Prolonging VR Haptic Experiences by Harvesting Kinetic Energy from the User

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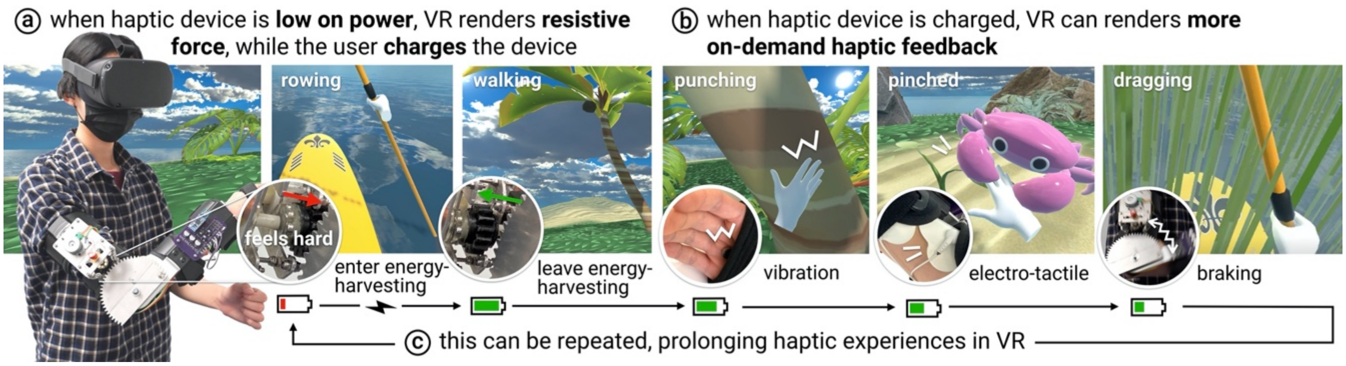

Figure 1: We propose a new technical approach to wearable haptics that requires no battery, yet it provides active haptic feedback. The key is (a) our motion harvester engineered from a geared-DC motor paired with a custom clutch, worn on the user's elbow. This enables haptics in long experiences, such as this "VR survival" that lasts for hours, which is not possible with existing haptic devices that render strong and power-hungry haptics. Using our approach, a haptic device harvests all the necessary energy from the user's own movement. However, the resistance felt while harvesting would become a distraction to the VR user as it does not match their experience. Our concept solves this by adjusting the VR world to render a situation in which the user expects to feel resistance, such as rowing this boat. (b) When its supercapacitors are charged, the device informs the VR and releases its clutch, so that the user no longer feels the resistance of the harvester; simultaneously, the VR renders a situation without resistance (e.g., walking on an island). The benefit is that the VR can "spend" the recently harvested energy with on-demand haptics (e.g., vibration, electrical stimulation). (c) If the battery is close to being depleted, this cycle repeats, ad infinitum; without the user even needing to be aware of the harvesting. This prolongs VR haptics beyond their usual short-lived durations and frees the user from large batteries & power tethers.

ABSTRACT

We propose a new technical approach to implement untethered VR haptic devices that contain no battery, yet can render on-demand haptic feedback. The key is that via our approach, a haptic device charges itself by harvesting the user's kinetic energy (i.e., movement)—even without the user needing to realize this. This is achieved by integrating the energy-harvesting with the virtual experience, in a responsive manner. Whenever our batteryless haptic device is about to lose power, it switches to harvesting mode (by engaging its clutch to a generator) and, simultaneously, the VR headset renders an alternative version of the current experience that depicts resistive forces (e.g., rowing a boat in VR). As a result, the user feels realistic haptics that corresponds to what they should be feeling in VR, while unknowingly charging the device via their movements. Once the haptic device's supercapacitors are charged, they wake up its microcontroller to communicate with the VR headset. The VR experience can now use the recently harvested power for on-demand haptics, including vibration, electrical or mechanical force-feedback; this process can be repeated, *ad infinitum*. We instantiated a version of our concept by implementing an exoskeleton (with vibration, electrical & mechanical force-feedback) that harvests the user's arm movements. We validated it via a user study, in which participants, even without knowing the device was harvesting, rated its' VR experience as more realistic & engaging than with a baseline VR setup. Finally, we believe our approach enables haptics for prolonged uses, especially useful in untethered VR setups, since devices capable of haptic feedback are traditionally only reserved for situations with ample power. Instead, with our approach, a user who engages in hours-long VR and grew accustomed

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to finding a battery-dead haptic device that no longer works, will simply resurrect the haptic device with their movement.

KEYWORDS

haptics, virtual reality, energy harvesting

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1 INTRODUCTION

In the past decades, interactive devices became mobile, moving into user's pockets and body, thanks to power-efficient computation and advances in battery technology. While sensing in devices now can be realized in a power-efficient manner [1, 18, 29, 48], output (e.g., displays or haptics) still remains a power-hungry factor in mobile devices [4, 19, 42]. Haptic feedback, specifically strong force-feedback, needs to push against the user to generate its effect, thus demanding even more power [10, 12, 31] (typically orders of magnitude above the power required for a sensor [48]). Therefore, most haptic devices are tethered to the powerline or require large and cumbersome batteries. While researchers have explored alternative actuators (e.g., muscle stimulation instead of mechanical motors; or brake-based actuators) for the sake of power efficiency, even these devices' batteries will likely last far less than a whole day of usage [17, 31].

We propose a new technical approach to implement untethered Virtual Reality (VR) haptic devices that contain no battery, yet can render on-demand & strong haptic feedback. The key is that via our approach, a haptic device charges itself by harvesting the user's kinetic energy (i.e., movement)—even without the user needing to realize this.

Figure 1 depicts how we achieve this: we integrate kinetic energy-harvesting directly into the virtual experience, in a *responsive manner*. For example, in our approach, whenever a batteryless haptic device is about to lose power, it switches to harvesting mode (by engaging its custom electropermanent magnetic clutch to a generator) and, simultaneously, the VR headset renders an alternative version of the current VR experience that depicts resistive forces (e.g., rowing a boat in VR). As a result, the user feels realistic haptics that corresponds to what they should be feeling in VR (i.e., it should "feel hard" to row a boat), while unknowingly charging the device via their movements. Then, once the haptic device's supercapacitors are charged (which charge/discharge much faster than traditional batteries), the device's microcontroller communicates with the VR headset. The VR experience can now use the recently harvested power to request more on-demand haptics, including vibration, electrical or mechanical force-feedback; this process can be repeated, *ad infinitum*.

We instantiated, explored, and validated a version of our concept by implementing an exoskeleton that harvests elbow movements and uses this energy to render on-demand haptic feedback intermittently, e.g., vibration, electrical & mechanical force-feedback.

We validated this via technical evaluation and a user study, in which participants (even without knowing the device was harvesting) rated a VR experience as more realistic and engaging using our device than with a baseline VR setup.

Finally, we believe our technical approach is fundamentally different from devices powered by batteries, as it affords new uses of haptics for prolonged use-cases, which are especially useful in untethered VR setups, since devices capable of haptic feedback are traditionally only reserved for situations with ample power. With our approach, a user who engages in hours-long VR and grew accustomed to finding a battery-dead haptic device that no longer works, will simply resurrect the haptic device with their movement. Moreover, our approach enables new ways to use haptic devices unthinkable for battery-powered devices today: namely, walk-up use. Even if the user forgot to charge the haptic devices or change their batteries, our technique enables these to wake up rapidly after the first interactions.

2 OUR APPROACH: HARVESTING THE USER'S KINETIC ENERGY TO PROLONG VR HAPTICS

To demonstrate our novel concept of harvesting the user's kinetic energy to prolong the lifetime of VR haptics devices, we engineered an exoskeleton worn on the user's arm that demonstrates one possible instantiation of our technical approach. This exoskeleton, depicted in Figure 1, can be charged by the user during VR even when it loses all its power. Then, it uses this harvested energy to render subsequent haptic effects. The fact that our approach is *cyclical* (the device automatically returns to harvesting *always* before losing power and always informs the VR accordingly) allows any device and VR experience built around our approach to run for *extremely long periods of time*, including being picked up after any arbitrary period of inactivity (the device will *always* switch to harvesting when power is low).

We first summarize the key technical insights that make our approach feasible: **(1) Harvest *kinetic energy* from the user.** While most intermittent-computing interactive devices typically harvest energy from the surrounding environment, such as solar, thermal, or ambient vibrations [38], these harvesting approaches are only suited to systems that operate on very low-power—in fact, most of these are sensing systems since sensors tend to require less power than their actuator counterparts (e.g., sensing a touch via capacitive sensing requires less power than delivering a haptic touch via electro-tactile stimulation or motor-based haptics). In contrast, we focus on a batteryless device designed for *strong haptic sensations* (e.g., vibration, electrical & mechanical force-feedback). Unfortunately, approaches that harvest small amounts of power do not scale to the magnitudes required for strong haptic sensations; thus, we turn to harvesting *kinetic energy from the user* as it provides a suitable power efficiency ratio [11]. **(2) Supercapacitors instead of batteries.** This is the technical insight that enables our approach to quickly charge with sufficient energy to generate strong haptic effects because, supercapacitors charge faster than batteries, and more importantly, balance energy storage with charge and discharge times. While supercapacitors do not hold as much energy as a comparably sized lithium-ion battery, they trade capacity with power density [26], which allows for fast charging/discharging speed (orders of magnitude faster than a battery of similar capacity). **(3) Conceal the harvesting in the VR experience.** Moreover, kinetic harvesting alone would pose a serious problem for VR. Since any time that such a device would try to harvest energy, users would notice the increased force required to move (resistance from moving against the harvester) and feel this as a *distraction*—this increase in resistance does not match their VR experience. Our concept solves this by adjusting the VR world to render a situation in which the user expects to feel resistance—this allows the resistance felt while harvesting to go unnoticed by the user.

Now that we, succinctly, laid out the principles (see *Technical Evaluation* as well as *Implementation* for more details) that allowed our device to render haptic feedback without a battery, we demonstrate its application in a VR example.

3 WALKTHROUGH: A VR SURVIVAL EXPERIENCE WITH *HOURS* OF HAPTICS WITHOUT BATTERIES

To help readers understand the applicability of our technical approach to achieving batteryless haptics, we demonstrate it in a VR experience that makes use of a range of haptic sensations, including tactile- and force-feedback. This VR user is wearing a device that uses our technical approach to enable non-stop haptics in their arm. The device takes the form of a forearm exoskeleton that pivots around the elbow joint. While our device has no batteries, it can harvest the user's kinetic energy into supercapacitors via a motion harvester engineered from a geared-DC motor paired with a custom-made switching clutch, which powers the VR experience' haptic effects.

At the start of this VR experience, users find themselves washed ashore on an unknown island. Their objective is to find food, water, and batteries to radio call a rescue team, as depicted in Figure 2. Note that many of these interactions could be made more immersive using two of our devices on both arms.

Figure 2: (a) A VR user with our batteryless haptic device worn on their arm. (b) At the start of our VR experience, the user finds themselves on a desert island. Their goal is to find water (coconuts), food (carrots), and batteries to radio call a rescue.

Bootstrapping a haptic device without any battery. As the VR experience starts, the user is stranded on a desert island. Upon starting the VR experience, the VR software attempts to contact the haptic device using Bluetooth. However, the haptic device has been idle for an unknown amount of time, potentially days, and therefore has no power. This would be a frustrating situation for existing wearable haptic devices that quickly deplete their batteries [20]. However, our batteryless device can provide non-stop haptics experiences by harvesting the user's kinetic energy on-demand. When the VR software does not receive a response from the haptic device in 300ms, it assumes the device is not charged and it is in harvesting mode, i.e., its clutch is engaged and the user's arm movements are connected to the device's high-transmission gear, which converts kinetic energy into electricity using a DC-motor and our harvesting circuitry. As such, the VR software immediately initiates the pre-programmed "harvesting" sequence depicted in Figure 3 (a) the tide rises and the user has to swim; (b) as the user moves their arm, they *feel the resistance* of swimming in water. This resistance is caused by our harvester's gears. The user is feeling passive haptics, which is being converted into usable energy, by charging supercapacitors on board of our device. While this might appear simplistic in hindsight, it is a key contribution in our work—*dynamically changing the VR experience to coherently justify why the user is feeling the strong resistive forces* from the harvester's gears. In fact, using this insight, participants in our *User Study* did not notice that the haptic device was harvesting their energy.

Figure 3: (a) When VR fails to connect to our batteryless haptic device, the VR assumes the device needs charging (and is in energy-harvesting mode) and renders a tide rising. (b) The user swims and feels resistance, *without even knowing they are charging the device.*

Charging on-demand = charging if haptics is needed. The VR experience can request haptic power on demand depending on events the user might encounter next, or what the designer intended the game narrative to be. For instance, if the user quickly charges the haptic device by swimming fast, the haptic device will harvest sufficient energy to boot its internal micro-controller and circuitry. At this point, the haptic device communicates via Bluetooth to the VR software and transmits its amount of internal power, sending a message with the voltage reading of its supercapacitors. If the VR software deems this to be sufficient, it can stop the harvesting and continue the narrative. Figure 4 depicts how this is achieved in our VR experience by the VR software spawning the next island (from the VR experience's pre-defined narrative) in the vicinity of the user. The user now swims to the island and the VR headset requests the haptic device to stop the resistive force. The haptic device responds by releasing its electro-magnetic clutch, which disconnects the user's arm from the harvesting gear. The user now moves their arm without any resistance and the device is fully charged and ready for delivering on-demand haptic effects.

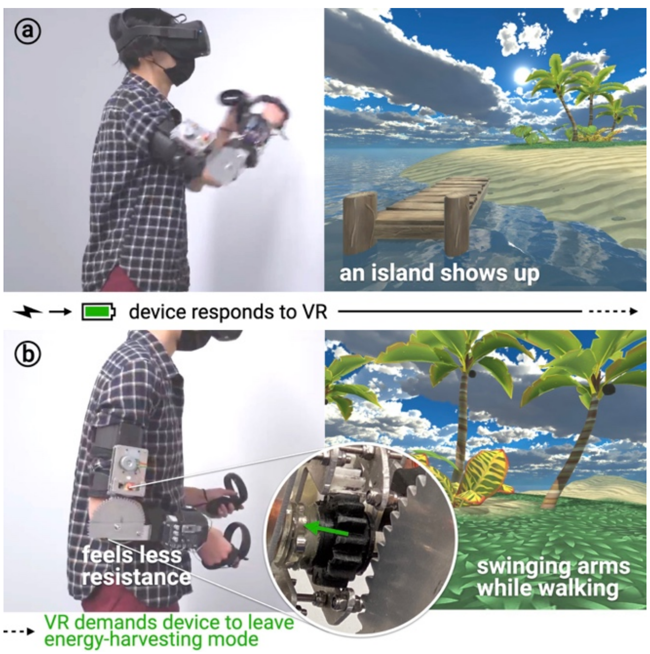

Figure 4: (a) The haptic device is now charged and responds to the VR of its charge capacity. The VR experience then renders an island. (b) The user walks on the island, so VR requests the device to stop harvesting mode: now the user's arm feels less resistance.

Spend harvested energy on active haptics. The user now explores the island to find food, water, or batteries to survive. Now, with the charged supercapacitors, different kinds of haptic feedback can be rendered. The user finds coconut trees and bangs their fist against the tree, to make the coconuts fall. Each time they hit the tree they feel a *vibration*. This is achieved by using the energy previously harvested from the user's kinetic movements. Subsequently, the user picks up the coconut and breaks it by smashing it against a spiky rock. When they crack the coconut on the rock, our device provides a force-feedback sensation to render the impact. This is achieved by sending electrical muscle stimulation to the user's forearm muscles, which causes them to involuntarily contract.

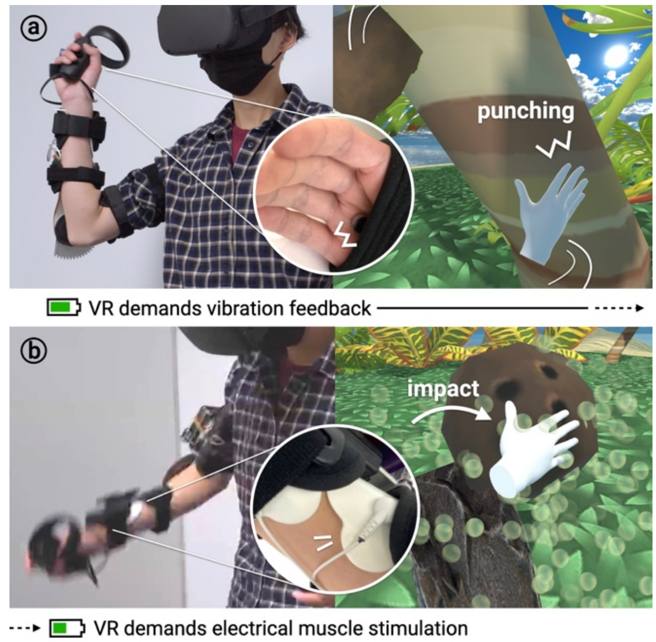

Figure 5: (a) As the user hits this coconut tree, they feel vibrations on their hand (via a linear resonant actuator in the arm device); the energy required for this haptic sensation was, unknowingly, just harvested by the user as they swam to the island. (b) Now, the user picks up the coconut and smashes it against a rock. As they hit the rock, they feel force feedback via electrical muscle stimulation—again, the energy required for this haptics was, unknowingly, harvested by the user as they swam to the island.

Handling the uncertainty of user's behavior = return to charging mode. All the interactions we depicted so far are *dynamic*. In other words, if the user gets lost on the island or remains idle for a long time (or even puts down the game and returns later), the supercapacitors will slowly discharge (see *Technical Evaluation* for measurements). However, this is not a problem for our approach: the key is that VR environments are *computer-generated in real-time*, and thus are easier to alter than physical systems (e.g., less disruptive for the user's sense of immersion than stopping and swapping batteries in a haptic device). As such, if the supercapacitors discharge, our haptic device will *always* engage the clutch (returning itself to charging mode) and *always* notifies the VR software. Upon receiving this message, the VR software immediately instantiates the next available "charging" sequence, such as our "tide raises" example from Figure 3 or "shaking the crab off the user's arm" from Figure 6.

Figure 6: (a) The device senses low power, enters energy-harvesting mode, and informs the VR, which responds by rendering a crab jumping to the user's hand. The user shakes off the crab by moving their arm, which charges the device, unknowingly. (b) When the device is charged, it leaves the energy-harvesting mode and informs the VR, which responds by rendering the crab let go.

Figure 7: (a) VR demands resistive force (device enters energy-harvesting mode) for this rowing interaction; (b) VR demands leaving energy-harvesting mode after the user lands on another island to walk again.

Figure 8: If there is a surplus of energy, the VR software launches one of the pre-made experience that can make use of this extra energy for a more immersive version of the current experiences. In this case, the user experiences paddling through dense reeds, which they experience a higher resistance as they paddle (which is achieved by braking the DC harvester itself).

Creating variation in harvesting experiences. Previously, when the device was about to run out of power, the VR rendered a tide that washed the user onto the sea (harvesting = swimming). However, the VR designer can incorporate more cyclical VR scenes that justify the felt harvesting resistance with more variety. In Figure 7, after exploring the island for a long time (which mostly involves "spending" energy enjoying haptic effects such as the coconuts breaking), if the device does not urgently need power, VR can instruct the user to walk to the boat where they start rowing—as the user moves their arm to row, they are now harvesting. More power can be used when they explore the next island.

Surplus of harvested energy? More haptics. Our VR experience can leverage a haptic device that is fully charged, despite no immediate need for haptics. While the VR software could simply ignore this, a VR designer could take advantage of this energy surplus and create multiple versions of the same experience that provide more realistic haptic experiences. (Obviously, these scenes could also be required as per the experience's narrative, and thus the player would be required to experience a charging sequence prior to those; but, in this section, we explore the situation where there's a surplus of energy). Figure 8 shows an example, while the user is paddling the boat, the VR experience spends the surplus of energy by rendering dense reeds, in which the user experiences even higher resistance than the harvesting resistance (which is achieved by braking the DC harvester via shortcutting it).

Just-in-time charging for quick haptic sensations. At last, the user explores the final island to find batteries to power their emergency radio. Again, this scene could take advantage of previously harvested power, but we choose to depict a worst-case scenario: the user has been idling and the haptic device has sufficient power for Bluetooth communication, but not enough for any haptic sensations. However, the next VR experience is to feel

Figure 9: The VR experience includes a haptic effect in which when the user inserts the last battery in their radio and feels an electrical tingling. However, if the haptic device is low on power (a) the VR experience dynamically renders a just-in-time harvesting sequence, with a crab that latches onto the user's arm. As the user shakes off the crab, the clutch is engaged and harvests for a brief moment. This way, the haptic device gathered enough energy just-in-time for the final (b) electrical tingling sensations to be felt.

an electrical tingling as the user's radio comes back alive upon inserting the battery. As such, the VR designer created a short, just-in-time charging experience, that ensures that there is always available power for the user to feel the electrical tingling sensation. When the user approaches the last battery, the VR software checks the available power reported by the haptic device. If it is below the requirement for the electrical tingling (which is rendered via electrical muscle stimulation), a crab appears next to the battery. As the user reaches for the battery, the crab jumps at them and latches to their arm. The VR software instructs the clutch to activate and harvest the user's arm movements in this very short "charging" sequence. The user shakes their arm twice, which generates enough power for the final electrical tingling effect. The VR scene immediately stops the harvesting and causes the crab to be flung off the user's arm. Finally, the user places the battery in their device and experiences the electrical tingling as the radio wakes up and calls for help.

While we depicted only a few key moments in this VR survival experience, this VR experience runs for a long time; Figure 10 depicts the entire VR experience's events, including a cold start (the device has absolutely no power), all harvesting VR sequences (scenes where the user is harvesting), spending sequences (scenes where the user receives on-demand haptics) and their inner loops (that connect harvesting to spending sequences).

4 CONTRIBUTION, BENEFITS & LIMITATIONS

Our main contribution is a novel technical approach for haptic devices that contains no battery and yet can deliver haptic sensations, even strong active haptics (e.g., vibration, electrical- or

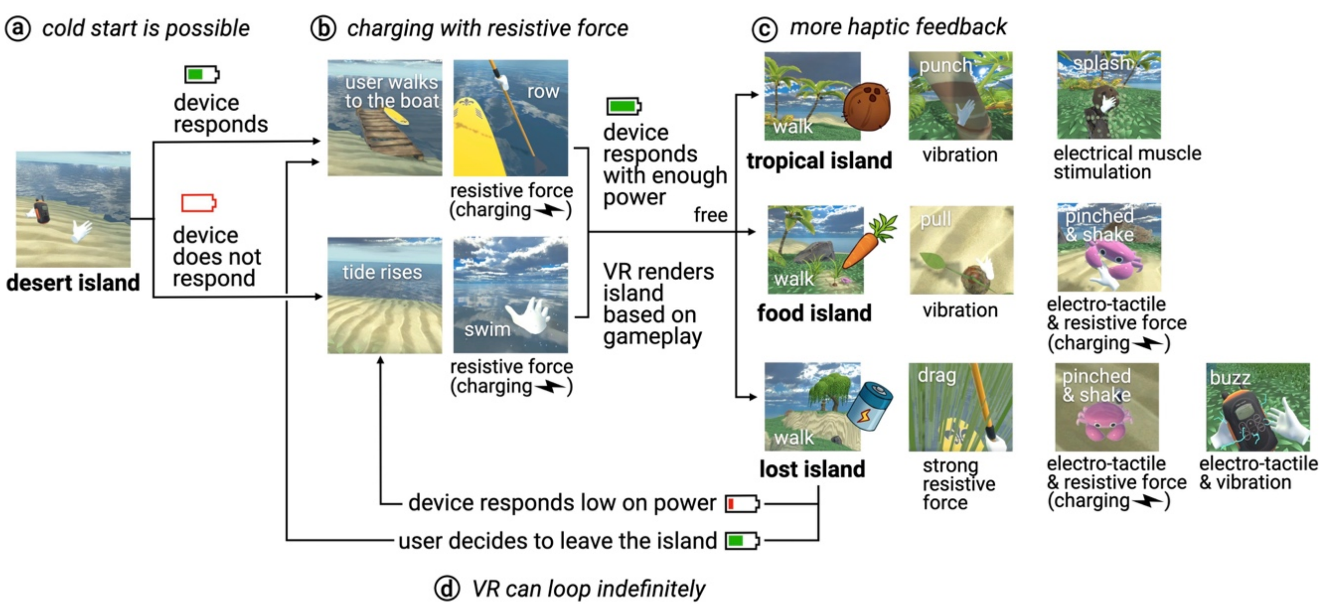

Figure 10: Flow of our exemplary VR experience, including when it renders the required harvesting and spending sequences.

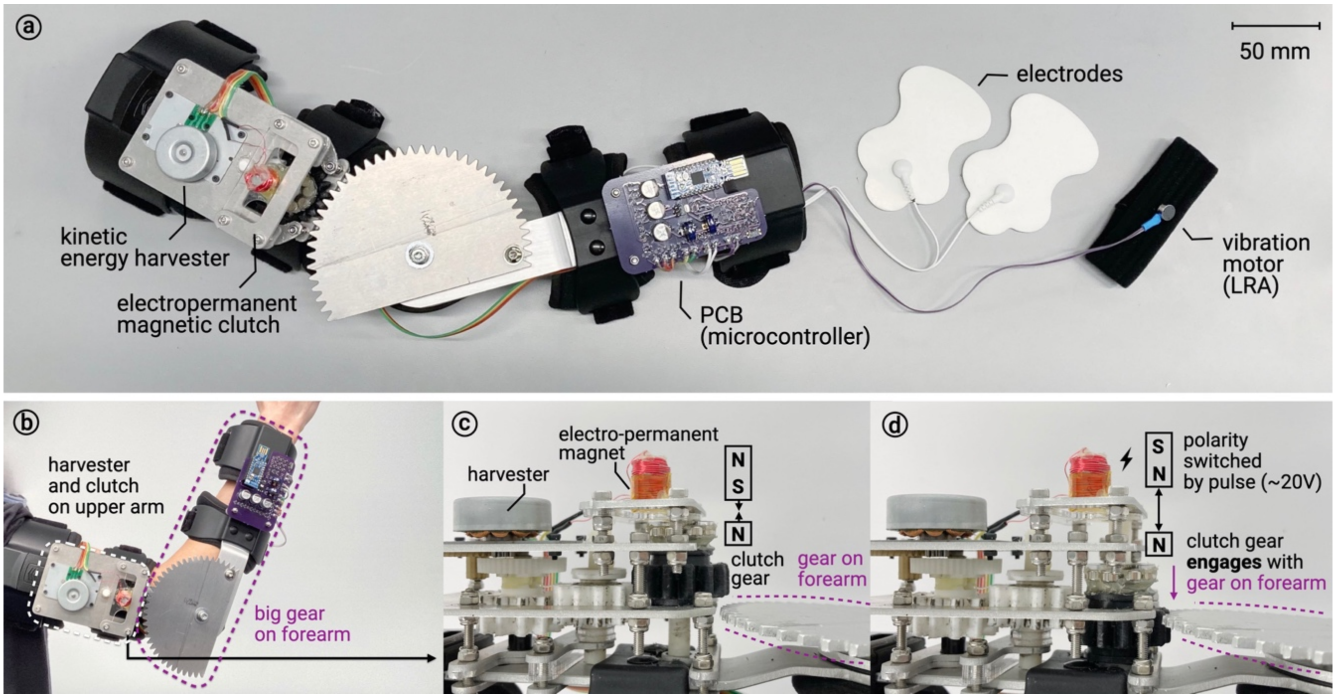

Figure 11: (a) Our wearable haptic device, which is untethered and batteryless (here, we show a version for the right arm). (b) Our device with a kinetic energy harvester, which features our custom electropermanent magnetic clutch (EPM). Close-up side view of the clutch: (b) In free mode, the clutch gear (with permanent magnets) is held by EPM and not engaged with the gear on the forearm, thus the elbow movement is not transmitted to the harvester. (d) To enter energy-harvesting mode, a single electric pulse (~20V) triggers EPM to switch its polarity, and as a result, repels the clutch gear to slide on the shaft and engage with gear on the forearm. To disengage the gear, simply apply another electric pulse through EPM that runs in the opposite direction.

force-feedback). Our key technical insight to enable this contribution is our implementation of a kinetic harvester with sufficient power efficiency to render haptic effects longer than the time the user spent harvesting. Secondly, our key conceptual contribution is that, while harvesting alone is not sufficient (as the increased resistance from the harvester would create a distraction to the VR experience), we solve this by adjusting the VR world to render a situation in which the user expects to feel resistance.

The benefits of our approach include: **(1) Technical approach to realize immersive haptics for long VR experiences**—contrast the fact our device can virtually last for days, with the typical lifetime of a wearable haptic device; moreover, in our study, we found that our device was more immersive than today's baseline VR setup; **(2) Technical approach that frees the user from large batteries & power tethers**—contrast this with the abundance of haptic devices connected to large batteries or powerlines; **(3) Users do not need to notice the harvesting**—because we use the VR dynamically to conceal the resistance felt by the harvester, users can use our device unaware of its inner workings; in fact, in our user study participants did not realize our approach was harvesting their movements. **(4) Haptic "walk-up use"**—our device can sit on the shelf for virtually any amount of time and will "wake up" once the user starts the VR experience and starts moving; and, **(5) Re-using power for heterogeneous haptic experiences**—our device harvests kinetic energy, but can deliver power to a wide range of actuators; we demonstrate how our implementation converts this energy into vibrations, electro-tactile, electrical muscle stimulation, and braking-based resistance.

Our approach is not without its limitations: **(1) Content creation for intermittent haptics**—our approach only supports haptic feedback that happens intermittently (up to a few minutes, rather than continuously for hours). This is a consequence of the switching between on-demand haptics and harvesting energy from the user's movements (which in our concept also provides haptics, but typically not on-demand as these are triggered by the haptic device, rather than by the VR content). This necessary switch from on-demand haptics to harvesting haptics, requires VR designers to create harvesting sequences, i.e., alternative moments in the VR experience that can be activated ad-hoc when the haptic device loses all power and returns to harvesting mode. **(2) Longer experiences**—another limitation of our approach is that it leads to longer experiences, since when using our device, the user performs additional actions designed to charge the device if the power is running low. Finally, **(3) Physical exertion**; our approach relies on physical movements, as such it also induces higher physical exertion and might not be suitable for all users or situations.

5 IMPLEMENTATION

We detail our prototype batteryless haptic device (Figure 11) with its custom energy-harvesting and the VR interactive system. To accelerate researchers interested in reproducing this device, all designs are made available and open-source[1].

5.1 Arm-worn exoskeleton haptic device

We implemented an exoskeleton that is untethered and batteryless, shown in Figure 11(a). It measures 42 cm in length (adjustable) and weighs 680 g (resistive gears & clutch 325g, exoskeleton 270g, harvester 35g, PCB 30g, electrodes & straps 20g). It harvests kinetic power from elbow movements, since at every triceps/biceps curl, ample mechanical energy is available to be turned into electricity. Also, the accompanying resistive haptic feedback on the elbow is easy to integrate into VR interactions since the hands are often involved in VR experiences (e.g., rowing a boat, lifting heavy objects, pushing against walls, etc.). We detail each component of our exoskeleton in the following sections.

Harvester mechanics. The core of our kinetic energy harvester is a 3-phase brushless DC motor (ZSFD-F1HD) with gear ratio 1:20.25, which we re-purposed as a power generator with rated output current 700mA. To incorporate a clutch (switching on/off energy-harvesting mode, which we describe later) into the gear set, we added two 12-teeth gear (20 degree-teeth; gear ϕ 28mm) for transmission, and a 15-teeth clutching gear (20 degree-teeth; gear ϕ 34mm), fabricated with PLA using FDM 3D printing, 12mm thick, fit into ABS rods (ϕ 8mm). The power generator, transmission gears, and clutching gears are mounted on the upper arm. The lower arm's half-gear (20 degree Metric, 60-teeth, 120 mm Pitch, ϕ 124mm, fabricated with 3mm-aluminum by water jet cutting) is attached directly to the exoskeleton brace, which increases the torque ratio by a factor of 5 when engaged with the generator. The enclosure of the upper arm gears is fabricated with 2mm aluminum plates (water jet cutting) and secured with M3 screws; finally, these are clamped onto an MOSCARE elbow brace with adjustable upper/lower arm length along with adjustable straps.

Switching harvester on/off using a custom clutch. To enable on-demand kinetic energy harvesting, ideally, the actuation of the clutch should take require harvesting a few arm movements. This is difficult to achieve since most types of clutches (e.g., motorized friction clutch) require actuating large motors to engage/disengage. In the process of designing our clutch, we implemented six different clutch designs (some depicted in Figure 12): a DC-motor horizontal linear-clutch, DC-motor vertical linear-clutch, one-directional ratchet clutch, one-directional spring-clutch, DC motor friction-clutch, but found these would require too much power to actuate compared to a magnetic clutch.

To clutch in an energy-efficient way, our custom magnetic clutch is based on electro-permanent magnet (EPM). In EPMs, the polarity can be switched by an electric pulse but remains stable for a long time [14, 25, 39] (contrast this with a solenoid, which only pulls when power is supplied). Our Figure 11(b) depicts our EPM clutch, consisting of a clutch gear that has a ring of permanent magnets (neodymium, ϕ 5mm, 3mm thick, 242 gauss), sliding on a plastic shaft to avoid magnetic materials. To move the clutch, the polarity of EPM is switched to attract (disengage) or repel (engage) the clutch gear on the shaft. Importantly, even if the gear ends up not perfectly aligned (did not slid all the way) the clutch will still slide

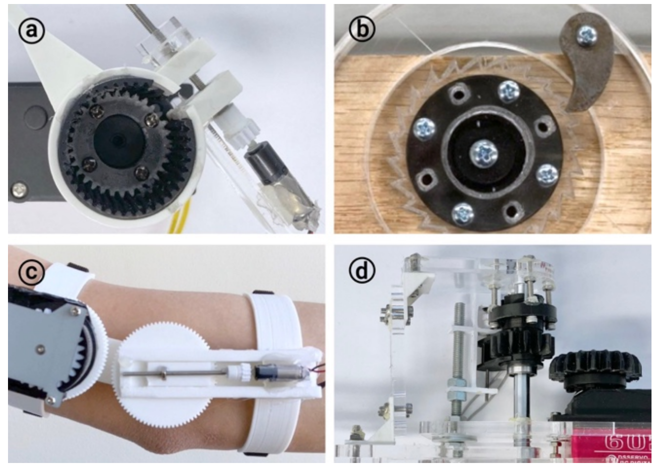

Figure 12: Four (out of six) examples of clutch designs that we implemented but proved inferior to our final EPM clutch design.

in to engage when the user moves the arm by just a small amount, since the EPM continues to push the clutch gear. Our EPM (Alnico Grade 5, ϕ 5mm, 15mm length) was wrapped in a coil with 80 windings (28 AWG). Finally, the magnetic field was measured at 59 gauss in both polarities, after switching.

Microcontroller. The complete circuit is layout in our custom PCB. Refer to the schematics in Figure 13. The control center is NRF52840 Dongle (Nordic Semiconductor), which is a Bluetooth Low Energy (BLE) enabled low-power microcontroller (1.6-3.6V, measuring 1.3mW under 1.8V, while BLE connected). A supercapacitor (0.33F) is used to store the harvested energy. The available power is sensed by the microcontroller through an analog reading pin. To lower the power consumption, we lowered the Bluetooth advertising rate to 100ms. We utilized UART for BLE communication.

Harvesting circuitry. We connect the output of the DC-generator to a 3-phase rectifier composed of six Schottky diodes (PD3S0230-7), high-voltage shunt diodes (20V MMSZ5250CT1G and 25V SZMMSZ5253BT1G), and a regulator (3.3V for low-power super-capacitors, NCP1117ST33T3G). This generated power is then fed into five parallel capacitors, each with its capacity and voltage rating, including three electrolytic capacitors (330μF, 25V) and two EDLC (electrostatic double-layer capacitors) supercapacitors (0.1F and 0.33F, 5.5V). Again, we chose supercapacitors rather than traditional batteries (e.g., LiPo, Li-Ion, NiMH) since supercapacitors charge faster than batteries, and more importantly, balance energy storage with charge and discharge times. While supercapacitors do not hold much energy as a comparably sized battery, they trade off capacity with charging/discharging speed [26] —this is the technical insight that enables our approach to quickly charge with sufficient energy to generate strong haptic effects. We will now explain the role of each of our five parallel capacitors, depicted in Figure 14.

Discharging power into haptic effects. Two 330μF 25V electrolytic capacitors are charged/discharged to engage and disengage our EPM-clutch (~20V, with peak current 6 A discharged in 2ms). With just a couple of biceps curls, we can harvest the needed 20V even without requiring a step-up circuit to engage/disengage the

[1] http://lab.plopes.org/#harvesting-haptics

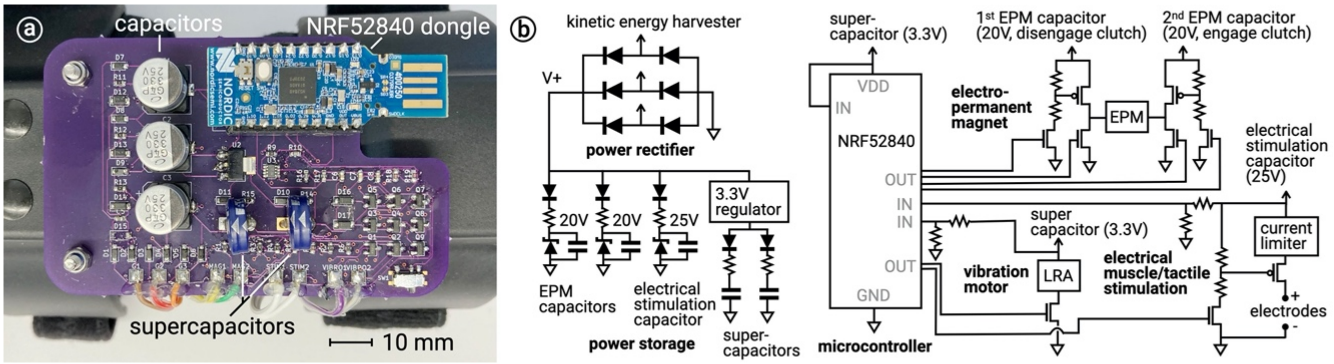

Figure 13: (a) Our custom PCB containing energy harvesting and haptic control circuits. (b) Schematics of our PCB, V+ depicts the DC power which can range from 0-35V when charged by the arm, regulated into sub-voltages for the microcontroller and actuators.

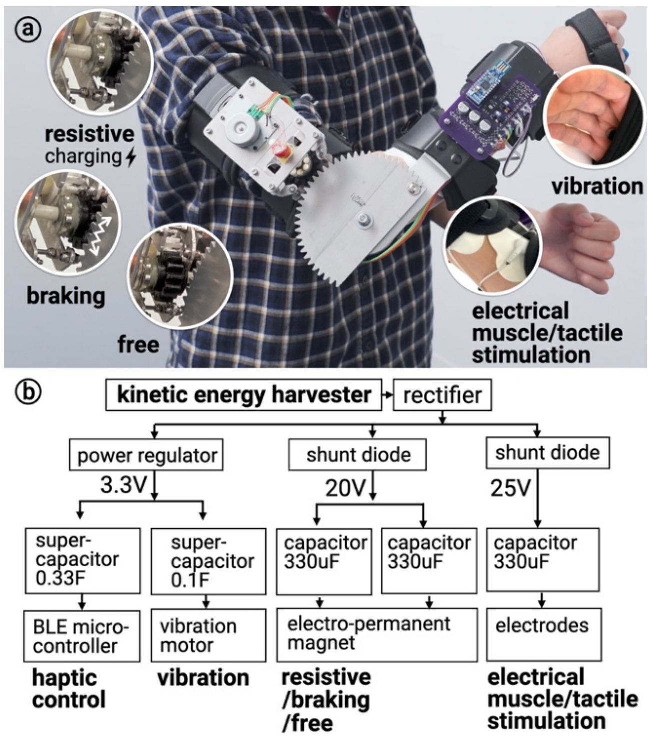

Figure 14: (a) The various available haptic output provided by our device. (b) Diagrammatic view of each sub-capacitor/supercapacitor depending on its haptic output.

clutch. To control the EPM we modified a traditional H-bridge circuit to allow charging up two capacitors at the same time but discharging at different times, ensuring there is power when it needs to disengage/engage the clutch. The H-bridges are manually implemented using 20V N-channel MOSFETs (SQ2310ES-T1_BE3) and 20V P-channel MOSFETs (SQ2351ES-T1_GE3), which can withstand a peak current of 12A. Next, the remainder 25V 330μF electrolytic capacitor stores energy for our simple electrical muscle stimulation (EMS) actuator, which can render either electro-tactile or force-feedback, depending on the stimulation time. For EMS output, we added a current regulator (LT3092) that we configured to limit the output current to 33mA (as most EMS systems that actuate the biceps do not require more than this [31, 32]). The stimulation signal is created by the microcontroller via a P-channel MOSFET (Si2371EDS) and an N-channel MOSFET (SQ2310ES-T1_BE3), at 50Hz with 200 microseconds pulse-width. Moreover, we added two parallel EDLC supercapacitors (0.1F and a 0.33F, 5.5V, PowerStor)—these are the highest storage capacitors in our circuit. The largest (0.33F) constantly discharges onto the microcontroller and the remainder (0.1F) discharges, on-demand, onto the vibration device. We actuate this linear resonant actuator (LRA, C10-100, 65mW at 2V, Precision Microdrives) using an N-channel MOSFET (SQ2310ES-T1_BE3) driven it at its resonant frequency (170Hz) using the microcontroller.

Finally, any capacitors' voltage drops gradually over long-time frames; thus. the voltage of supercapacitors and the EMS capacitor is sensed, by using a voltage divider circuit and the microcontroller. We estimate the voltage of the EPM capacitor by reading the EMS capacitor as a workaround for limited analog reading pins available on this microcontroller dongle.

5.2 Available haptic feedback modes

We wanted our prototype device to be representative of the wide variety of haptics that our approach can enable. In our prototype, four actuators can be driven (motor braking, magnetic clutch, electrical stimulation & vibration motor) enabling six different haptic sensations, which we present in ascending energy-consumption order:

1. Resistive force feedback (energy-harvesting). This is when the clutch is engaged with the kinetic harvester and makes the user feel resistance in their movements. We measured the torque to be 1.29 N·m. Since this is the default state of our device (i.e., left alone it will eventually lose power and switch to this mode) it consumes the least power.

2. Stronger resistive force-feedback (braking). This is when the clutch is engaged and we brake the motor by shortcutting it, which we achieve by discharging the EPM engage-capacitor into the motor terminals. We measured torque of 1.61 N·m, higher than in harvesting—this allows users to feel force-feedback sensations of higher resistance [2].

3. Free (disengaged). Upon disengaging the clutch from the kinetic harvester, the user experiences virtually no resistance from the device (0.05 N·m).

4. Electro-tactile (using EMS). By actuating our simple electrical muscle stimulation circuit for very short periods, such as 10ms, we render an electrical tingling sensation similar to electro-tactile sensations [22]. In our main VR experience, we delivered these impulses via two electrodes on dorsal side of user's forearm.

5. Force feedback (using EMS). By actuating our simple electrical muscle stimulation circuit for longer periods, such as 100 ms or longer, we render involuntary muscle contractions sensation similar to force-feedback [30]. In our main VR experience we deliver this stimulation via the same electrodes as for electro-tactile (same circuit) close to the wrist extensor muscles. These can be attached to other parts of the body for different applications. Note that our EMS implementation is simplistic. First, the difference between our electro-tactile and EMS is how long the actuation is (long induces muscle twitches; very short feels like electro-tactile). Second, our EMS approach induces only small movements since it uses only 25V. However, this still depicts the range of haptics that can be easily added to our harvesting-based approach. Obviously, our simple EMS sub-circuit can be swapped for more powerful EMS circuits, such as *bioSync* [36].

6. Vibration. We create vibrations using a linear resonant actuator (LRA) attached to a strap on the user's palm. It can be attached to other parts of the body for different applications.

5.3 VR-side implementation

We developed our VR experiences using Unity 3D and render these via an Oculus Quest 1. The VR experiences are rendered in a laptop but displayed in the VR headset via *Oculus Link* connection over Wi-Fi. The haptic device sends all its messages over Bluetooth (BLE), which arrive at the laptop. We capture these *Bleak (*handles the low-level BLE connection) and we convert them messages to Open Sound Control (OSC), which are delivered via TCP to Unity3D. While typical OSC implementations utilize UDP, we switched to the TCP protocol to ensure the delivery of messages.

VR searching for haptics device. At the start of our VR, our Unity3D class (that can be added to any Unity3D project that wishes to extend or use our approach), automatically starts searching for the haptic device via BLE. If the device does not respond within 300ms, it assumes the device is out of power and in harvesting mode. Thus, the VR experience triggers the next available "charging scene", which in our *Walkthrough*, was the swimming scene.

Anatomy of a "charging" VR scene. The idea behind these VR scenes that justify the presence of the resistive force from the harvester is that they are cyclical, i.e., they can be looped or instantiated in sequence until the VR receives confirmation that the amount of power is sufficient. We implemented such scenes in Unity3D using two design strategies: (1) *transport-to-charging-area*; and (2) *in-place-charging*. For *transport-to-charging-areas*, these are scenes that take place in a specific place (literally a software scene as determined by Unity3D). We transport the user to this scene by, for instance, fading the previous scene (e.g., we use a thick fog to transport them from "swimming" from the island to swimming in the open ocean). Now that the user is in this scene, the scene can loop itself (or be infinite/procedurally generated) while it constantly is charging the device. Examples of this scene included also our "rowing the boat", which even includes procedurally generated clouds and rocks on the water, to ensure the user feels there is a lot of variety—while, strictly speaking, they are caught in the charging loop (again, users in our *User Study* did not realize this at all). As for *in-place-charging* scenes, these are events that happen in place where the user is currently at. We recommend these, especially, when needing to harvest smaller amounts of power for the next haptic effect. Examples of this scene include our "shake-the-crab" scene, which we simply trigger on-demand when needed by toggling its visibility.

Power thresholds for each scene. Each scene or haptic effect in our VR experiences extends from our "spending" or "charging" Unity3D classes. Any VR event that extends from a "spending" class will behave dynamically and will require the designer to indicate what type of feedback (from our six possible types, at fixed durations). Using this information, our Unity3D class automatically estimates the required power from our measurements (see *Technical Evaluation*). If the power threshold is not satisfied (under voltage) this will cause the next "charging scene" to appear. For example, in our *Walkthrough* application, the threshold is set to 2.4V, which we measured to last for about 5 minutes (on idle). We also determined a low power threshold in our program to trigger energy-harvesting mode in the device and render the respective scene (e.g., "tide rises" scene). We set the threshold of the supercapacitor for the microcontroller to be 1.85V as the microcontroller will shut off with 1.7V remaining in supercapacitor.

Communicating available power. Unity requests voltage readings from our device every 100ms. Since supercapacitors consist of two-layers, the voltage sensed by the microcontroller can be higher than what is charged, especially in a relatively quick charging in kinetic harvesting; thus, to obtain a reliable reading of the current voltage, our Unity3D class employs a 20-sample moving average.

6 TECHNICAL EVALUATION

When engineering energy-harvesting devices it is paramount to characterize their behavior with respect to how long they take to charge and for how long they operate (discharge) under different conditions (idle vs. delivering haptics).

Apparatus. Measurements were performed using our prototype (described in *Implementation*) connected to a factory-calibrated precision-multimeter (0.01 mV resolution, accuracy of 0.02%, 4 ½ digits of precision and USB logging). For the technical evaluation, unless where noted, all the movements were performed using biceps/triceps curls at a period of 2 seconds by a participant with no arm injuries but a relatively low muscle mass (biceps diameter 22 cm, much below the average of 34.3 cm [13]).

Kinetic harvester's electrical output. Figure 15 depicts the voltage of our harvester in two exemplary situations: (a) a ~30V peak from a slow biceps curl (~1.4 seconds per complete flexion/extension) and the ~35V peaks from a faster biceps curl (~1 second per complete flexion/extension). Moreover, we measured a current of 70mA averaged across one complete elbow movement (one elbow flexion followed by one elbow extension) at the slower pace, and 65mA at the faster pace—this minimal difference illustrates how we tuned the gear ratio to be effective at slower movements.

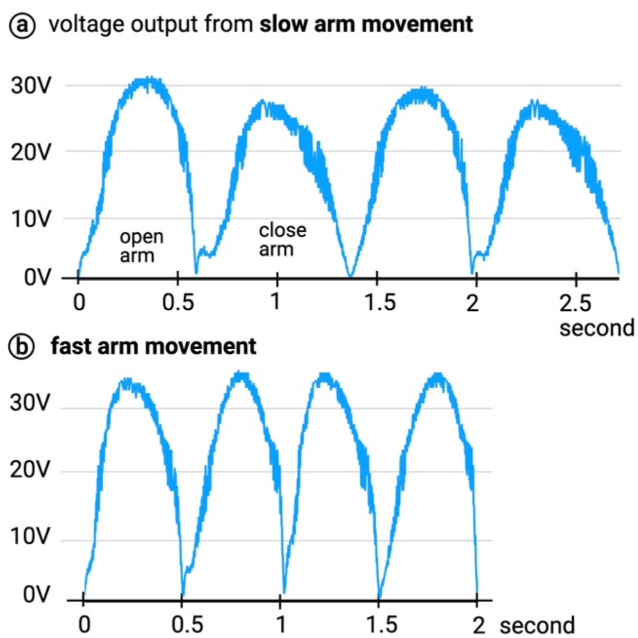

Figure 15: Voltage (rectifier output) of our harvester for two consecutive elbow movements (flex/extend for each movement).

Measuring harvesting for the microcontroller. Microcontrollers require a stable power source to remain operational. In Figure 16(a), we depict a *cold-start* of our haptic device. In this exemplary run, it took ~30 seconds to charge the 0.33F supercapacitor to 1.8V, which wakes up the NRF52840 microcontroller (including Bluetooth). However, this 1.8V region is close to the shutdown voltage (around 1.7V), as such, our device remains in harvesting mode (clutch engaged) until the voltage is at least 2.4V at this supercapacitor. As depicted in Figure 16(a), it took ~1 minute of harvesting to reach this point, at which microcontroller clutches off to leave harvesting mode. Left alone, this stable mode would last for ~5 minutes; thus, the idle efficiency is 1:5 (1 minute of harvesting provides 5 minutes of idling).

Measuring harvesting for clutch operation & braking mode. While the previous measurements evaluated how fast our implementation can wake up the microcontroller (~30 seconds), we now turn to measuring how long it takes to harvest sufficient energy to engage/disengage the clutch. Since the microcontroller is already charged, the two clutch capacitors are also charged. As depicted in Figure 16(b)(1), at the 5s mark, we discharge the first EPM capacitor, which clutches off (leaving harvesting mode). The device is now in free mode and the user feels no resistance. Note that our second EPM capacitor is also charged, which we trigger to re-enter the energy-harvesting mode at the 12s mark, in Figure 16(b)(2). Now, both capacitors are discharged, and the system does not have sufficient energy to move the clutch; however, the system is in harvesting. As shown at the 13s mark, the user starts charging by moving their arm: a single elbow movement charges both capacitors immediately; it is already ready to leave the energy harvesting or deliver haptics on-demand. This depicts a fast turn-taking efficiency (i.e., 1 movement charges the clutch switching). In Figure 16(b)(3) depicts a later case in which the device activates the braking mode (which feels harder to move than in harvesting mode). Because the clutch capacitors are already charged after a single movement, our device can render the braking mode by discharging the second EPM capacitor to shortcut the DC motor. The capacitor is charged again when the shortcut is off, as shown in Figure 16(b)(4). Finally, we found that, while in idle mode, the capacitors conserve adequate charge for clutch operations for ~5 minutes.

Measuring harvesting for electrical muscle stimulation. In Figure 16(c) depicts the efficiency of harvesting power to drive our simple electrical muscle stimulation subcircuit. We found that a single arm movement can charge its capacitors sufficiently for 11 electrical stimuli (300 ms each) to be delivered to the user. Since our electro-tactile circuit is the same, its performance is similar. The VR experience can request another arm movement when more EMS-based effects are needed. This depicts also a quick turn-taking from our system (1 arm movement, 11 EMS impulses). Moreover, we found that while in idle mode, the EMS capacitors conserve adequate charge for EMS stimulation for ~5 minutes.

Measuring harvesting for vibration. in Figure 16(d) depicts the efficiency of harvesting power to drive our vibration subcircuit. We found that from the microcontroller's stable mode, we can deliver 56 vibrations on our LRA (300ms each) before these become too weak, which happens when the LRA voltage drops below 1V. We also found that harvesting for vibrations takes longer when compared to clutch, braking, or EMS. We found that ~30s of harvesting are required to charge up to ~2.1V, which allows delivering ~37 vibrations. Note this was to be expected, since we used a large supercapacitor for vibration (0.1F) but not for EMS (330μF). Yet, this still results in an efficiency of 30s of harvesting to ~1 minute of vibration. Finally, we found it to conserve adequate charge for their vibration operations for ~24 hours.

Limitations. The operation of any force-based device (including kinetic-based harvesters) depends on the operators' force. As such, we advise to take our results as illustrative of a typical performance of our device rather than a lower (e.g., users with less muscle force) or higher (e.g., users with more muscle force) bound for its performance.

Summary. We characterized the efficiency of our device. We found that for all haptic modes, users will tend to spend less time in harvesting mode (where they provide energy by means of their movement) than in enjoying on-demand haptics. In fact, we found that our microcontroller requires ~30s-1min of charging for 5 minutes of operation; our vibration circuit can be charged in ~30s and lasts for one minute of vibration; and, finally, our clutch's operation, as well as the EMS stimulator, can be charged in a few seconds (i.e., these are charged in a single arm movement). Moreover, if left alone, our device tends to discharge in ~5 minutes; however, it will always return to its harvesting mode (sending a message to the VR and clutching), so it is always ready to be picked up by a user and will always wake-up on charge.

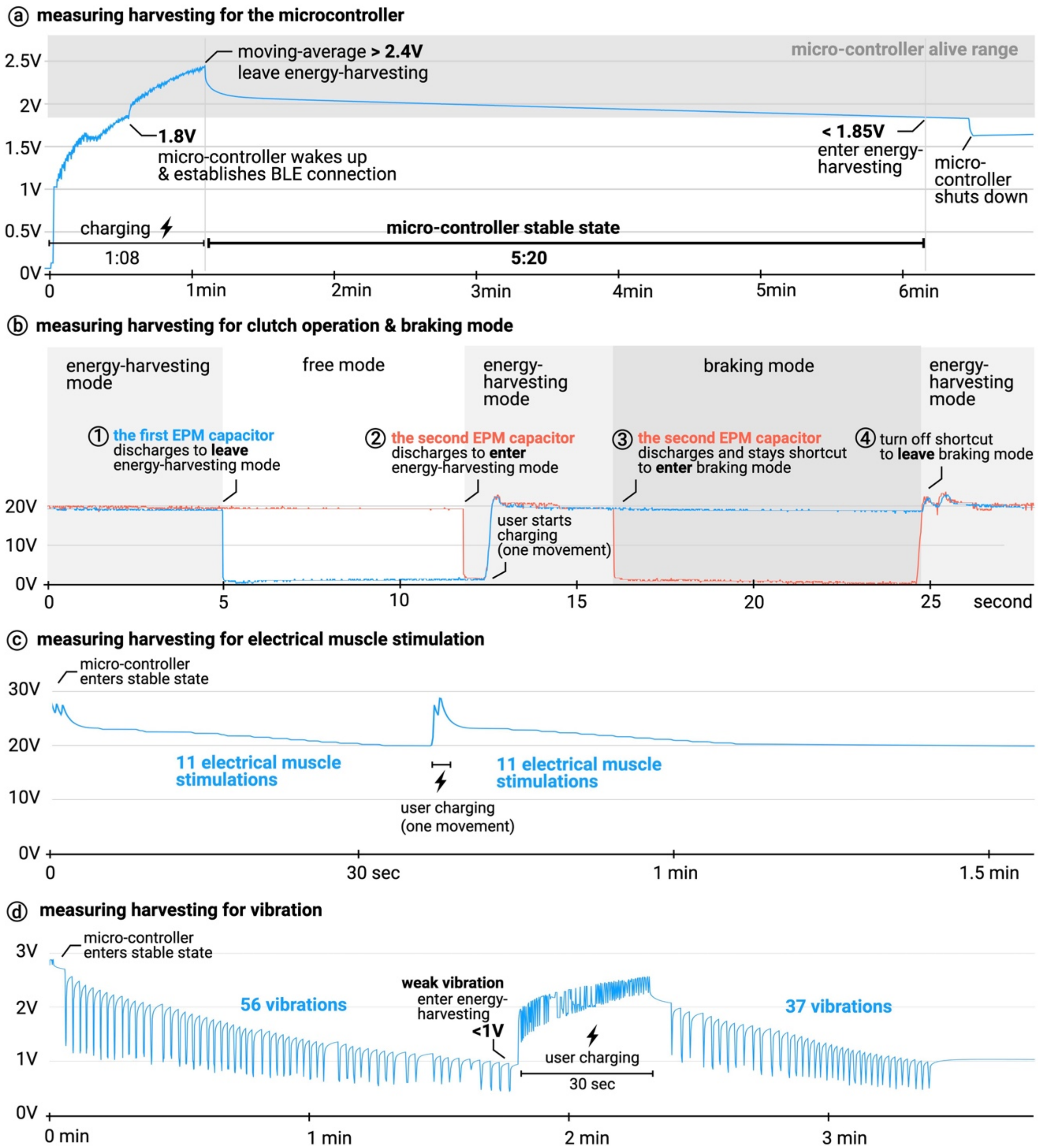

Figure 16: (a) Charging and discharging profile of our 0.33F supercapacitor used to power the haptic device's microcontroller. (b) Charge/discharge profile of the two capacitors that switch our haptic device's EPM clutch and the braking mode. (c) Charge/discharge profile of the capacitor used for electrical muscle stimulation, of 300ms in duration. (d) Charge/discharge profile of the super-capacitor used for vibrations, of 300ms in duration.

7 USER STUDY

In our study, we evaluated whether wearing our haptic harvesting device impacted actual VR experiences. To do this, we created a long VR experience (the island survival experience shown in our *Walkthrough*), in which players could be immersed for longer periods. This is the type of experience that would deplete existing haptic devices, and, at some point, the user would find themselves with just input but not enough power for haptics. As such, in this study, we compared our harvesting approach to a baseline condition where the participants use only input controllers. Moreover, this study was conducted with *incomplete-disclosure*, i.e., our participants consented that "something about this study" was not told until the complete study was done. In fact, **we did not inform our participants that our device had no battery nor that it was harvesting their movements**. This study was approved by our institutional ethics committee (IRB22-0467).

Hypotheses. Our hypotheses were as follows: **(H1) our approach would lead to more realism than the baseline condition**, since we hypothesized that the addition of haptics would be felt as more realistic because—even though our participants would be required to exert more force to harvest the haptics' power—our harvesting technique charges while simultaneously rendering passive haptics that are, in themselves, also realistic. Moreover, we hypothesized that, with our approach, participants would **(H2) feel their senses are more engaged**, which is a key feature in immersion [41]. Furthermore, we expected that **(H3) our approach would lead to more fatigue than the baseline condition** since the harvesting of our haptics comes at the expense of the user's physical exertion. Because of the latter, we also hypothesized that the **(H4) experience duration would increase with our approach.** Still, despite this expected physical exertion and longer gameplay, we further hypothesized that **(H5) participants would find this exertion more enjoyable with haptics than in the baseline condition.**

Preview of study results. We found that our device increased the realism and sensory engagement, which suggests it is useful for increasing the immersion of VR experiences, especially for very long VR experiences that could not easily befit from wearable haptics. Moreover, we also confirmed two expected limitations of our device, i.e., it makes the experiences longer and more physically demanding (since the charging is via physical movement).

7.1 Interface conditions and apparatus

Conditions. Participants were asked to play our island survival VR in two conditions: (1) **harvesting-device**, in which they wore our harvesting device on the arm and held input controllers to navigate and interact with objects; and (2) **controllers-only**, in which where they did not wear our device and used controllers to navigate and interact with objects. Note that we only use controllers for sensing purposes in both conditions and we did not use the built-in vibration motor in controllers, since we were interested in rendering all haptics using the power harvested by the participant without the need for batteries. Interface condition order was counterbalanced across participants.

Apparatus. An inside-out 9DOF tracking VR headset (Oculus Quest 1) with controllers in both hands, and our device. In the harvesting condition, the experimenter discharged all the capacitors so that the **device started with zero power**.

7.2 Participants

We recruited ten right-handed participants (M=22 years old, SD=2; five self-identified as female and five as male). Four of them had prior experience with VR, but none had experience with our device or haptics beyond vibration in controllers. It is important to note that, all participants did not have prior knowledge about the device in terms of its harvesting capability—as aforementioned, this information was withheld from participants until the end of the study (Incomplete Disclosure).

7.3 Tasks

We utilized our island survival VR experience (see *Walkthrough*). The experience was configured to be shorter than our walkthrough by requesting participants to find three coconuts, three carrots, and three batteries. Pilot tests were used to inform how long the task should last. We designed it to last ~10 minutes in baseline condition. To prevent a sequence effect in which participants memorize the location of the objects and puzzles, we changed the order of the first two islands and locations of the objects; moreover, we also counterbalanced the condition order. With participants' consent, we recorded their VR screen for later labeling of events and time duration. After each condition, participants were asked to rate the perceived realism, enjoyment, sensory engagement, and physical fatigue on a 7-point Likert scale. The experimenter conducted semi-structured interviews with the participants to collect subjective feedback. Breaks were given in between the condition.

Finally, **only at the end of the interview**, **we disclosed that our device charged by harvesting kinetic energy.**

7.4 Results

Figure 17 depicts our main findings, which were analyzed using paired t-tests.

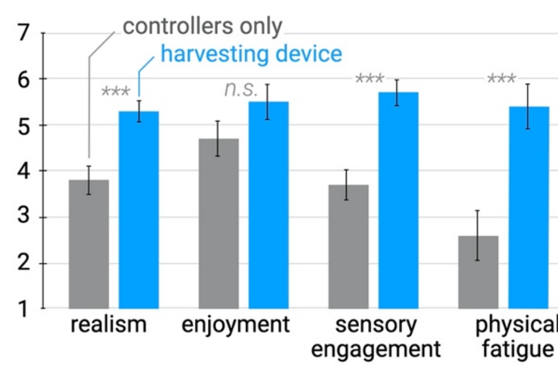

Figure 17: Study results, error bars show standard errors.

H1 (realism). First, we found that participants rated significantly higher (F(9)=5.6, p<.0005) realism in harvesting device (M=5.3, SD=0.7) than controllers only (M=3.8, SD=0.9). This finding suggests that our **H1 was confirmed (our approach led to more realism).**

H2 (sensory engagement). We found the participants rated significantly higher (F(9)=7.7, p<.0005) in sensory engagement with harvesting device (M=5.7, SD=0.8) than with controllers only (M=3.7, SD=0.9). This finding suggests that our **H2 was confirmed (our approach led to more sensory engagement),** which is a key factor in immersion [41]. Taken together, our H1 and H2 suggest that our approach to generating haptic feedback from power harvested from the user, improved the realism of VR experiences**.**

H3 (fatigue). We found the participants rated significantly higher (F(9)=5.7, p<.0005) in physical fatigue with harvesting device (M=5.4, SD=1.5) than with controllers only (M=2.6, SD=1.6). This confirmed our **H3 (a harvesting approach leads to more fatigue)**, and confirms this as a limitation of our approach.

H4 (duration). We found that participants took significantly longer (F(9)=4.9, p<.0005) to complete the experience with the harvesting-device (M=18.3 min, SD=4.41) than with the controller-only (M=11.3 min, SD=2.75). This was to be expected since when using our device, the user performs several additional actions (e.g., more rowing, swimming, etc.) while they charge the device in case the power is running low. This supports our **H4 (harvesting increases the duration of the VR experiences)** and confirms this as a limitation of our approach.

H5 (enjoyment). We did not find a significant difference (F(9)=1.6, p=0.14) in enjoyment even though harvesting device (M=5.5, SD=1.2) was rated higher than controllers only (M=4.7, SD=1.2). As such, our H5 was not supported.

7.5 Subjective feedback

Disclosure of harvesting. No participant realized our device was harvesting their movements. After disclosure of the working principle of the harvesting device, all participants found it unexpected and felt the integration was well executed. For example, P2 realized why "[I] had to row more to reach the islands!", P4 commented "makes sense now that I think about it"; P6 commented "wow, that is unexpected"; and P8 expressed "definitely it [the integration] works".

Harvesting-device. All participants mentioned that they felt the resistive force from our device when rowing the boat, and that this also contributed to the realism of VR. Regarding this, participants stated, for instance, that "it felt heavy" (P2) and "heavy when I moved my arm" (P3) and "the fact that you have to work your arm for it to go increased the realism" (P7). Some limitations were also brought up: P5 added that our device did not replicate the exact "physical experience of paddling since resistance in other joints is missing", and P8 mentioned it was "less fatigued than rowing in real life". However, most participants felt it to be enjoyable, e.g., "the rowing made it more enjoyable" (P9). The rising tide on the island happened at least once to seven (out of 10) participants—in fact, one participant experienced it twice because they wandered for a longer time exploring the island. The remaining two participants did not experience flooding because they found items quickly and immediately left the current island in search of the next one.

On-demand haptics. As for the remainder, on-demand, haptic sensations, most participants had a vivid impression of their experience with the electro-tactile feedback. Participants stated the crab felt like "I was pinched" (P4, P10), "a shock" (P2, P10), and "kinda sharp" (P3). In fact, P2 and P4 subsequently tried to avoid the next crabs to prevent them from getting pinched. Inserting batteries felt "some electricity" (P2) and "tingly" (P3) and, similarly, participants recalled the coconut's EMS impact as "crashing" (P9) and "tingly" (P3). Participants also positively recalled their vibration experience. All participants felt it when hitting the palm trees; one participant stated that "vibration pulled me into the world, especially the thunking on the tree" (P8).

Baseline. Compared to the baseline, without haptic feedback, all participants mentioned it felt less real and less engaging to their senses. For instance, they said, "I did find myself missing the stimuli even though it hurt" (P8), "without the thing on my arm rowing was easier" (P10), or "I was just looking around [instead of feeling] for this condition" (P6).

Study conclusion. Our qualitative and quantitative findings suggest that our approach can prolong VR haptic experiences that lend themselves well to intermittent haptics. Furthermore, we found that our harvesting approach might go unnoticed by unknowing participants, which are likely to feel the passive haptics from the harvesting as a source of realism and sensory engagement, leading to immersion even during harvesting periods. Naturally, we also found that our approach to prolonging haptics leads to more physical exertion and to longer experiences.

8 EXPANDING OUR CONCEPT TO MORE FORM-FACTORS AND APPLICATIONS

To further expand our approach, we explored additional applications, form factors, and other actuators in this section.

Fire-training simulator. To use our approach in a VR experience, the key is to design *harvesting sequences* that are adequate for the user's expected experiences and can be triggered seamlessly. Figure 18 depicts another illustration of using our approach in VR, with the example of a fire-training simulator, in which users must put out a fire in a building with an unknown room layout: (a) shows the start of this experience. (b) The user yields a heavy ax to break down a door of the building on fire. As the user moves the heavy ax, they feel resistance; while, at the same time, they are charging our device from a cold-start (no power). Once the microcontroller wakes up, the haptic device communicates to the VR experience. (c) The VR experience responds and breaks the door into pieces, instructing the clutch's release—the user now moves freely into the first room, they are no longer harvesting. Then, the user puts out fires in this room, and the VR experience requests on-demand haptics: such as (d) the feeling of flames (electro-tactile) or (e) the vibration from a fire extinguisher. Anytime that the haptic device is about to lose power, it extinguishes the fires in the current room and shows another locked door, which the user will have to ax down (harvesting) to reach the next room on fire.

Endless VR running. Different usage of our haptic device by attaching it to the knee joint is depicted in Figure 19. In this VR experience, users play a running VR game, akin to endless VR runners where users *walk in place.* However, our VR endless runner is complete with haptic feedback, even for hour-long game runs.

Figure 18: This VR experience immerses the user in a simple fire-fighting exercise, complete with haptic sensations.

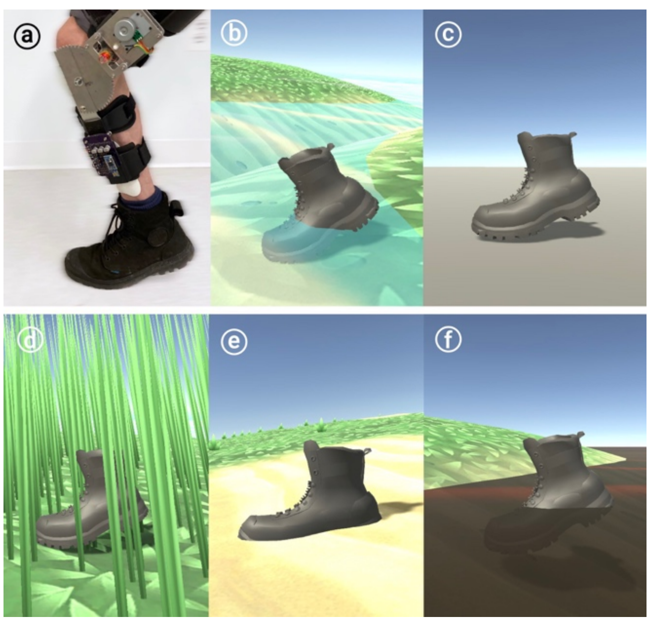

Figure 19: Our batteryless haptic device is worn on the foot in a VR running experience with haptic feedback.

Figure 19 depicts: (a) The user wearing our device runs in place. (b) As they run inside water through a shallow stream, they feel an added resistance from our harvester. (c) As always, once the microcontroller wakes up and reads a stable power, the haptic device communicates to the VR experience, which responds and stops rendering the shallow water and instructs the crutch to be released—the user now moves freely and runs on solid ground; they are no longer harvesting. Then, as users run through different sections of the terrain, the VR experience requests on-demand haptics, such as (d) grass brushing the user's legs (electro-tactile on legs), (e) a sandy terrain (vibration), or (f) running on mud (braking-mode, high resistance). Anytime that the haptic device is about to lose power, it informs the VR experience, which renders another section of the shallow water, so that the device can harvest energy from the user's leg movements.

Other haptic actuators. We believe our approach is not limited by the actuators used in our current prototype. One can envision a plethora of haptic actuators to provide richer haptic experiences, such as pressure, temperature, wind/airflow/fluid. In our preliminary explorations, we found that our device could successfully drive: (1) a small DC motor (26:1 Gearmotor Polulu) for ~5 seconds, which can be used for pressure or skin stretch feedback; (2) a solenoid (ZMF-1632d) for 100ms, which can be used to create impact; and finally, (3) a small Peltier element (CP081030-M) for ~5 seconds, which can be used for thermal feedback; the latter required an additional capacitance of 0.2F due to its high power consumption.

9 RELATED WORK

The work presented in this paper builds primarily on the field of haptics, with particular emphasis on sensations that require high-energy devices, such as force-feedback (motor-based exoskeletons, friction-based haptics, etc.). Moreover, we take inspiration from recent approaches to batteryless computing, which have predominantly focused on harvesting energy from the user or the environment for sensing applications. Finally, as our technical approach requires not only a hardware component (our clutch & kinetic harvester) but also a dynamic VR environment, we also review prior work on adaptive VR systems that render scenes to users in real-time depending on different constraints (e.g., space).

9.1 Batteryless computing devices

The growth of ubiquitous computing devices, internet of things (IoT) and wearable devices, has brought attention to the problem of powering devices that cannot reach a powerline or include a large battery. As such, many researchers across HCI and electrical engineering have been exploring new ways to power devices without the need for batteries.

Wireless transfer & RF backscattering. While power can be transferred wirelessly using Tesla coils, the power required can be dramatically high (i.e., this approach's efficiency is low) and the coils tend to be very large even at close distances (also removing the heat from the coils is nontrivial). As such, to power up small devices, radio frequency (RF) *backscattering* is a popular technique, in which the batteryless device's antennas pick up RF and convert it into power [1, 35]. In this way, multiple devices can be powered using one RF transmitter, making the receiving devices easier to set up around users [49]. One widespread usage of this is RFID technology, which leverages the same concept for powering ID badges and transit cards. For interactive devices, researchers utilized RFID for sensing gestures on surfaces [27] and tangible props [21]. In fact, we take inspiration from a recent endeavor to push batteryless devices to the tactile domain, such as an NFC-powered tactile device [47]. Overall, these devices based on wireless-transfer/RF are promising and popular for sensors using small amounts of current, but these require installation of a transmitter with a large battery or tethered to wall power—these are not ideal for mobile haptics applications such as free-walking VR.

Energy harvesting. Without instrumenting the device with a power supply or without instrumenting the environment with power transmitters, the energy must be *harvested* directly from the *environment* or its *user*. Next, we overview the most common techniques to realize this and their application area (for a comprehensive review of energy harvesting, see [46]). For powering small devices, solar ambient light or heat can be harvested. However, using small solar panels (the kind that would fit in a user or haptic device) requires constant and ample sunlight, but lighting conditions vary throughout the day. Therefore, harvesting using small solar panels is mostly suitable for sensors that operate at low power and in an intermittent manner [16]. As for harvesting energy from the human body, body heat and kinetic energy from movements can be used [50]. Body heat can be harvested using Peltier elements, which are exciting in that they harvest passively (the user does not need to engage in a harvesting behavior). However, their efficiency is low in the small sizes that are wearable, e.g., even very large skin areas covered can only generate μW of power [24]— not sufficient for driving large haptic devices. A source of larger energy efficiency is body movement. On a smaller scale, even micro-movements can be harvested via MEMS energy harvesting devices, e.g., piezoelectric [15, 28] and triboelectric [44] harvesters—again, these are promising but outside the range needed for driving strong haptics. Finally, to harvest more power from the body, large body movement from the joints can be harvested using electromagnetic generator (e.g., a DC motor)—the most powerful way to harvest kinetic energy from the body [11].

As our goal is to harvest energy for haptic feedback, where the power ranges from mW to W [10, 31, 42], and considering the mobility of the device (i.e., untethered), we see *kinetic energy* as the most promising power source.

9.2 Energy harvesting for interactive applications

HCI researchers have been exploring concepts to blend energy harvesting in our everyday appliances and devices [3, 37]. Here, we specifically overview energy harvesting applications for interactive devices.

For example, *Peppermill* [43] is a handheld input knob that is powered by the user's motions. *Paper Generator* [23] harvests power from the user rubbing an electret harvester on paper for lighting LEDs or driving an e-ink display. *Battery-free Gameboy* [45] integrates energy harvesting into an interactive system, utilizing solar panels and button clicks to power an interactive game, even bootstrapping between power losses—we take conceptual inspiration in this as well, since we engineered our device to be able to bootstrap itself from absolutely no battery (by ensuring the default state is harvesting mode). *Interactive Generator* [2] is a handheld knob that harvests energy when the user turns the knob, which it uses for RF communication to the interactive application. Moreover, while it does not provide a wide range of haptic feedback (e.g., vibration or others), it does provide on-demand resistance changes, by shortcutting the terminals of its DC motor—we take inspiration in this to realize our braking force. Furthermore, *SPIN* [5] integrates triboelectric nanogenerators into wearables that power LEDs and a buzzer. In fact, more recently, a similar approach has even been used to generate electro-tactile feedback [40]. However, the output power is still low at the μA level, while stronger stimulations tend to require mA level intensities. As such, with these previous harvesting approaches, electrical muscle stimulation or vibration has not been demonstrated and might not be readily achievable.

Generally, these previous devices incorporated energy harvesting by harvesting for a *short duration of time* (e.g., a button push [45], or a twist of a knob [2, 43]), which limits the amount of harvested energy (i.e., short harvesting = small energy). As such, this small amount of energy limits applications of these techniques to devices using relatively low power when compared to more power-hungry haptic actuators (e.g., vibrations, EMS, etc.). While we take inspiration from all these approaches, we take two conceptual turns: (1) *harvesting large movements for much longer*—thus harvesting larger output currents that are sufficient to power stronger haptic devices; and (2) *concealing the harvester's side-effects* (i.e., resistance that users would feel as distracting) as part of the VR experience & interactions.

9.3 Adaptive VR systems

Our system adapts the user's VR experiences in real-time to properly integrate the energy harvesting in the experience. This is inspired by works that utilize VR to adjust to different constraints (e.g., space), while preserving immersion. For instance, *Scenograph* [33] adjusts the VR experience dynamically according to the empty space available in the room, while preserving the same VR narrative. *VirtualSpace* [34] takes this further by enabling multiple users to overload the same limited physical space; to achieve this, the system generates *alternative VR scenes* in run-time (such as rendering an effect in a particular location, or making a new "power up" to appear), which causes users to move, even without needing to realize that there are sharing the space with other users. Moreover, motivated by the high power demand for haptic feedback, a series of research works have been exploring the idea of using humans as actuators in VR systems [6–9]. Specifically, in *Mutual Turk*, VR users, without even knowing other users are present, trade haptic forces with one another. Again, in this system, the VR experience also dynamically renders the content according to the motion of the other person to render realistic haptic feedback. Like these approaches, we take inspiration from VR experience's ability to be dynamically generated in real-time and use it to justify the resistive force felt while wearing our harvesting device.

10 DISCUSSION ON BATTERYLESS HAPTIC DEVICES

Even though there exists plenty of research on haptic devices, they are rarely mobile. One prominent issue is their high power consumption [12], leading them to be often tethered; or to have short battery lives if not having cumbersome batteries (e.g., *CLAW* [10] estimates the use of 1000mAh LiPo to yield only ~1 hour). This happens because devices generating haptic feedback require more power, typically orders of magnitude above, than a sensor.

While researchers have explored alternative actuators for the sake of power efficiency (e.g., using muscle stimulation instead of mechanical motors; or using brake-based actuators instead of motor-based actuators), even these alternative devices still feature batteries that will likely last far less than a whole day of usage. For example, *Dexmo* [17] uses a 800mAh LiPo battery, which allows it to provide haptic feedback for 4h, but only provides resistive force. Similarly, *Impacto* [31] uses a 1050mAh LiPo battery, which allows it to provide haptic sensations for ∼200 seconds. In fact, as devices attempt to simulate richer sensations, they require adding more haptic modalities, which implies even more power consumption and shorter uptime. We see an urge of seeking alternative solutions to batteries in haptic devices.

We demonstrate that integrating intermittent energy harvesting is a viable approach for VR. While the aforementioned battery-powered *Impacto* [31] provides ∼2000 haptic sensations (each 100ms), we estimate, with our approach, these sensations can be replicated with 3 seconds of charging prior to each stimulation (during runtime, i.e., after the process of bootstrapping the micro-controller and communications). Our device can provide ∼2000 of these sensations within 100 minutes, and it can continue doing this for as long as the user intends, 10 hours, etc. For *Impacto* to match this, it would need more than its current battery (1050mA LiPo). For example, to prolong its usage to 2.5h, it would require a 3150mA LiPo, weighing ∼0.5kg (three times heavier than the original battery). Naturally, adding more weight to wearables is undesirable as it creates fatigue, hinders movement, and creates unwanted haptic sensations. Moreover, to make matters worse, even this now heavier battery (lasting 2.5h) would still need to be charged at some point—the bigger the battery, the longer the charging time.

We believe that without batteries, haptic devices can be more mobile and more readily available, without users needing to worry about having enough charge. Finally, while we focused on the extreme case of having *no batteries at all*, one can also integrate batteries in our approach—in this way, the device can provide continuous haptic feedback when its batteries have charged, or switch to our intermittent harvesting approach when its batteries are depleted.

11 CONCLUSIONS & FUTURE WORK

We propose a new technical approach to implement untethered VR haptic devices that contain no battery, yet can render on-demand haptic feedback. The key is that via our approach, a haptic device charges itself by harvesting the user's kinetic energy (i.e., movement)—even without the user needing to realize this. This is achieved by integrating the energy-harvesting with the virtual experience, in a responsive manner. We instantiated a version of our concept by implementing an exoskeleton (with vibration, electrical & mechanical force-feedback) that harvests the user's arm movements to power haptics intermittently. We validated this device by means of a user study, in which participants (even without knowing the device was harvesting their movement) rated a VR experience as more realistic & engaging using our device than with a baseline VR setup. We believe our technical approach affords new uses of haptics for prolonged use-cases, especially useful in untethered VR setups, since devices capable of haptic feedback are traditionally only reserved for situations with ample power. Instead, with our approach, a user who engages in hours-long VR and grew accustomed to finding a battery-dead haptic device that no longer works, will simply resurrect the haptic device with their movement. Moreover, our approach enables new ways to use haptic devices unthinkable for battery-powered devices today: namely, walk-up use. Even if the user forgot to charge the haptic devices or change the batteries, our technique enables these to work rapidly during the interaction.

As for future work, we envision how researchers might expand our approach to integrate different haptic actuators (e.g., Peltier elements) or create new renditions of our approach for other body parts (e.g., neck, shoulder, and so forth).

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