OrigamiSpeaker: Handcrafted Paper Speaker with Silver Nano-Particle Ink

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ABSTRACT

In this study, we present an OrigamiSpeaker which can be handcrafted with silver nano-particle ink on a paper substrate. The OrigamiSpeaker is based on the "electrostatic loudspeaker" technique. The audio signal is amplified to a high voltage and applied to an electrode that vibrates to generate sound. By using Origami techniques, users are able to design various shapes of OrigamiSpeaker.

CCS CONCEPTS

• **Human-centered computing** → **Auditory feedback**.

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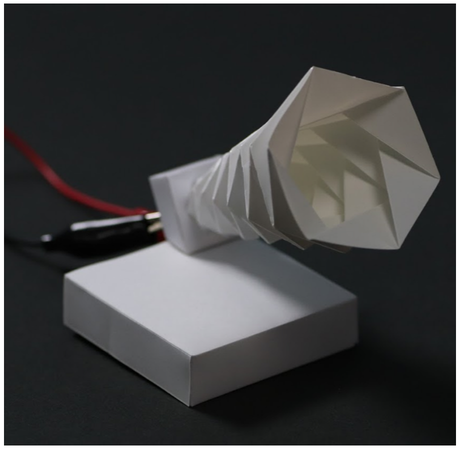

Figure 1: OrigamiSpeaker.

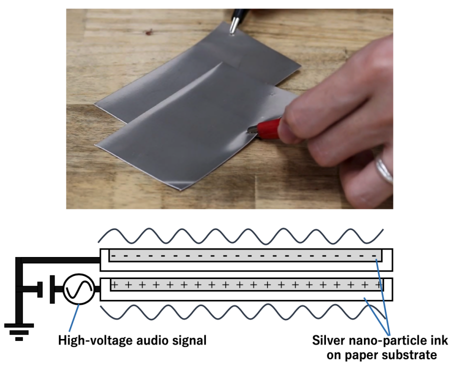

Figure 2: Basic structure of the OrigamiSpeaker.

KEYWORDS

Printed electronics; electrostatic loudspeaker; origami.

INTRODUCTION

Printed electronics have been utilized for the fabrication of functional devices and in prototyping techniques in the recently developed field of humanâĂŞcomputer interactions (HCI). Compared to the 3D printed plastic objects, the paper simplifies the handcrafting process for users (e.g., cutting, folding, and bending) and inspires creative expressions. Numerous studies have been published which utilized conductive ink for inkjet printing. Additionally, several studies focused on the fabrication process of the loudspeaker. Accordingly, some of these studies utilized common electromagnetic speakers with coil pattern electrodes and magnets [7, 8]. However, the use of physical magnets limits the degree of design freedom of flexible devices.

We focused on the electrostatic loudspeaker technique and its application for the printing of electronic devices. In addition, the Origami technique allowed the users to fabricate a variety of uniquely shaped speakers with printed electronics using simplified processes at a low cost. Figure 1 shows an application example of an OrigamiSpeaker. Furthermore, our method allows the construction of an interactive speaker that can generate sound only when the users touch the printed electrode.

RELATED WORKS

Fabrication of Uniquely Shaped Speakers

The development process of the loudspeaker has been the focus of numerous studies in the HCI community. Rowland et al. proposed the construction of a flexible speaker with flat conductive materials and magnetic strips [7]. Oh et al. proposed printed electronic papercrafts (PEP) [8]. One of the applications they developed was a loudspeaker with silver nanoparticle ink on a paper substrate. Compared to other relevant studies, the Origami speaker does not require a permanent magnetic attachment and be can easily fabricated with inkjet printing paper.

Ishiguro et al. proposed a method to develop interactive loudspeakers with a 3D printer [4]. electrostatic loudspeakers were realized with the application of conductive and insulating paint to 3D printed objects. In addition, the production of signals at ultrasonic frequencies allowed interactive functionalities. Ishiguro et al. also developed the “Uminari,” which is a free-form interactive speaker made from thin, flexible, conductive materials [3]. The implemented Uminari allowed spatial sound experiences from a variety of used surfaces.

Inspired by the previously conducted work outlined above, we utilized the electrostatic loudspeaker technique and applied it to construct printed electronics. In addition, use of the Origami structure allowed the construction of a variety of uniquely shaped speakers with printed electronics.

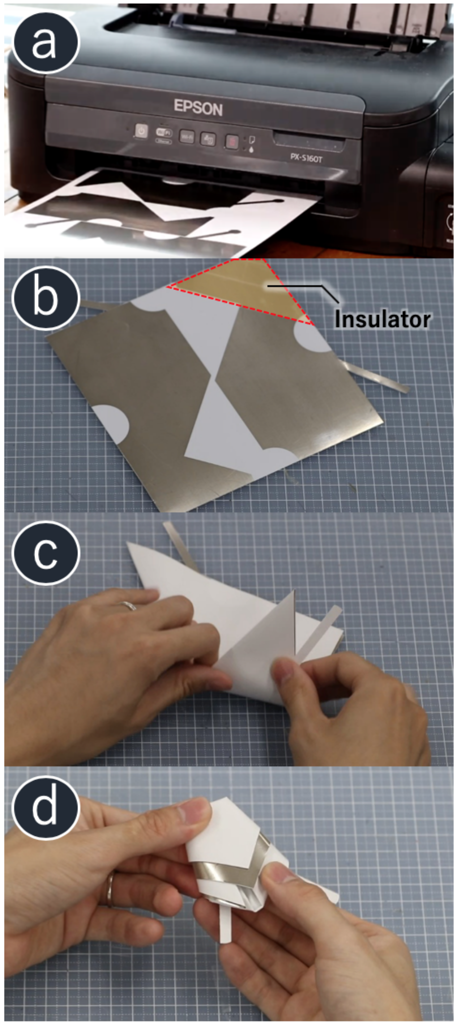

Figure 3: Fabrication process of the OrigamiSpeaker.

Conductive Ink

In recent years, numerous studies have utilized conductive ink for inkjet printing. Kawahara et al. proposed a fabrication technique for the construction of electrical circuits using silver nano-particle ink [6]. This technique is useful for the prototyping of electronic circuits and interactive devices, such as sensors [2], actuators [9], and tactile displays [5].

ORIGAMISPEAKER

We propose a method to create a speaker structure with conductive ink on a thin paper substrate. The OrigamiSpeaker is based on a technique referred to as *electrostatic loudspeaker*. Figure 2 shows the basic structure of the OrigamiSpeaker. The speaker consists of two charged electrodes that are printed with conductive ink. One electrode is connected to a high-voltage supply and the other is connected to the ground. The audio signal is amplified to a high voltage, which is then applied to the electrode that in turn vibrates to generate sound.

In our method, users handcraft speaker by bending printed electrodes on the thin paper substrate. Figure 3 shows the fabrication process of the OrigamiSpeaker. Two independent electrodes are printed on a square paper substrate (Figure 3(b)). One of the electrodes is connected to the ground and the other to a high-voltage source. In this example, we fabricated a cicada-shaped OrigamiSpeaker (Figure 3(d)). An insulator is partially placed on one conductor, and two other conductors are electrically disconnected. Additionally, when the user folds the paper, both electrodes make contact and form an electrostatic loudspeaker. Different shapes of electrode patterns are printed for different Origami designs.

The inkjet printer is an EPSON PX-S160T. The electrode patterns are printed with silver nano-particle ink (NBSIJ-MU01, Mitsubishi Paper Mills) on a special paper (NB-TP-3GU100, Mitsubishi Paper Mills) with a thickness of 270 Îijm. An insulating layer is formed with commercial tape (MP-18S, Scotch) on several electrodes. Instead of attaching the tape, we can also use the back side of the paper substrate as an insulation layer (Figure 2). The amplified audio signal is applied to each electrode with a high-voltage power supply (MHV 12-1.0K2000P, Bellnix Co., Ltd), which is controlled by a microcomputer (mbed LPC 1768, ARM Ltd).

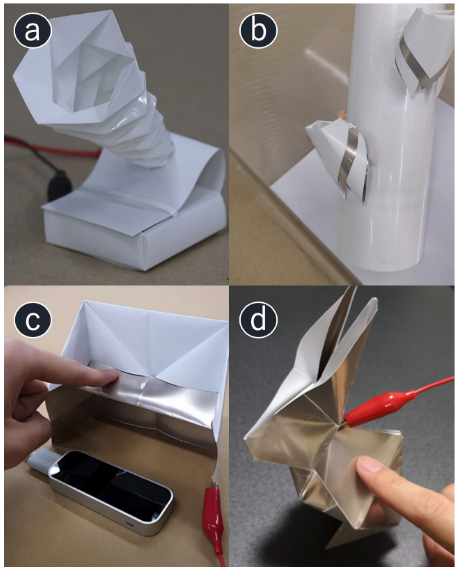

Figure 4: Application examples, (a) Origami horn speaker, (b) uniquely shaped speaker, (c) musical instrument interactive speaker, and (d) animal-shaped interactive speaker.

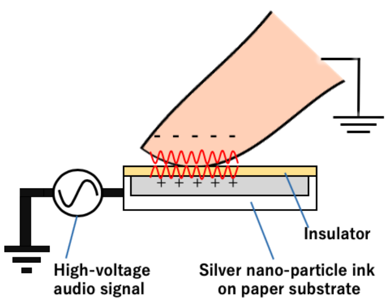

Figure 5: Principle of interactive speaker.

APPLICATIONS

In this section, we present applications of the proposed method.

Uniquely Designed Speaker

Figure 4(a) shows an example of a horn speaker. In this application, a speaker horn was fabricated according to the Origami structure design and was connected to a simple electrostatic loudspeaker.

Figure 4(b) shows the cicada-shaped OrigamiSpeaker. In this example, the same construction process described in Figure 3 was used. In effect, the speaker is created by bending a piece of the conductive pattern which is printed on a paper substrate. Audio signals of insect sounds are amplified to a high voltage and are applied to the Origami. In this way, the speaker generates sounds by itself. Using the Origami techniques, users are able to design various speakers with unique shapes (e.g., animals, insects, audio instruments, vehicles, among others).

Interactive Speaker

According to the method of the electrostatic loudspeaker, the sound cannot be generated unless the two electrodes which are connected to the high-voltage source and the ground are in contact. In other words, it is possible to create an interactive speaker that can generate sound only when the two electrodes are in contact with each other. In this section, we propose a method to generate sounds between the printed electrode and the user's finger (Figure 5). The design methodology of this speaker utilized a technique known as *electrovibration* [5]. This technique is often used for tactile displays that induce tactile sensation to the human skin. Thus, the surface of the human finger vibrates and ultimately causes the generation of sounds. Figure 4(c) shows an example of an instrument-shaped interactive speaker. In this example, different sounds are generated depending on the position of the human finger. In addition, this method also applied to the interactive speaker that generates sounds when the user rubs on the animal-shaped OrigamiSpeaker (Figure 4(d)). In consideration of the safety of the users, our system can apply a maximum current of 0.6 mA.

EVALUATION

In this section, we evaluated the performance of the OrigamiSpeaker using a simple sign input signal. We measured the frequency response of the simple inkjet-printed speaker. We printed two electrode patterns on the PET substrate sheet (NB-TP-3GU100, Mitsubishi Paper Mills). The electrode dimensions were 50 × 50 mm, and one of them was covered with a commercial tape for insulation (MP-18S, Scotch tape). The sound was measured with a conventional microphone (Shure, SM58) placed 10 cm away from the surface of the inkjet-printed speaker. The microphones were connected

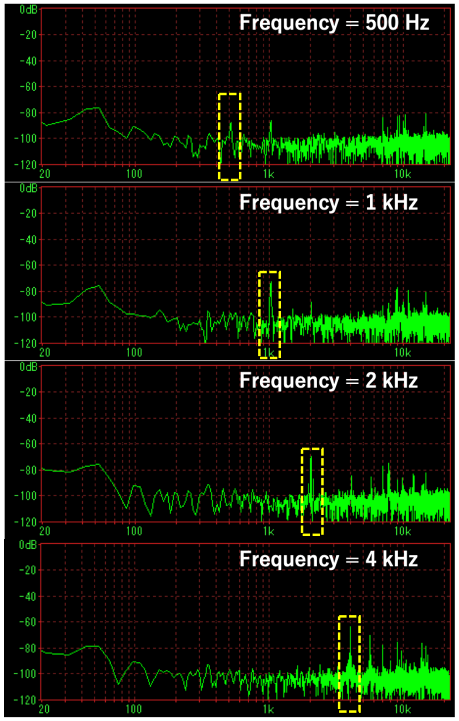

Figure 6: FFT spectra of electrostatic loudspeakers at 500 Hz, 1000 Hz, 2000 Hz, and 4000 Hz.

to a PC through audio equipment (ZOOM, UAC-2). We applied four different sine wave frequencies which were amplified to a high voltage (~600 V).

Figure 6 shows the fast Fourier transform (FFT) spectrum of the measured sound signal at 500 Hz, 1 kHz, 2 kHz, and 4 kHz. These results confirmed the existence of a sound with a small intensity, and the frequency of each sound can be identified except at 500 Hz. The distortion of the 500 Hz sine wave is similar to the measurements in the previous study [3].

The loudness level of the electrostatic loudspeaker is depended on the amplitude of the applied voltage. Our prototype, high-voltage power supply, can apply a maximum voltage of 600 V. Thus, the loudness problem can be improved by utilizing a more powerful power supply. We also confirmed that users can recognize acoustic sounds with the unaided normal human ear by applying various audio signals (e.g., music, or the calls of animals and insects).

We applied several signals to the OrigamiSpeaker. As a result, we confirmed that the loudness level also depended on the signal waveforms. For example, when we applied a pulse signal and controlled the pitch by changing the frequency, the sound was heard clearly compared to the application of an audio signal.

CONCLUSIONS

In this study, we proposed the OrigamiSpeaker. The Origami technique enables easy and inexpensive fabrication of a variety of uniquely shaped speakers with printed electronics. Compared to other related studies, the OrigamiSpeaker does not require permanent magnet attachments, and can be constructed with silver nano-particle ink on a paper substrate. Furthermore, our method can create an interactive speaker that can generate sounds only when the users touch the speaker.

Currently, we are designing electrode patterns with illustration software, such as the Adobe Illustrator. Future improvements will include design software that can automatically fabricate the suitable conductive pattern to create an electrostatic loudspeaker. We focused on the electrostatic loudspeaker technique and applied it to printed electronics. However, this method is limited because it requires a high-voltage power supply. We are currently considering the utilization of other techniques (e.g., speakers with piezoelectric ink [1]) to reduce the voltage of the audio signal.

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