PaperIO: Paper-Based 3D I/O Interface Using Selective Inductive Power Transmission

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Abstract. In this paper, we introduce *PaperIO*, a paper-based 3D I/O interface, in which a single piece of paper can be sensed and actuated at the same time in three dimensions using the technology of selective inductive power transmission. With this technology, paper material with multiple embedded receivers, can not only selectively receive inductive power to perform paper-computing behavior, but also work as input sensors to communicate with power transmitter wirelessly. In addition, due to the simplicity, this method allows users to easily customize their own paper I/O devices. This paper presents the detailed implementation of the system, results of the technical experiments, and a few sample applications of the presented paper-based 3D I/O interface, and finally discusses the future plan of this research.

Keywords: Paper Computing, 3D User Interface, Tangible User Interface.

1 Introduction

Throughout the evolution of paper, artists and designers have created various art forms through techniques such as folding, bending, and pop-up [13]. Today, paper craft is used in many other areas, such as storytelling, education, and medical treatment [6]. Paper craft can also be used to enhance in-class communication among teachers and children [2]. In addition, researchers who are interested in paper material to bring up the concept of Paper Computing [3], which explored paper as input or output in human computer interaction. However, few of them allow paper to both control and be controlled physically by digital contents at the same time, which separated the usage of paper as input and output in different contexts.

This paper presents *PaperIO*, a new type of paper-based I/O interface based on the technology of selective inductive power transmission [8]. It is able to selectively provide inductive power to different receivers in the context of multiple receivers embedded in paper material, and further actuate the shape-changing of paper as an organic output method. Based on this technology, we developed a technique to enable power receivers to send feedback back to power transmitter while receiving power wirelessly at the same time, thus allow the system to sense the 3D information (Here we define 3D information as the presence, the positions and the orientations) of power receivers, integrating both output and input interfaces in paper material with

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embedded power receivers. Compared to existing research, *PaperIO* doesn't required complex electrical sensor and actuator circuit embedded in the paper where power receivers are the sensors themselves, and it is real-time and camera-free to avoid the problems such as lighting and hand occlusion.

In the rest of this paper, an overview and comparison of the related work in paper input and output will be presented and discussed in the next section. As follow, the detailed implementation of *PaperIO* will be presented with experimental results of technical performance. Then a few examples of interaction will be described as using *PaperIO* as a 3D input interface for pure virtual reality, and using *PaperIO* as both input and output interfaces at the same time for paper-based interaction. Finally, the paper concludes with the discussion and the future work of *PaperIO*.

2 Related Work

PaperIO falls on the general research of Paper Computing, which using the 3D information of paper as input and output interfaces. This section will review and compare *PaperIO* with these related works.

2.1 Paper as Input

The presented system is highly related to using paper material as an input medium based on hardware implementation. In order to overcome the shortage of computer-vision-based paper input, researchers started to explore the hardware based solution for 3D paper input. RFID [14] is one of the earlier hardware-based paper input technologies. However, it can only sense the presence of the paper-like tag, instead of more advanced information such as position and orientation. Yingdan Huang et al. [16] developed Easigami, a tangible user interface which embeds potentiometers on the edge of paper, so that users can construct different shapes of paper models by combining paper which is then reflected in a 3D virtual representation. In Pulp-based Computing [11], Marcelo Coelho et al. developed a paper-based bending sensor by infusing carbon resistive ink in between two layers of paper. Therefore, the resistance of the paper bending sensor would change while the paper is being bended. Byron Lahey et al. [1] developed PaperPhone, which is the combination of a flexible E-Ink display and a bending sensor connected to the external processing circuit. Paper-Phone allows users to navigate the digital content through a set of pre-defined bending gestures.

While the existing works in hardware-based paper input required complex processing circuit either embedded in or connected to the sensors and the paper material, *PaperIO* doesn't contain any complex circuit in the paper, besides the flat power receiving coils which are providing the 3D input. This fact simplifies the design of *PaperIO* sensors, and makes it possible for end-users to design and implement their own *PaperIO* sensors.

2.2 Paper as Output

PaperIO is also motivated by how to actuate paper output automatically. Greg Saul et al. [4] developed a set of interactive paper devices with embedded electronics, which can actuate light, sound and movement in paper. In these paper devices, conductive paths are inkjet-printed on the paper to form the complex schematics of circuits, and electrical components, such as microprocessor, speaker, and shape memory alloy, are soldered to the conductive paths. In Pulp-based Computing, the circuits are screen-printed on the paper material with components embedded during pulp making process. Using Pulp-based Computing and LilyPad [9], Jie Qi et al. developed Electronic Popables [5], the interactive pop-up books that integrates electronics and pop-up mechanisms as a complete user interface. Animated Paper [12] was presented as a versatile platform created from paper and shape memory alloy (SMA), which is easy to control using a range of different energy sources from sunlight to lasers. In Animated Paper, the paper craft attached with SMA can be controlled to move with a high-power laser pointer. More recently, AutoGami [7] was developed as one step forward for allowing end-users to create their own automated movable paper-craft.

In summary, there are three main contributions we claimed for *PaperIO* technology over existing paper interfaces. Firstly, compared to computer-vision-based paper input, *PaperIO* doesn't rely on any light condition, and it allows users to manipulate the paper with embedded receivers with hands directly and freely. These features overcome the disadvantage of lighting and hand-blocking. Secondly, while comparing with most of the existing hardware-based solutions for paper input and output, *PaperIO* utilizes the technology of selective inductive power transferring, and only simple coils are embedded in paper material. We believe these could enhance the tangibility and the customizability of the paper interface. Finally, in the technical aspect, *PaperIO* could provide a wide range of variations in the input of 3D information, including gradual changes in position and orientation, as shown in the experiments.

3 System Description

3.1 Overview of Theoretical Principle

The basic principle of *PaperIO* is based on the theory of inductive power transmission. As shown in Figure 1, the power receiving coil is connected to a capacitor C1, which tunes the resonant frequency of the receiving coil to a specific value, and a diode D1, which will be turned on only when the receiving coil is closed enough to the power transmitter for receiving enough power. When D1 is turned on, the negative part of the AC current in the receiving coil would be cut-off, and the receiving coil generates a new magnetic flux with almost twice of its resonant frequency. Therefore, the power feedback sensor with the capacitor C2 could sense the change of the magnetic flux, as its resonant frequency is tuned by C2 to the twice value of the resonant frequency of the power receiving coil.

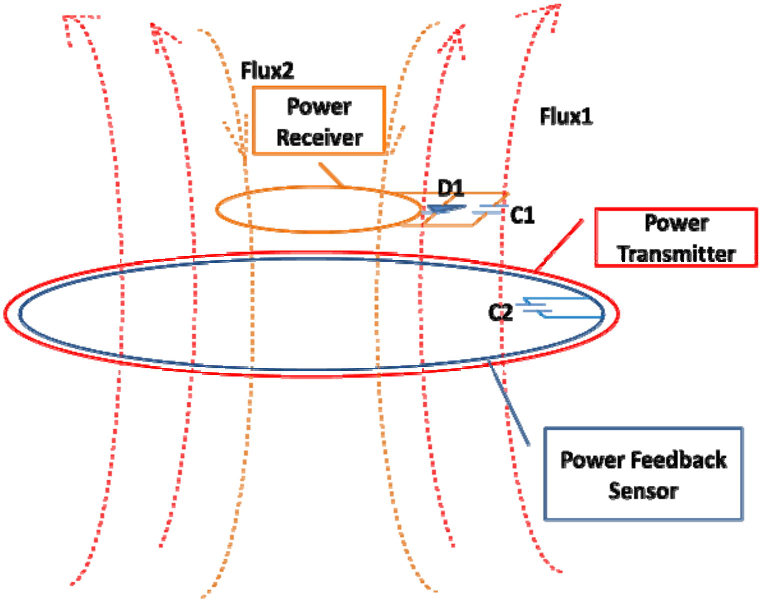


Fig. 1. Basic theoretical principle of *PaperIO*

The magnetic flux generated by the power receiver (Flux2 in Figure 1) would change when the power receiver's position and orientation are changed. Therefore, this sensor should be able distinguish the difference when the receiver is moving, and further enable it as a 3D input device. In addition, by controlling the value of C2, the power feedback sensor can have multiple resonant frequencies to differentiate the presence of different power receivers. Finally, receivers with simple actuators, such as shape memory alloy, embedded in paper material, make paper as both input and output devices.

3.2 Simulation

Based on the theoretical hypothesis described above, we first simulated *PaperIO* in SPICE software environment [10]. As shown in Figure 2, there are three resonant circuits in the schematic: transmitter (L1), receiver (L2) and feedback sensor (L3), while L1 and L2 are linked by coupling coefficient K1, L2 and L3 are linked by coupling coefficient K2, and L1 and L3 are linked by coupling coefficient K3. On the left side of the simulated schematic, the transmitting coil is excited by a sinusoid power source with the amplitude of 12V. For the purpose of simulation, we picked 510 kHz for the value of transmitting frequency. The transmitter is modeled as a two-turn coil (L1) with the diameter of 10cm and the resistance (R1), and the feedback sensor is modeled as a two-turn coil (L3) with the diameter of 5cm and the resistance (R2), and placed 2mm above L1. The right side of the schematic shows the model of power receiver, which is a 2-turns circular coil with the diameter of 5 cm, and it is connected to diode D1 and capacitor C1 for the resonant frequency of 510 kHz. In this model, we assume the closest distance between L1 and L2 is 1 cm. According to the equations in [8], we calculated the values of L1, L3 and K3 as shown in Figure 2. Additionally, Fast Fourier Transform (FFT) was employed to process and analyze the raw signal from the feedback sensor in the frequency domain in the simulation.

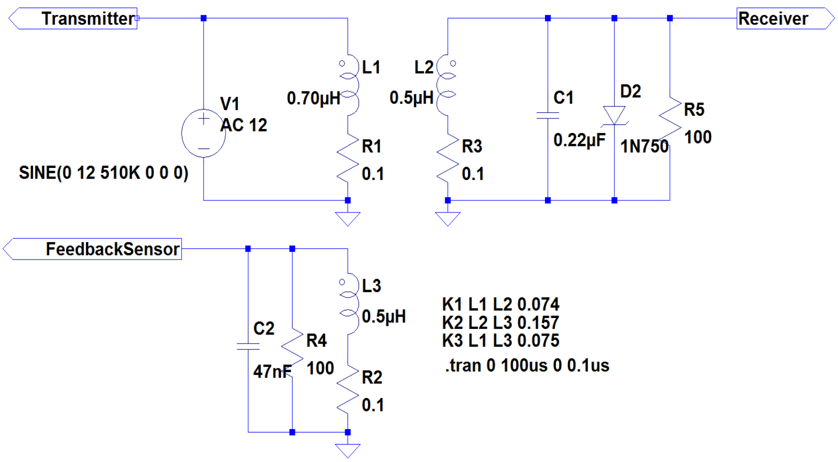
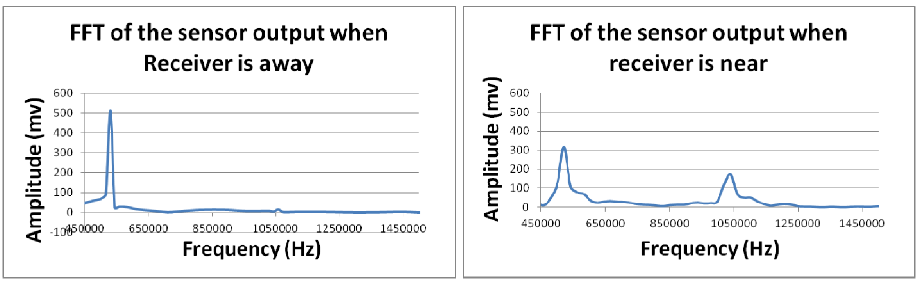


Fig. 2. Simulation Schematic for *PaperIO*

When the receiver is not present near the transmitter, there is only one active coupling K3 between the feedback sensor and the transmitter. The simulation results of this situation are shown in Figure 3(a), where the signal detected by the sensor only shows one peak value in the frequency domain at the frequency of 510 kHz. When the receiver is moving closer to the transmitter and the sensor, the coupling K1 and K3 are activated. The simulated results (Figure 3(b)) show that different values of amplitude occur in the frequency domain at the value of 1.02 MHz, which is twice of the value of the resonant frequency of the receiver.



(a) (b)

Fig. 3. (a) The FFT result of sensor signal when the receiver is away; (b) The FFT result of sensor signal when the receiver is near

When the values of K1 and K2 are changed, due to the change of the receiving coil's position or orientation, the amplitude at the frequency of 1.02 MHz would also change. Therefore, we can develop a circuit prototype to detect this value-changing in the frequency domain, and further map this change to the 3D information of the power receiving coil.

3.3 Hardware Implementation

Based on the theoretical hypothesis and the software simulation, we designed implemented the hardware prototype for detecting power feedback signal for *PaperIO*. For the first prototype of the feedback sensing coil, we designed its dimension similar to the power receiving coil with the diameter of 5cm, as shown in Figure 4, and it is installed 2mm above the transmitting coil. In order to detect different receiving coils in different frequency, the sensing coil is connected to an array of capacitors which would be controlled to switch on or off by the relays, to achieve different resonant frequencies.

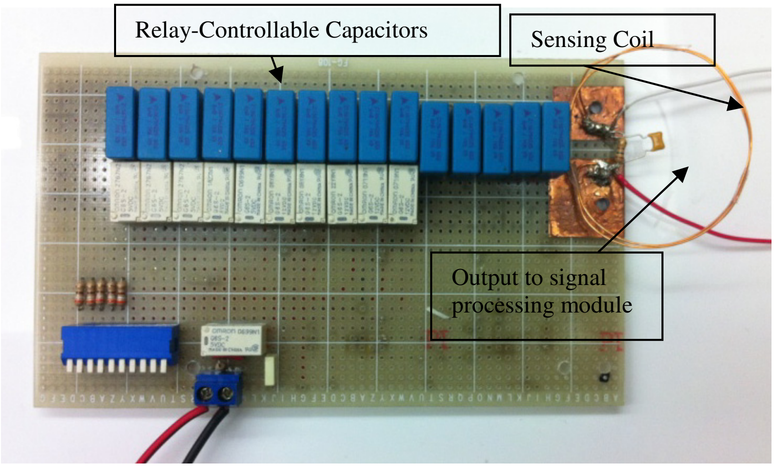


Fig. 4. Prototype of *PaperIO* sensing coil with controllable capacitors

In addition, a noise-reducing module is required in order to increase the robustness and the accuracy of the sensing coil. In the system diagram in Figure 5, the feedback sensor coil receives two different signals from the transmitting coil and the receiving coil, and only the signal with two-times frequency from the receiving coil is useful for the 3D input detection. Therefore, we designed the *PaperIO* Signal Processor module, as the core of the hardware system, to reduce the noise signal from the transmitting coil.

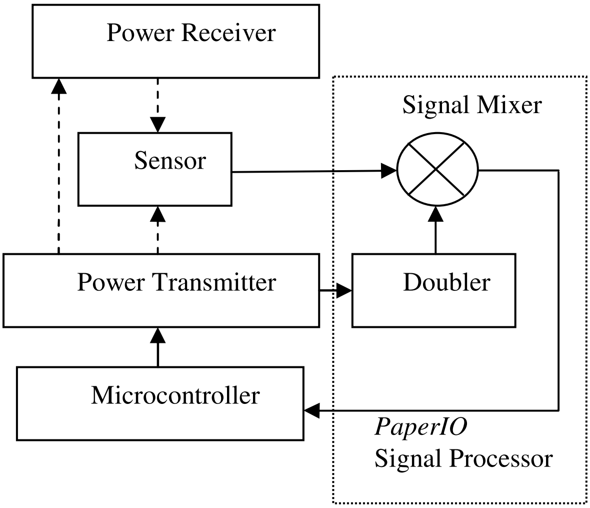


Fig. 5. System Diagram of *PaperIO*

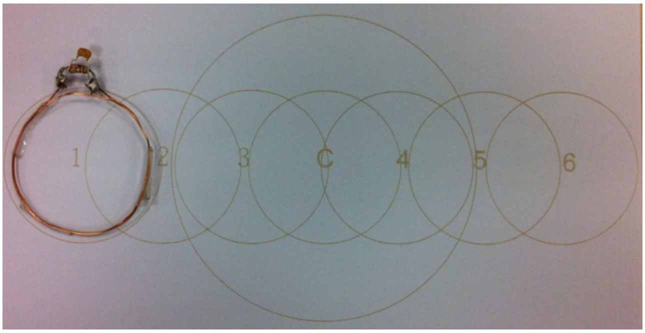
The *PaperIO* Signal Processor module contains two main units: the frequency doubler and the signal mixer. As the raw signal from the sensing coil is a mixed signal with the frequency whose value is twice of the transmitting frequency, a double-frequency signal is required, in order to reduce the noise using digital operational mixer circuit. The frequency doubler is designed based on the theory of Phase-Locked Loop (PLL), and the doubled signal is passed to one input of the signal mixer which is an operational subtractor, while the other input signal is the raw signal detected by the feedback sensing coil. Finally, the output result from the signal mixer is the signal detected only from the power receiving coil. Furthermore, the de-noised signal is passed to the anlog-to-digital module of the microcontroller to control the power transmitter.

4 Performance Experiment

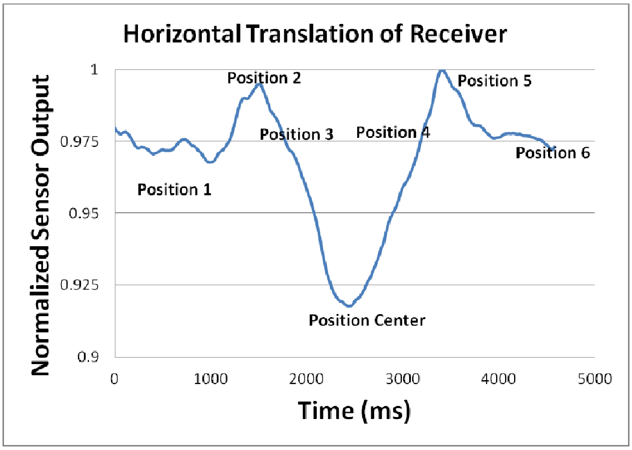
4.1 3D Input: Horizontal Translation

In the experiments of sensing the horizontal translation of the receiver, the target was to find out whether the sensor output would change when the receiver is moved on the horizontal level. The receiver was placed at the starting 1 positions not aligned with the sensor, as shown in Figure 6(a). During this experiment, the receiver was placed closed to the transmitter, and moved from the position 1 to position 6 through the center position for the distance of 15 cm, and the sensor output was recorded accordingly.

The results in Figure 6(b) show that the sensor gives different output when the receiver is at different horizontal positions. When the receiver is moving from center to the other position, the transient pattern of the sensor output can be recorded as the input for interactive systems. To be noted specially, when the receiver reached position 2 and position 5, the sensor output increased to higher than the output when the receiver was not presence, such as position 1 and position 6.



(a)

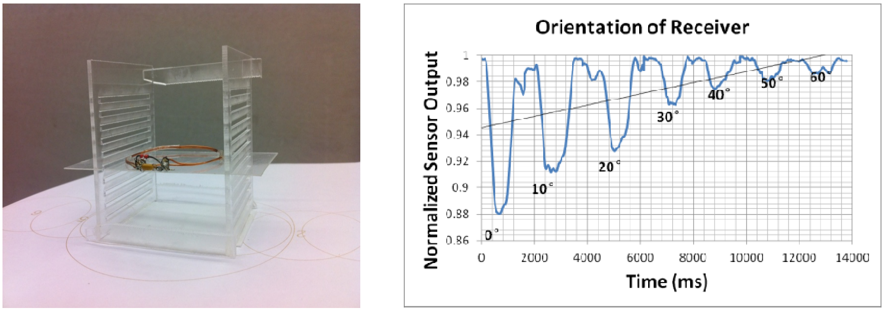


(b)

Fig. 6. (a) Experiment to detect the horizontal movement of receiver, (b) *Paperio* sensor output of the horizontal movement of receiver

4.2 3D Input: Vertical Translation

For the experiment of moving the receiver vertically, we aimed to determine to which height the receiver can be sensed by the sensor and different sensor output for different height of the receiver. The set-up of the experiment is shown in Figure 7(a). The acrylic box contains slots for inserting a flat and thin plastic sheet to hold the receiver at a certain height, and the vertical distance between two nearby slots is 5mm. This structure allowed us to control the vertical distance between the receiver and the sensor. When the distance was changed, the receiver was removed from the scene and placed back after changing the distance. In this experiment, the vertical distance was changed from 0mm to 20mm.



(a) (b)

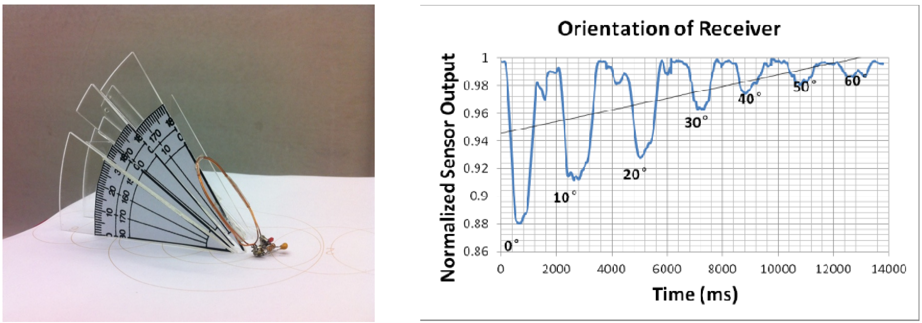
Fig. 7. (a) Experiment setup for sensing vertical translation of receiver; (b) *Paperio* sensor output of the vertical movement of receiver

Figure 7(b) illustrates the results of sensing the vertical translation of the receiver. The normalized sensor outputs were clearly distinguished as the receiver was placed at different height above the sensor. Therefore, the concept of using *PaperIO* as a height sensor is proofed.

4.3 3D Input: Orientation

For the setup of sensing the orientation angle of the receiving, a set of angle models with the specific values of 5º, 10º, 20º, and 30ºwere made using acrylic material as shown in Figure 8(a), and other values of angle can be realized by stacking these models together.

During this experiment, the angle model was placed on the surface right above the sensor, and the receiver was fixed on the model as shown in Figure 8(a). The model would be changed from 0º to 60º, in order to measure sensor output in different values of orientation angles of the receiving coil.



(a) (b)

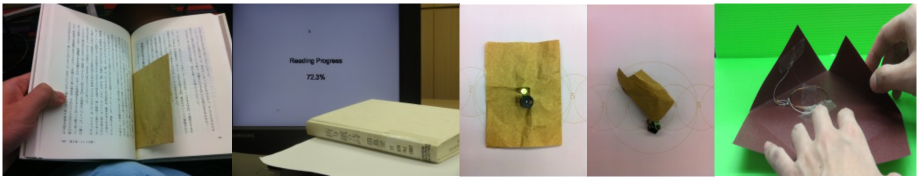
Fig. 8. (a) Experiment setup for sensing orientation of receiver, (b) *Paperio* sensor output of the tilting of receiver

The experimental result, as illustrated in Figure 8(b), shows that the output value of the sensor decreases when the receiver is present near the transmitter, and the output value increases along with the increase of the angle between the receiver and the transmitter. This provides a proof of concept that *PaperIO* can also be used as an orientation input.

In summary of the series of experiments for 3D information input using *PaperIO* technology, *PaperIO* is able to provide the distinguishable analog output continously according to the receiving coils' positions and orientations while it doesn't require explicit wire connection to the power receivers. Due to the flatness of the power receiving coils, *PaperIO* technology can be easily integrated with paper material to facilitate paper-based human computer interaction.

5 Example Interaction

For the application of *PaperIO* sensor, we focused in paper-based ubiquitous computing, mainly daily activities, gaming entertainment, and social networking. As the proof of concept, we designed four examples of the interaction, Paper Controller for Virtual Reality, Paper-based Digital Bookmark, Scrunch-able Paper Alarm, and Origami Interaction.



(a) (b) (c) (d) (e)

Fig. 9. (a) Using *Paperio* as a bookmark, (b) *Paperio* senses the reading progress of the book, (c) LED and speaker are turned on to alarm; (d) Scrunch to switch of the alarm, (e) Paper-folding sensor to trigger automatic folding

5.1 Paper-Based Digital Bookmark

As the *PaperIO* could indicate different height of the receiver, the paper sheet integrated with receiver could be inserted into a physical book as a piece of bookmark, to indicate the current reading progress, and connect the physical book with digital book library, as shown in Figure 9 (a) and Figure 9 (b).

5.2 Scrunch-able Paper Alarm

PaperIO interface provides the ability of controlling inductive power output by sensing the receivers, and allows users to destroy and remake them. As shown in Figure 9(c) and 9(d), the user can easily "destroy" the presence of the input receiver and stop the alarm by scrunching the paper alarm, if he or she is woken up or wants to continue sleeping.

5.3 Physical Origami Interaction

The ability of detecting the orientation of receiver makes *PaperIO* a origami-folding interface. As shown in Figure 9(e), the *PaperIO* sensor can detect the folding of one corner which contains a receiving coil being tilted due to the folding, and control the power transmitter to provide power to the receiver in the other part of the paper, to activate the connected shape memory alloy and trigger the automatic paper-folding. This origami interaction provides users a physical and tangible feedback of origami making, and gives the possibility of physical creative interface for origami co-designing between human and computer.

6 Discussion and Future Work

Since *PaperIO* is in the early stage of prototyping for the proof of concept, there are still a few limitations and space for improvement in the current system. Firstly, although the experiments showed that *PaperIO* could provide quite accurate results for the 3D information of the power receiving coils, the results are still affected by the environmental noise, either from the peripheral electromagnetic signals or from the unstable hand movements by the users. Therefore, a better noise-reducing module is required for more accurate results from the *PaperIO* system. Secondly, it is difficult for the current version of *PaperIO* to work as translation input and orientation input at the same time. Therefore, advanced interaction skills would be employed to support *PaperIO* interface.

In conclusion, we have developed *PaperIO*, a paper-based 3D I/O interface using the technology of selective inductive power transmission, and proved its performance through a series of hardware experiments. *PaperIO* is able to sense the 3D information of power receivers when they are closed to the power transmitter, and convert the input to further control the output of the power transmitter. In addition, *PaperIO* can be easily integrated with flexible paper material for paper-based human computer interaction. Various examples of interaction were presented as the proof of concept. We believe *PaperIO* provides a new venue for creating paper-based human computer interaction.

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