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

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The trend toward ubiquitous deployment of electronic devices demands novel low maintenance power schemes to alleviate the burden of maintaining such a large number of devices. In our paper [14], 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 such devices, and enables them 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. Evaluation results show that during interaction, TouchPower is able to provide stable power supply to these devices with only a small sacrifice with regard to interaction naturalness.

Mark Weiser envisioned a computer on almost every object to enable ubiquitous computing in his famous article "The Computer for the 21st Century" [12]. But here we are, almost 20 years into the 21st century, still waiting for the coming of age of ubiquitous computing. The power issue is considered one of the major hindrances for Wieser's vision [4]. Currently, most electronic devices are powered by batteries, which are rigid, demand periodic maintenance (charging or replacing), and scale slower than electronics in size and cost. Ubiquitous deployment of electronic devices demands alternative power schemes with less maintenance and constrains on devices.

Various power schemes have been proposed over the years to alleviate users' burden of power maintenance. Wireless power transfer (WPT) techniques replace charging cables by radiating electromagnetic waves to transmit power. The receiving antenna on the device is usually large though, and the power transferred decreases rapidly with increasing distance. Human-powered devices like a shake-driven flashlight take advantage of the affordance of interaction, but usually require extra effort from users and suffer scalability issues. There are also special surfaces that can supply relatively high power to devices put on them through contacting electrodes [9].

We propose *Interaction-based Power Transfer* (IPT), an alternative power solution for electronic devices [14]. We observe that many electronic devices only need to be powered up during interaction (e.g., stylus), which we refer as power-as-needed devices henceforth. As opposed to supplying power to such devices at all time, we can power them up only during interaction. There is usually proximity or contact between the user and the target device during interaction, which forms a natural channel for power transfer. By getting rid of batteries on the device end, IPT systems enable further reduction of electronic devices' size and cost. The whole device can also be flexible without the rigid battery. Well-designed IPT systems have little or no impact on the original interaction process, and can be readily scaled to most power-as-needed devices. The overall power maintenance effort is greatly reduced by using IPT systems. Instead of maintaining many batteries scattered around the rooms, users only need to charge one on-body battery. We can even leverage the batteries inside wearable devices [13] and energy harvested from the human body [2,5,7] to achieve a truly maintenance-free power solution.

The system architecture of typical IPT systems is shown in Figure 1, including the user-end and the device-end. To validate the concept of IPT, we built a contact-based prototyping system: *TouchPower*[1] (Figure 1, b to d). TouchPower can supply power during ad-hoc contact of a user's hand and the device. The user end of TouchPower takes the form of a glove with seven electrodes. The electrodes on both the glove and the target device are thoughtfully placed, so that TouchPower can work with various devices with little impact on the original interaction. TouchPower transfers power in DC form, which can supply higher power with simpler converting circuits compared with WPT techniques. Compared to previous power surfaces, TouchPower's power supply surface can actively adapt to devices with different shapes and align the electrodes, thanks to the dexterity of human hands. As a minimum viable prototype, the design goal of TouchPower is validating and exploring the scheme of IPT. Therefore, we used a battery as the energy source to focus on the on-body to off-body power transfer during interaction.

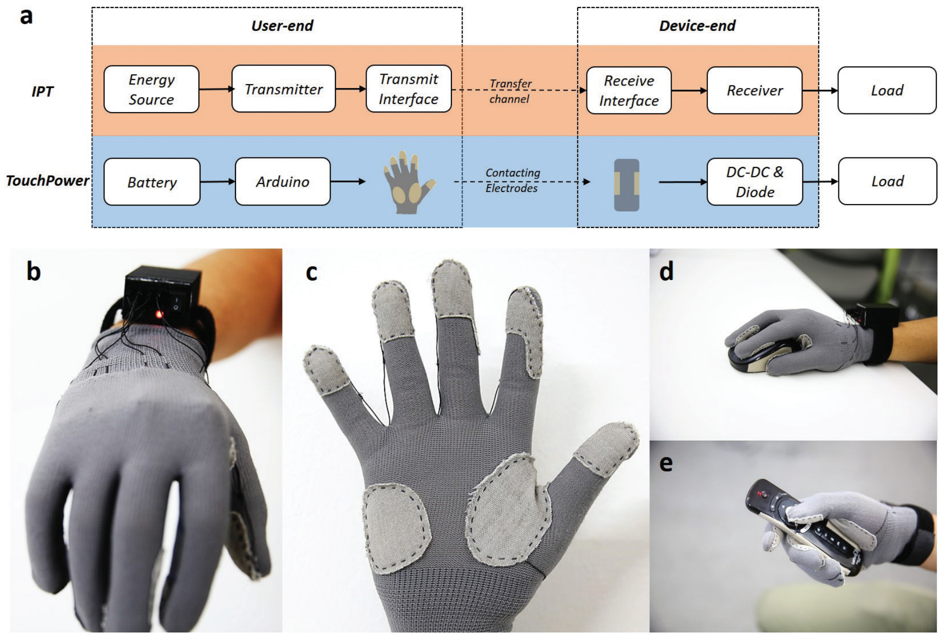

FIGURE 1. (a) System components of IPT (orange) and TouchPower (blue). Arrows point in the direction of power flow. (b and c) A user wears the user-end of TouchPower. The 3D printed box is 25 × 40 × 45 mm with a Lithium-polymer battery and an Arduino Pro Mini inside. (d and e) Use cases of mouse and remote controller.

DESIGNING THE USER-END OF TOUCHPOWER

The designing of the user-end of TouchPower includes two parts: 1. electrode placement on the glove so that it can work with most devices; 2. flexible circuits to supply power during ad-hoc contacts between electrodes.

Humans have different ways of grasping devices, and there are distinct contact areas on the hand for each type of grasp. 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. [3] on task-independent analysis of hand contact areas during manipulation and exploration. According to their results, the five fingertips along with index and middle finger's external lateral surfaces are the most contacted areas. 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 [1]. The electrode on the thenar eminence also covers the 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 [1]. The sizes of electrodes are carefully designed so that they are large enough to cover the target areas, but not too large to short with each other 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 per cent

[1] Video available at https://youtu.be/MTWtAI0XuUQ

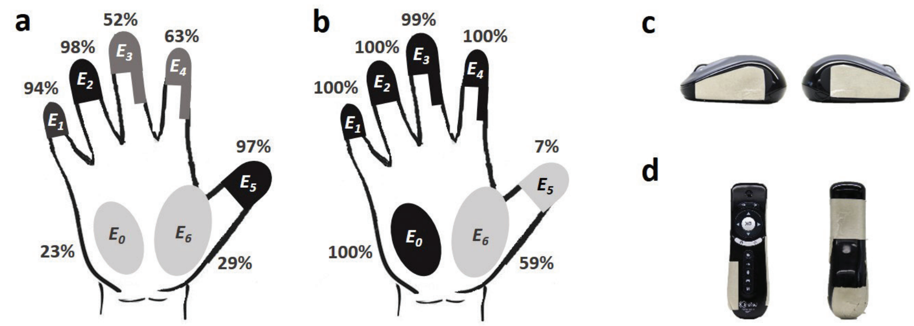

FIGURE 2. (a) Contact time ratio for mouse (b) Contact time ration for remote. The darker color indicates a higher CTR. (c and d) The placement of electrodes for mouse and for remote are then decided by picking contact areas with the highest CTR.

of grasps used by the four subjects) [1]. We show the placement of electrodes on the TouchPower glove in Figure 1c.

We connected the General Purpose Input Output (GPIO) ports of the Arduino to the electrodes on the glove to supply power. The flexibility of GPIOs to sense and control current flow on the run enables power supply for ad-hoc electrodes contact. A device can be powered up by connecting VDD to one port pulled HIGH (5V), and GND to another port pulled LOW (0V). There are three possible system states depending on the contact status of the electrodes. 1) *Open*: the electrodes are not connected with any device, 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 contacting the electrodes on the device, and a moderate amount of current is flowing, $0 < I < 40mA$. The system scans through all combinations (including different polarities) of electrodes and determines the system status at runtime, and only stops scan at *Load* state to supply power. A complete scan process takes about 100ms.

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 detect the polarity of electrodes by measuring current. The receiver components can be added as necessary, and take little extra space since they can be integrated onto the circuit board already existing on the device.

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. We conducted a Wizard-of-Oz user study to understand how the seven electrodes make contact with the devices during interaction. Ten right-handed participants were recruited from campus with an average age of 25.0 (SD 3.6). We asked them to finish designed daily tasks by using a mouse and a remote, both powered by batteries. The two devices are covered with conductive fabric, which is connected with the positive end of the battery. Then the contact status with different electrodes on the glove could be recorded by measuring voltages of these electrodes. We wanted to know how long and in what combination each electrode on the glove contacts the device during interaction. 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 *Contact Time Ratio* (CTR) as the ratio between electrode contact time and total interaction time. Figure 2(a)(b) shows the CTR of each electrode averaged among all participants for the two devices. We noticed that fingers moved around during interaction, resulting 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. In the end, the only combination that can be used for the mouse is $\{E_{1,2}, E_5\}$ (Figure 2c). Similarly, the only valid combination for the remote controller is $\{E_{1,2,3,4}, E_0\}$ (Figure 2d).

TOUCHPOWER EVALUATION

We conducted a second study to evaluate the users' subjective preferences of TouchPower and their feelings of its impact on interaction. We recruited 12 participants (8 males, 4 females) for this study, with an average age of 23.8 (SD 3.8). The mouse and the remote used are solely powered by TouchPower, with no batteries inside. Therefore, 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 gain insight into user preference on the IPT scheme without the impact of the glove. The participants are asked to complete daily tasks similar to those in the previous study, but with interruptions (e.g., keyboard usages for mouse tasks) to mimic a more realistic situation. Such interruptions allow us to measure possible latency that occurs when aligning the electrodes at the beginning of interaction.

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.

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 Battery 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.

TABLE 1. Subjective ratings for each test condition, with standard deviation 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)

FIGURE 3. Applications for TouchPower. Two electrodes made of conductive tape (shown in blue and orange) are applied to each device.

DISCUSSIONS, CHALLENGES AND CONCLUSION

One major limitation of TouchPower is the discomfort caused by the glove, which greatly deteriorates the user experience and narrows the scope of applications. For scenarios in which people already wear gloves, TouchPower can be adapted to use the existing glove to avoid extra discomfort (e.g., gym gloves). One promising technique that can help get rid of the glove is skin electronics [6]. The electrodes of TouchPower could be etched onto ultrathin skin-compatible elastomer and stuck directly on the hand [11].

A major challenge of designing the IPT system is to balance the amount of transferable power and the impact on interaction, while still ensuring human safety. For example, intrabody power transfer [8, 10] can help to get rid of the glove, but the transferred power is low due to the lossy nature of human body and safety concerns. The proximity-based IPT system relies on energy radiation to transfer power, which must be examined with scrutiny to avoid any damage to users. In most cases, this means the amount of power that can be safely transferred is quite limited. A directive power transmitter can steer the energy beam away from the human body, but such techniques usually require highly complicated circuits, resulting in low overall efficiency.

The ubiquitous deployment of electronics demands novel power schemes. In our paper [14], we proposed *Interaction-based Power Transfer*, a novel and scalable mechanism to power up power-as-needed electronic devices only during interaction. IPT takes advantage of the natural contact or proximity between users and objects during interaction to transfer power. To prove the concept of IPT, we designed and implemented TouchPower, a contact-based prototype IPT system. We explained in detail the design process of TouchPower, and validated its feasibility through user studies. We also demonstrated various TouchPower applications in living room (TV remote/book), office (stylus/slides controller), and gym (dumbbell/bike) environments (Figure 3). Note that TouchPower is only an early prototyping IPT system using off-the-shelf hardware. We expect future IPT systems to have better performances in terms of transferrable power, efficiency, and interaction impact. We believe our definition and exploration of IPT opens up many possibilities for future research, both in human-centered power schemes and affordance of interaction. ■

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