TouchPower: Interaction-based Power Transfer for Power-as-needed Devices

TENGXIANG ZHANG, Tsinghua University
XIN YI, Tsinghua University
CHUN YU, Tsinghua University
YUNTAO WANG*, Tsinghua University
NICHOLAS BECKER, University of Washington
YUANCHUN SHI, Tsinghua University

The trend toward ubiquitous deployment of electronic devices demands novel low maintenance power schemes to decrease the burden of maintaining such a large number of devices. In this paper, we propose *Interaction-based Power Transfer (IPT)*: a novel power scheme for power-as-needed devices (i.e., devices that only require power during interaction). IPT allows for the removal of built-in batteries on these devices, and to instead be powered up through direct contact interaction with the user (e.g. gripping a mouse, holding a pen). We prove the concept and show the potential of IPT through our *TouchPower* prototype. TouchPower transfers on-body power to off-body power-as-needed devices through contact between electrodes on a glove worn by the user and those on the target device during the interaction process. We design TouchPower to automatically detect the contact topology at runtime to supply power accordingly, and place electrodes on the glove so that TouchPower is compatible with various interactions with different objects. We also show the methodology of placing electrodes on the device-end, and evaluate it on a mouse and a remote controller. Results show that during interaction, TouchPower is able to provide stable power supply to these devices with only a small sacrifice in regards to interaction naturalness. At last we demonstrate six applications of TouchPower, and discuss the limitations and potential of TouchPower and IPT systems.

CCS Concepts: • **Human-centered computing → Ubiquitous computing**; *Usability testing*;

Additional Key Words and Phrases: interaction-based power transfer, human computer interaction, wearable device

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*Corresponding author

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1 INTRODUCTION

Mark Weiser envisioned a computer on almost every object to enable ubiquitous computing [51]. However, it's not easy to maintain the power supply of so many electronic devices. In fact, power is considered one of the major issues delaying the coming of age of ubiquitous computing [15, 33, 41]. Currently, most electronic devices are powered by batteries, which poses three challenges: 1) Batteries demand periodic maintenance (charging or replacing), which requires too much effort when it comes to ubiquitous devices as there may be over one hundred smart devices and batteries in a single smart room [51]; 2) Batteries have scaled down much slower in size and cost (linearly) than electronics (exponentially following Moore's law) [33, 41]; 3) Batteries have remained mostly rigid whereas other electronic components have become flexible. These issues make it expensive to deploy electronics ubiquitously, limits further miniaturization of electronic devices, and does not allow for flexible electronic devices.

To alleviate these problems, we propose *Interaction-based Power Transfer (IPT)* as an alternative power scheme for certain electronic devices. As opposed to supplying power to devices at all times using batteries, IPT allows devices to be powered up only while being interacted with by using power transferred from the user. The idea of IPT is based on three observations: 1) Many electronic devices only need to be powered up during interaction (e.g. stylus, pens, mouses, keyboards, and remote controllers). We refer to these devices as *power-as-needed* devices henceforth; 2) A considerable amount of energy can be leveraged from users' body, including both the energy stored in batteries within wearable devices and cellphones, and energy that can be harvested from human body. For example, tens of watts could be scavenged from the human body [24, 29, 33, 39], and new textiles are being developed to generate power from the body and environment [3, 4, 6, 38]; 3) The interaction between users and devices usually requires proximity or contact between the user's hands and the target device, which forms a channel for power transfer naturally.

IPT systems enable battery-free power-as-needed devices with no maintenance required for power, making it possible to further reduce the size and cost of such devices. The whole device could also be flexible without the rigid battery. IPT could also be used to switch on or off circuits on device through interaction, thus enabling more interaction possibilities. A maintenance-free power solution for power-as-needed devices can be achieved by combing IPT with on-body energy harvesting and power distribution techniques. Even with a battery as the energy source, IPT still greatly reduces the overall maintenance effort, since charging one on-body battery is much easier than maintaining lots of batteries scattered around the rooms.

A typical IPT system consists of two components: the user-end and the device-end (see Figure 1(a)). On the user-end, a transmitter converts the power from the energy source to a transferring form, and applies the converted power on the transmit interface only when a transfer channel is formed between interfaces on both ends. On the device-end, the receiver converts the power from receive interface to Direct Current (DC) form, which is the typical power form required by the electronic devices. A different power transferring form would require a different transmitter, receiver and interface.

To validate the concept of IPT, we built a prototype: *TouchPower* (system components shown in Figure 1(a), two use cases shown in Figure 1(b)(c)). TouchPower transfers power in DC form during interaction. For a minimum viable prototype, the design goal of TouchPower is focused on validating and exploring the scheme of IPT. Therefore, in this paper we used a battery as the energy source, and leaves energy harvesting and distribution techniques for future work. Since users' hands contact power-as-needed devices for most interactions, we designed a glove with several electrodes sewn onto it as the transmit interface. By referring to previous researches on grasp types used during manipulation [2, 5, 8], electrodes are placed on the glove in such a way as to be compatible with interactions of various devices. We used an Arduino Pro Mini as the transmitter, and developed an algorithm so that it can auto detect the contact pattern at runtime, and supply power during ad-hoc contacts of electrodes. The receiver interface is a pair of electrodes connected with positive and negative terminals of load circuits on

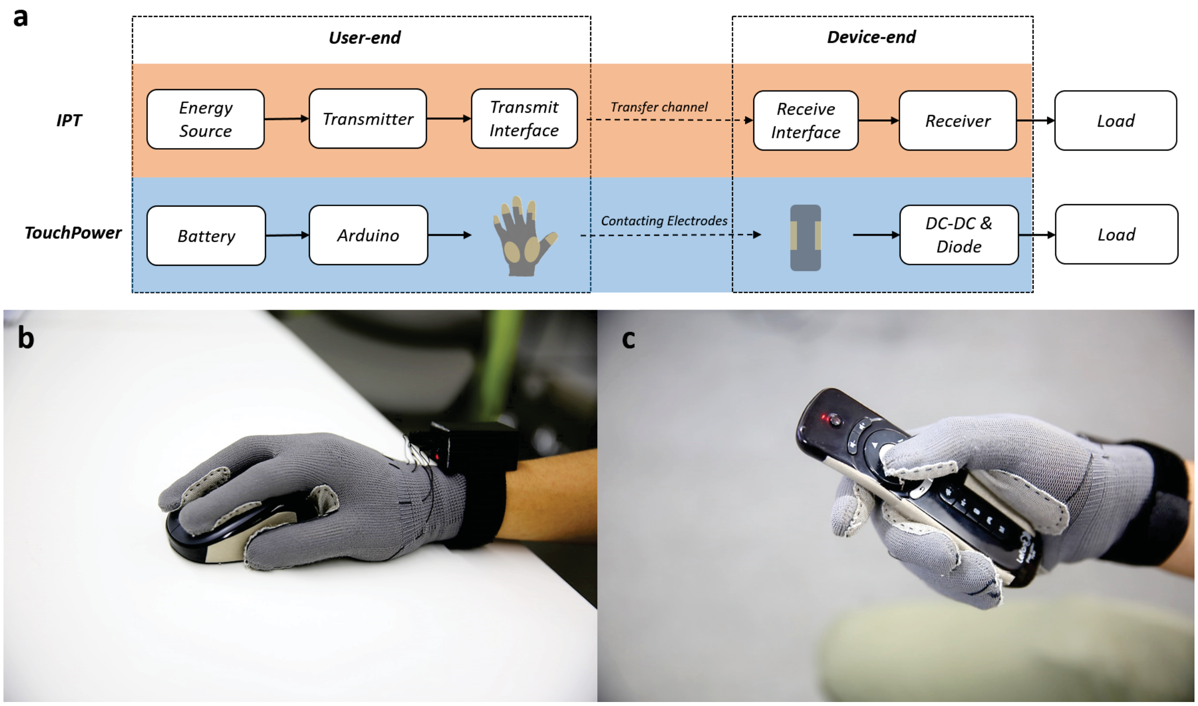

Fig. 1. (a) System components of IPT (orange) and TouchPower (blue). Arrows point in the direction of power flow. A user wears the user-end of TouchPower and uses a mouse (b) and a TV remote controller (c).

the device respectively. A device is powered up when electrodes on both ends make contact with each other and form a complete circuit. We illustrated the design of electrode placement for two power-as-needed devices: a mouse and a remote controller. The design methodology can be used for other power-as-needed devices as well.

We then evaluated the usability of TouchPower through a user study. Subjective ratings and feedback indicated that TouchPower is capable of providing stable power to the mouse and remote controller during typical interactions, with minor impact on user experience. Finally, we demonstrated six applications of TouchPower in daily scenarios: a stylus, a presentation remote controller, a smart dumb-bell, a bike computer, a book light, and electronic device charging. Through these applications and later discussions, we showed IPT can provide new interaction possibilities and has the potential to be extended to more use cases.

Our contributions in this paper are four-fold. 1) We proposed the concept of *Interaction-based Power Transfer* for power-as-needed electronic devices, which is the first in literature to our knowledge; 2) We designed and implemented TouchPower, a proof-of-concept IPT prototype. We developed the transmitter to work with ad-hoc contacts, and illustrated the design process for electrode placement both on glove and on device; 3) We evaluated the effect of TouchPower on users' interaction experience, confirming the feasibility of IPT; 4) We demonstrated various application scenarios of TouchPower, which showed the potential of IPT in ubiquitous computing environments.

2 BACKGROUND AND RELATED WORKS

In this section, we first introduce possible energy sources for IPT systems. Then we look at alternative power schemes that are related to IPT: human-powered devices and wireless power transfer. At last, we look at surface power supplies that use similar techniques as TouchPower to deal with ad-hoc contact.

2.1 Energy Sources

Aside from batteries, energies can also be harvested from ambient environment, such as solar/light energy [10], RF signal [12, 45, 48], kinetic energy [27, 29, 43], and thermal energy [49]. The human body is also a great energy source [31, 33, 39, 40]. For example, several Watts of power can be scavenged from limb motions, and theoretically up to 320mW thermal energy can be harvested by a brace covering skin on the neck. Kymissis et al. collected 250mW power from shoes during walking [24]. Recent advances in thermoelectric fabrics enables novel clothes that can harvest thermal energy from the human body [6, 7, 14]. One recent research scavenges $1.2mW/cm^2$ from sweat on the human body using soft and stretchable biofuel cells [18]. Novel textile can harvest triboelectric energy generated from frictional contact between different materials [4, 38]. Chen et al. harvested solar and triboelectric energies at the same time, achieving 0.5mW power output from a 4cm by 5cm fabric worn on a person walking under sunlight of intensity $80mW/cm^2$ [3].

The energy scavenged can be transferred to other places on body for storage. Conductive fabric can be weaved into clothes and distribute power to different areas on body. Malleable conductive materials can also be applied on skin to transfer power [23]. Worgan et al. connected two coils with a pair of long elastic conductive strips to relay power from one coil to the other [55]. The coils are made from flexible material so that they can be easily stitched onto normal clothes [56]. The energy harvested and distributed on body can be the energy source of IPT, enabling a maintenance free power solution for power-as-needed devices.

2.2 Human-powered Devices

Human-powered devices are powered or charged by users' physical manipulation. Hand-cranked dynamo chargers generate power when a handle is winded. Mechanically powered flashlights are charged by shaking the flashlight or squeezing a handle on it [52]. For such devices, power generation is not part of the original interaction. They mandate extra physical efforts, make the whole interaction unnatural, and can be tiring.

Interaction-powered devices integrate the power generation process into the interaction process, which enables a more natural interaction experience. MIT Button [32] powers a wireless battery-free remote controller by energy generated during button pushes. The mechanical energy generated from button pushes is converted to electrical energy by a piezoelectric element, and used to power up the rest of the circuit. The whole process is quite natural, since button pushing is part of the original interaction flow. Peppermill [47] and InGen [1] are rotary remote controllers that are powered by twisting upper parts with geared motors inside. A special control sequence is defined so the twisting becomes a part of the interaction. Paper Generators [21] harvest triboelectric energy from paper-like materials. Various paper-based interactions are proposed so that power can be generated during such interactions.

It's important to highlight the differences between human-powered devices and IPT. Human-powered devices require extra physical or mental efforts for power generation. The users either need to provide mechanical energy through extra efforts (e.g. shake-driven flashlight), or need to learn new interaction sequences (e.g. Peppermill). Also, the power generation mechanisms used in such devices cannot be readily scaled, since the harvesting modules are quite specific to different motion types. For example, the power generation mechanism used in the MIT Button cannot be applied to devices that don't have buttons. The amount of power generated is also dependent on interaction effort, which is inconsistent and can be small. In comparison, IPT provides stable and continuous power supply during interaction, which does not involve any extra physical efforts. Since IPT does not alter the original interaction, users are able to interact with devices in ways already familiar to them. Also, IPT can be scaled to other devices as long as the same receiver is used on the target devices.

2.3 Wireless Power Transfer (WPT)

WPT transfers power in the form of electromagnetic waves from specially designed transmitters to receivers on devices. Near-range WPT can transfer Watts level power, but its performance decreases rapidly as the distance between transmit and receive coils increases [53]. To have the two coils close to each other, Qi-ferry [25] carries transmit coils with a roaming wheeled robot, and approaches devices before changing. However, the robot can only change devices that it can reach, which is limited to devices that reside on the same surface. Magnetic MIMO [19] places multiple transmit coils on a table surface, and uses beamforming technique to automatically track and charge devices. The tracking range is limited though, and a large surface is required to accommodate the many transmit coils. IPT systems, however, establish the power transfer channel naturally during interaction, when users actively and accurately track and approach the devices. Humans are much more flexible than a wheeled robot, and the on-body transmitter takes much less space than the array of coils.

2.4 Ad-hoc Contact Power Transfer

The topologies of electrodes on both ends of TouchPower need to be thoughtfully placed for stable power during ad-hoc contacts of electrodes. Networked Surfaces [37] is an early exploration in this area. Devices can extract power from Networked Surfaces when the electrodes on both ends make contact, regardless of their relative position and orientation. The electrodes on the surface are scanned to find the correct electrodes for power and communication. Open Dots alliance [30] is a surface power open protocol that has been deployed in cars to provide power for compatible devices, which uses similar electrode topology. Smart Table [44] uses a slightly different topology, which isolated signal electrodes from the underlying power plane. VoodooIO [46] uses coaxial pins instead of flat pads as electrodes on the device end, enabling malleable power supply surfaces. Tobiko [13] is a self-configuring power interface which handles the uncertainty and possible defects of electrodes contact with soft and flexible power surfaces.

Power surfaces supply power from near-flat surfaces in the environment (e.g. desks, textiles), while TouchPower supplies power from the surface of the glove worn on human body. Both require careful design of electrode topologies in order to work with a variety of devices, and use algorithms for smart detection and circuits configuration. They differ in that previous power surfaces can only supply power to devices put on them, while the glove surface of TouchPower can actively adapt to devices with different shapes and electrodes alignment, thanks to the dexterity of human hands. Previous power surfaces need to scan through a large number of electrodes that covers the whole surfaces, while TouchPower uses fewer electrodes by covering only the areas that are most frequently contacted during interaction, which can decrease the scan time and enable faster power up of the target device.

3 DESIGNING THE USER-END OF TOUCHPOWER

In this section, we explain the design thinking and technical details of the user-end of our first IPT prototype system: TouchPower. The user-end of TouchPower consists of glove with electrodes (transmit interface), Arduino Pro Mini (transmitter), and battery (energy source). To reduce the glove's negative impact on interaction, we use an elastic nylon glove, which is thin and light. We make *seven* electrodes from conductive fabric, and sew them on the glove to increase the chance of electrode contact while interacting with different objects (Figure 2(a)). We modify a 5V 16MHz Arduino Pro Mini (referred to as Arduino henceforth) as the transmitter, which is powered by a 7.4V Li-Polymer battery. Each electrode is connected to the Arduino with thin jump wire weaved into the glove. The Arduino and battery are held within a 3D printed box strapped onto the wrist, with an LED to indicate

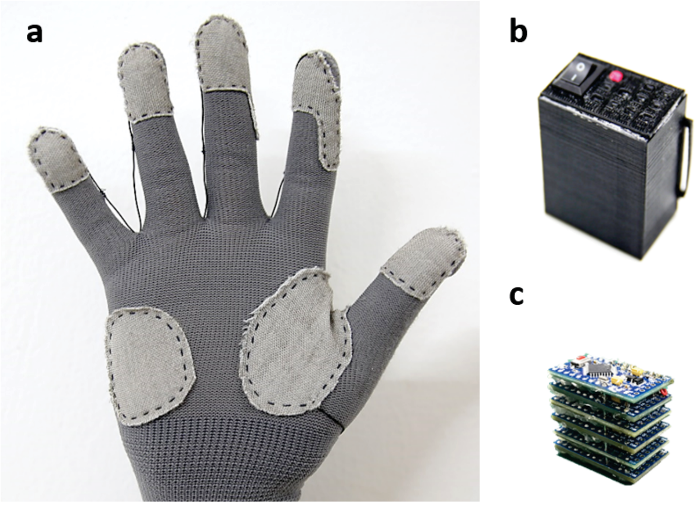

Fig. 2. The user-end of TouchPower has seven electrodes (a). The 3D printed box is 25×40×45mm for the low-power version (b), and 25×40×60mm for the high-power version. The stacked Arduinos for the high-power version are shown (c).

the working status (Figure 2(b)). We design the glove to be separable from the box so that the glove can be used with different sets of transmitters. For this paper, we only use right-handed glove to study the power transfer process during single hand interactions.

3.1 Electrodes Placement on Glove

Humans grasp different devices with different grasp types, and there are distinct contact areas on the hand for each type of grasp[5, 8, 20]. Electrodes on the glove should cover the most contacted areas so that it can be used with more devices. To determine the positions and sizes of electrodes on the glove, we referred to the work of Gonzalez et al. on task-independent analysis of hand contact areas during manipulation and exploration [9]. They analyzed 7.45 hours of video showing the hand usage of two housekeepers and two machinists, and they calculated the contact time ratio for different areas on the hands during interaction and manipulation processes. According to their results, the five fingertips along with index and middle fingers' external lateral surfaces are the most contacted area while the four subjects were interacting with objects. Therefore, we placed *five* electrodes to cover those areas. We also placed *two* electrodes on the thenar and hypothenar eminences to cover the palm area, providing extra contact for medium wrap grasp (grasp type when holding a TV remote), the most used grasp type in Bullock et al.'s study [2]. The electrode on the thenar eminence also covers thumb-index web to provide an auxiliary contact point for a tripod grasp (grasp used when holding a pen), the fourth most used grasp type [2]. The sizes of electrodes are carefully designed so that they are large enough to cover the target areas, but not too large to short together during manipulation. In the extreme case that all electrodes are shorted, TouchPower won't work since at least two isolated electrodes are needed to transfer power. We designed the size such that the electrodes are not all shorted for the top 10 grasps used (added up to 71% of grasps used by the four subjects) [2]. We show the placement of electrodes on the TouchPower glove in Figure 2(a).

3.2 Hardware and Algorithm

The transmitter should be able to scan through each pairs of electrodes, and supply power continuously once the correct pair is found. This requires highly flexible hardware and algorithm that are able to sense and control current flow, and quickly switch between different pairs of electrodes. We used the General Purpose Input Output (GPIO) ports of the Arduino to provide power. The circuits on device can be powered up when it's connected between two ports, one is pulled HIGH (5V) while the other is pulled LOW (0V). Each GPIO port of the Arduino is specified to be able to source or sink 20mA current at 5V, while current larger than 40mA would damage Arduino ports [28]. There are 14 GPIO ports on the Arduino and 7 electrodes need to be connected, so two ports are shorted and toggled together to provide a theoretical maximum output power of 0.2W. An 80mA resettable fuse is added to protect ports from potential current surges, and a 1Ω series resistor R_s is added to each pair of ports. We monitored the current flow for each pair of ports to determine the system state. The current is calculated by $I = \Delta V/R_s$, in which ΔV is the voltage drop across R_s measured by analog ports.

There are three possible system states depending on the contact status of the electrodes. 1) *Open*: the electrodes are not connected with anything, thus $I = 0$; 2) *Short*: the electrodes are connected with each other and there is excessive current flowing, $I \geq 40mA$. 3) *Load*: the electrodes are connected with a load via contacting the electrodes on the device, and a moderate amount of current is flowing, $0 < I < 40mA$. An example schematic and current flow in all states is shown in Figure 3(a).

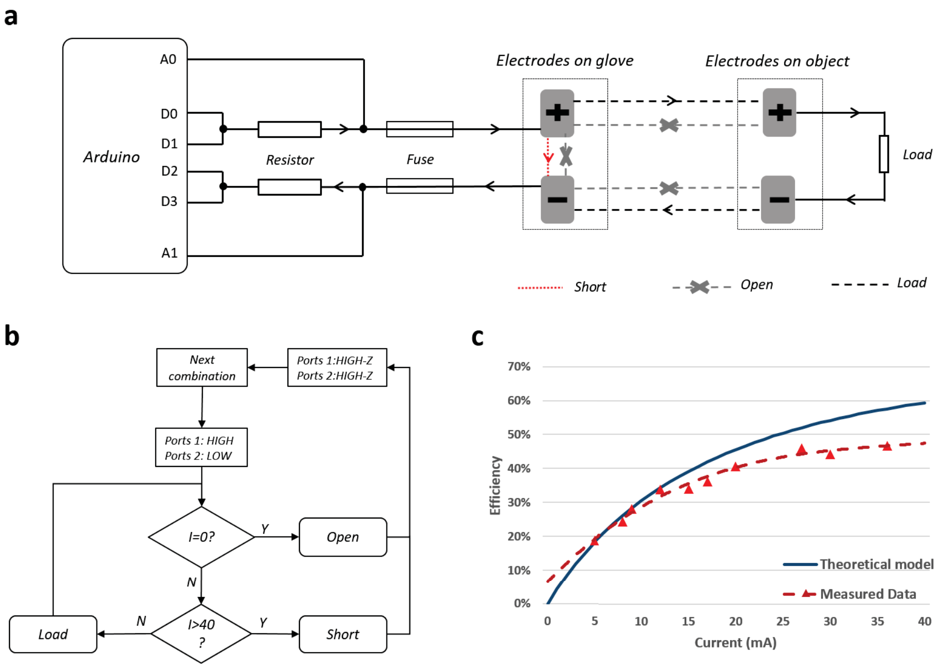

Fig. 3. We show an example transmitting schematic (a), in which D0 and D1 are pulled HIGH while D2 and D3 are pulled LOW. Arrows indicate the direction of current flow. The flowchart of the system is shown in (b). When in *Open* and *Short* states, the system puts ports into high impedance (HIGH-Z) states and moves to next combination of ports. In *Load* state, the system keeps previous ports configuration, and checks current periodically. Theoretical (blue) and measured (red) power transfer efficiency of TouchPower are shown in (c)

The system scans through each combination of electrodes and determines the system status at runtime, according to the flow chart shown in Figure 3(b). A complete scan process takes around 100ms. When there is load, the system will start supplying power through the first usable pair of electrodes found during the scan. Note that the system will scan two combinations for each pair of ports (HIGH/LOW and LOW/HIGH), so that power can be supplied regardless of electrode polarity on the device end.

One Arduino can only provide 0.2W maximum power. One way to increase output power is to connect ports with those of other Arduinos in parallel. Then N Arduinos can provide a $0.2N$ W maximum power. We built a high-power transmitter by stacking six Arduinos on top of each other (Figure 2(c)). One Arduino (master) runs the scanning algorithm as discussed above, and the other five (slave) Arduinos toggle their ports to follow the master accordingly (HIGH/LOW/OPEN).

3.3 Power Transfer Efficiency

The transmitter of the IPT system consumes power itself, which will reduce the total power transfer efficiency from energy source to devices. Even though TouchPower is a proof-of-concept system that uses off-the-shelf hardware, we still show its efficiency as a reference for future IPT systems. The measured power consumption is 0.11W when Arduino is in *Open* state with 5V power supply, which is large considering the maximum safe output power is only 0.2W. Assuming power consumption is constant for all system states, the calculated theoretical curve and measured data with fitted curve is shown in Figure 3(c). The maximum power transfer efficiency is 46.7% when the system is sourcing its maximum current. To compare, the widely used Qi system has a measured total efficiency of 35% for low-power devices when load current is less than 100mA, while a efficiency close to 70% for high-power devices consuming Watts level power [35]. The difference between theoretical and measured efficiency is mainly due to the decreased output voltage when sourcing higher current, which falls short of the specification of Arduino. The wire resistance and imperfect connection between electrodes on the glove and on the device can also contribute to the difference. The maximum overall efficiency could be improved by using power-optimized custom hardware, adding an external GPIO driver to boost maximum output power, using high quality materials with less resistance, etc.

4 DESIGNING THE DEVICE-END OF TOUCHPOWER

The device-end of TouchPower includes two electrically isolated electrodes (receive interface), and receiver circuit (receiver, if necessary). The receiver is simple since the power transferred is already in DC form. A DC-DC converter can be used for voltage conversion and regulation, in case the load requires power voltages other than 5V. A series Schottky diode is used to protect circuits and limit possible reverse current, so that the transmitter can auto detect the polarity of electrodes by measuring current. The receiver components can be added as necessary, and take little extra space since it can be integrated onto the circuit board already existing on the device.

4.1 Methodology for Electrodes Placement on Device-end

The main challenge for designing the device-end of TouchPower is to determine the *amount, position* and *size* of the electrodes on the surface of the target device, such that they can provide stable connection during interaction for power transfer. Intuitively, this design should be device-specific, as the grasp and interaction for individual devices could be largely different. To this end, it is valuable to find a common methodology to determine electrodes placement on any specific device.

The main idea of our methodology is to observe users' interactions with a Wizard-of-Oz device (e.g., a normal device that has a built-in battery), and analyze the "contact pattern" between the electrodes on the glove and on the surface of the device. That is, for each electrode on the glove, we want to know when it is in contact with the target device, and when it is not. Such information will validate whether there will be at least two electrodes on glove contacting the device during interaction, and it will help determine the placement of electrodes on the device. We denote the electrodes on the glove as E_i ($i = 0, .., 6$). Only two groups of electrodes should be placed on the device, one connected with the positive terminal of circuits (positive electrode), and the other connected with the negative terminal (negative electrode). So we divide E_i into two groups, one for each terminal. TouchPower only functions when at least one positive electrode and one negative electrode are in contact with the device at the same time.

We define *Power Supply Time Ratio (PSTR)* as the ratio between the elapsed time that TouchPower is functional and the total interaction time. Our goal is to find the optimal combination of E_i among different candidates that maximizes PSTR. Figure 4 shows an example of three electrodes, where the combination $\{E_{1,2}, E_0\}$ yields the highest PSTR (87.5%). Once we have found the optimal combination, we can then trace back the location of the contact points (e.g. by reviewing video), and put electrodes on these surface areas on the device. We will evaluate the impact on interaction indicated by PSTR in Section 5.

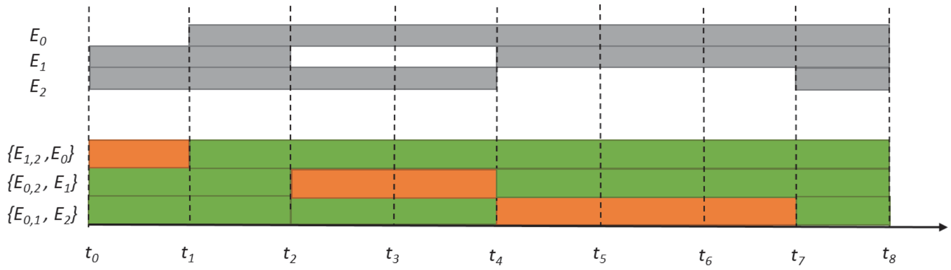

Fig. 4. Three electrodes (E_0, E_1, and E_2) make contact (dark color) with the device at different times. For all three possible combinations ($\{E_{1,2}, E_0\}$, $\{E_{0,1}, E_2\}$, and $\{E_{0,2}, E_1\}$), we mark the time slots that can be used by TouchPower to supply power in green while those that cannot are marked in orange.

It's challenging to measure PSTR since it is hard to monitor the contact status between hand and object. We covered the devices with conductive fabric and connected it with the positive terminal of the battery in the device, and connected the battery negative terminal with the ground of an Arduino Mini Pro, which was used to measure voltage levels on seven electrodes on the glove. The contact status of each electrode on glove is then determined by checking the corresponding voltage: in contact if it equals the battery voltage, and not in contact otherwise. Thanks to the separable design of the user-end of TouchPower, we were able to easily replace transmitter with the measurement hardware. This allows our test settings to be the same as those in evaluation.

We illustrate this procedure for two devices: a mouse, and a smart TV remote controller. We chose these devices for two reasons: 1) They correspond to the top two most common grasp types: *medium wrap* and *precision disk*, which covers over 40% of daily interaction time [2]; 2) Interaction with these devices involves frequent fingers and palm movements, which provides rich contact features and is more difficult to design for. As a result, the design would be indicative of the lower bound of TouchPower's performance. As we will see, this methodology requires only a little configuration of the target device, and can also be applied to other devices with different form factors or functions.

4.2 Participants and Apparatus

We recruited 10 right-handed participants from campus (7 male, 3 female), with an average age of 25.0 (SD = 3.6). All of them use a mouse on a daily basis, and have experience with smart TVs. Each participant was compensated $10 for his or her time. We used a LogiTech M325 mouse and a Lefant smart TV remote controller in this study.

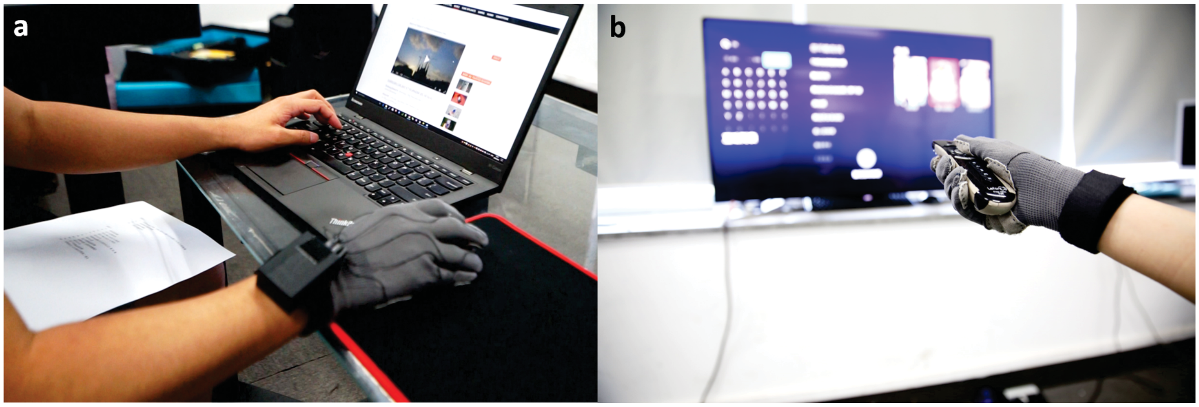

Fig. 5. Experimental set up for the mouse study (a) and the remote study (b).

4.3 Experiment Design and Procedure

We designed tasks to mimic daily usage of the apparatus. Tasks for the mouse include document browsing, text editing, and formatting. The participants were not allowed to use the keyboard during the experiment since this study focuses on contact pattern observation (keyboard interruptions are evaluated in Section 5). The tasks for the remote controller included changing settings, and browsing and searching for movies on a smart TV.

We used a within-subjects design. Participants completed two sessions of tasks, one for the mouse and the other for the remote controller. In each session, participants completed two blocks of tasks. In each block, participants were first introduced about the task by the experimenter. They then wore the glove and warmed up for about one minute to get familiar with the device. After warming up, the participants completed the tasks themselves. Participants were asked to perform the tasks "as naturally as possible, as you would normally do in daily life". To avoid biasing their behavior, participants were not told about the details of TouchPower. The order of different sessions and blocks are balanced across participants, with a two-minute break between different blocks. To keep track of each electrode, we used two cameras to record users' hands during the study. Each mouse task took about three minutes, and each remote controller task took about two minutes.

4.4 Results

All participants successfully completed the tasks with an average completion time of 185.8s (SD=30.5s) for mouse tasks and 121s (SD=24.5s) for remote controller tasks.

4.4.1 Contact Time Ratio.

We noticed that during interaction, some of the electrodes on the glove barely made contact with the device and could thus be discarded from the electrode combination to reduce the size of electrodes on the device. We eliminated such electrodes by defining *Contact Time Ratio (CTR)* for each electrode, which is the ratio between electrode contact time and total interaction time. A CTR of 100% implies that the electrode was always in contact with the device during interaction.

Figure 6(a)(b) shows the CTR of each electrode averaged among all participants for the two devices. For the mouse, E_1 (little finger), E_2 (ring finger), and E_5 (thumb) are potential candidates to support stable power supply with CTR values all larger than 94%. This is consistent with the experience of how we grip a mouse in daily life. For the remote controller, E_0 (hypothenar), E_1 (little finger), E_2 (ring finger), E_3 (middle finger), and E_4 (index finger) all yield a CTR greater than 99%.

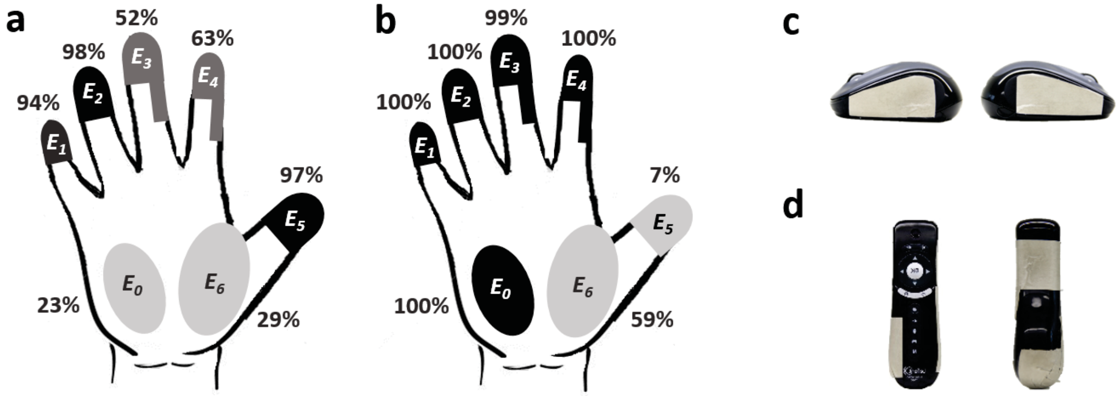

Fig. 6. Contact time ratio for mouse (a) and remote (b). Darker color indicates a higher CTR. The placement of electrodes for mouse (c) and remote (d) are then decided by picking contact areas with the highest CTR.

4.4.2 Design of Electrodes. With the candidates of electrode combinations, we then divided them into two groups in order to yield the highest PSTR. We noticed that not all combinations are valid to be used by TouchPower. For example, we found that participants' fingers move around within a certain range during interaction when using the mouse, which results in different fingers touching the same position at different times. Therefore, the electrodes corresponding to these fingers cannot be divided into different groups, otherwise the contact position would be ambiguous. So the only combination that can be used for the mouse is $\{E_{1,2}, E_5\}$. Similarly, the only valid combination for the remote controller is $\{E_{1,2,3,4}, E_0\}$.

We compared the PSTR of the chosen combination with the PSTR calculated for all seven electrodes to validate the result. The PSTR for the mouse with combination $\{E_{1,2}, E_5\}$ is 96.5%, which is only 2% lower than that for all electrodes (98.6%). For the remote controller, the PSTR with combination $\{E_{1,2,3,4}, E_0\}$ is 99.6%, while that for all electrodes is 99.7%. This result suggested that our chosen combination is close to the optimal solution, and the electrode sizes were smaller yet reasonable.

After reviewing the video, for the mouse we placed positive and negative electrodes on the left and right side respectively, corresponding to the electrodes on the thumb (E_5) and the ring/little finger (E_1 and E_2) (Figure 6(c)), and left enough room to account for movements during interaction. For the remote controller, we placed the positive electrode on the bottom to provide contact for electrodes on the hypothenar eminence (E_0), and the negative electrode covering the left side and upper back of the remote for the four fingers E_1, E_2, E_3, E_4 (Figure 6(d)).

5 EVALUATION

In this section, we evaluate whether TouchPower could provide stable and natural interaction experience for the two devices studied above. Users were asked to perform daily tasks using TouchPower instead of a normal device with batteries. We are interested in users' subjective preference on TouchPower in different dimensions, and how they feel while using TouchPower.

5.1 Participants and Apparatus

We recruited 12 participants (8 male, 4 female) for this study, with an average age of 23.8 (SD=3.8). For generality, ten of the participants had not participated in the previous study. The other two were participants in the previous study with the lowest CTR for the designed placement of electrodes. All of the participants use a mouse on a daily basis, and have experience with smart TVs. Each participant was compensated $10 for his or her time. We used the low-power version of the distributing hardware in the evaluation, as mouse and remote controller are both low-power devices. DC-DC converters were used to convert voltages from 5V to 1.5V for the mouse, and to 3V for the remote. The devices are solely powered by TouchPower, with no batteries inside.

5.2 Experiment Design and Procedure

The goal of this experiment is to compare the interaction experience using TouchPower to that of normal devices (i.e., with built-in batteries). In our pilot study, some participants commented that the form factor of the glove would affect their subjective preference of the technique. However, as our goal is to evaluate the IPT scheme, we did not want the measured result to be biased toward a specific implementation. Therefore, to avoid this bias, we tested two conditions: 1) glove + TouchPower-ready device, which is the typical TouchPower setting; 2) glove + normal device, which requires the user to wear the glove when interacting with normal devices with built-in batteries. By comparing the results of the two conditions, we can get an insight into user's preference on the IPT scheme while eliminating the effect of the glove.

Similar to the previous study, we designed tasks that approximate the daily use of the mouse and the remote controller. We added mode switching in this experiment for a more realistic experience. For the mouse tasks, we added some text entry tasks using the keyboard, and the participants had to switch several times between the mouse and the keyboard. And for the remote controller tasks, we asked the participants to put down the device after a subtask, and to pick it up later for the next subtask. This allows us to measure possible latency that occurs when aligning the electrodes at the beginning of an interaction.

We used a within-subjects design. Participants completed two sessions, one for each device. For the task sessions of each device, they completed two blocks of tasks, each for a test condition (TouchPower-ready or normal device). In each block, participants were first introduced about the task by the experimenter. They then wore the glove and warmed up for about one minute to get familiar with the device and TouchPower system. After warming up, the participants completed the tasks themselves. They were asked to perform the tasks "as naturally as possible. But if you feel the device is not working, please adjust your grasp posture". The order of different sessions and blocks are balanced across participants, with a two-minute break between different blocks. After the experiment, we used a questionnaire to gather their subjective preference about the devices, and interviewed them for feedback.

5.3 Results

5.3.1 *Subjective Ratings.*

We used a 7-point Likert scale questionnaire to gather users' subjective preference. Dimensions include perceived latency, comfort, naturalness and overall preference. Table 1 shows users' ratings for different device and test conditions. As expected, all ratings of TouchPower were lower than those of the normal device. However, the differences were small.

Perceived Latency Describes whether the participant felt any latency during interaction. The difference between TouchPower and Battery device was 1.1 and 1.0 for mouse and remote controller, respectively. This indicates that participants felt a little latency when using TouchPower. During the interview, we found that this usually happened when users started to interact before a stable grasping is established. Note that the final rating for mouse and remote controller reached 5.7 and 5.8 respectively, indicating that users were still positive regarding this dimension.

Table 1. Average ratings for each test condition, with standard deviations shown in parenthesis. 7 means the most positive and 1 means the most negative.

Device	Mouse		Remote Controller	
Test Condition	**TouchPower**	**Battery**	**TouchPower**	**Battery**
Perceived Latency	5.7 (1.3)	6.8 (0.4)	5.8 (1.1)	6.8 (0.4)
Comfort	4.5 (0.8)	4.9 (1.1)	5.4 (0.7)	5.8 (0.9)
Naturalness	5.0 (1.1)	5.4 (0.9)	5.3 (1.0)	5.8 (0.9)
Overall Preference	4.7 (1.2)	5.2 (1.3)	5.2 (0.9)	6.0 (0.8)

Comfort Describes whether the participant felt comfortable when grasping the device. The ratings for TouchPower were only 0.4 lower than that for the battery device for the mouse and remote controller. This suggested that TouchPower would not significantly change the grasp posture of users. Noticeably, the rating for both TouchPower and normal devices were relatively low (< 5 for mouse and < 6 for remote controller). We speculate this was due to the discomfort introduced by the glove. During the interview, participants also commented that they felt uncomfortable wearing the glove. However, they felt little difference when using battery-powered devices and TouchPower powered devices.

Naturalness Describes whether the TouchPower system affects users' behavior during interaction. The difference between TouchPower and battery device was 0.4 and 0.5 for mouse and remote controller, respectively. This confirmed that TouchPower could provide stable power supply during interaction, allowing users to interact in a natural way.

Overall Preference Describes the difference in preference between TouchPower and normal device. The ratings for TouchPower were 0.5 and 0.8 lower for mouse and remote controller, respectively.

5.3.2 Subjective Feedback. We now summarize some subjective feedback from the user interview. Although some participants were not familiar with the TouchPower system in the beginning, they got used to it very quickly, as the placement of the electrodes allowed them to interact naturally with the device:

"The design of the electrodes fit well with my interaction habit. Therefore, I felt natural using it." (P6)

Some participants were excited about the idea of TouchPower, and even began to envision the use scenarios:

"It is amazing to use the devices without a battery. I really like this idea, and would like to use it in my home." (P1)

Although the design of TouchPower was appreciated, five participants felt uncomfortable wearing the glove.

"I am not used to wearing a glove when using a mouse or remote controller. This makes me feel uncomfortable." (P8)

Eight participants commented that they felt mental pressure during interaction.

"I am worried about the disconnection during interaction. I guess I will feel better after more practice." (P4)

5.4 Discussion

In this section, we evaluated TouchPower with a mouse and a remote controller, and compared the subjective preferences between devices that were powered by TouchPower to the same devices powered by battery. The naturalness rating for the TouchPower mouse is only 7% lower than that of the battery powered mouse, and 8% lower for remote controller. The results confirmed that TouchPower could enable a near-natural interaction experience. The perceived latency rating for the mouse is lower than that for the remote, which is expected since the PSTR of the mouse (96.5%) is lower than that of the remote (99.6%). A lower PSTR means more power disconnections during interaction, leading to a larger latency. One of the reasons for the lower overall acceptance of TouchPower for the mouse is that daily mouse tasks are more complicated than daily remote tasks, so people have lower tolerance to latency and discomfort while using the mouse. This is backed by feedback from two participants (P9 and P11).

6 APPLICATIONS

We implemented the device-end of TouchPower on six devices, and used TouchPower to power or charge them. We show that TouchPower can enable new hardware applications and interactions, and charge battery powered electronic devices.

Stylus A user is shown holding a TouchPower powered stylus writing on the Surface laptop in Figure 7(a). The stylus of Microsoft's Surface Pro 4 is powered with one 1.5V AAAA battery. We removed the battery, and connected the positive and negative terminal of the stylus to two electrodes on surface of the stylus. One electrode was placed near the stylus tip, where thumb, index finger, and middle finger will make contact with. The other one was put on the upper side of the stylus, where the thumb-index web will make contact with. A DC-DC converter was used to convert voltages from 5V to 1.5V.

Presentation Remote Controller In Figure 7(b) we show a user presenting with the TouchPower powered presentation remote controller. The electrode placements are similar to that on the TV remote studied earlier as they share the same medium wrap grasp type [5].

Smart Dumb-bell In gym people already wear gloves, so the electrodes of the user-end of TouchPower can be stitched directly on such gloves. We added an Arduino Nano and an Inertial Measurement Unit (IMU) module to a dumb-bell, and used an LED to indicate whether or not the dumb-bell is lifted up enough. A DC-DC converter was also added to provide a stable 5V supply voltage to the Arduino module. The electrodes on the dumb-bell were placed to make contact with electrodes on the thenar and hypothenar eminences. We then used TouchPower to power up the whole setup, shown in Figure 7(c). This configuration can be easily applied to many other pieces of equipment in a gym, enabling a smart gym that logs details of people's exercise and makes suggestions accordingly.

Bike Computer In Figure 7(d) we show the user riding a bike with a bike computer powered by TouchPower. Since the dumb-bell and bike handle share the same grasp type (small diameter [5]), the placement of electrodes were similar to that on the dumb-bell. Regular biking gloves can also be modified so TouchPower could be used with outdoor bikes as well.

Book Light We fixed a USB powered LED light on a book, and show that the book can be lit during reading by TouchPower in Figure 7(e). One electrode was added on the front cover of the book, the other on the back cover. When holding the book with right hand, the electrodes on fingers will contact the electrode on front cover, while the electrode on the thenar eminence will contact the one on the back cover. The light can be easily switched on or off by adjusting holding gesture to make or avoid contact with electrodes on the book.

Electronic Devices Charging TouchPower can also be used to charge battery powered electronic devices. The 5V output voltage of Arduino makes it convenient to charge devices that can be charged by a USB cable, since its output voltage is also 5V. We cut open a Micro USB charging wire, and connected the ends of VCC and GND wires to two electrodes on the back of a cellphone. TouchPower can charge the phone with no extra receiving hardware on the device-end, since they are already integrated in the charging circuits inside the cellphone as shown in Figure 7(f). The charging current is small with current implementation of TouchPower though.

7 DISCUSSION AND FUTURE WORKS

In previous sections, we have proposed the concept of IPT, illustrated the design process of TouchPower, and showed the feasibility of IPT by user study and several applications. As a prototype, TouchPower has several

Fig. 7. Applications for TouchPower. Two electrodes (shown in blue and orange) are applied to each device. All electrodes are made from conductive tape. We show TouchPower used in an office setting with a stylus (a) and a presentation remote controller (b), as well as in a gym setting with a dumb-bell (c) and a gym bike (d). TouchPower can also light a book (e) and charge a cellphone (f). We zoom in to show the charging status on the top right corner of (f).

limitations, including the discomfort introduced by the glove, its scalability, and battery maintenance issue. We also discuss the limitations and potentials of IPT system, including cold reboot, other possible IPT systems, the establishment of communication links, and suitable use scenarios.

7.1 TouchPower

7.1.1 Glove. A major disadvantage of TouchPower comes from the discomfort introduced by the glove, which greatly deteriorates the user experience. In this paper, we use a full-fingered glove to better study and evaluate the power transfer performance of TouchPower. However, TouchPower doesn't require a full-fingered glove to function properly. For example, a half-finger glove that covers the thenar and hypothenar eminence is enough for most gym applications, due to the similar grasp types used with different gym equipment. For scenarios in which people already wear gloves, TouchPower can be adopted to use the specific type of glove, thus introduces no extra discomfort.

One promising technique that can help get rid of the glove is skin electronics [22, 23, 26, 42]. The electrodes of TouchPower could be etched onto ultra thin skin-compatible elastomer and stuck directly on hand. For example, iSkin [50] makes thin film electrodes (≈100μm) from carbon-filled polydimethylsiloxane (cPDMS), and embeds them into normal non-conductive PDMS (≈60μm). One application shown in iSkin, FingerStrap, takes the form of a thin film wrapped around one finger. Five FingerStraps can cover the five fingertips, where the most frequently used electrodes of TouchPower are placed. Conductive meshes or AgPDMS can be used instead of cPDMS to reduce resistance.

Another way to remove the glove is to transfer power through bare hands. Previous researches on intrabody power transfer [36] explored the possibilities to transfer power through human body. However, human body is quite lossy, so the transfer efficiency is quite low [17, 34]. For TouchPower, however, the transmitting path through body is much shorter, approximately the length of hand if transmitter is wrist-worn, and even shorter if it's finger-worn. The shorter path could deliver higher output power, especially if it is transferred at high frequencies and high voltages [17]. A better shared ground could also improve power transfer efficiency between body and the device.

7.1.2 Scalability. We design the user-end of TouchPower to be compatible with as many devices as possible. The electrodes on glove are carefully arranged to cover the most contacted areas, and the Arduino are programmed to auto detect load connection between all electrode pairs, and transfer power accordingly. Only seven electrodes are used in the current implementation, which is limited by the number of GPIO ports of the Arduino Pro Mini. More electrodes on glove will improve the chances to maintain two electrically separate contact points with the device, thus provide a more stable power supply. For example, small electrode grids can be used to cover fingers and the whole palm for more contact points. However, too many electrodes would increase the scan time, which would slow down the power up process during initial grasp or intermittent realignment. We plan to find the balance of electrodes number and perceived latency in future studies.

The current algorithm stops scanning and uses the first pair of usable electrodes when load is detected. This can supply power as fast as possible, but the electrodes used are not necessarily optimal. For example, the used contact pair may be due to accidental touch, which will rarely happen again during interaction. One solution is to prioritize the usable pairs based on time, CTR history, etc. The pair that is just used for a long time, or has highest CTR over a certain period should be tested and used first.

TouchPower requires thoughtful placement of electrodes on the device-end. However, we believe that it's not necessary to design electrodes for every device from scratch. In previous sections, we show that similar arrangements of electrodes can be used for devices held by the same grasp type, with only minor adjustments. For example, the TV remote, slide remote controller, and cellphone all use medium wrap grasp [5, 8]. They share a similar arrangement of electrodes on device, with one electrode for four fingers, the other for thenar and hypothenar eminences. A bike handle and a dumb bell are both grasped with small diameter grasp [5, 8], and they share similar electrodes arrangement as well. A study of electrodes placement on a limited number of grasp types could provide design guidance for a wide range of devices.

Also, there are many ways a device can be picked up and manipulated, and it's difficult to design electrodes that work for all of them. However, thoughtful industrial design (e.g. concave surface around electrodes) could improve the affordance of TouchPower by guiding users' grasps, and thus help prevent the user's fingers from migrating away from electrodes on device during interaction. Visual or sound feedback can also be used to remind users to realign. For example, an LED could be turned on to indicate the power is on, and turned off when the power is lost. We also believe more practice with TouchPower may help to mitigate this issue based on observations in the user study.

7.1.3 Battery Maintenance. For simplicity, the current implementation of TouchPower uses a battery as the energy source since our focus in this paper is the power transfer process. Even though no power maintenance is required on the device-end, we still need to charge the on-body battery. However, the energy can come from batteries within wearable devices on human body (e.g. smart watch), which are already maintained by people. The on-body batteries can be charged from the environment [19, 54], or from a cellphone in one's pocket [55]. Also, the power transfer direction can be reversed to be from off-body devices to an on-body battery, automatically charging the battery during interaction from plugged in devices like wired mouses, laptops, etc. As explained in Section 2.1, TouchPower's battery could also be used as storage of energy harvested from the human body, eliminating maintenance needs.

7.2 IPT

7.2.1 Cold Reboot. Battery-free devices powered by IPT will be cold rebooted each time, since IPT only provides just-in-time power. Even though the reboot process is quite short and almost negligible for some devices (e.g. the mouse and remote controller used in the evaluation), there are some devices that require much longer time to start up. This leads to large perceived latency and deteriorated user experience. A secondary battery can solve these issues, supplying power during no interaction period to enable hot reboot. Then during interaction, IPT systems can both supply power for the device's normal operation and charge the secondary battery so that the device can sleep until next interaction. Then such devices will still be power maintenance free even though there are batteries inside.

7.2.2 More IPT Systems. TouchPower is just one manifestation of an IPT system. The transfer channel for TouchPower is formed when two electrodes on glove and device make contact. Sometimes such conditions cannot be met during interaction, such as when we use only one finger to push a button on a remote that is placed on a table. We'd like to point out that there are other possible IPT systems that could form power transfer channels with looser constraints than those of TouchPower. For example, IPT systems that transfer power in electromagnetic (WPT) or acoustic forms do not even require contact between the user and the device.

7.2.3 Communication Links. The current implementation of TouchPower only transfers power when a transfer channel is formed. The channel could also be used to transfer information at the same time [11], thus establishing a communication link between the user and device. This will enable much richer interaction experience when using IPT systems. For example, an IPT enabled stylus could authenticate users by checking the biometrics measured by and transferred from the on-body transmitter [16].

7.2.4 Use Scenarios. We believe that IPT is especially useful in public spaces, where many people share and interact with a large number of devices. For example, in a gym there are hundreds of pieces of equipment that people share with each other. If these were all smart equipment powered by batteries, the maintenance efforts would be huge even if the battery in each piece of equipment was changed only once per year. With IPT, however, power maintenance is not necessary since each piece of equipment is powered up or charged each time it's being used.

8 CONCLUSION

The ubiquitous deployment of electronics demands novel power schemes. In this paper, we proposed *Interaction-based Power Transfer*, a way to power up power-as-needed electronic devices only during interaction. To prove the concept of IPT, we designed and implemented TouchPower, a prototype IPT system. We explained in detail the design of electrode positions and circuits for the user-end of TouchPower, and conducted a user study to determine the placement of electrodes on the device-end. We then evaluated TouchPower by analyzing subjective feedback from users. Lastly, we demonstrated various TouchPower applications in living room (TV remote/book), office (stylus/slides controller), and gym (dumb-bell/bike) environments. We believe our exploration of IPT system opens up many possibilities for future research, both in affordance of interaction and active power schemes for ubiquitous electronic devices.

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