Power-on-Touch: Powering Actuators, Sensors, and Devices during Interaction

Alex Mazursky
University of Chicago
Chicago, Illinois, USA
alexmazursky@uchicago.edu

Aryan Gupta
University of Chicago
Chicago, Illinois, USA
aryan05g@gmail.com

Andre de la Cruz
University of Chicago
Chicago, Illinois, USA
andredlcruz@uchicago.edu

Pedro Lopes
University of Chicago
Chicago, Illinois, USA
pedrolopes@uchicago.edu

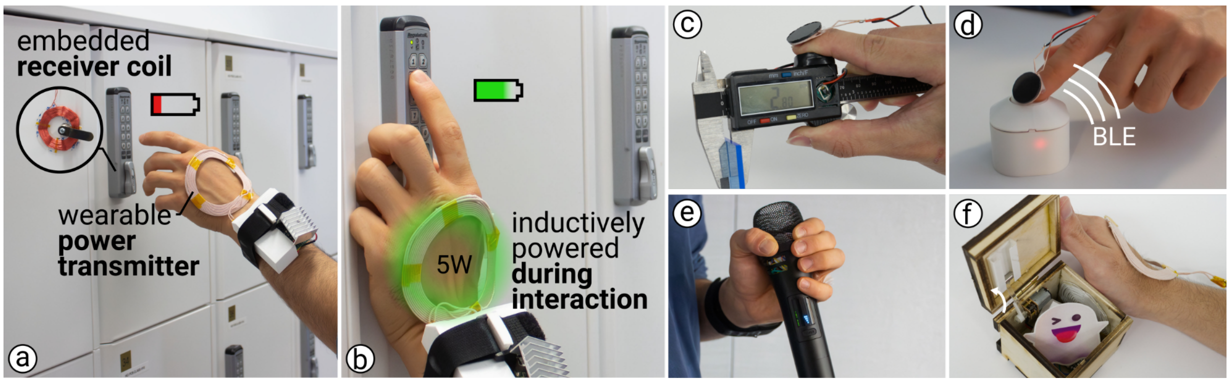

Figure 1: (a) We propose a new method for powering devices only during user interaction. It comprises of two parts: a wearable transmitter-module worn by the user and receiver-tags with coils that can be used to power devices without batteries. (b) When the user interacts with devices with receiver tags, energy is inductively transferred between the user's coil and the device's coil. This energy is sufficient for powering sensors, microcontrollers, and even actuators. (c-f) Our approach offers a new pathway for a greater number and diversity of battery-free devices in ubiquitous computing.

Abstract

We introduce *Power-on-Touch*, a novel method for powering devices during interaction. Power-on-Touch comprises two main components: (1) a wearable-transmitter attached to the user's body (e.g., fingernail, back of the hand, feet) with wireless power-coils and a battery; and (2) receiver-tags embedded in interactive devices, making them battery-free. Many devices only require power during interaction (e.g., TV remotes, digital calipers). We leverage this interactive opportunity by inductively transferring energy from the user's coil to the device's coil when in close proximity. To achieve this, we engineered receiver-tags and coils, including thin pancake-coils best-suited for wearables and spherical-coils that receive power omnidirectionally. To understand which coils best support a wide range of interactions (e.g., grasping, touching, hovering), we performed technical characterizations, including impedance and 3D efficiency analysis. We believe our technical approach can inspire ubiquitous computing with new ways to scale up the number and diversity of battery-free devices, not just sensors (μWatts) but also actuators (Watts).

ACM ISBN 979-8-4007-1394-1/2025/04
https://doi.org/10.1145/3706598.3713987

CCS Concepts

• **Human-centered computing** → Human computer interaction (HCI); Interaction devices; Haptic devices.

Keywords

wireless power transfer, wearable, ubiquitous computing, haptics

ACM Reference Format:
Alex Mazursky, Aryan Gupta, Andre de la Cruz, and Pedro Lopes. 2025. Power-on-Touch: Powering Actuators, Sensors, and Devices during Interaction. In *CHI Conference on Human Factors in Computing Systems (CHI '25), April 26–May 01, 2025, Yokohama, Japan.* ACM, New York, NY, USA, 16 pages. https://doi.org/10.1145/3706598.3713987

1 Introduction

Mark Weiser envisioned a future where computing devices are seamlessly embedded in nearly every object, enabling an era of ubiquitous computing [67]. While this vision is becoming increasingly feasible with advancements in technology, a significant hurdle remains: *power supply.* Currently, most interactive devices rely on batteries, which do not present a major hassle if users just interact with a limited number of devices in a room. However, as the number of interactive objects in a single environment increase, users find themselves requiring charging or replacement of batteries, which becomes impractical if we truly envision potentially hundreds of devices in a single smart environment [67].

In fact, supplying power is one of the primary practical obstacles in ubiquitous computing [15, 17, 49, 53]. There have since been significant strides made in ubiquitous sensing [16, 68, 78, 79], visual displays [13, 41, 45], low-power computers and microcontrollers [64], and even battery-free devices that harvest energy from users and operate intermittently [8]. However, these do not represent the full-power spectrum of interactive devices. While sensors or displays might require less power, most devices that contain actuators are not eligible for most forms of low-powered computing or energy harvesting [61, 71]. In fact, most interactive devices containing haptic actuation, motor-based tangibles, or other power-hungry actuators (e.g., ultrasound, electromagnets, and much more), are not typically featured in research on ubiquitous computing or in visions of this future.

To explore a new technical approach towards these challenges, we propose *Power-on-Touch*, a one-to-many wearable approach designed to power devices on-demand. By eliminating the need for built-in batteries and enabling scalable power transfer, *Power-on-Touch* not only mitigates the maintenance burden associated with batteries but also meets the power required for actuators, facilitating wider adoption of haptic and actuated devices in ubiquitous computing.

2 Related Work

The work presented in this paper builds primarily on ubiquitous interfaces, particularly instrumented interactive surfaces, and wireless power transfer, with emphasis on wearable approaches.

2.1 Adding Output to Everyday Objects & Surfaces

To achieve the vision of ubiquitous computing [67], researchers have developed various techniques to integrate input & output into everyday objects & surfaces—attempting to make these come alive and become responsive. One main challenge when adding interactivity to objects is how to power the input & output components. Since these objects and surfaces are meant to be scattered around users, powering them with batteries is challenging due to repetitive charging.

In addition to input, researchers have explored adding output to everyday objects and surfaces. For instance, researchers have added visual [13], audio [19], and actuated output [40]. On the haptics side, the common approach to adding haptics is to simply embed a vibromotor in the object [42, 43, 73]. On the actuation side, *Robiot* generated mechanisms for adding actuation to everyday objects, such as augmenting a lamp with robotic movements [30]. Evidently, when compared with adding input to the environment, adding actuation is far less explored, likely a symptom of their limited battery life. This is because actuators require orders of magnitude more power (100-1000x) than their sensing counterparts, making their burden of battery maintenance substantial.

To address this issue, some have argued for making actuators wearable so that a *single* device can overlay sensations onto *many* objects [21, 35, 60]. For example, *MagnetIO* added feedback to objects via passive magnetic patches that vibrate against the user's finger in a magnetic field [36]. These techniques have furthered the scale of haptics; however, they rely on *modality-specific* approaches that limit them to single modalities (only vibration, only friction, etc.).

To overcome this limitation, *Power-on-Touch* takes a *generalizable* approach. Instead of being tied to a specific actuation modality, our device directly addresses the bottleneck of actuation at scale: providing *power* to many devices. This is only possible because our concept uses *battery-free* devices in the user's environment. To power these devices on-demand, we are inspired by and build upon techniques from (1) wireless power transfer and (2) battery-free devices. Such ideas explore the notion of the user becoming the battery (i.e., bringing power with them for on-demand use).

2.2 Wireless Power Transfer

Wireless power transfer denotes transferring energy from a source to a receiver without the need for physical connectors, like wires or cables, making it especially attractive for reconfigurable and mobile devices. Several techniques have been developed for transferring power over a distance, such as electromagnetic [47], capacitive [26], laser-based [56], and ultrasonic [38]. In our review, we group approaches into three main categories: (1) *instrumented environments*, (2) *body-as-wire*, and (3) *encountered-type*, which we summarize and compare in Table 1.

Instrumented environments. Researchers have experimented with stationary transmitters built into the environment for transferring power to devices. For example, *UltraPower* used focused ultrasonic waves pointed at a receiver to transfer up to 50 mW [38]. Similarly, Su et. al combined lasers with photovoltaic cells for powering vibration motors via light [56]. However, these mediums are difficult to integrate into daily life because they require very precise tracking and alignment between the transmitter and receiver. Alternatively, others have used wireless power transfer coils to augment desks [7, 22, 50, 69] and even entire rooms [48] with wireless power. These have the advantage of being able to transfer high amounts of power (>10W) over a large space without precise alignment, but unfortunately require very specific construction, such as encasing entire rooms with metallic cages and poles [6, 48]. As such, it is difficult to scale instrumenting the environment, and there are cases in which it is infeasible, such as outdoors and on-the-go.

Body-as-wire. To make wireless power transfer mobile, others have focused on wearable and environmental transmitters that can send small amounts of current through the skin. Often, this approach is used to power battery-free wearable devices that are augmented with a receiving electrode [31, 37, 39, 62, 63]. For example, *SkinnyPower* demonstrated intra-body power transfer to transmit power from an electrode on the wrist to an accelerometer worn on the index finger [51]. *Power-Over-Skin* improved upon this approach to intra-body power transfer to scale to powering multiple receiver devices, sensors, and microcontrollers (typically <1 mW, dependent upon electrode size) [25].

Intentio had a similar principle, but for non-wearable, or encountered objects [26]. When a user wearing a transmitter touches an electrode on a receiving object, power is transferred through the skin to the receiving object. However, the user and object must share a common ground, which can require instrumentation and sensitive tuning of the capacitive coupling to ensure efficiency. Unfortunately, for body-as-wire techniques, the power that can be transferred through the skin is limited by the current that can travel through the skin without inducing tactile sensations (typically <0.5

Table 1: Comparison of *Power-on-Touch* with prior work on wireless power systems. *Power-on-Touch* addresses all the stated design goals to provide a solution to scaling on-demand power through touch (✗): not available, ♦: partially available, ✓: available).

Category	Related Work	Design goals		
		Easy to scale	Versatile across spectrums of power	Robust to various touch interactions
instrumented environments	desk-scale inductive power [7, 22]	✗	✓	✓
	room-scale inductive power [6, 48]	✗	✓	✓
	laser power [56]	✗	✓	♦
	UltraPower [38]	✗	♦	♦
body-as-wire	*SkinnyPower* [51]	✗	✗	♦
	Power-over-Skin [25]	♦	✗	♦
	Intentio [26]	♦	✗	♦
encountered-type	*MagnetIO* [36]	✓	♦	♦
	PowerShake [70]	✓	✓	✗
	Meander Coil++ [59]	✓	✓	✗
	TouchPower [76]	✓	♦[a]	✗
	***Power-on-Touch* (our work)**	✓	✓	✓

[a] *TouchPower*'s efficiency/output were described as very low (46%, 200 mW). We see no reason why they cannot be improved, thus we bumped it up in our rating.

mA [27]). While this is sufficient for sensing and microcontrollers, it is not enough power to realistically drive actuation.

Encountered type. Alternatively, other works aim to power devices that the user *encounters* within their environment. *Meander Coil++* [59] and its predecessor *Twin Meander Coil* [58] leveraged inductively coupled wireless power transfer on the user by embedding coils into the user's t-shirt. This work inspires us with examples of encountered and wearable sensors, LEDs, and a robot. Similarly, *PowerShake* [70] demonstrated using wireless power to transfer energy between users' phones and watches via device-to-device contact. However, the form factors of *Meander Coil++* and *PowerShake* limit interaction, since the user must either contact objects with their torso or tap devices together. Instead, we leverage a more natural channel: *interactions via one's hands*—we use our hands heavily to interact with and manipulate objects in the environment, and many existing devices are designed around this channel. *TouchPower* [76] shares our vision of powering devices during touch, recognizing that many electronic devices only need to be powered up during interaction (e.g., TV remotes, digital calipers, karaoke microphones, etc.) and that interaction with devices usually requires proximity or contact between the user's hands or body and the target device, forming a natural channel for power transfer. However, *TouchPower*'s working principle is fundamentally different from ours. *TouchPower* is a glove with electrodes, that, when aligned with receiving electrodes, powers battery-free devices during grasping. The downside to an electrode-based approach is that it requires at least two electrodes to be precisely aligned (actual physical contact, no gaps), to connect both power & ground and complete the electrical circuit. Therefore, this technique is only suitable for objects in which the geometry dictates a precise grasp—moreover, it assumes that all users will grasp the object in the same way, i.e., not robust to variations in pose. In contrast, our approach does not require precise alignment, and therefore accommodates a wider range of grasps and interaction poses, as we later show in our *Technical Evaluation*.

Comparing approaches. When comparing approaches, a few trends emerge across the categories. *Instrumented environments* tend to be versatile across spectrums of power and robust to various touch interactions; however, they are intrinsically limited in scale because it is infeasible to implement in *every* environment. In contrast, *body-as-wire* tends to enable scale due to wearables' travelling with the user (with minor drawbacks of requiring common grounds, which necessitates instrumenting objects with electrodes); however, passing current through the skin is limited to low-power devices like sensors and microcontrollers, and is too low for actuation. Finally, *encountered-type* ensures scalability and is generally versatile across power spectrums depending on the working principle. However, to our knowledge, *encountered-type* devices have not been robust to various touch interactions. In contrast, *Power-on-Touch* is tolerant to alternative touches because inductive power transfer does not require precise alignment to the extent that electrodes do, while leveraging natural touch channels, such as the hands and fingers. Thus, *Power-on-Touch* achieves all three goals.

2.3 Energy-Harvesting and Battery-Free Devices

Finally, we draw inspiration energy harvesting and battery-free devices [1, 72, 77]. For instance, *interactive generator* presented a rotary input device that provided haptics with energy entirely harvested from the rotation itself [2]. Teng et. al used a similar approach in a wearable to harvest energy from the user while providing resistance as haptics [61]. While *Power-on-Touch* can transfer high power from the user to devices, we use this to actuate power-hungry devices, which can lead to intermittent power. Thus, we employ similar strategies to works on intermittent power sources [8].

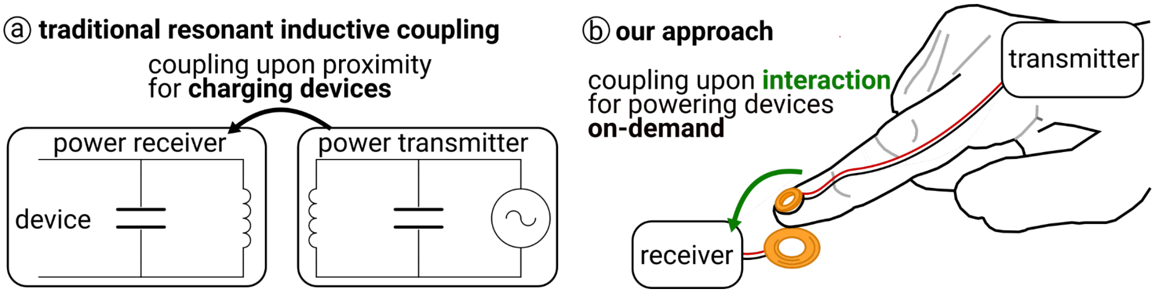

Figure 2: Our approach uses (a) resonant inductive coupling to power devices. (b) However, rather than placing transmitters in the environment to which users must bring their devices to charge (i.e., coupling upon proximity), our transmitter travels with the user to power devices during interaction (i.e., coupling during interaction).

3 Our Approach: Power-on-Touch

Power-on-Touch consists of a wearable wireless power unit that enables users to power many battery-free devices as they encounter and interact with them. We augment devices with our custom-engineered receiver-tags so that they can be powered inductively during interactions that require close proximity. The key enabler of our approach is that our device is: (1) encountered-type, which enables scale; (2) versatile across power requirements, which enables powering not only sensors, but also actuators; and (3) robust to various touch interactions due to its non-contact working principle.

Our approach is based on inductive power transfer, not unlike the principle used in common wireless phone or electric toothbrush chargers, as shown schematically in Figure 2a. In these chargers, when a receiving device is placed on a charger in the environment, the transmitter and receiver become inductively coupled, enabling power transfer. However, we take a conceptual turn from typical wireless chargers—we developed a *wearable* power transmitter (Figure 2b). Rather than placing transmitters in the environment for users to bring their devices to (i.e., coupling upon proximity), our transmitter travels with the user to power devices *during interaction* (i.e., coupling during interaction). By turning the user into a mobile power source, devices that only need power during interaction no longer need to have batteries and can instead be powered *on-demand*. Eliminating the need for built-in batteries reduces maintenance efforts while enabling powering actuators, which can broaden adoption of haptic and actuated devices in ubiquitous computing.

Synergies between our work and other approaches. Powering devices in the environment is a longstanding challenge, and numerous approaches have been proposed. Today, users are typically equipped with mobile and wearable battery-powered devices (e.g., cellphones, smartwatches). Thus, there are increasing opportunities to share power between the user's devices and devices in the environment. For instance, sharing energy between devices like phones and watches is already integrated in some commercial devices [9, 70]. Others showed transmitting energy through the skin from a central battery to power peripheral wearables [25]. There has also been growing focus on new ways to charge wearable batteries, such as through kinetic interactions with objects [72] or harvesting from the user [61]. Rather than *supplanting* these approaches, Power-on-Touch *complements* them, enabling its battery to be charged through harvesting or shared power while also facilitating energy transfer back to devices in the environment on demand.

4 Contribution and Limitations

Our key contribution is that we propose, explore, and engineer a novel method for powering devices during interaction. Our technical approach enables new ways to scale the number and diversity of battery-free devices in ubiquitous environments, such as going beyond ubiquitous sensing and into the realm of *ubiquitous haptics*.

Our approach has the following benefits: (1) While traditional devices and actuators each require their own power supply, often in the form of batteries or tethered outlet connections, *Power-on-Touch* instead places the battery on the user and augments devices with receiver tags to receive power *on-demand*, resulting in scalability; (2) *Power-on-Touch* is versatile across spectrums of power, enabling not only sensors and microcontrollers to be deployed ubiquitously, but also *actuators*; (3) *Power-on-Touch* is robust to various touch interactions, from hovering to single-finger touch to grasping and resting as it does not depend on direct or perfect contact with devices; (4) *Power-on-Touch* can sufficiently provide power without obstructing the user's palms and fingers (e.g., wearing a glove); instead, coils can be placed on the back-of-the-hand and fingernail, leaving the user free to interact with devices.

Our approach is limited in that: (1) inductive power transfer will never be as efficient as wired power transfer due to additional losses—still, to minimize this, we employ tuning techniques (see *Implementation*); (2) our approach requires proximity between the user and devices, thus it is most applicable to devices that only need to power on when the user is close or touching them; (3) our approach requires modification of existing devices to be compatible with wireless power, which can result in requiring some retrofitting and possible changes to form factor; (4) metallic obstacles (e.g., a metal enclosure) will introduce unintended losses via eddy currents and may interfere with effective power transfer [20, 75]; (5) for our complete vision in which every user can power devices on-demand, all users must be equipped with wearable transmitters/coils. While the latter is a limitation, it can also be a strength and a worthwhile vision for research, as this allows us to explore the goal of a *one-to-many* and *natural* power delivery system, as there are many more devices in the world than there are people [18].

5 Implementation

To help readers replicate our design, we now provide the necessary technical details and fabrication process. Furthermore, to accelerate replication, we open-source our implementation[1]. *Power-on-Touch* consists of two principal components: (1) *many* battery-free devices in the environment that are powered wirelessly with our receiver tags and (2) our wearable wireless transmitter (battery, microcontroller with BLE, voltage booster, switching circuit, and coils).

5.1 Achieving Resonant Inductive Coupling

Ordinary inductive charging (e.g., commonly used with electric toothbrushes) is efficient when the transmitting and receiving coils are especially close together and well-aligned. However, as the gap between coils increases or the alignment skews, this efficiency plummets. Therefore, the key to achieving our approach at reasonable efficiencies is to *tune* our transmitting and receiving circuits to *resonate* at the same resonant frequency. This is called resonant inductive coupling, and greatly improves both the efficiency and power transfer over distance/misalignment. For example, early seminal work demonstrated 40% efficiency over a distance of 8 coil diameters [29]. Had these coils not been carefully tuned, this efficiency would be many orders of magnitude lower. Thus, to maximize efficiency, and therefore enable a wider range of interactions (e.g., powering while hovering, stronger actuators, etc.), we carefully tune all our circuits.

Tuning consists of a series of steps. First, each coil has its own *quality factor*, (*Q-factor*) a measure of the frequency at which the coil experiences the lowest losses. In other words, driving our coils at frequencies for which a coil has a high *Q-factor* results in greater efficiency (and lower temperatures). In our *Technical Evaluation*, we use impedance analysis to find coils that have high *Q-factors* at our desired frequency. Then, the coils are tuned to the resonant frequency by placing a capacitor in parallel. This turns the circuit into an *LC* circuit, which has a well-defined equation for undamped resonant frequency: $f = \frac{1}{2\pi\sqrt{LC}}$. In practice, damping occurs; as such, we hand-tune the capacitor value to ensure resonance at the transmitting frequency. These steps are taken for both our transmitting and receiving coils, and as we show in our circuits, we leave room for multiple parallel capacitors in our PCBs to enable fine-grain tuning. In the future, integrating dynamic frequency tuning may automate this process [47].

5.2 Coil Design

We implement and characterize three types of coils in our approach: (1) *large-coils* typically worn on the back-of-the-hand and used in grasping or palmar interactions; (2) *small-coils* typically worn on the fingernail and used in single-finger touches; (3) *spherical-receivers* designed to receive power omnidirectionally. We investigate both traditional spiral coils and spiderweb coils for their low self-capacitance [34]. In general, we recommend pairing the receiving coil's diameter to be close to that of the transmitting coil for maximal efficiency [66].

Large-coils. Large diameter coils are our default coils. The larger a coil's diameter, the further its field travels [52]. Thus, larger coils tend to enable greater magnitudes of power transfer and higher efficiencies. Therefore, we use larger diameter coils when the interaction permits (i.e., the user's body part can accommodate a larger coil, like on the back of the hand, foot, arm, etc.) and when the receiving object can fit a large coil without dramatic consequence to form factor.

Small-coils. In instances where larger coils are unsuitable (e.g., fingernail for power over single-finger interactions), we opt for smaller diameter coils. As shown in our *Technical Evaluation*, this comes at a small cost to efficiency. However, as we also show, the power transfer of smaller coils can be increased by adding ferrite backings that direct the field [54].

Spherical-receivers. To best enable our vision of robustness to various types of touches (e.g., angles, etc.), we wound and characterized spherical coils designed to receive power omnidirectionally—as we show in our *Technical Evaluation*, no matter the direction from which user approaches, power is received, unlike traditional, flat coils, which have dead zones when coils are arranged perpendicularly [12, 23, 24]. We recommend these coils in devices that don't have affordances that suggest directionality, such as cylindrical devices (e.g., microphones).

Coil Wearability. Figure 3 shows three distinct coil materials that we explored, each with their own benefits. First, we engineered rigid coils made from solid copper wire. While these coils prove effective for receivers, their rigidity becomes problematic for wearable transmitter applications, as demonstrated by the difficulty in bending a sample coil in Figure 3a. In contrast, Litz wire presents a more conformable alternative, comprising multiple thin individual wires that enable significantly greater flexibility compared to solid wire of equivalent gauge (Figure 3b) [55]. At the opposite end of the spectrum, we engineered stretchable coils by embedding liquid metal channels within silicone (as in [59]). While these stretchable coils offer superior flexibility (Figure 3c), they did not match the efficiency of our flexible or rigid coils. Ultimately, we found Litz wire to strike a better balance between being *flexible* for wearability and *performance* in our transmitter's frequency range; Litz wire is effective at reducing losses due to skin effect and proximity effects within 100kHz-1MHz [46]. Some body parts do not require as much flexibility (e.g., the fingernail is rigid); for these, we can use ferrous backing to boost the field strength, despite its rigidity.

We deliberately chose to wear transmitter coils on body parts that *minimize* interference with manual interactions, such as the back of the hand or fingernail, as opposed to gloves [76]. While we could have placed coils on the palmar side of the hand or finger—which would significantly increase transmission efficiency—this would have correspondingly and dramatically reduced user dexterity. We attached these coils to the user's body using double-sided tape and tacky silicones, though future work might explore alternative attachment strategies, such as semi-open gloves. Moreover, while our current implementation employs traditional coil form factors, our approach remains compatible with other materials and fabrication techniques. Potential future iterations could integrate

[1]https://anonymous.4open.science/r/PowerOnTouch-E266/README.md (firmware, schematics, etc.)

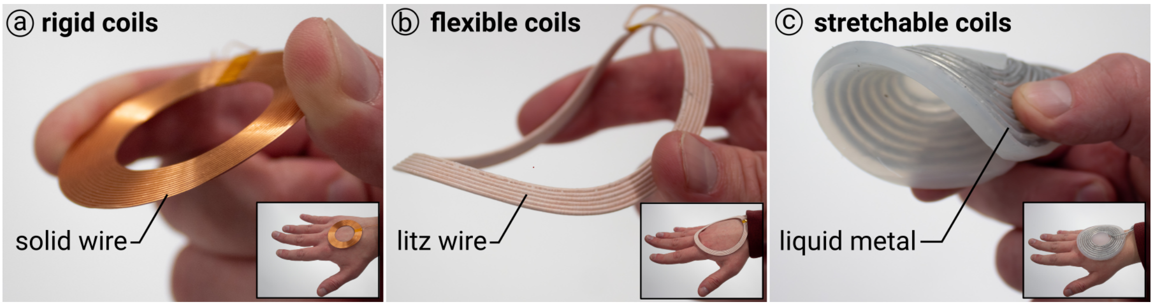

Figure 3: We tested coils made of (a) solid wire, (b) flexible Litz wire, and (c) liquid metal wires (silicone tubing filled with EGaIn).

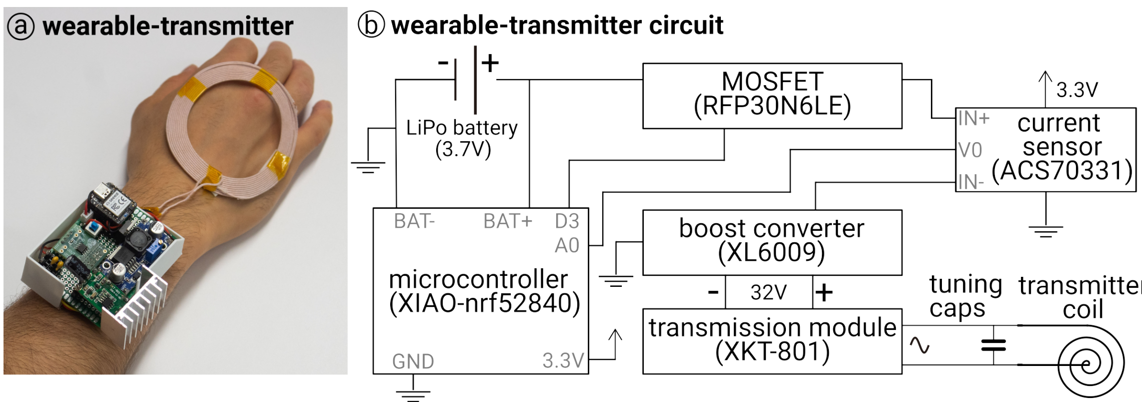

Figure 4: (a) Our wearable transmitter and (b) its schematic.

coils into knitted textiles [44] or jewelry [57], for improved social acceptance and wearability.

5.3 Engineering our Wearable-Transmitter and Receiver-Tags

We engineered (1) a wearable-transmitter and (2) receiver-tags, as shown in Figure 4 & Figure 5.

Wearable-transmitter. Our wearable transmitter primarily consists of a battery (1200mAh), microcontroller with BLE (Seeeduino XIAO nrf52840), DC-DC voltage booster (XL6009), transmission switching module (XKT-801: 50-900kHz adjustable, Taidecent), and coils worn on the user. We selected this frequency range based on compatibility with the Qi standard (100-200kHz), a common standard in commercial devices [33, 65]. Thus, many commercially-available coils are optimized for this range, enabling prototyping with proven coils. This is just one physical implementation of the conceptual principle of Power-on-Touch, and implementing other standards (e.g., NFC at 13.56MHz) is possible. In fact, higher frequencies may lead to improved wearability, as they afford coils with fewer turns/smaller diameters [32, 74].

The battery powers the microcontroller, which uses a MOSFET (RFP30N06LE) to control the current flow from the battery through the voltage booster, which steps the voltage up from 3.7V to 32V, before being fed into the transmission module. Our wearable transmitter contains a power-monitoring circuit consisting of a current sensor (ACS70331) in combination with the nrf52840's built-in battery voltage monitor to actively sense the reflective load presented by nearby receiving coils. While our implementation of a transmitting circuit is made from individual modules assembled on protoboard, the device can be miniaturized with a custom PCB.

The transmitter's power consumption varies based on its operational mode. During active power transmission for our typical large-coil, the transmitter draws 3.2W (0.85A), and this increases to 4.5W (1.2A) when a receiver coil is nearby. With a 1200mAh battery, the transmitter can continuously emit power for ~1h. However, we conserve battery life by only transmitting at full power when a receiving coil is detected. In standby mode with test-pulses to detect if a receiver is present, power consumption drops to an average of 0.3W, extending battery life to ~9.5 hours.

Receiver-tags. We engineered a custom PCB for our receiver-tags containing a rectifying circuit, a supercapacitor, microcontroller with BLE (Seeeduino XIAO nrf52840), and MOSFETs for controlling high-power devices (actuators, displays, etc.). It can accommodate up to three receiver coils with various tuning capacitors. The received AC power is rectified through fast-switching diode bridges (1N4148, while we experimented with rectifier-specific diodes, we found fast-switching to be necessary to reduce losses at high frequencies). The rectified DC power is then smoothed

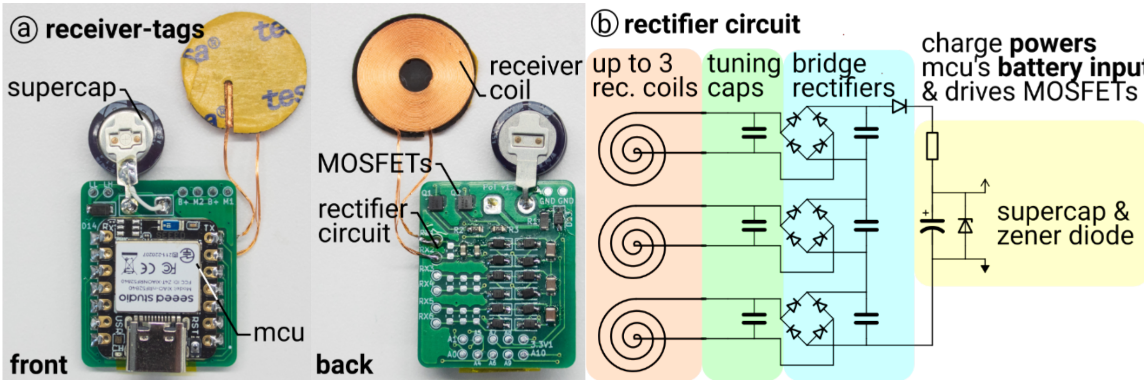

Figure 5: (a) Our custom receiver tag PCB and (b) its schematic.

through capacitors. Since our rectifiers are wired in series, the voltages from each coil add together. This total voltage is used to charge the supercapacitor (330mF, 5.5V). The benefit is that our tags can accommodate multiple coils for added robustness to variations in touch, as well as our spherical-receivers, which consist of three coils on orthogonal planes.

The supercapacitor directly powers the microcontroller, which was chosen for its fast boot time, low minimum operating voltage (1.7V), and simple footprint for producing and deploying receiver tags rapidly. Our PCB exposes all but two of the XIAO's I/O pins for easy prototyping. Two pins are dedicated to controlling on-board MOSFETs (SIA436DJ). We use these MOSFETs to control high-power components; when the supercapacitor is charging, the MOSFETs remain open until a sufficiently high voltage is reached for actuation. This is especially critical as many high-power devices have an "activation energy" that must be overcome to turn on. Using MOSFETs isolates higher-power components from draining the supercapacitor. Supercapacitors enable our approach to quickly charge with sufficient energy to generate high power actuation and short-term sustained power 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 [28], which allows for fast charging/discharging speed (orders of magnitude faster than a battery of similar capacity). The supercapacitor circuit can be tuned to balance storage (increasing capacity) vs. charging time (decreasing capacity).

5.4 Detecting Receiver Tags and Communication

While our primary goal focused on implementing a wireless power technique for powering battery-free devices to scale up the number and diversity of devices (including actuators) in ubiquitous computing, we also implemented a basic tag detection and communication schema. Rather than our transmitter constantly emitting power into the environment and needlessly wasting energy, we implemented a simple protocol for detecting when receiving tags are nearby. Our transmitter periodically sends out short (50ms) test pulses at monitored power draw. When a receiving coil is nearby, the transmitting and receiving coils' coupling increases and the receiving coil naturally draws more power from the transmitter during the test pulse. If a test pulse's power draw exceeds our threshold for knowing a potential receiver is nearby, our transmitter switches from test pulses to transmitting at full power. Since our receiver tags feature a BLE microcontroller, upon receiving power, the tag can begin advertising itself as a BLE device to let the transmitter know its specific needs or its supercapacitor's voltage to strategically control transmission for better energy use. This type of reflective load sensing is very similar to how wireless chargers based on the popular Qi standard operate [65].

We acknowledge that there are multiple ways to implement sensing (e.g., RFID). While BLE requires time to pair and energy to stream, it is a simple protocol to demonstrate our full vision with communication. In the future, lower power and faster communication can be established by implementing an ultrasonic chirping circuit (inspired by Sozu [77]).

6 Technical Evaluation

To characterize our effectiveness and seek out improvements, we performed a series of technical evaluations. These aimed at finding efficient coils to enable applications that are otherwise not feasible. As electromagnetic fields decay dramatically over distance, even marginal gains can unlock new interactions and more robustness to variation in touch.

1. First, we measure the quality factor (*Q-factor*) of a variety of coils, both commercially available and custom-made based on prior work. This gives us a view of how efficient each coil is with respect to frequency.

2. Next, we measure the power transfer efficiency for pairs of candidate coils with respect to distance and alignment. This gives us insights into what kinds of devices we can power with different form factors, spacings, and alignments.

3. Additionally, we test the robustness of these coils to changes in the angular alignment between coils. While flat coils are very effective when aligned angularly, their efficiency drops as the angular difference increases [10, 14]. As such, we propose and demonstrate a spherical-receivers that can effectively receive power along all three planes.

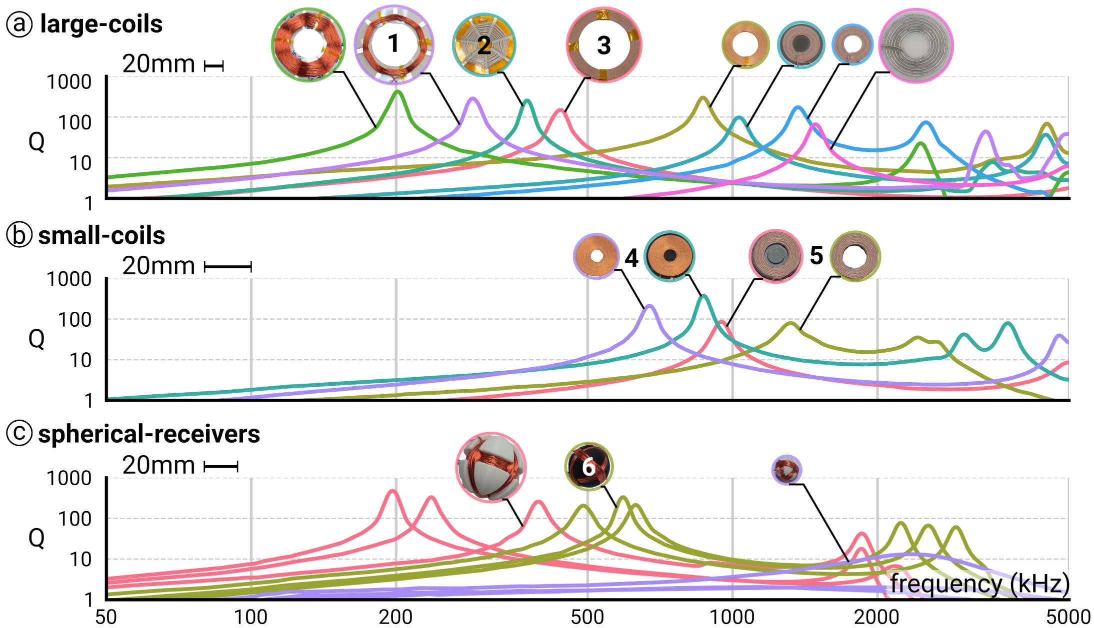

Figure 6: Quality factor with respect to frequency for (a) large-coils, (b) small-coils, & (c) spherical-receivers.

4. Finally, to characterize our approach's ability to power real devices during interaction, we tested our approach on three example objects with different form factors and output modalities.

5. We perform a safety and thermal analysis to validate safe levels of electromagnetic field and heat.

In summary, our *Technical Evaluation* demonstrates our approach's ability to transfer a wide spectrum of power while being robust to different types of touch.

6.1 Quality Factor Analysis

First, we measure the quality factor, Q, of a variety of coils, both commercially available and custom-made based on prior work. Figure 6 presents Q vs. frequency for our three types of coils. The Q-factor is defined as $\frac{2\pi f L}{R}$, where f is frequency, L is inductance, and R is resistance. Since inductance and resistance also depend on frequency, the *Q-factor* is a frequency-dependent measure of where the coil experiences the lowest losses. In other words, to optimize our system's efficiency, we want to select coils with high Q-factors at our transmitting frequency. To perform this analysis, we used an impedance analyzer (Analog Discovery Studio), which gave insight into each coil's resonant frequency and the Q-factor and bandwidth, especially in relation to other coils. We swept a 5V sine wave through each coil and a known value resistor at frequencies from 1kHz to 5MHz in 1001 steps, taking the average at each point over a 500ms excitation. We performed impedance analysis for a variety of palm-sized coils, nail-sized coils, and spherical coils.

This impedance analysis, depicted in Figure 6, provided insight into the coils that perform efficiently at our wearable transmitter's effective frequency range (50-900kHz). In each of our applications, we select coils with *Q-factor* greater than 95 for our selected transmitter frequency to support increased efficiency. In a similar effort to increase efficiency, we pair transmitting and receiving coils with similar resonant frequencies/bandwidths so that both perform maximally. In the following subsections, we further evaluate pairs of coils (individual coils labeled in Figure 6) following this principle. Generally, we find that large-coils have lower resonant frequencies and greater *Q-factor* than small-coils. This trend is highlighted by our spherical coils, where, for the same number of turns, decreasing coil diameter led to higher resonant frequencies and reduced *Q-factor*. As such, to maximize efficiency, we often aim to use the largest coils that an application permits. Finally, we found that ferrite backings shifted the resonant peaks. In the following subsection, we further investigate how ferrite backings can affect the power transfer efficiency.

6.2 Power Transfer with respect to Distance and Alignment

Next, we measure the power transfer efficiency for pairs of coils with respect to distance and alignment. This gives us a view of the types of devices we can power with different form factors, coil spacings, and affordances. We built a test apparatus using a pegboard with a grid of holes (7.5mm spacing) and adjustable height; we 3D-printed jigs that fixed the relative position between pairs of

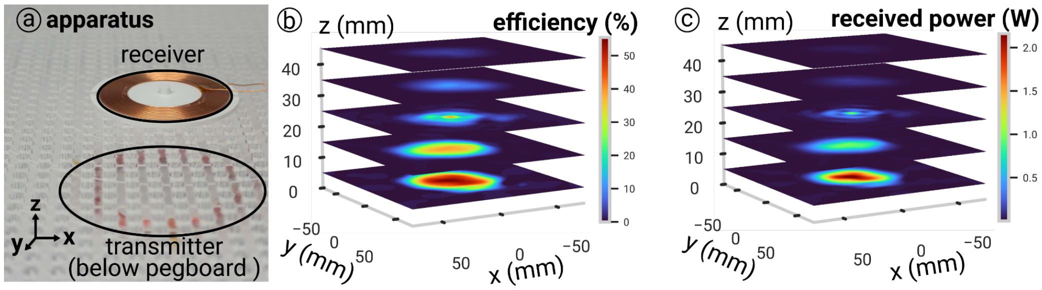

Figure 7: (a) Our pegboard apparatus for controlling 3D alignment between coils. Power transfer with respect to distance and alignment for a pair of large-coils: (b) efficiency and (c) received power.

coils as shown in Figure 7. By sampling (4MHz sampling rate) the transmitted and received power over points in the grid at different heights, we can construct a 3D view of the power transfer. Here, we measured the "end-to-end" power transfer, i.e., we monitored the DC power draw of our transmission circuit and the rectified DC power through a load (250ohm) of our receiver circuit. All coils were tuned to the selected transmission frequency. Following these results in air, sections 6.4 and 6.6 investigate efficiency when coils are worn on the hand.

Large-coils. We tested the power transfer of coils 1 (transmitter) and 2 (receiver) at 320kHz. Figure 7 shows the 3D plot of efficiency and received power. We found a peak efficiency of 55% when coils were well-aligned and separated by 5mm; this corresponds to 2.2W received for this pair of coils.

Our efficiency is comparable to other wireless power approaches within HCI, e.g., *Meander Coil++* and *TouchPower* had end-to-end efficiencies of 25% and 46%, respectively [59, 76]. Given our aim to pass power through to the palm from the back of the hand, as well as enabling hovering, we are also interested in the performance at greater distances. For example, at 25mm gap (approximately the thickness of a hand) and no offset, the received power was 1.03W, suggesting that higher power devices (e.g., motors) can be powered through the thickness of the hand. At 45mm gap, the received power was 38mW; modern microcontrollers (e.g., nrf52840 used in our tags) consume well below this power even without entering power-efficient modes, suggesting that *Power-on-Touch* can power microcontrollers upon hovering [81]. Additionally, we found that the received power was maximal when coils were aligned and decreased as the offset reached approximately the coils' radius.

Small-coils. We tested the power transfer of coils 4 (transmitter) and 5 (receiver) at 640kHz. Specifically, we aimed to determine whether ferrous backing, which typically is used in commercial wireless chargers to improve coupling, is beneficial for small-coils, which typically exhibit worse efficiencies than larger coils. As such, we tested our small-coils both without any ferrous backing (Figure 8a) and with ferrous backing (Figure 8b) to determine their effect. We found that the peak received power nearly doubled when ferrous backing was used (no ferrous backing peak received power: 0.87W; ferrous backing peak received power: 1.63W). At approximately finger thickness (15mm), ferrous backing also led to greater received power (no ferrous backing peak received power: 121mW; ferrous

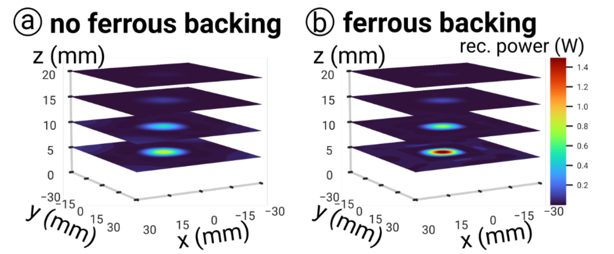

Figure 8: Power transfer with respect to distance and alignment for a pair of small-coils (a) without and (b) with ferrous backing.

backing peak received power: 88.4mW). As such, we use ferrous backings on our small coil pairs to boost their efficiency.

6.3 Robustness to Angles

While flat coils are compact and very effective when aligned angularly, their efficiency drops as the angular difference increases [10, 14]. As such, to ensure robustness to different angles of touch, especially in applications where the angle of touch is expected to vary, we implement and characterize spherical-receivers designed to receive power in multiple dimensions. We performed this evaluation by rotating a spherical-receiver (coil 3) 360 degrees about its three axes while measuring the power received from a transmission coil (coil 6) at 15-degree increments. The z-spacing of the coils was set to 30mm and we tested both when the coils were axially-aligned and offset by the transmitting coil's radius. Figure 9 shows the average received power for each axis and alignment. As shown, the average received power for each axis is similar, indicating that spherical-receivers can be expected to receive power omnidirectionally. When the coils are axially-aligned, we found an average received power of about 130mW, enough to power a small vibration motor. As expected, the received power decreases with axial misalignment, but the received power is still roughly equal across the three axes. It is important to note that this test was performed with a 25mm diameter sphere, which strikes a compromise between compact size for embedding into objects and power transfer efficiency. Increasing the size of the sphere and decreasing the gap between coils both lead to increased power when designing applications.

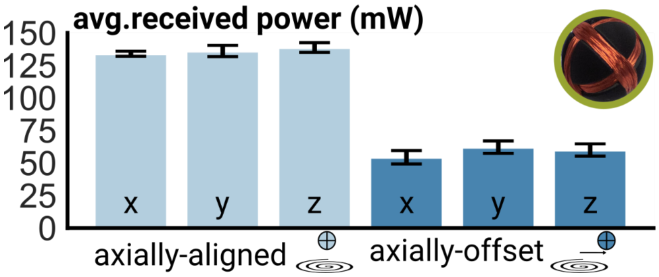

Figure 9: Average received power (mW) rotated about three axes of our spherical coils.

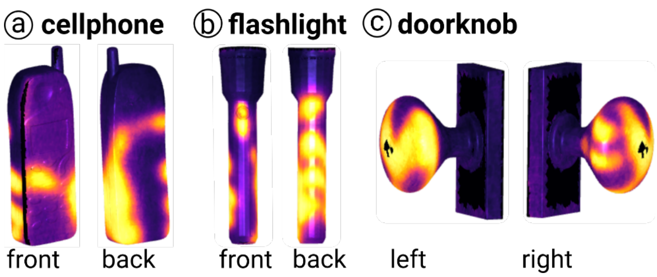

Figure 10: Contact likeliness heatmaps from ContactDB [4] that we used to inform touch interactions during characterization.

6.4 Characterizing Performance in Real Devices

Up to this point, we have characterized our system within a lab; however, real-world objects and environments often do not align with the ideals of the lab. As such, we now evaluate our system using real devices and interactions (e.g., grasping, touching, hovering) to measure the power transfer and the time to charge to produce useful outputs (e.g., sending a signal or driving a motor). To inform the likeliness of an interaction pose, we leverage the ContactDB dataset [4], which contains data on grasping 50 common objects (e.g., doorknob, cellphone, etc.) from 50 participants to create heatmaps of contact likeliness. In this study, we mimic likely touches from three of these objects (shown in Figure 10), as well as test alternative, less-likely touches while interacting with our devices.

TV Remote. First, we tested a TV remote, from which we removed the batteries and converted to being powered by our receiver tag and two coils, as shown in Figure 11. First, we measured the power consumed by the remote. As shown in Figure 11a, the remote consumes very little power when idle, but wakes upon a button press, followed by sending short a transmission signal, with a peak power of about 34mW (and total energy consumption of 0.9mJ).

To inform our touches, we refer to the heatmaps from the ContactDB dataset [4] for a similarly shaped device with similar buttons for interaction, a cellphone. We mimic the likely touch from the dataset's heatmaps, as well as our own, alternative touch which rotates the hand 180 degrees from the likely touch, as shown in Figure 11c. Figure 11d presents the received power in both interactions. We found that the likely touch resulted in 100mW of received power, while the alternative touch resulted in 40mW. Given the remote's peak power draw of 34mW, both touches can sufficiently power the remote. In fact, the spare power during the likely touch can even be used to *add haptic feedback* to the remote; as shown in Figure 11b, we added a vibration motor to augment the remote with eyes-free feedback and notifications.

Figure 11e shows the supercapacitor's charge over time starting at picking up the dead remote in the likely touch (rapid increase in supercapacitor charge indicates initiating pickup). As shown, the tag's microcontroller wakes about two seconds after the remote is picked up; the remote can then immediately function as though it were powered by batteries. Moreover, we demonstrate augmenting the remote with vibration feedback, which results in a brief supercapacitor voltage drop, followed by a rapid rise upon ceasing vibration.

Karaoke Mic. Second, we tested a karaoke microphone, from which we removed the batteries and converted to being powered by our receiver tag and a spherical-coil, as shown in Figure 12. We measured the karaoke microphone's power draw, which consists of powering the microphone transducer, streaming audio over BLE, and a small OLED display. Figure 12a plots this power draw along with a moving average. The microphone's average power consumption was 60mW, with spikes up to 130mW.

To inform our touches, we refer to the heatmaps from the ContactDB dataset [4] for a similar, cylindrical device with similar buttons, a flashlight. We mimic the likely touch from the dataset's heatmaps, as well as an alternative touch in which the microphone is held lower, increasing the misalignment between the coils, as shown in Figure 12c. Figure 12d illustrates the received power in both interactions. We found that the likely touch resulted in 138mW of received power, while the alternative touch resulted in 73mW. Thus, both touches exceed the average power draw of the microphone. However, spikes in power draw may exceed the instantaneous received power. This is where the benefits of our tags' supercapacitor become clear: the supercapacitor stores energy when there is an excess and can help compensate the instantaneous received power when the power draw spikes.

Figure 12e plots the supercapacitor's charge over time beginning with picking up the dead microphone in the likely touch. As shown, the tag's microcontroller wakes about two seconds after the microphone is picked up. As the supercapacitor charges, more functionalities become available, such as the screen turning on at six seconds and streaming audio over BLE at seven seconds. After this initial charging from 0V, the microphone functions stably.

Doorknob (with motor-controlled lock). Finally, we directly adapted an object from the ContactDB dataset [4]; we 3D-printed the studied doorknob from the dataset and hollowed it to embed a receiver coil directly inside, as shown in Figure 13. To illustrate how our approach enables powering actuators without batteries during interaction, we made a motorized latch that locks and unlocks a cabinet to which we attached the doorknob. Figure 13a shows the power draw of the latch's motor, which exceeds 600mW for 350ms.

Again, we mimic the likely touch from ContactDB, as well as an alternative, looser touch in which the palm doesn't touch the knob, as shown in Figure 13c. Figure 13d shows the received power for both touches, where the likely and alternative touches resulted in 548mW and 83mW, respectively. While each of these is below

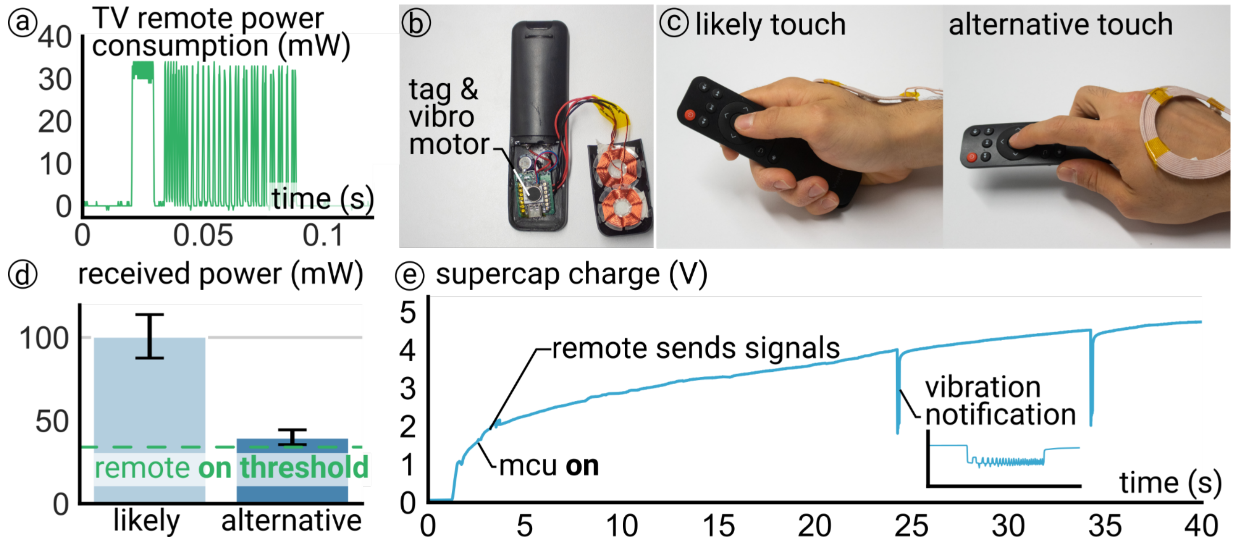

Figure 11: (a) Measured power consumption of the TV remote during a button press. (b) Our modified, battery-free remote, including two receiver coils and a vibration motor. (c) Our mimicry of the likely touch and our alternative touch. (d) The measured received power for both the likely and alternative touch (five repetitions). (e) Supercapacitor charge vs. time in the likely pose, detailing the microcontroller's waking, sending signals upon button press, and added vibration notifications.

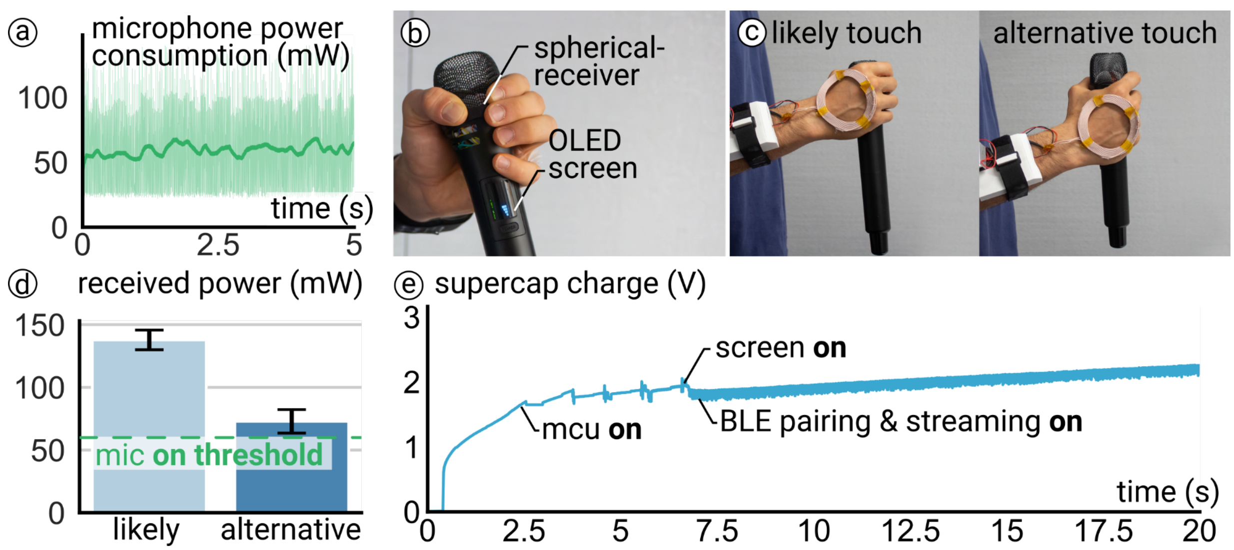

Figure 12: (a) Measured power consumption of the microphone. (b) Our modified, battery-free microphone including our spherical-coil. (c) Our mimicry of the likely touch and our alternative touch. (d) The measured received power for both the likely and alternative touch (five repetitions). (e) Supercapacitor charge vs. time in the likely pose.

the instantaneous power draw of the motor, our supercapacitor again aids by charging until it has stored sufficient energy to drive the motor. As shown in Figure 13e, this only takes about two seconds after grabbing the doorknob since the circuit's idle power consumption is low.

6.5 Discussion: Design strategies for specific applications

While we used the same circuit components in our technical evaluation to reduce complexity, our tags' supercapacitor circuit can be tailored to each specific application. Each of the examples in our technical evaluation were designed to be complex to demonstrate the high-power capabilities of our approach. For example, TV remotes are not normally augmented with vibrotactile feedback,

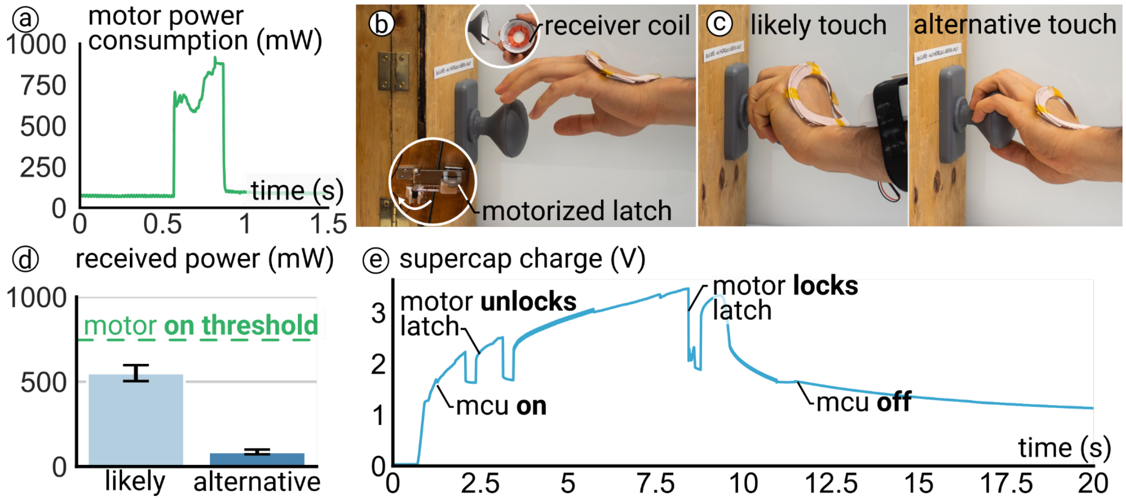

Figure 13: (a) Measured power consumption of the motorized latch. (b) Our cabinet features a battery-free, motorized latch that triggers upon doorknob touch. (c) Our mimicry of the likely touch and our alternative touch. (d) The received power for both the likely and alternative touch (five repetitions). (e) Supercapacitor charge in the likely pose while the user opens/closes the cabinet.

thus their power demands are much lower and would therefore not require a large supercapacitor (or even a supercapacitor at all). In fact, if both the required power and the received power have been determined, the supercapacitor and its series resistor (determines charge/discharge rate) can be selected to to speed up the device's time to turn on. In cases where the delay may impact experience, analog circuits that give indication to the user that the device is receiving power and will turn on soon can mitigate uncertainty. As an example, an LED can be placed after the power is rectified, in a way that its brightness signals the power is being transferred. Moreover, additional LED or other forms of user feedback (e.g., the vibrations we use in some of our examples) can be controlled by a microcontroller to signal to the user that the device is now fully charged and operational. Ultimately, Power-on-Touch can take advantage of many design patterns used in modern devices to signal their readiness to their user.

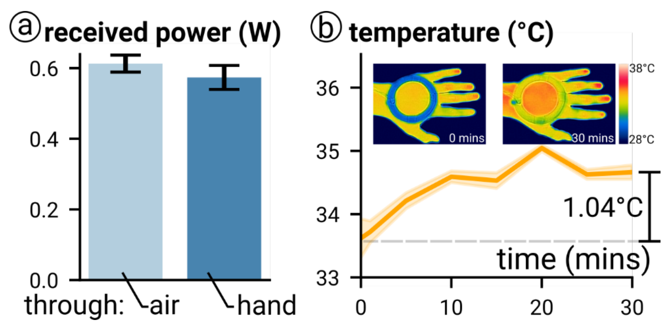

Figure 14: Safety and thermal performance of a 4.5W transmitter on the back of the hand: (a) Received power through the hand and through the same distance in air. (b) Skin temperature vs. time. Shaded error denotes 95% confidence interval.

6.6 Safety and Thermal Performance

Finally, we perform a safety and thermal analysis to validate that our wearable system transmits safe levels of electromagnetic field and does not significantly heat the skin. The IEC 60601-2-33 guideline defines the safe specific absorption rate of radiated energy in extremities (e.g., hands) at 20W/kg during occupational exposure and 4W/kg during general public exposure [80]. To determine the specific absorption rate of our system, we designed an experiment based on prior biomedical work on wearable wireless power [3]. We placed a transmitter coil on the back of the hand and aligned it to a receiving coil on the palm while measuring the received power. We then measured the received power across the same distance and angle in air, while keeping the transmitted power the same (4.5W). The difference between the received power in air and through the hand indicates the amount of power being absorbed by the hand. This was repeated five times for each condition. Figure 14a shows the received power for each condition. We found that efficiency decreased by 0.82% and received power by 0.04W when transmitting through the hand. Considering the weight of a human hand is about 400 grams [11], the absorbed power averages ~0.1W/kg for a 4.5W transmission. Thus, our system is ~40x below the suggested limit, which suggests a factor of safety below the safe absorption rate.

While specific absorption rate is one measure of safety, thermal performance is also of interest as tissue heating can occur even at levels below absorption rate limits. As such, we measured the change in surface temperature of the back of the hand while wearing a 4.5W transmitter for 30 minutes, as shown in Figure 14b. Over the course of the experiment, we found that the skin temperature increased by only 1℃ while the coil's temperature warmed to equilibrium with the skin. Given that our designed interactions are brief,

Figure 15: (a) A digital caliper is powered while the user holds it. (b) A digital body scale is powered on when the user, wearing shoes embedded with transmitter coil, steps on it. (c) A batteryless thermostat that contains an ink display and a thermistor.

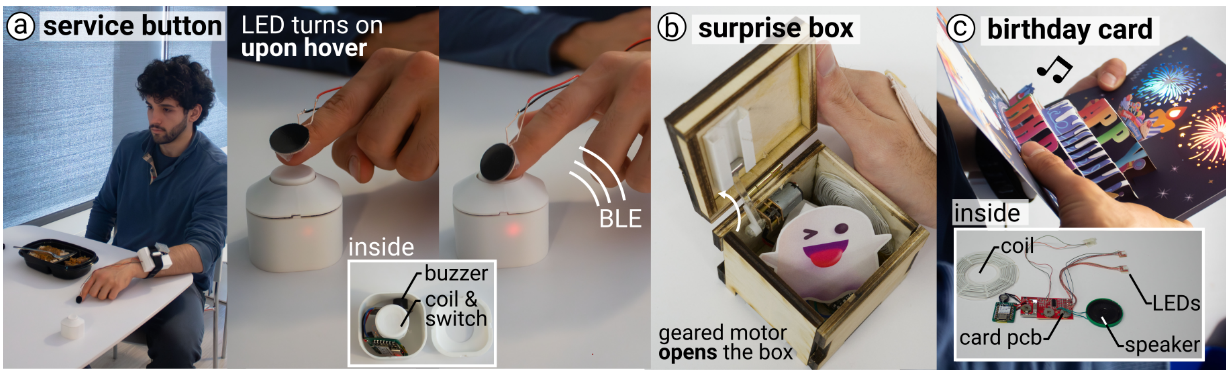

Figure 16: (a) A user in a restaurant uses a batteryless service button equipped with our receiver coil to call for service. (b) A surprise box opens automatically when touched by the user wearing a coil. (c) A birthday card that plays a melody and lights up when held.

on-demand, and well below 30 minutes of constant transmission, we can conclude that our particular implementation (i.e., transmitting at <1MHz) is safe when considering tissue heating. Note that there are additional safety cases that should be evaluated before deployment to a wide audience, such as characterizing potential interference with safety-critical devices like pacemakers [5].

7 Additional Applications

To illustrate the versatility of our approach, we demonstrate a wide range of applications, where we use *Power-on-Touch* to propose new opportunities for battery-free, interactive devices in ubiquitous environments. We implemented nine applications, including the three presented in our *Technical Evaluation.*

7.1 Communal Devices

Communal devices that are shared among users can be retrofitted into *Power-on-Touch* devices (Figure 15), so that the devices receive power directly from the user, without needing additional maintenance (changing/charging batteries).

Digital calipers. We retrofitted a battery-powered digital caliper with our receiver-tag and coil, making it batteryless. The receiver coil is attached to the outer case where users typically hold. The user, who wears our nail-type transmitter on their finger, will power on the caliper by simply picking it up.

Digital body scale. We retrofitted a battery-powered digital scale with our receiver-tag and coil. The receiver coil is attached to the top surface of the scale. This allows a user, who wears shoes with our transmitter coil embedded in the insole, to power the scale upon stepping on it.

Thermostat. We created a batteryless thermostat that works upon the touch from the user. Utilizing a small transmitter coil, the thermostat can draw power from the user to power on the microcontroller with a temperature sensor, an e-ink display, and buttons for control.

7.2 Quick/Disposable Interactions

Power-on-Touch can be made into devices that offer quick or disposable interactions (Figure 16).

Service button. We showcase a batteryless service button that can be used in restaurant settings. When the user's finger, wearing a transmitter coil, hovers over the button with an embedded receiver coil, the microcontroller inside is powered up and lights up an LED to indicate it is "on." When the user presses the button (to call for service), a buzzer beeps and the microcontroller sends out a wireless message through BLE containing the table number to the staff.

Actuated surprise box. We created a surprise box with an automatic-opening mechanism. When a user, wearing the palm-mounted transmitter coil, touches the box, the geared motor inside the box is powered on and lifts the lid to reveal a surprise figure.

Interactive birthday card. Since our receiving-tag is slim, it can be embedded into a birthday card, making it interactive. When the card receiver, wearing the transmitter coil on their palm opens the card, they power up the circuit inside the card, play a melody through the speaker, and light up LEDs.

8 Conclusion

We introduced *Power-on-Touch*, a novel method for powering devices *during* interaction using wireless power transfer between a user-worn coil and object-embedded coils. To enable many possible interactions with our novel concept, we performed technical characterizations (e.g., impedance and 3D-efficiency analysis) to reveal which coils best support a wide range of interactions (e.g., grasping, touching, hovering). On the technical side, this technical approach can inspire ubiquitous computing with new ways to scale up the number and diversity of battery-free devices, not just sensors (μWatts) but also actuators (Watts). We believe that future researchers in HCI equipped with our approach can improve our approach's efficiency with dynamic impedance matching/capacitive tuning as well as its range via alternative coil architectures to unlock further interactions.

We tend to think of Power-on-Touch not as an end-product but as a design technique that will inspire the creation of a new type of battery-free interactive devices that can even unlock new use cases. Thus, we will publish the detailed fabrication process, hardware schematics and code as open-source to accelerate future research.

Acknowledgments

We would like to thank Yasha Iravantchi for his valuable feedback.

References

[1] Abul Al Arabi, Xue Wang, Yang Zhang, and Jeeeun Kim. 2023. E3D: Harvesting Energy from Everyday Kinetic Interactions Using 3D Printed Attachment Mechanisms. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 3 (September 2023), 1–31. https://doi.org/10.1145/3610897

[2] Akash Badshah, Sidhant Gupta, Gabe Cohn, Nicolas Villar, Steve Hodges, and Shwetak N. Patel. 2011. Interactive generator: a self-powered haptic feedback device. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems* (*CHI '11*), May 07, 2011. Association for Computing Machinery, New York, NY, USA, 2051–2054. https://doi.org/10.1145/1978942.1979240

[3] Juan Barreto, Gianfranco Perez, Abdul-Sattar Kaddour, and Stavros V. Georgakopoulos. 2021. A Study of Wearable Wireless Power Transfer Systems on the Human Body. *IEEE Open J. Antennas Propag.* 2, (2021), 86–94. https://doi.org/10.1109/OJAP.2020.3043579

[4] Samarth Brahmbhatt, Cusuh Ham, Charles C. Kemp, and James Hays. 2019. ContactDB: Analyzing and Predicting Grasp Contact via Thermal Imaging. In *2019 IEEE/CVF Conference on Computer Vision and Pattern Recognition (CVPR)*, June 2019. IEEE, Long Beach, CA, USA, 8701–8711. https://doi.org/10.1109/CVPR.2019.00891

[5] Tommaso Campi, Silvano Cruciani, Valerio De Santis, and Mauro Feliziani. 2016. EMF Safety and Thermal Aspects in a Pacemaker Equipped With a Wireless Power Transfer System Working at Low Frequency. *IEEE Trans. Microwave Theory Techn.* (2016), 1–8. https://doi.org/10.1109/TMTT.2015.2514087

[6] Matthew J. Chabalko, Mohsen Shahmohammadi, and Alanson P. Sample. 2017. Quasistatic Cavity Resonance for Ubiquitous Wireless Power Transfer. *PLoS ONE* 12, 2 (February 2017), e0169045. https://doi.org/10.1371/journal.pone.0169045

[7] Xiang Cui, Hao Zhou, JiaLin Deng, Wangqiu Zhou, Xing Guo, and Yu Gu. 2022. Mag-E4E: Trade Efficiency for Energy in Magnetic MIMO Wireless Power Transfer System. In *IEEE INFOCOM 2022 - IEEE Conference on Computer Communications*, May 02, 2022. IEEE, London, United Kingdom, 440–449. https://doi.org/10.1109/INFOCOM48880.2022.9796771

[8] Jasper De Winkel, Vito Kortbeek, Josiah Hester, and Przemysław Pawełczak. 2020. Battery-Free Game Boy. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 4, 3 (September 2020), 1–34. https://doi.org/10.1145/3411839

[9] Aashish Dhungana and Eyuphan Bulut. 2020. Peer-to-peer energy sharing in mobile networks: Applications, challenges, and open problems. *Ad Hoc Networks* 97, (February 2020), 102029. https://doi.org/10.1016/j.adhoc.2019.102029

[10] Junjie Feng, Qiang Li, Fred C. Lee, and Minfan Fu. 2019. Transmitter Coils Design for Free-Positioning Omnidirectional Wireless Power Transfer System. *IEEE Trans. Ind. Inf.* 15, 8 (August 2019), 4656–4664. https://doi.org/10.1109/TII.2019.2908217

[11] Elisa R. Ferrè, Jonathan Joel, Denise Cadete, and Matthew R. Longo. 2023. Systematic underestimation of human hand weight. *Current Biology* 33, 14 (July 2023), R758–R759. https://doi.org/10.1016/j.cub.2023.05.041

[12] Hesam Sadeghi Gougheri and Mehdi Kiani. 2016. Optimal wireless receiver structure for omnidirectional inductive power transmission to biomedical implants. In *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, August 2016. IEEE, Orlando, FL, USA, 1975–1978. https://doi.org/10.1109/EMBC.2016.7591111

[13] Chris Harrison, Hrvoje Benko, and Andrew D. Wilson. 2011. OmniTouch: wearable multitouch interaction everywhere. In *Proceedings of the 24th annual ACM symposium on User interface software and technology*, October 16, 2011. ACM, Santa Barbara California USA, 441–450. https://doi.org/10.1145/2047196.2047255

[14] Nam Ha-Van, Yining Liu, Prasad Jayathurathnage, Constantin R. Simovski, and Sergei A. Tretyakov. 2022. Cylindrical Transmitting Coil for Two-Dimensional Omnidirectional Wireless Power Transfer. *IEEE Trans. Ind. Electron.* 69, 10 (October 2022), 10045–10054. https://doi.org/10.1109/TIE.2022.3151961

[15] Josiah Hester and Jacob Sorber. 2017. The Future of Sensing is Batteryless, Intermittent, and Awesome. In *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems*, November 06, 2017. ACM, Delft Netherlands, 1–6. https://doi.org/10.1145/3131672.3131699

[16] Josiah Hester, Kevin Storer, and Jacob Sorber. 2017. Timely Execution on Intermittently Powered Batteryless Sensors. In *Proceedings of the 15th ACM Conference on Embedded Network Sensor Systems*, November 06, 2017. ACM, Delft Netherlands, 1–13. https://doi.org/10.1145/3131672.3131673

[17] Steve Hodges. 2013. Batteries Not Included: Powering the Ubiquitous Computing Dream. *Computer* 46, 4 (April 2013), 90–93. https://doi.org/10.1109/MC.2013.125

[18] IoT.Business.News. 2024. State of IoT 2024: Number of connected IoT devices growing 13% to 18.8 billion globally. *IoT Business News*. Retrieved December 5, 2024 from https://iotbusinessnews.com/2024/09/04/26399-state-of-iot-2024-number-of-connected-iot-devices-growing-13-to-18-8-billion-globally/

[19] Yasha Iravantchi, Mayank Goel, and Chris Harrison. 2020. Digital Ventriloquism: Giving Voice to Everyday Objects. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, April 21, 2020. ACM, Honolulu HI USA, 1–10. https://doi.org/10.1145/3313831.3376503

[20] Nathan Seongheon Jeong and Francesco Carobolante. 2017. Wireless Charging of a Metal-Body Device. *IEEE Transactions on Microwave Theory and Techniques* 65, 4 (April 2017), 1077–1086. https://doi.org/10.1109/TMTT.2017.2673820

[21] Arata Jingu, Nihar Sabnis, Paul Strohmeier, and Jürgen Steimle. 2024. Shaping Compliance: Inducing Haptic Illusion of Compliance in Different Shapes with Electrotactile Grains. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, May 11, 2024. ACM, Honolulu HI USA, 1–13. https://doi.org/10.1145/3613904.3641907

[22] Kazunobu Sumiya, Kazunobu Sumiya, Takuya Sasatani, Takuya Sasatani, Yuki Nishizawa, Yuki Nishizawa, Kenji Tsushio, Kenji Tsushio, Yoshiaki Narusue, Yoshiaki Narusue, Yoshihiro Kawahara, and Yoshihiro Kawahara. 2019. Alvus: A Reconfigurable 2-D Wireless Charging System. 3, 2 (June 2019), 68. https://doi.org/10.1145/3332533

[23] Sadeque Reza Khan and Marc P.Y. Desmulliez. 2019. Towards a Miniaturized 3D Receiver WPT System for Capsule Endoscopy. *Micromachines* 10, 8 (August 2019), 545. https://doi.org/10.3390/mi10080545

[24] Sadeque Reza Khan, Sumanth Kumar Pavuluri, Gerard Cummins, and Marc P. Y. Desmulliez. 2019. Miniaturized 3-D Cross-Type Receiver for Wirelessly Powered Capsule Endoscopy. *IEEE Trans. Microwave Theory Techn.* 67, 5 (May 2019), 1985–1993. https://doi.org/10.1109/TMTT.2019.2893204

[25] Andy Kong, Daehwa Kim, and Chris Harrison. 2024. Power-over-Skin: Full-Body Wearables Powered By Intra-Body RF Energy. In *Proceedings of the 37th Annual ACM Symposium on User Interface Software and Technology*, October 13, 2024. ACM, Pittsburgh PA USA, 1–13. https://doi.org/10.1145/3654777.3676394

[26] Michinari Kono, Hiromi Nakamura, and Jun Rekimoto. 2017. Intentiō: power distribution through a potentialized human body. In *Proceedings of the 8th Augmented Human International Conference*, March 16, 2017. ACM, Silicon Valley California USA, 1–10. https://doi.org/10.1145/3041164.3041175

[27] Michinari Kono, Takumi Takahashi, Hiromi Nakamura, Takashi Miyaki, and Jun Rekimoto. 2018. Design Guideline for Developing Safe Systems that Apply Electricity to the Human Body. *ACM Trans. Comput.-Hum. Interact.* 25, 3 (June 2018), 1–36. https://doi.org/10.1145/3184743

[28] R. Kötz and M. Carlen. 2000. Principles and applications of electrochemical capacitors. *Electrochimica Acta* 45, 15–16 (May 2000), 2483–2498. https://doi.org/10.1016/S0013-4686(00)00354-6

[29] André Kurs, Aristeidis Karalis, Robert Moffatt, J. D. Joannopoulos, Peter Fisher, and Marin Soljačić. 2007. Wireless Power Transfer via Strongly Coupled Magnetic Resonances. *Science* 317, 5834 (July 2007), 83–86. https://doi.org/10.1126/science.1143254

[30] Jiahao Li, Jeeeun Kim, and Xiang "Anthony" Chen. 2019. Robiot: A Design Tool for Actuating Everyday Objects with Automatically Generated 3D Printable Mechanisms. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, October 17, 2019. ACM, New Orleans LA USA, 673–685. https://doi.org/10.1145/3332165.3347894

[31] Jiamin Li, Yilong Dong, Jeong Hoan Park, and Jerald Yoo. 2021. Body-coupled power transmission and energy harvesting. 4, 7 (June 2021), 530–538. https://doi.org/10.1038/s41928-021-00592-y

[32] Rongzhou Lin, Han-Joon Kim, Sippanat Achavananthadith, Selman A. Kurt, Shawn C. C. Tan, Haicheng Yao, Benjamin C. K. Tee, Jason K. W. Lee, and John S. Ho. 2020. Wireless battery-free body sensor networks using near-field-enabled clothing. *Nat Commun* 11, 1 (January 2020), 444. https://doi.org/10.1038/s41467-020-14311-2

[33] Xun Liu. 2015. Qi Standard Wireless Power Transfer Technology Development Toward Spatial Freedom. *IEEE Circuits and Systems Magazine* 15, 2 (2015), 32–39. https://doi.org/10.1109/MCAS.2015.2419011

[34] Amal Ibrahim Mahmood, Sadik Kamel Gharghan, Mohamed A. A. Eldosoky, Mustafa Falah Mahmood, and Ahmed M. Soliman. 2021. Wireless Power Transfer Based on Spider Web–Coil for Biomedical Implants. *IEEE Access* 9, (2021), 167674–167686. https://doi.org/10.1109/ACCESS.2021.3136817

[35] Alex Mazursky, Jacob Serfaty, and Pedro Lopes. 2024. Stick&Slip: Altering Fingerpad Friction via Liquid Coatings. In *Proceedings of the CHI Conference on Human Factors in Computing Systems*, May 11, 2024. ACM, Honolulu HI USA, 1–14. https://doi.org/10.1145/3613904.3642299

[36] Alex Mazursky, Shan-Yuan Teng, Romain Nith, and Pedro Lopes. 2021. MagnetIO: Passive yet Interactive Soft Haptic Patches Anywhere. In *Proceedings of the 2021 CHI Conference on Human Factors in Computing Systems*, May 06, 2021. ACM, Yokohama Japan, 1–15. https://doi.org/10.1145/3411764.3445543

[37] Noor Mohammed, Rui Wang, Robert W. Jackson, Yeonsik Noh, Jeremy Gummeson, and Sunghoon Ivan Lee. 2021. ShaZam: Charge-Free Wearable Devices via Intra-Body Power Transfer from Everyday Objects. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 2 (June 2021), 1–25. https://doi.org/10.1145/3463505

[38] Rafael Morales González, Asier Marzo, Euan Freeman, William Frier, and Orestis Georgiou. 2021. UltraPower: Powering Tangible & Wearable Devices with Focused Ultrasound. In *Proceedings of the Fifteenth International Conference on Tangible, Embedded, and Embodied Interaction*, February 14, 2021. ACM, Salzburg Austria, 1–13. https://doi.org/10.1145/3430524.3440620

[39] Adiyan Mujibiya. 2015. Haptic feedback companion for Body Area Network using body-carried electrostatic charge. In *2015 IEEE International Conference on Consumer Electronics (ICCE)*, January 2015. IEEE, Las Vegas, NV, USA, 571–572. https://doi.org/10.1109/ICCE.2015.7066530

[40] Fabrizio Pece, Juan Jose Zarate, Velko Vechev, Nadine Besse, Olexandr Gudozhnik, Herbert Shea, and Otmar Hilliges. 2017. MagTics: Flexible and Thin Form Factor Magnetic Actuators for Dynamic and Wearable Haptic Feedback. In *Proceedings of the 30th Annual ACM Symposium on User Interface Software and Technology - UIST '17*, 2017. ACM Press, Quebec City, QC, Canada, 143–154. https://doi.org/10.1145/3126594.3126609

[41] Claudio S Pinhanez, Frederik C Kjeldsen, Anthony Levas, Gopal S Pingali, Mark E Podlaseck, and Paul B Chou. Ubiquitous Interactive Graphics.

[42] Ivan Poupyrev and Shigeaki Maruyama. 2003. Tactile interfaces for small touch screens. In *Proceedings of the 16th annual ACM symposium on User interface software and technology*, November 02, 2003. ACM, Vancouver Canada, 217–220. https://doi.org/10.1145/964696.964721

[43] Ivan Poupyrev, Shigeaki Maruyama, and Jun Rekimoto. 2002. Ambient touch: designing tactile interfaces for handheld devices. In *Proceedings of the 15th annual ACM symposium on User interface software and technology*, 2002. 51–60. https://doi.org/10.1145/571985.571993

[44] Thomas Preindl, Cedric Honnet, Andreas Pointner, Roland Aigner, Joseph A. Paradiso, and Michael Haller. 2020. Sonoflex: Embroidered Speakers Without Permanent Magnets. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, October 20, 2020. ACM, Virtual Event USA, 675–685. https://doi.org/10.1145/3379337.3415888

[45] Ramesh Raskar, Greg Welch, Kok-Lim Low, and Deepak Bandyopadhyay. 2001. Shader Lamps: Animating Real Objects With Image-Based Illumination. In *Rendering Techniques 2001*, Steven J. Gortler and Karol Myszkowski (eds.). Springer Vienna, Vienna, 89–102. https://doi.org/10.1007/978-3-7091-6242-2_9

[46] Bradley A. Reese and Charles R. Sullivan. 2017. Litz wire in the MHz range: Modeling and improved designs. In *2017 IEEE 18th Workshop on Control and Modeling for Power Electronics (COMPEL)*, July 2017. 1–8. https://doi.org/10.1109/COMPEL.2017.8013391

[47] Alanson P. Sample, Benjamin H. Waters, Scott T. Wisdom, and Joshua R. Smith. 2013. Enabling Seamless Wireless Power Delivery in Dynamic Environments. *Proc. IEEE* 101, 6 (June 2013), 1343–1358. https://doi.org/10.1109/JPROC.2013.2252453

[48] Takuya Sasatani, Chouchang Jack Yang, Matthew J. Chabalko, Yoshihiro Kawahara, and Alanson P. Sample. 2018. Room-Wide Wireless Charging and Load-Modulation Communication via Quasistatic Cavity Resonance. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 2, 4 (December 2018), 1–23. https://doi.org/10.1145/3287066

[49] M. Satyanarayanan. 2001. Pervasive computing: vision and challenges. *IEEE Pers. Commun.* 8, 4 (August 2001), 10–17. https://doi.org/10.1109/98.943998

[50] Lixin Shi, Zachary Kabelac, Dina Katabi, and David Perreault. 2015. Wireless Power Hotspot that Charges All of Your Devices. In *Proceedings of the 21st Annual International Conference on Mobile Computing and Networking*, September 07, 2015. ACM, Paris France, 2–13. https://doi.org/10.1145/2789168.2790092

[51] Rishi Shukla, Neev Kiran, Rui Wang, Jeremy Gummeson, and Sunghoon Ivan Lee. 2019. SkinnyPower: enabling batteryless wearable sensors via intra-body power transfer. In *Proceedings of the 17th Conference on Embedded Networked Sensor Systems*, November 10, 2019. ACM, New York New York, 68–82. https://doi.org/10.1145/3356250.3360034

[52] Cem Som and Michael De Rooij. 2019. *Trilogy of wireless power transfer: basic principles, WPT Systems and application* (1st edition ed.). Swiridoff Verlag, Künzelsau.

[53] T.E. Starner. 2003. Powerful change. 1. Batteries and possible alternatives for the mobile market. *IEEE Pervasive Comput.* 2, 4 (October 2003), 86–88. https://doi.org/10.1109/MPRV.2003.1251172

[54] Charalampos A. Stergiou and Vassilis Zaspalis. 2016. Impact of Ferrite Shield Properties on the Low-Power Inductive Power Transfer. *IEEE Trans. Magn.* 52, 8 (August 2016), 1–9. https://doi.org/10.1109/TMAG.2016.2536669

[55] Robert S Stormont, Gareth R Davies, P James Ross, David J Lurie, and Lionel M Broche. 2023. A flexible 8.5 MHz litz wire receive array for field-cycling imaging. *Phys. Med. Biol.* 68, 5 (March 2023), 055016. https://doi.org/10.1088/1361-6560/acb9d0

[56] Yuning Su, Yuhua Jin, Zhengqing Wang, Yonghao Shi, Da-Yuan Huang, Teng Han, and Xing-Dong Yang. 2023. Laser-Powered Vibrotactile Rendering. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 7, 4 (December 2023), 1–25. https://doi.org/10.1145/3631449

[57] Ryo Takahashi, Masaaki Fukumoto, Changyo Han, Takuya Sasatani, Yoshiaki Narusue, and Yoshihiro Kawahara. 2020. TelemetRing: A Batteryless and Wireless Ring-shaped Keyboard using Passive Inductive Telemetry. In *Proceedings of the 33rd Annual ACM Symposium on User Interface Software and Technology*, October 20, 2020. ACM, Virtual Event USA, 1161–1168. https://doi.org/10.1145/3379337.3415873

[58] Ryo Takahashi, Wakako Yukita, Takuya Sasatani, Tomoyuki Yokota, Takao Someya, and Yoshihiro Kawahara. 2021. Twin Meander Coil: Sensitive Readout of Battery-free On-body Wireless Sensors Using Body-scale Meander Coils. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 5, 4 (December 2021), 1–21. https://doi.org/10.1145/3494996

[59] Ryo Takahashi, Wakako Yukita, Tomoyuki Yokota, Takao Someya, and Yoshihiro Kawahara. 2022. Meander Coil++: A Body-scale Wireless Power Transmission Using Safe-to-body and Energy-efficient Transmitter Coil. In *CHI Conference on Human Factors in Computing Systems*, April 29, 2022. ACM, New Orleans LA USA, 1–12. https://doi.org/10.1145/3491102.3502119

[60] Yujie Tao, Shan-Yuan Teng, and Pedro Lopes. 2021. Altering Perceived Softness of Real Rigid Objects by Restricting Fingerpad Deformation. In *The 34th Annual ACM Symposium on User Interface Software and Technology*, October 10, 2021. ACM, Virtual Event USA, 985–996. https://doi.org/10.1145/3472749.3474800

[61] Shan-Yuan Teng, K. D. Wu, Jacqueline Chen, and Pedro Lopes. 2022. Prolonging VR Haptic Experiences by Harvesting Kinetic Energy from the User. In *Proceedings of the 35th Annual ACM Symposium on User Interface Software and Technology*, October 29, 2022. ACM, Bend OR USA, 1–18. https://doi.org/10.1145/3526113.3545635

[62] Thoams Guthrie Zimmerman, T. G. Zimmerman, and Thomas G. Zimmerman. 1996. Personal area networks: near-field intrabody communication. *Ibm Systems Journal* 35, 3 (September 1996), 609–617. https://doi.org/10.1147/sj.353.0609

[63] Virag Varga, Gergely Vakulya, Alanson Sample, and Thomas R. Gross. 2018. Enabling Interactive Infrastructure with Body Channel Communication. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 4 (January 2018), 1–29. https://doi.org/10.1145/3161180

[64] Amit Vasudevan and Sagar Chaki. 2018. Have Your PI and Eat it Too: Practical Security on a Low-Cost Ubiquitous Computing Platform. In *2018 IEEE European Symposium on Security and Privacy (EuroS&P)*, April 2018. IEEE, London, 183–198. https://doi.org/10.1109/EuroSP.2018.00021

[65] Dries van Wageningen and Toine Staring. 2010. The Qi wireless power standard. In *Proceedings of 14th International Power Electronics and Motion Control Conference EPE-PEMC 2010*, September 2010. S15-25-S15-32. https://doi.org/10.1109/EPEPEMC.2010.5606673

[66] Benjamin H. Waters, Brody J. Mahoney, Gunbok Lee, and Joshua R. Smith. 2014. Optimal coil size ratios for wireless power transfer applications. In *2014 IEEE International Symposium on Circuits and Systems (ISCAS)*, June 2014. IEEE, Melbourne VIC, Australia, 2045–2048. https://doi.org/10.1109/ISCAS.2014.6865567

[67] Mark Weiser. 1999. The computer for the 21 st century. *SIGMOBILE Mob. Comput. Commun. Rev.* 3, 3 (July 1999), 3–11. https://doi.org/10.1145/329124.329126

[68] Michael Wessely, Ticha Sethapakdi, Carlos Castillo, Jackson C. Snowden, Ollie Hanton, Isabel P. S. Qamar, Mike Fraser, Anne Roudaut, and Stefanie Mueller. 2020. Sprayable User Interfaces: Prototyping Large-Scale Interactive Surfaces with Sensors and Displays. In *Proceedings of the 2020 CHI Conference on Human Factors in Computing Systems*, April 21, 2020. ACM, Honolulu HI USA, 1–12. https://doi.org/10.1145/3313831.3376249

[69] Paul Worgan and Mike Fraser. 2017. CoilMove: An Actuated to-body Energy Transfer System. In *Proceedings of the 2017 Conference on Designing Interactive Systems*, June 10, 2017. ACM, Edinburgh United Kingdom, 791–795. https://doi.org/10.1145/3064663.3064693

[70] Paul Worgan, Jarrod Knibbe, Mike Fraser, and Diego Martinez Plasencia. 2016. PowerShake: Power Transfer Interactions for Mobile Devices. In *Proceedings of the 2016 CHI Conference on Human Factors in Computing Systems*, May 07, 2016. ACM, San Jose California USA, 4734–4745. https://doi.org/10.1145/2858036.2858569

[71] Xinge Yu, Xinge Yu, Zhaoqian Xie, Zhaoqian Xie, Yang Yu, Yang Yu, Jungyup Lee, Jungyup Lee, Abraham Vázquez-Guardado, Abraham Vázquez-Guardado, Haiwen Luan, Haiwen Luan, Jasper Ruban, Jasper Ruban, Xin Ning, Xin Ning, Aadeel Akhtar, Aadeel Akhtar, Dengfeng Li, Dengfeng Li, Bowen Ji, Bowen Ji, Bowen Ji, Yiming Liu, Yiming Liu, Rujie Sun, Rujie Sun, Jingyue Cao, Jingyue Cao, Qingze Huo, Qingze Huo, Yuncheng Zhong, Yishan Zhong, Chan Mi Lee, ChanMi Lee, Chan Mi Lee, Seung Yeop Kim, Seung Yeop Kim, Philipp Gutruf, Philipp Gutruf, Changxing Zhang, Changxing Zhang, Changxing Zhang, Changxing Zhang, Yeguang Xue, Yeguang Xue, Qinglei Guo, Qinglei Guo, Aditya Chempakasseril, Aditya Chempakasseril, Peilin Tian, Peilin Tian, Wei Lü, Wei Lu, Ji Yoon Jeong, JiYoon Jeong, Ji Yoon Jeong, Yong Yu, Yongjoon Yu, Yong Joon Yu, Jesse Cornman, Jesse Cornman, Chee Sim Tan, Chee Sim Tan, Bong Hoon Kim, BongHoon Kim, Bong Hoon Kim, Kun Hyuk Lee, Kun Hyuk Lee, Xue Feng, Xue Feng, Xue Feng, Yonggang Huang, Yonggang Huang, Jinghua Li, and John A. Rogers. 2019. Skin-integrated wireless haptic interfaces for virtual and augmented reality. *Nature* 575, 7783 (November 2019), 473–479. https://doi.org/10.1038/s41586-019-1687-0

[72] Xiaoying Yang, Jacob Sayono, Jess Xu, and Yang Zhang. 2024. Interaction-Power Stations: Turning Environments into Ubiquitous Power Stations for Charging Wearables. In *Extended Abstracts of the CHI Conference on Human Factors in Computing Systems*, May 02, 2024. ACM, Honolulu HI USA, 1–8. https://doi.org/10.1145/3613905.3650769

[73] Koji Yatani and Khai Nhut Truong. 2009. SemFeel: a user interface with semantic tactile feedback for mobile touch-screen devices. In *Proceedings of the 22nd annual ACM symposium on User interface software and technology - UIST '09*, 2009. ACM Press, Victoria, BC, Canada, 111. https://doi.org/10.1145/1622176.1622198

[74] Huizhong Ye, Chi-Jung Lee, Te-Yen Wu, Xing-Dong Yang, Bing-Yu Chen, and Rong-Hao Liang. 2022. Body-Centric NFC: Body-Centric Interaction with NFC Devices Through Near-Field Enabled Clothing. In *Designing Interactive Systems Conference*, June 13, 2022. ACM, Virtual Event Australia, 1626–1639. https://doi.org/10.1145/3532106.3534569

[75] Pengcheng Zhang, Qingxin Yang, Xian Zhang, Yang Li, and Yongjian Li. 2017. Comparative Study of Metal Obstacle Variations in Disturbing Wireless Power Transmission System. *IEEE Transactions on Magnetics* 53, 6 (June 2017), 1–4. https://doi.org/10.1109/TMAG.2017.2657517

[76] Tengxiang Zhang, Xin Yi, Chun Yu, Yuntao Wang, Nicholas Becker, and Yuanchun Shi. 2017. TouchPower: Interaction-based Power Transfer for Power-as-needed Devices. *Proc. ACM Interact. Mob. Wearable Ubiquitous Technol.* 1, 3 (September 2017), 1–20. https://doi.org/10.1145/3130986

[77] Yang Zhang, Yasha Iravantchi, Haojian Jin, Swarun Kumar, and Chris Harrison. 2019. Sozu: Self-Powered Radio Tags for Building-Scale Activity Sensing. In *Proceedings of the 32nd Annual ACM Symposium on User Interface Software and Technology*, October 17, 2019. ACM, New Orleans LA USA, 973–985. https://doi.org/10.1145/3332165.3347952

[78] Yang Zhang, Gierad Laput, and Chris Harrison. 2017. Electrick: Low-Cost Touch Sensing Using Electric Field Tomography. In *Proceedings of the 2017 CHI Conference on Human Factors in Computing Systems - CHI '17*, 2017. ACM Press, Denver, Colorado, USA, 1–14. https://doi.org/10.1145/3025453.3025842

[79] Yang Zhang, Chouchang (Jack) Yang, Scott E. Hudson, Chris Harrison, and Alanson Sample. 2018. Wall++: Room-Scale Interactive and Context-Aware Sensing. In *Proceedings of the 2018 CHI Conference on Human Factors in Computing Systems - CHI '18*, 2018. ACM Press, Montreal QC, Canada, 1–15. https://doi.org/10.1145/3173574.3173847

[80] 2011. *IEC 60601-1-SER* ([Ed. var.] ed.). IEC, Geneva.

[81] https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf. Retrieved September 12, 2024 from https://infocenter.nordicsemi.com/pdf/nRF52840_PS_v1.1.pdf