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Taxonomy of Hand-Object Haptics for Virtual Reality

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***Abstract*—Manipulation of hand-held objects in Virtual Reality (VR) requires input tracking with high freedom of movement, as well as haptic feedback of hand-object interactions. Through our prototypes we demonstrate a pragmatic approach to haptic feedback on controllers that render human scale forces. Our devices manifest haptic simulation of compliance, texture, surface normals, sizes, weights, and kinematic forces. These are brought to bear on hand-object interaction primitives such as palpation, manipulation, grasping, squeezing, cutaneous touch, stable grip, dexterity, and precision manipulation, which are collected as a taxonomy and represent a layer between the inherent haptic properties of the objects and the hand interaction of the operator. We implement prototypes that simulate the functional affordances of each of these aspects, and characterize their performance in human perception studies. Our work offers a model of hand-object interactions that goes beyond force rendering on a finger-by-finger basis (as typical of hand exoskeletons and gloves).**

***Index Terms*—Controllers, Haptics, Touch, Taxonomy, Virtual Reality, Force feedback, kinetic, palpation, manipulation, holograms.**

I. Introduction

There is a need in Virtual Reality (VR), and Augmented Reality (AR) [1] scenarios to render haptic sensations that will let users feel, touch, push, grab and manipulate virtual objects around them in a more natural way. The challenge is to achieve a fidelity of tactile and force perception that improves task performance. One way to do this might be to generate perceptions similar to those found in the real world. Current capabilities of interaction devices used in commercial Virtual Reality systems lag far behind on rendering of haptics sensations, especially in comparison to the highly realistic visual and spatial audio content in these systems. To address this imbalance, our goals are 1) to understand which haptic interactions are necessary for Virtual Reality controllers, 2) to find a taxonomy that prioritizes hand-object interactions needed to create convincing haptic feedback, and 3) to propose practical implementations that realize various aspects of these haptic primitives.

To achieve plausible illusions of haptics inside VR, the sensory-motor and perceptual systems of the user need to be stimulated and work together with the touch. In particular, while precision-grip control derives from the cutaneous pressure-sensitive fingertips, power-grip actions involve the muscular level (4). Both precision and power grip are part of the same input-output loop, sometimes referred as afferent/efferent [1]. For every motor action (input to the VR system, such as grasp of an object) the user expects an output (haptics and vision) that stimulates their senses correspondingly. In a bottom-up fashion, the visual sense is stimulated through the display, while the tactile sense needs to be stimulated haptically through the controller. If there is no correspondence between the multiple senses that a user expects, the illusion can be broken [1], through either a body semantic violation if there is a motor mismatch [2] or directly through an uncanny valley of haptics [3].

From this perceptual description, we conclude that the devices must be able to render forces exhibited by both rigid and deformable objects but also need to deliver cutaneous stimulation at the fingertips. A controller with both abilities can provide for the muscular power needs to render enough touch fidelity, while also remaining compliant for varying object behaviors and material properties.

A special challenge beyond perception, for any haptic device targeted towards Virtual Reality applications, is that it should allow users to move freely in space. This implies that practical haptic rendering devices should be either handheld or worn on the user's body, and ideally not grounded to a room-fixed location which limits user freedom of movement in the environment. While grounded devices such as 3D Systems Phantom or Haption Virtuose 6D [4], [5] provide realistic feedback, their workspaces are rather restricted, and they only provide a single point of contact of 3 to 6 degree of force feedback. Such constraints are inconsistent with the demands of Virtual Reality in consumer or open-world settings [6]. In this context, developments in handheld controllers could be the answer to a new awakening of haptics in Virtual Reality.

Our work extends handheld controllers, mainly used for input in current practice, to provide multipurpose haptics in VR. We take a pragmatic approach by selecting the form-factor of controllers to deliver haptic experiences to a broad audience at a reasonable price-point, rather than grounded armatures, exoskeletons and the like that might provide more perfect rendering but that are too costly, bulky, or impractical for actual spaces of work and play outside of a dedicated laboratory. To do so we analyze what is necessary to simulate (or create the illusion of) interacting with a virtual object held in one's hand. As opposed to the traditional replication of the hand that is the common approach when building exoskeletons and gloves, we look at the properties of the objects.

We focus on a prioritized subset of sensations that relate to physical manipulation of hand-held objects. This includes

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[1] In the text we use the term Virtual Reality to refer to both VR and AR (Augmented Reality).

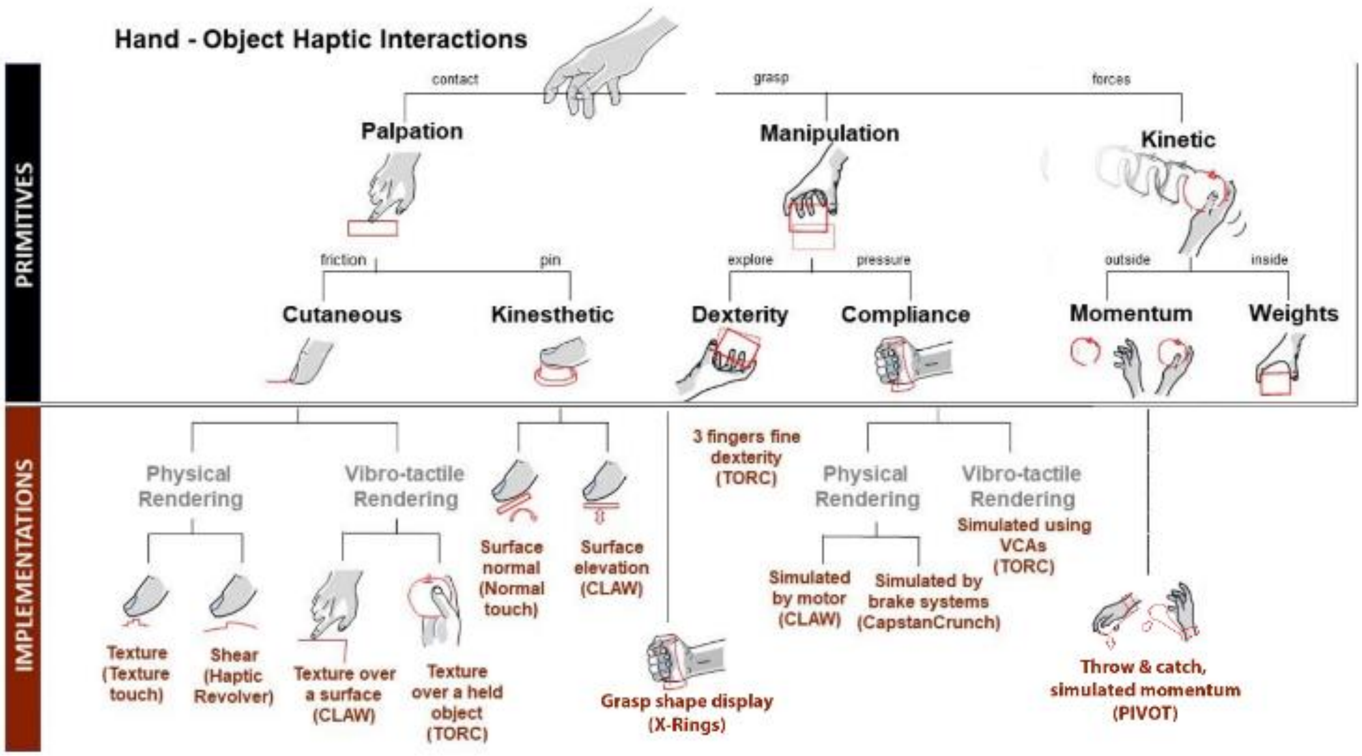


Fig. 1. Haptic Taxonomy. Canonical primitives that are the basis to achieve a successful interaction with a virtual object. The figure also summarizes the prototypes that are presented in this paper to test each of the modalities. As per the acronyms on the implementations of the graph, they are the names of our controller prototypes that will be described in the Prototypes section.

primitive interactions such as perceiving momentum when an object lands on our palm, to rendering its mass on the hand. It also includes hand-object interactions such as picking up, releasing, manipulating, and tumbling (rotating) the object in one's fingers. Through tactile exploration one can also concentrate on the object's material composition, compliance, and texture. This framework of interactions, although limited to certain size of ungrounded objects that will fit within the hand, enables a large variety of direct manipulation of artifacts inside VR – as well as the simulation of handheld tools.

Through our exploration we present multiple forms and implementations to achieve natural haptics on a series of prototypes: Texture touch, Normal Touch, Haptic Revolver, CLAW, TORC, CapstanCrunch, Pivot and X-Rings. We further define the workspace of haptic hand-object manipulation in a taxonomy that encompasses these diverse prototypes. The result is a subset of haptic controllers that cover many natural hand-object haptic interactions, and that hint at further promising combinations and hybrids that could be explored in the future.

II. A TAXONOMY OF HAPTIC INTERACTIONS

To establish the primitives of hand-object interactions and their hierarchy, we borrow concepts from device independent design to try to establish the interactions as device agnostic needs [7]. This helps us explore the canonical actions needed to achieve a successful manipulation of a virtual object, even if there are multiple device implementations that could provide the desired response. For the particular case of touching and manipulating virtual objects, it is clear that we need to have a power grip (as introduced in the grasping taxonomy by Cutkosky [8]) precisely to create the illusion that the object is actually present within the user's hand [1]. This power grip is needed at all times when you are holding something to achieve the optimal minimum force to prevent an object from slipping from the user's grasp. Hence the power grasp may also remain a necessary element for precision dexterity and compliance while in VR. That is, for the particular case of VR haptics, precision grasp and power grasp will not be presented as opposing tasks but as two necessary elements that need to be combined [8] in the same device.

This analysis leads us to a new set of canonical hand-object interactions, as characterized by three main atomic primitives – palpation, manipulation, and kinetic forces – with six further 6 sub-level primitives (Figure 1), defined as follows:

- Palpation. Refers to the sensitivity of the fingertips to perceive and recognize textures, shapes and object surfaces with active touch, as well as the kinesthetic feedback provided by skin deformation during cutaneous exploration.
- Manipulation. Refers to the action of manual interactions with an object that can be grasped and released. There are two main types of manipulation depending on the forces applied and rigidity of the objects.

○ Dexterity. Is the type of manipulation where objects are moved and rotated between the fingers with high precision and ability.

○ Compliance. During manipulation when forces are applied, we can perceive the stability, rigidity and stiffness that are determined by the properties of the object. By adding pressure on the object we can squeeze to create stable and credible grasps on different types of objects.

- Kinetic Forces. Refers to the energy and physics of the objects that it possesses due to its motion but also due to gravity. The energy can be gained during an acceleration for a given mass. The physics occur as a result of that energy. In practice these properties of the object include momentum (e.g. for catching or throwing), and weight.

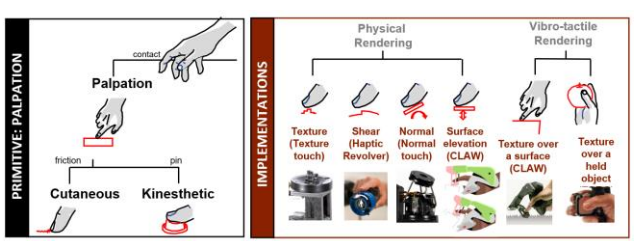
Other hand-object interactions not covered by this taxonomy might help describe temperature, grounding of the objects, friction, and other properties. Further aspects like grounded world-scale forces (pushing on a door...) are deemed out of scope for our focus on pragmatic handheld controllers because they require to transmit force to the ground via some form of coupling.

To explore this new taxonomy of interactions and how each primitive can be delivered, we created a series of haptic prototype controllers discussed in the remainder of this paper, namely Texture touch, Normal Touch, Haptic Revolver, CLAW, TORC, CapstanCrunch, and Pivot [9]–[14]. Each prototype implements different hand-object interactions.

III. PROTOTYPES

In this section, we describe a series of prototypes that we have built to respond to our taxonomy needs, and to allow for a natural haptic hand-object interaction using a handheld controller. For each of the prototypes, we explain the rationale behind our implementation, and comparable research by other authors. The particularities of the testing and implementation for each of the prototypes are further detailed in the Materials section.

Note that our controllers here can be considered platforms to check different haptic renderings. They are not exclusive, i.e. the different haptic rendering may be combined to one supper controller (and indeed we did combine some successful renderings into different controllers).



A. Palpation

The first contact that a hand has with an object even when it does not involve grasping includes palpation of the surface (Figure 2). In order to facilitate palpation, we created three controllers that physically rendered the properties of object surfaces: TextureTouch, NormalTouch and Haptic Revolver. We further implemented two prototypes that simulated texture effects using Voice Coil Actuators (VCA): TORC and CLAW.

In this section we focus on our physical rendering prototypes aiming at palpation. The three prototypes are all single-purpose devices that either focus on rendering cutaneous touch at the fingertip (Haptic Revolver, TextureTouch) or at rendering the kinesthetics associated with the normals of objects on the handheld controller (NormalTouch).

TextureTouch:

Using a matrix of real-time extrudable pins we created a prototype that could provide 3D impressions of shapes while moving the handheld controller at a fingertip level against a virtual object. The user's finger would rest on the platform as the controller moved around the virtual scene. The pins under the platform could rise or fall and create physical 3D patterns in real-time when the finger was in contact with virtual objects. In the most basic operation, the 6 DOF controller (with 3DOF actuators) tracks and detects when the finger penetrates the surface of a virtual object, and the texture matrix extends to compensate for the penetration, thus rendering the surface in contact (Figure 2).

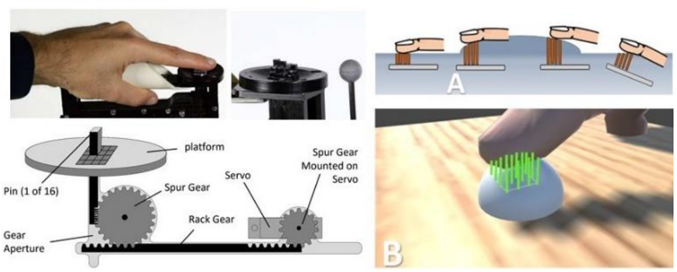


Fig. 2 TextureTouch. Prototype and working example inside VR.

NormalTouch:

In order to provide 3D impressions of shapes while moving the handheld controller, we attached a tilt-able and extrudable platform to this prototype (Figure 3). The user's finger rests on the platform as the controller is moved around the virtual scene. The platform is retracted by default and activates whenever the finger makes contact with virtual objects. Upon object contact, it extrudes and tilts the finger platform so that is parallel to the object's surface at the point of contact. This controller also employs a force sensor under the finger-pad to sense contact force and, with real-time feedback, is was able to simulate a rigid, compliant or other material property.

NormalTouch has less descriptive power than TextureTouch, however it is much less costly to produce as it reduces significantly the number of actuators and overall complexity. In fact, after the development and user testing of NormalTouch, we kept checking cost/effectiveness and reduced the rendering of the pad's orientation even further to elevation only (with one actuator).

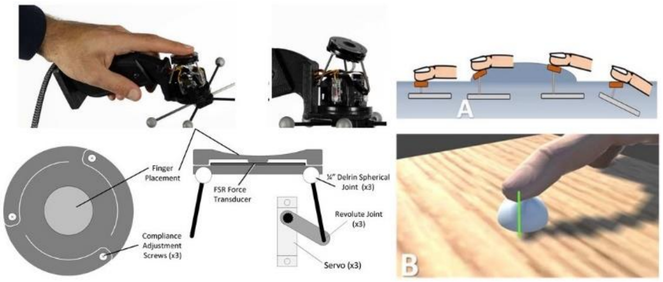


Fig. 3. NormalTouch. Prototype and working example inside VR.

Haptic Revolver:

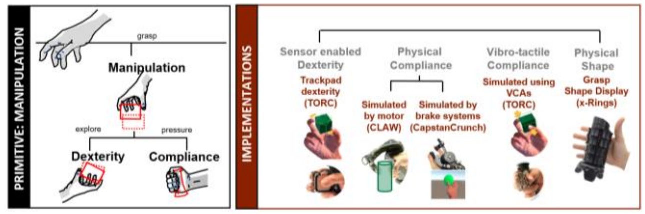
Haptic Revolver represents an exploration of fingertip sheering forces. This prototype causes a spinning cylinder to contact at the (Figure 4). This way it is able to simulate cutaneous experiences of shearing, edges and textures. The wheel and rotation servo are mounted to a vertical actuator that simulated a reduced-function NormalTouch for elevation only. When a user operates the controller, they feel the contact force with the surface when touched and can explore its texture and shape by sliding the finger laterally where the cylinder spins in synchrony with the finger-surface velocity. This device is designed as a reconfigurable system in which different cylinders could be attached, each one featuring particular elements or materials. The cylinder's speed and position can also be programmed and will physically retract away from the finger when the user breaks contact with the surface.

Fig. 4. Haptic Revolver. Examples of use and configuration.

VCA Simulated:

We further implemented simulated texture effects using Voice Coil Actuators (VCA) in CLAW and TORC (Figures 6 and 8). They both work on the same paradigm, and despite their location (TORC has the VCA on the thumb and CLAW on the index) they use the same principles.

In 'Touch' mode, both prototypes simulate various textures by actuating a VCA on the fingertip. The microcontroller in the device plays back pre-generated haptic patterns. The texture actuator loop runs at 14kHz, and data is played back with speeds corresponding to the user's calculated finger speed and required amplitude information (i.e., grit size of the surface). There are currently existing libraries of sounds that can serve the purpose of VCA simulated touch, such as VibViz [15].



B. Manipulation

The manipulation of objects held in the hand typically involves multiple fingers (Figure 2). A user will grasp the object or press to feel stiffness. In this section we present a series of prototypes that were designed to explore these operations: CLAW, had the ability to grasp an object, squeeze it and release it using Physical rendering with motors; CapstanCrunch, also renders compliance using physical actuation with brakes. CapstanCrunch can be considered a passive modification of CLAW without expensive and power consumptive motors. TORC further implemented compliance and dexterity through vibro-tactile simulation.

CLAW:

The CLAW is a multi-purpose prototype that integrates both touching and grasping (Figure 5). It provides articulated movement and force feedback actuation to the user's index finger which allows for convincing haptic rendering of: (a) finger forces when grasping virtual objects, (b) rendering of a virtual object's shapes, stiffness, extent, and texture and (c) realistic trigger feedback. The design includes a thumb rest that exhibits an opposing force when grabbing objects.

Fig. 5. CLAW. Prototype and examples of the haptic renderings inside VR.

CapstanCrunch:

CapstanCrunch is a force resisting prototype, and creates finger haptics similar to CLAW (Figure 6). The controller renders haptic feedback for grasping both rigid and compliant objects [13]. In contrast to previous controllers, such as CLAW, CapstanCrunch renders human-scale forces without the use of large, high force, electrically power consumptive, and expensive actuators. Instead, CapstanCrunch integrates a friction-based capstan-plus-cord variable-resistance brake mechanism that is dynamically controlled by a small internal motor. The capstan mechanism magnifies the motor's force by a factor of around 40. Since most brake mechanisms only provide resistive forces with no energy storage capability (necessary for compliance), we added an additional capstan clutch to engage a spring at a programmable grasp position.

Compared to active force control devices, such as CLAW, the CapstanCrunch is potentially low cost, low electrical power, robust, safe, fast and quiet, while providing high force control to user interaction.

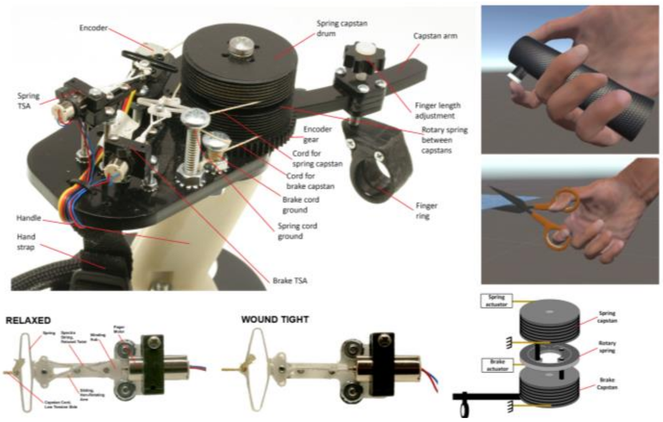


Fig. 6. CapstanCrunch. Prototype details and examples of the haptic renderings inside VR.

TORC:

TORC eliminates all moving parts but at the same time is able to simulate dexterity, grasping and compliance of a virtual object simultaneously (Figure 7).

This supports the precision grip [16] using multiple fingers employing the thumb and two fingers, as well as the power grasp. Instead of providing more degrees of freedom to the index finger this prototype tracks the thumb's position, allowing for it to freely move on a touch pad, parallel to the plane of two fingers. With TORC the thumb rest is modified and through a sensed platform, allows extra dexterity and easy manipulation of the held objects.

A common problem in the previous prototypes was the use of moving parts, which make the controllers more complex, requiring large forces and are breakable. In this prototype we aim to create a rigid device, which is more robust, but could nevertheless simulate perceptual levels of stiffness and texture.

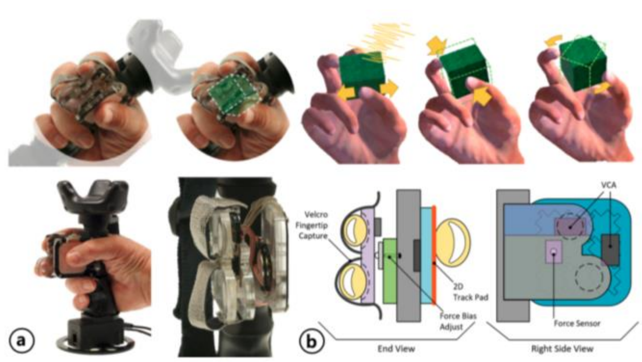


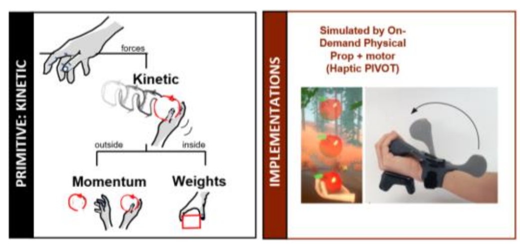
Fig. 7. TORC. Prototype and examples of the haptic renderings inside VR.

X-Rings:

Is a Hand-mounted 360◦ Shape Display for Grasping in Virtual Reality that renders objects in 3D and responds to user-applied touch and grasping force (Figure 9).

Through a series of concentric rings that can change shape, x-rings provides a combination of grip and palpation experience while holding an object [17]. The monitoring of current applied on each of the motor rings, this controller can also measure the applied force and provide experiences similar to the brake mechanisms of CapstanCrunch, and allowing effects like breaking an egg or cracking a can.

Fig. 8. X-rings. Prototype and examples of the haptic renderings inside VR.



C. Kinetics

For rendering kinetic forces exerted by the objects on the user hand (Figure 2). Prototypes need to allows the perception of mass momentum and weight. With that in mind we envisioned a wrist grounded controller prototype: Haptic Pivot. The grounding approach had additional challenges as well as benefits, such as the ability of the controller to be used only on-demand and leave a hand free for other uses the rest of the time.

Haptic Pivot:

Haptic Pivot renders haptic dynamic forces through a wrist-mounted design that can dynamically pivot the controller handle—including its built-in haptic elements—into and out of the user's grasp. In essence the controller acts as a proxy when grabbing virtual objects, as well as to simulate dynamic forces by actively driving it when grasped in hand [14].

This prototype has the ability to add kinetic forces into the objects that then are translated to the user at the moment of interaction (Figure 10). The strategy here is to use a haptic handle that pivots into and out of the user's hand on-demand. Haptic Pivot addresses forces that operate on the palm. In this way it generates a perception that the user is holding an object with programmable weight. While it also supports the precision grip [16] using multiple fingers. By grabbing or releasing the Haptic Pivot handle when approaching virtual objects, it creates the haptic sensation of touching, holding and releasing, as well as catching, or throwing virtual objects. Haptic Pivot's active pivoting mechanism enables rendering static and dynamic forces acting on virtual objects in-hand such as inertia, gravity, or sliding friction.

Fig. 10. Haptic Pivot. Prototype and examples of the haptic renderings inside VR.

IV. Materials and Methods

In this section, we describe in detail how we built and tested the different prototypes presented in the paper.

A. TextureTouch

Testing. To test this device participants were repeatedly presented with one of the three target types that encompass features in virtual objects that are (a) smaller than a user's finger, (b) within the dimension of a finger, and (c) substantially larger than a finger. Using this prototype participants significantly increased accuracy to detect the surfaces of the three types of objects rather than using traditional vibro-actuated controllers [9].

Implementation. The core of TextureTouch comprises of 16 linearly actuated adjacent pins in a 4×4 configuration. Each pin is individually driven by a small servo motor (HiTec HS-5035HD). We used rack and pinion mechanisms to convert the servos' rotary output to linear travel. An additional rack and pinion pair turns the motion at right angles for an optimized configuration and minimum volume as shown in Figure 2. A Pololu Mini Maestro24 servo controller relays the extrusion levels determined by the virtual reality system from the PC to each servo motor. TextureTouch draws 800mA in average use (1.5A peak).

B. NormalTouch

Testing. To test this device participants were repeatedly presented with one of the three target types that encompass features in virtual objects that are (a) smaller than a user's finger, (b) within the dimension of a finger, and (c) substantially larger than a finger. Using this prototype participants significantly increased accuracy to detect the surfaces of the three types of objects than using traditional vibro-actuated controllers [9].

Implementation. The core of NormalTouch is an acetal (Delrin) platform actuated by three servo motors (Hitec HS-5035HD) that impart the mechanical three-dimensional freedom of a Stewart Platform. The servos' control arms are connected with revolute joints, through small rigid linkages to ball-and-socket spherical joints under the platform. The rigid linkages are restricted in movement to be always perpendicular to the servo's axis. This allows the three degrees of freedom imparted by the three servos to be mechanically transformed to the finger pad's yaw and pitch angles plus linear extruding movement along the roll axis (towards and away from the user).

A force sensor (Interlink Electronics FSR-402) inside the finger-pad's 13mm disk detects touch input force with a range of 0.2–20 N, which is adequate for finger pressure use. The sensor is configured such that with applied force levels of less than 0.2 N, the sensor responds with infinite resistance (is not in contact with the FSR material and results in no voltage to the ADC, allowing us to reliably detect moments during which no touch is present. A small force applied to the sensor (>~0.2 N) results in contact and a reliable force reading.

All components are designed in CAD and laser cut in Delrin plastic. An advantage of our configuration is that the overall 3D mechanism occupies a minimum volume compared to other implementations. To control the servos, we integrated an off-the-shelf multi-servo USB controller (Pololu.com Mini Maestro-12) into the 3D printed controller handle.

C. Haptic Revolver

Testing. The fundamental haptic capabilities were completed in a study that measured the impact of speed gain and direction. The results showed maximum realism of touch when the wheel moved, however, the direction of the skin deformation did not impact realism [10].

Implementation: This prototype has two degrees of freedom, each of which are actuated by a motor. In order to provide cutaneous contact with the fingertip, whenever necessary a servo motor (Hitec HS-5070MH) raises and lowers the wheel assembly. The wheel assembly's axis is positioned along the axis of the index finger and consists of a 12 V DC motor+encoder (Faulhaber 1524_SR) housed in a 3D printed mount. The motor includes a 19:1 gearhead and a 4096 count 2-channel magnetic encoder. A special wheel mount allows custom wheels to be easily interchangeable. With this gear ratio, the motor can spin at up to 180 rpm, which corresponds to a linear motion underneath the finger of 565 mm/s, assuming a 60 mm wheel diameter. The peak power consumption of the system is 2.5W and the max force against the finger is 3.35N. The device is controlled by firmware running on a Cypress Programmable System on Chip (PSoC) 5LP.

D. CLAW

Testing. This prototype was tested to explore how well could people use a multipurpose device and switch between modes, in this case between grab or touch. Objects were presented randomly, and participants had to switch from one mode to the other using the opposed thumb. Overall, participants took 5.9 seconds to complete the grabbing task while the touching task took 2.9 seconds [11].

Implementation: The core element of CLAW is the rotating arm that is mechanically powered by a Hitec HSB-9370TH servo motor, powerful enough to actuate against the force of the user even when they try to penetrate into a particular virtual object. This would generate up to 30N of grasping force and up to 10 N/degree (5.73 N/mm) of stiffness. An HX711 ADC board is used for strain gauge-based sensing the force imparted by the index fingertip with a 0.000023 N resolution. The force sensing together with the servo motor create a close-loop force control system. Using this feature, we can simulate various stiffnesses of different materials like rigid (wood, metals) and soft objects (clay, rubber balls, sponges) and even non-linear properties like breaking glass or plastic. The controller also allows for material hysteresis rendering as in pushing a click button.

The handle grip encloses a Teensy 3.2 microcontroller, and a DRV8833 motor driver to power a VCA at the index fingertip that renders textures and the high frequency values of touch and grasp. The controller also incorporates an optical proximity sensor (QRE1113) for detecting thumb positions. The different positions allow the users to naturally switch between operation modes. We designed all connecting components using CAD and printed them on an Objet Connex 3 printer.

E. CapstanCrunch

Testing: This prototype was tested for compliance simulation against the CLAW controller and against a fixed spring. This prototype outperformed the use of the CLAW and the fixed spring for rendering objects of a wide range of compliances and outperformed the use of fixed springs. The CLAW however, was the best device to provide the illusion of a rigid object.

Implementation: CapstanCrunch employs the resistive friction of a programmable brake capstan for resisting human finger movements. Unlike most capstan systems where the cord moves with respect to the drum, the capstan drum in our controller is rotated by the user's finger. A small internal actuator applies a low-tension force on a cord and the higher tension side of the cord is fixed (grounded) to the handheld device. Thus, when the user tries to rotate the capstan in a finger closing direction with small or no actuator tension, the capstan drum rotates more or less freely. As the tension is increased by the actuator, the drum becomes harder to turn in the finger-closing direction. The capstan friction relationship between cord and drum is either static (non-moving capstan with respect to the cord) or dynamic (capstan rotating). When the user rotates the drum in the opening direction, is automatically lessened by moving the cord exit point of the drum closer to the internal actuator.

To add the haptic perception of compliance, we added a second capstan that is connected to the brake capstan through a rotary spring. This second capstan acts as a clutch to engage the spring at the appropriate finger position. To overcome the lower speed of an earlier used motor+gears actuator, we exploit the technology of a Twisted String Actuator (TSA). The TSA in our prototype consists of a small pager motor with a hub attached that winds up a pair of strings (Spectra fishing line, 100 lb test) which in turns moves a slider assembly linearly to tension the capstan cord. Overall this capstan system creates an asymmetric force system that is however not perceivable for users [18]. A Teensy 3.6 microcontroller runs the firmware in our controller, converting and processing the rotary encoder signal directly to produce a PWM signal for the actuator. The PWM terminals if the microcontroller connect to a current limiting DRV6671 motor driver H-bridge which drives an E-flite EFL9052 coreless motor.

F. TORC

Testing: This prototype was tested against a classical hand-held controller in the operation of manipulating a virtual object while also gasping it. In the traditional controller, the grasping was simulated using a trigger button. In this case the prototype outperformed the button approach [12].

Implementation: Under each finger rest we mounted force sensors (Honey-well FSS1500) and voice coil actuators (VCA, Dayton Audio DAEX9-4SM). 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 instrumentation 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. The prototype initially used three force sensors and three VCAs on each finger/thumb rest.

To render the compliance on a rigid device via the VCAs, we used Kildal's method [19], which presents a vibration burst for certain force changes. We rendered a 6 ms pulse of vibrations (170 Hz) to the appropriate VCA for every 0.49 N change in the system force.

The prototype includes a 2D trackpad [20] using printed 3 × 3 copper pads. We wired the 9 pads to 9 capacitance 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 conductance 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.

G. X-Rings

Testing: This prototype was tested in a force choice test against 6 different virtual objects that span a range of curvatures where we found an error rate of 20% in discriminating among the different objects. While some objects were below 10% error others were harder to distinguish.

Implementation: X-Rings is assembled entirely from of-the-shelf parts and 3D printed components. Each layer of X-Rings is powered by a 12V DC gearmotor (Pololu #4789, 15:1 gear ratio). Motor rotation is measured using a magnetic encoder (Pololu #4760) mounted to the rear motor shaft, and controlled using a TB9051FTG motor driver through a software PID loop. Motor current is also monitored by the driver, and output as an analog voltage proportional to the motor current (500 mV/A). A set of 3D printed bevel gears (40:12 ratio) transmit motor power at 90 degrees to the extending arms via a spiral cam coupled to the bevel gear. A 3 mm ball-bearing aligns the rotation of the larger bevel gear. Each arm consists of an exterior wedge, a sliding pin, and an 2 mm ball-bearing which contacts the spiral cam. The four expanding layers are then mounted to the 3D printed controller handle via M2 screws. A Teensy 3.6 microcontroller governs all sensing and actuation on X-Rings, and receives commands from a PC via USB serial. Position control for each layer is maintained using a 1000 Hz PID loop, while four analog inputs are used to monitor the current of each motor.

H. Haptic Pivot

Testing: This prototype was tested against a classical hand-held controller in the operation of Catching and Throwing a virtual object. And also in the operation of comparing balls of different weights.

Implementation: Haptic Pivot's key element is the single-servo pivoting design. Most parts are 3D printed from ABS material. The hand cuff itself is printed from flexible material (Form2 - Flexible) to accommodate different arm diameters and shapes. To drive Haptic Pivot's handle, we modified an off-the-shelf servo motor (Hitech HS-7115TH) to gain control over: (1) torque and speed, (2) back-drivability, and (3) real-time position feedback. To achieve this, we removed its original control circuit and replaced it with our custom driver electronics and software running on the Teensy controller. The implemented PID loop has a time-based protection mechanisms to prevent overpowering the motor.

Haptic Pivot's control board is built around a Teensy3.6 microcontroller that interfaces to a custom I/O daughter-board. This daughterboard contains the motor driver and VCA PWM circuits, an inertial sensor to detect hand motions, a BLE chip (Nordic nrf52832) for wireless communication, and operational amplifiers to process the analog strain gauge full bridge output and the position from the servo's potentiometer encoder. We use the Teensy's inbuilt capacitive sensing functionality to sense the copper-based coating capacitance of the handles inside electrodes in active loading mode to detect touch events. The handle also contains a VCA to render vibrotactile feedback as well as a trigger button as commonly found in VR controllers. here are four touch sensitive patches inside the handle that are important to distinguish different grasps, and help Haptic Pivot to predict users intention.

V. Discussion

Virtual Reality type of systems allows us to use our body to interact in natural ways with the content. Although *status quo* handheld controllers represent a reasonable proxy of real-world interaction, they still do not enable the direct use of our hands for proper dexterous manipulation that are needed for full immersion [21], [22]. To enable this more meaningful interaction with Virtual Objects, we created a new haptic interaction taxonomy and tested it in a set of prototypes that emphasize direct manipulation of objects in-hand. We use device-independent design while trying to distill the fundamentals of what should be incorporated into a Virtual Reality haptic controller. We then built a subset of prototypes (NormalTouch, TextureTouch, Haptic Revolver, CLAW, CapstanCrunch, TORC, X-Rings and Haptic Pivot) that rendered select haptic primitives—Palpation (touch), Manipulation (grabbing, compliance and dexterity), and Kinetic forces (momentum and weight)—that ultimately create the illusion that you are holding and interacting with a virtual object held in your hand. But as a nod to pragmatism our prototypes did not aim for overloaded functionality of all possible combinations. For example, one could imagine devices with a tactile wheel for each fingertip (essentially a hybrid of HapticRevolver with either our CLAW or CapstanCrunch prototype); such a contraption would be unwieldy for general use, yet still might be of future interest as a research vehicle or for highly specialized applications—or if alternative technical realizations become possible in the future.

However, given all the possible combinations of primitives and implementations, the quest towards a multipurpose device is hard; there is a huge space of potential designs that needs to meet the versatility and individuality of users. Our own research prototypes have made inroads by tackling one particular aspect at a time (see also the *Materials* section). But this work together with the contributions from the scientific community are clarifying what the minimal properties and sensations need to be, in order to propose viable Virtual Reality haptic controllers.

We have proposed a set of canonical primitives for haptic interactions that include grabbing and releasing, compliance and dexterity, and touch at the cutaneous and kinesthetic levels (Figure 1). These primitives have intrinsic dependencies, such as the need to grab an object before compliance or dexterity can be simulated. Yet we believe that this dependency distinguishes our approach from previous work that focuses on single types of feedback, or that attempts to cover more than previous taxonomies of grasp [8].

Our device-independent methodology, with a focus on haptic primitives that can be combined in different ways, offers another noteworthy aspect of our approach. These primitives naturally suggest various combinations and techniques beyond those currently manifest in our prototypes. Additionally, it is clear that the same primitive can be resolved in multiple ways and other authors and researchers can have created other prototypes that are also perfectly valid. Previous prototypes by other researchers have precisely explored mechanisms that create illusions of weight and gravity on objects in other ways [23]–[25].

In certain applications other haptic primitives, such as temperature [26], [27], or grounding of the objects, may be relevant as well. Although we did not build our own prototypes to test these and other mechanoreceptive units in the glabrous skin [28], our proposed taxonomy could accommodate properties such as gravity, inertia, temperature, and pain in the kinetic aspects of the object. Alternatively, these properties could be accommodated within the touch/cutaneous/sub-tip resolution/physical texture space. It seems plausible or even likely that future haptic controllers, at least in certain applications, will incorporate such aspects to create richer sensory experiences.

Additionally, our focus on haptic interactions rather than devices allows for future links between two hands [29]. For example, Haptic Links [30] merges interactions, while multitouch has evolved in other less immersive technologies [31]–[33]. Further, our focus on haptic interactions also opens avenues for increasing the complexity of controllers that might want to combine a wider diversity of haptic sensations into a single device. We demonstrate some initial steps along this direction in prototypes such as CLAW, TORC or Haptic Pivot. These were envisioned as multipurpose haptic controllers, and we evaluated the transition between different haptic modes or features. Our research revealed that it would indeed be possible to simulate multiple sensations in a single device, if (and only if) they are presented in context with the rest of the Virtual Reality experience to avoid an uncanny valley of haptics [3].

We believe that to achieve a true immersive Virtual Reality, systems must allow our human bodies to interact in natural ways [34]. As our research suggests, touch and haptics will be key to creating a practical, multi-purpose controller for natural virtual reality interaction that passes the test of time. Our contributions--and the range of haptic controllers we have explored—pave the way for a new generation of multipurpose haptic controllers that enable users to touch and manipulate objects within Virtual Reality.

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