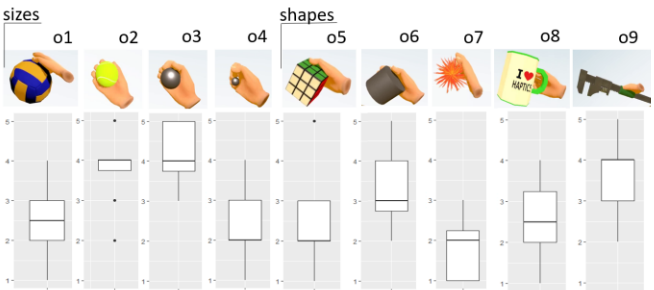

Figure 15. Task 1: Grasping objects of different shapes and sizes. We presented participants with: (o1) a big ball larger than PIVOT's grip (12cm), a (o2) tennis ball (7 cm), (o3) a ball about the size of PIVOT's grip (5cm), and (o4) a small ball (1.5cm). Additionally, participants interacted with: (o5) a Rubik's cube (7cm), (o6) a cylinder (7cm), (o7) a spiky sphere (7cm), (o8) a mug (2cm handle), and (o9) a wrench (4cm handle).

Participants rated objects of different shape (o5-o9) lower, even though their overall dimensions were within the accepted range of 5 ± 2cm. Shapes that deviate from a sphere were perceived less realistic. For example, the spiky o7 (averaged score 1.9) was rated the lowest ($V = 78$, $p < 0.01$). Objects o5 and o8 performed low (average score 2.16). Objects o6 and o9 performed significantly better ($V=0$, $p < 0.01$) with average score 3.35. We hypothesize that o6 and o9 performed well because their cylindrical shape is not that far from PIVOT's slightly elliptic handle shape. As the hand only covers part of the handle its perception appears similar to a cylinder.

On the questionnaire, filled out after the virtual part of the experiment, participants stated their agreement with a set of statements from 1 (completely disagree) to 7 (completely agree) Likert scale. Participants perceived grabbing objects using PIVOT as a realistic interaction (Q1: "It felt realistic to grab the objects", mean=5.19, sd=0.45, one-sample Wilcox signed rank against mu=0 $p < 0.01$) and were happy to have haptics (Q2: "I liked to have haptic feedback", mean=5.9, sd=0.28, $p<0.001$). They perceived their hand to be touching the virtual objects (Q3: "It felt like my hand was in direct contact with the virtual object", mean=5.4, sd=0.8, $p < 0.01$) and not a device that interfaced with the object (Q4: "It felt my hand was grabbing a device instead of the object", mean=4.25, sd=1, p=0.4, paired comparison Q3 vs Q4, $p < 0.05$). These results highlight the ergonomic design of the controller.

Task 2: Catching and throwing virtual objects

In the second task, we measured PIVOT's ability to enable catching and throwing. In addition, were aiming to identify potential ergonomic differences while catching and throwing a ball coming from different directions. Even though PIVOT moves together with the user's hand in space, there are certain anatomic differences in catching and throwing when the palm is facing upwards, downwards, to the front or to the side. We tasked participants to catch a virtual ball thrown at them from two meters away coming from four different directions (front, side, down, up). They repeated this task four times and varied the speed at which the ball was thrown, each with four repetitions at increasing speeds (4 m/s, 9 m/s, 16 m/s, and 25 m/s). To account for the system's latency in case of catching fast balls, the balls were not bouncing off or penetrating through the hand, but snapping to it. This gave all participants a similar and satisfactory experience across all the speeds and individual skills. After each ball, participants were asked to throw the ball back in the direction it came from with approximately the same speed.

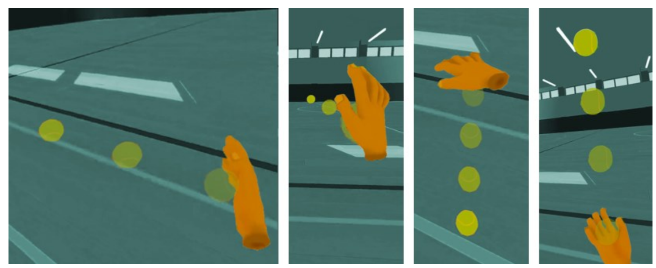

Figure 16. Task 2: Catching and throwing balls from different directions (here: side, front, up, and down) with different velocities.

Results

After each trial, participants were asked to rate the realism of the haptic experience by "How realistic did the catch/throw haptic experience feel?" on a 1 (not real at all) to 5 (very realistic) Likert scale directly inside the HMD. We aggregated all the responses for each different speed and catching/throwing direction.

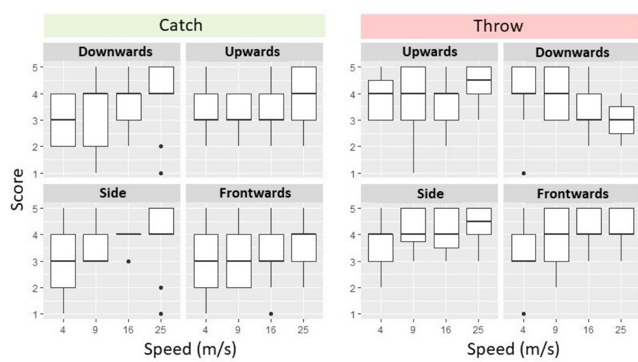

Figure 17. Results of Task 2 catching and throwing at different speeds in the 4 directions.

<u>Catching:</u> Participants found the haptic experience for catching realistic (Figure 17), with an average score of 3.5

±1 (mean, sd). No significant differences were found for the direction of the ball, despite the balls coming from the front were found a bit the less realistic (avg score = 3.3), most likely because of the ergonomics of the device. Participants found catching faster balls more realistic (Pearson correlation of r=0.25, $p < 0.01$). We did not simulate gravity, which, with the slow balls, might have been more apparent.

Throwing: Participants found the haptic experience of throwing more realistic than that of catching (Wilcoxon signed rank paired test $p < 0.001$), with an average score of 4 ±1 (mean, sd). The reason for this might be the previously described importance of self-generated actions for haptic acceptance [5]. No significant differences were found in the realism between throwing to the side, up and to the front. Only for the down direction we found a significant negative correlation (r=-0.31, $p < .05$). Further investigation would be necessary to understand this effect. For the three other directions, the correlation of speed and realism was maintained: the fastest the throw the more realistic it seemed (Pearson correlation r=0.24, $p < 0.01$).

On the questionnaire participants filled out after the virtual part of the experiment, participants agreed with the statements of catching (Q6: "Throwing felt realistic", mean=5.6, sd=0.6, $p < 0.01$) and throwing (Q7: "Catching felt realistic", mean=5.4, sd=0.5, $p < 0.001$) feeling realistic. They rated these statements on a scale from 1 (completely disagree) to 7 (completely agree).

Task 3: Perception of weight

In the last task, we measured PIVOT's ability to produce the perception of weight. We asked participants to grab three different virtual balls and select the one they perceived to be heaviest and the one they found the lightest (Figure 18). Participants naturally assessed the balls weight by holding the balls upwards, downwards, turning them, and weighting with up-down movements. The rendered weights of the objects were 90g, 200g and 300g (the force exerted at the end of the handle lever). Similarly as illustrated in Figure 5, the device was rendering only the perpendicular component of the gravitational force to the plane of the palm. This resulted in full weight sensation when the palm was facing upwards or downwards, and proportionally less in the in-between positions.

Figure 18. Task 3: Participants were presented three virtual balls (90g, 180g, 270g). They had to estimate their weight and pick the heaviest and the lightest.

The weights of the balls were randomly assigned for each participant. After participants completed the task, still inside VR, we asked them to compare the virtual objects to some real objects of their own choice (e.g., mobile phone, cup, pencil, shoe, keys, tennis ball, chocolate bar, water bottle).

Results

Participants selected the heaviest ball correctly in 83% of cases. The lightest ball was correctly selected in 91% of the cases. Based on Bernoulli test and Bayes theorem with three balls, participants did not assign balls at random (binomial test of significance $p < 0.05$).

Figure 19 shows that participants had a good sense of the actual weight of the balls. Participants compared the light ball (90g) to real objects that were around that magnitude (real objects ranged between 50-150g, for example Participant 5 compared it to a ~60g tennis ball). Participants estimated the heavy ball with similar accuracy (real objects ranged from 200-500g). Overall, there was a slight tendency to overestimate the weight. This could be a normal human tendency or a fatigue effect. Two participants were clear outliers in overestimating.

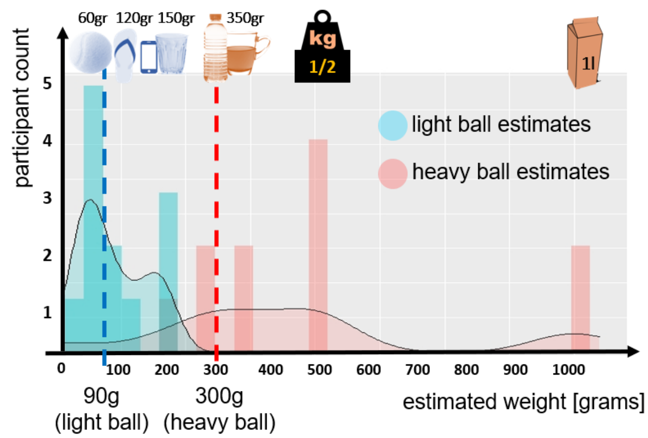

Figure 19. Results of task 3: Participants subjective weight estimation for the lightest and the heaviest ball (dotted lines shows the weight PIVOT rendered)

On the questionnaire after the virtual part of the experiment, participants stated that they perceived the weights differences clearly (Q5: "I could feel the difference between the weight of the objects", mean=5.08, std=0.33, $p < 0.015$). During the study none of the participants reported being disturbed by the reaction force exerted by the cuff on their forearm. We assume this effect would become more prominent in case of rendering larger forces.

Overall the study demonstrated the main capabilities of PIVOT to grasp objects just in time, just in space, with added dynamics such as weights and forces. It also revealed some of its limitations and extent of its versatility to produce realistic haptic effects.

EXPLORATORY PROTOTYPES

To explore the possibilities of the wrist mounted design, we created numerous prototypes early on, two of them shown in Figure 20. In Figure 20a, PIVOT's handle is retrofitted with a commercial Windows Mixed Reality VR controller. This is a straightforward functional design; however, the shape of the controller is less satisfying to simulate grasping various objects.

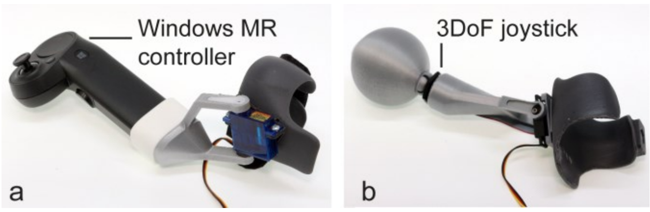

Figure 20. Exploratory prototypes: (a) PIVOT's mechanism retrofitted with a Windows Mixed Reality controller, (b) PIVOT equipped with a 3DoF joystick ball that enables dexterous navigation.

Figure 20b shows a version of PIVOT that is equipped with a 3DoF joystick ball that can be bent and rotated. This input mechanism enables dexterous input in VR and additionally makes grabbed VR objects feel less constrained in the hand due to the loose coupling between the joystick ball and the forearm. However, this prototype makes force rendering less realistic, due to the loose coupling between the handle and the motor.

LIMITATIONS AND FUTURE WORK

While iterating on PIVOT's design and evaluating it in our study, we discovered a couple of areas for improvement.

On the mechanical end, PIVOT's design is sturdy and aligns with the wearer's arm so as to stay out of interactions with real-world objects. However, wearing the device for longer periods (1h+) may cause a numbing sensation in the arm, which is not the case with conventional hand-held controllers. Future versions could alleviate this by reducing the weight, e.g., by substituting the VIVE tracker.

Sideward movements of the hand are currently only addressed by the passive radioulnar pivoting of the handle that adapts to the hand's natural position. However, in extreme hand rotations, the handle might not land exactly in the user's palm. In case the handle misses the users grasp for any reason, the system naturally recovers by not attaching the virtual object to the user's hand, and leaves the chance for another try. Better aiming to the palm could be addressed by adding one or more motorized joint to the device. However, it would also increase the device's complexity and cost.

When using PIVOT as a pointing device (for example as a spotlight in the supplementary video), the user's wrist movement is still constrained to roughly ±30 degrees in both flexing-extending and radioulnar directions. This limitation could be alleviated by using the design shown in Figure 20b where the grip-ball is mounted to a joystick that allows further 3DoF movement.

The fixed size of the handle limits the range of objects to be approximated effectively. Therefore, when the shape of objects is too dissonant, interchangeable handles could be combined with shape changing technology, such as adding different shapes and textures covers to the controller or inflatable pockets on the handle, similar to [11] and [20].

On the interaction level, we see potential in further augmenting PIVOT to sense more user input to inform its behavior. For example, a future version that integrates finger tracking around the handle (e.g., through a self-capacitive array [32] or a wearable camera [27]) could better approach the user's palm and fingers during interaction and provide haptic feedback for dexterous input. In addition, sensing the applied torque on the handle by a strain gauge could aid PIVOT's force rendering accuracy.

CONCLUSION

In this paper, we presented a novel interactive haptic device for use in AR and VR scenarios. Unlike existing commercial controllers and haptic devices presented in recent research projects, PIVOT presents an approach that dynamically appears and vanishes a haptic proxy in the user's palm. This enables compelling haptic effects and force rendering, as well as free-hand interactions with physical objects in the real world. What enables PIVOT's unique capability is a forearm-grounded pivoting mechanism that rotates a handle into and out of the user's palm on demand. We demonstrated several use-cases of this key feature in this paper, such as grasping, catching, and throwing virtual objects, which PIVOT renders in an analog manner. In addition, our controller enables rendering dynamic forces excreted by the grasped objects. In our user study, participants rated the use of PIVOT as a realistic proxy and highlighted the ergonomics of the design that made them feel like their hand was in direct contact with the object. These results support PIVOT's potential for future use.

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