3D Printed Interactive Speakers

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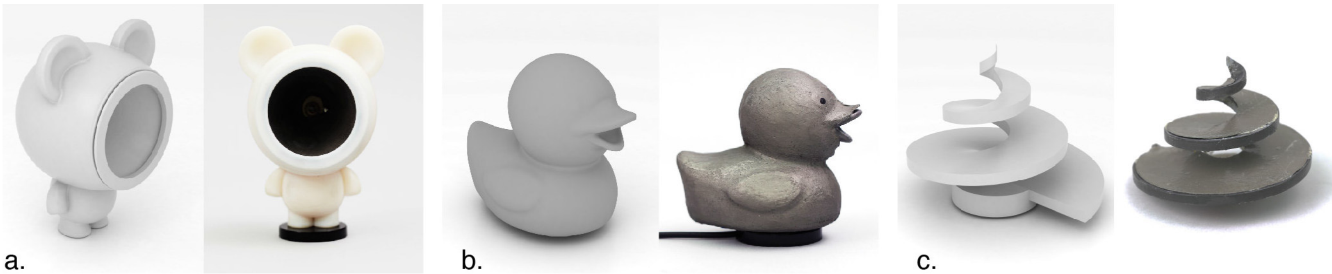

Figure 1. 3D printed speakers: (a) Speaker is embedded into toy (b) The entire 3D printed object is a speaker, (c) Printed speakers can have arbitrary geometries

ABSTRACT
We propose technology for designing and manufacturing interactive 3D printed speakers. With the proposed technology, sound reproduction can easily be integrated into various objects at the design stage and little assembly is required. The speaker can take the shape of anything from an abstract spiral to a rubber duck, opening new opportunities in product design. Furthermore, both audible sound and inaudible ultrasound can be produced with the same design, allowing for identifying and tracking 3D printed objects in space using common integrated microphones. The design of 3D printed speakers is based on electrostatic loudspeaker technology first explored in the early 1930s but not broadly applied until now. These speakers are simpler than common electromagnetic speakers, while allowing for sound reproduction at 60 dB levels with arbitrary directivity ranging from focused to omnidirectional. Our research of 3D printed speakers contributes to the growing body of work exploring functional 3D printing in interactive applications.

Author Keywords
3D printing; speakers; audio; ultrasonic; tracking; rapid prototyping; tangible; additive manufacturing

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INTRODUCTION
3D printing technology has expanded from being a tool for rapid prototyping of shapes to printing *functional objects*, including everything from providing a simple enclosure for a printed circuit board to replacing a broken airplane part [4]. Furthermore, with the development of sophisticated multi-material 3D printers [18,27] it is becoming possible to take the next step and fabricate not only passive mechanical components, but functional electromechanical devices as well. Here the shape and functionality are designed simultaneously and then fabricated in one step [18]. Although still in the early stages, recent research has demonstrated how functional Zn-air batteries, organic-polymer transistors and electromechanical relays can be fabricated using additive 3D fabrication techniques [17]. With the continued development of novel materials and 3D printing technologies [26], we believe that the capability to 3D print functional electrical circuits and conductive electrode surfaces as an integral part of a 3D printed object is within reach.

The importance of 3D printing techniques has been recognized in the human-computer interaction (HCI) community. There is a rapidly growing body of work that explores applications of this emerging fabrication technology, including the possibility of creating novel 3D printed interface controllers [9,23,28], of developing interactive tools for the design and rapid fabrication of interactive systems [13,20,22] and many others [2,5,14,28].

We, in particular, are inspired by the vision of a future where interactive devices are not assembled from mass-produced components, but rather designed and 3D printed on-demand locally as individual objects. The establishment of such a manufacturing technology would have a profound and lasting impact on the way future interfaces and interactive devices are designed and developed. It would introduce an unprecedented degree of personalization and customization and a much higher degree of interface components integration, which would allow for nearly arbitrary product geometries. Furthermore, the physical interfaces can be designed and re-designed in an ad-hoc manner by the end user in a way that may terrify professional product and interaction designers, but that could unleash unprecedented freedom and creativity within the broader user community. As noted in [28] the ability to "*... digitally fabricate high fidelity, highly customized, 'ready-to-go' devices will be a powerful enabling technology for HCI research.*"

In this paper we contribute to this vision by presenting the design, fabrication principles, experimental evaluation and some potential applications of an *interactive 3D printed loudspeaker.* The production of the 3D printed speaker is based on principles of *electrostatic sound reproduction* (ESR) which were investigated in depth as early as the 1930s [8] but have not been broadly used before today except in high performance audio systems [e.g. 29]. However, in the course of our research we discovered that there is a natural fit between 3D printing technology and ESR speaker design. Because of the simplicity of ESR, it allows us to design and fabricate speakers that are seamlessly integrated into physical objects of arbitrary geometries, including spherical and omnidirectional shapes. Furthermore, 3D printed speakers can produce both audible and ultrasound frequencies and, therefore, can provide tracking and object identification in addition to sound reproduction. Experimental evaluation demonstrates that our technology produces high quality sound at 60 dB levels. Figure 1 presents 3D speakers that we have designed and manufactured.

The current design and implementation of 3D printed speakers still requires manual steps because we are unable to access multi-material printers that are capable of printing with 3D print conductive polymers and inks [26]. Therefore, all conductive layers in our prototypes were painted using commodity conductive spray paints. However, the fundamental principles of the design and application of 3D printed speakers outlined in this paper are general and are not contingent on the limitations of technology available today. In the near future 3D printers capable of printing with conductive materials will become commonplace, and the vision of printing functional speakers embedded into objects with no human involvement will become the reality.

This paper's contributions are as follows:

1) We introduce the concept and implementation of 3D printed speakers, including the principles of their operation, as well as details of their design and fabrication;

2) We report their properties as well as results of our experimental evaluation of 3D printed speakers; and

3) We describe applications, advantages and limitations of 3D printed speaker technology, including their interactive applications, e.g., ultrasound tracking and identification.

RELATED WORK

In the last two decades there has been rapid growth in the application of print-based techniques in device manufacturing, including printing circuits using electro-conductive inks, printing transistors, microprocessors and even displays [3,6,10,16]. At the same time, free-form 3D printing technology based on additive fabrication techniques has been used to create both passive objects as well as integrated functional devices, such as actuators, relays, batteries and other items [17].

Recently, growing efforts have been focused on developing new materials and processes to 3D print integrated objects where enclosures, shapes, and functional elements (such as electronics, power, storage and optics) are all printed in one step. An example of such an effort is Printed Optics [28] that uses the Objet Eden260V multi-material printer to integrate custom optical elements, such as light pipe bundles, into passive 3D printed shapes. When combined with some minimal electrical components, it allows for the design of novel interactive display and input devices that are not feasible using any other current fabrication technology.

We are not aware of any previous attempt to investigate the fabrication of 3D printed speakers. *A loudspeaker* is one of the most fundamental output devices in interactive systems. It is a transducer that converts an input electrical signal into an audible acoustic signal. The most common speakers are based on electromagnetic and piezoelectric operational principles that have important limitations.

Electromagnetic speakers include a voice coil and a magnet, and the sound is generated by the vibration of a paper cone induced by moving the magnet. Electromagnetic speakers are relatively large and consist of multiple materials and moving parts. The shape of the electromagnetic speaker is usually limited to a classic cone or one of its variations. Although mass-produced speakers are relatively cheap, designing and producing custom speakers is expensive and requires a significant engineering effort. It would be difficult, if not impossible, to 3D print a functional electromagnetic speaker of an arbitrary shape.

Piezoelectric speakers consist of two electrodes with a thin piezoelectric element, e.g., lead zirconate titanate (PZT), sandwiched in between. As a signal is applied to the electrodes the piezoelectric element bends, producing an audible vibration. Although piezoelectric speakers are simple and inexpensive, they are produced by baking ceramic paste at very high temperatures. Therefore, it is difficult and expensive to produce them in anything other than a flat shape, particularly in small quantities. Increasing the size of the piezoelectric elements is particularly challenging because their audio response rapidly decreases with increased size and thickness. Piezoelectric speakers are also capable of creating *ultrasonic* sound sources and they are commonly used in designing various sensors.

Classic speaker technologies, by the very nature of sound production, place significant constraints on their form factors, thus limiting their application. It is relatively difficult and expensive, for example, to create *omnidirectional* speakers that produce sound equally in all directions. There have been many efforts to overcome the form factor limitations and produce alternative speaker designs. *Film speak-*

ers, for example, can be very thin, flexible and transparent. They are usually based on vibrating thin sheets of film with PZT or electroactive polymer actuators [25]. *Stretchable speakers* use silicon substrates and ionic conductors to produce audible sound [11]. *Cylindrical speakers* create omnidirectional sound by using PZT tubes [12] or arrays of transducers placed on cylindrical surfaces [1,24].

Currently one of the least commonly used techniques for sound production is *electrostatic loudspeaker* (ESL) technology which was intensively investigated in the early 1930s through 1950s [8,15,19]. ESL technology had certain limitations that inhibited its wider adoption, and we discuss them in the next section. Nevertheless, ESL technology has very attractive properties for 3D printing: it is very simple, it has almost no moving parts, and it can be made out of inexpensive common materials. ESL does not require complex assembly or involved production processes; in fact, speakers can easily be made at home by hand and can take various geometrical shapes. Electrostatic sound production forms the basic foundation of the 3D printed speaker technology we propose in this paper.

3D PRINTED SPEAKERS

This section presents the design of 3D printed free-form speakers based on *electrostatic sound reproduction principles* (ESR). It discusses the principles of their *operation and design* and then outlines the basic *categories of 3D printed speakers* investigated in this paper. We discuss the details of speaker fabrication techniques, their properties, and report on their experimental evaluation.

Electrostatic Sound Reproduction

The basic principles of electrostatic sound reproduction are simple and were explored in depth in the 1930s. A thin conductive diaphragm and an electrode plate are separated by insulating material, e.g., air, with the dielectric permittivity ε (Figure 2a). The audio signal is amplified to ~1000 V and applied to the electrode, charging it relative to the ground level that is connected to the diaphragm. As the electrode is charging, an electrostatic attraction force is developed between the electrode and diaphragm. According to Columb's Law this attractive force can be calculated as follows:

$$\vec{F} = \frac{q_1 q_2}{2\varepsilon S} = \frac{\varepsilon S V^2}{2d^2}, \tag{1}$$

where ε is permittivity, S is electrode surface size, d is distance and V is a potential difference between the electrode

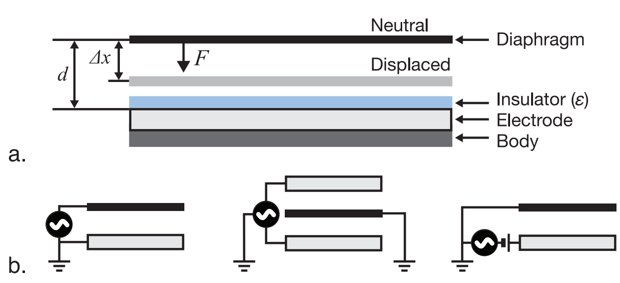

Figure 2. a) Construction of electrostatic speaker. b) Electrostatic speaker configurations

and the diaphragm [8,15]. This electrostatic force would deform or displace the diaphragm by Δx (Figure 2a) and, as an alternating audio signal is provided, the displaced air would create an audible signal. Thus, the diaphragm actuated with electrostatic force would create a speaker.

The sound quality of an ESR speaker depends on several factors. According to Equation 1, a larger surface, a higher insulator permittivity and a smaller distance between plates creates a stronger force, increasing both Δx and sound pressure levels. We cannot increase the size of the electrode and diaphragm indefinitely: a lighter diaphragm produces better speaker response. Therefore, a lighter speaker would by louder then a larger ESR device with a heavy diaphragm.

The ESR speaker forms a capacitor and, therefore, another key property is the electrical time constant τ, which defines how fast the induced charge builds on the capacitor plates:

$$\tau = C \cdot R = \frac{\varepsilon S R}{d}, \tag{2}$$

where R is the input impedance of the speaker. A larger τ would degrade speaker response at higher frequencies. The design of the speaker, therefore, is a question of tradeoffs between loudness and the frequency response.

It has been demonstrated that ESR speakers allow for high quality sound reproduction, outperforming traditional electromagnetic speakers in both high and medium sound frequency ranges [15]. Nevertheless, they have a number of limitations that inhibite their broad application. The sound reproduction industry was established in the 1930s, and high voltage amplification was difficult before the invention of the transistor. Even today, the selection of high-voltage audio drivers is very limited. Furthermore, achieving high sound volume in a living room, for example, depends on large diaphragms (~0.5m^2) with a uniform surface tension. This requires relatively high precision manufacturing, limiting ESL applications to the HiFi audio niche. These limitations, however, become significantly less crucial when ESR technology is used for low cost, low sound volume speakers embedded in toys and embodied interaction devices.

In the ESR speakers reported here we connect the ground to the diaphragm and the audio signal to the electrode (Figure 2b right). This is contrary to the ESR speaker design proposed previously [8,15], where the signal was connected to the diaphragm or a two-electrode configuration was used (Figure 2b left and middle). In designing home audio speakers the choice is irrelevant. However, it becomes important in 3D printed speakers embedded in toys and objects that can be touched by the user. The grounded diaphragm protects the user touching the speaker from the high-voltage audio source, making it safe to handle and manipulate the object with embedded speakers. This becomes particularly important in the interactive applications that we describe later in the paper.

Designing 3D Printed Speakers

The overall design of 3D printed speakers is presented in Figure 3 using the example of a toy character with an inte-

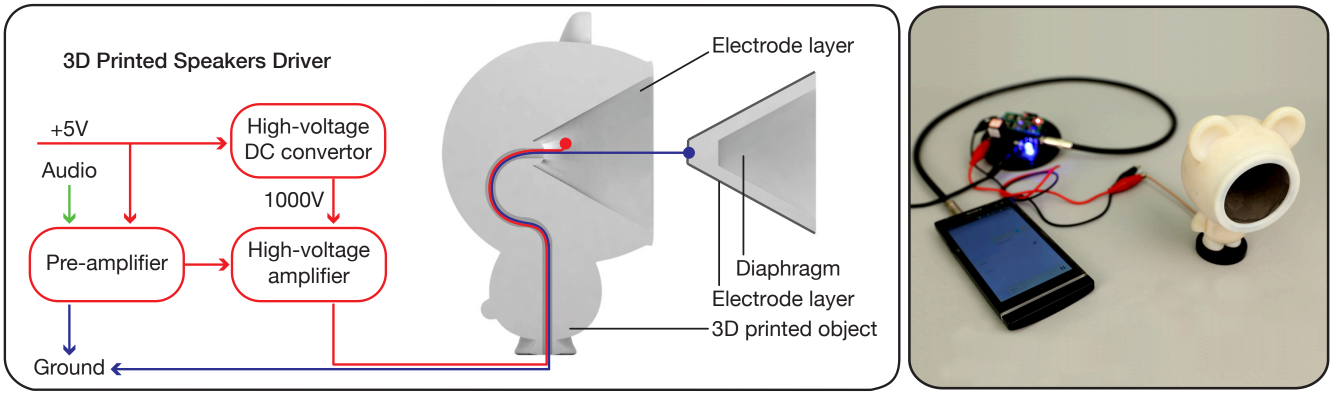

Figure 3. 3D printed speaker system diagram, here the speaker is integrated into the toy character

grated speaker. The body of the toy is 3D printed using currently available 3D printing technology. In our case, we used an Objet Eden260V 3D printer with triple material printing head. However, it is not capable of printing conductive materials, and thus was supplemented with a nickel-based conductive spray paint (MG Chemicals Super Shield™ Nickel conductive coating). Painting conductive layers is a simple procedure; it will become unnecessary when printing heads capable of printing conductive materials become available. In the future the painting process will be eliminated altogether.

The conductive layer painted on the body of the toy becomes an inner electrode layer where the audio signal in injected (Figure 3). The sound-producing diaphragm is then 3D printed and painted with conductive paint as well. In addition, it is also coated with a silicone-based coating spray (TechSpray® 2102-12S) that insulates the electrode and sound-making diaphragm. The diaphragm is next inserted into the toy and held in place using the 3D-printed connector ring. The diaphragm and painted electrode are finally connected to both the ground and audio outputs of the custom-designed high-voltage audio driver.

The *audio driver* for printed speakers amplifies the input audio signal from nominal amplitude (~1.0 V peak-to-peak) to 1000 V peak-to-peak signal by using a high-voltage transistor amplification circuit. A miniature step-up converter (EMCO QH10-5) boosts voltage from 5 V DC to 1000 V DC, which is used as a voltage source for the transistor amplifier. The output current of the voltage converter and, therefore, the audio driver is ~1.25 mA. The entire driver runs at 5 V DC and consumes 250 mA maximum current.

Air electrical breakdown can occur between high-voltage traces [21]. Therefore, it is important that an appropriate distance (> 1 mm) is maintained between all high-voltage traces and connectors on the controller board. In addition, silicone-based insulator spray can be used to improve the insulation between the contacts.

The implemented printed speaker system is presented in Figure 3 on the right. It can operate using either a standard Li-Ion battery or a USB connection. It accepts any standard audio source, such as a mobile phone.

3D Printed Speakers Design Space

3D printed speakers can take a variety of forms and shapes leading to many unique applications. Figure 4 explores some of the forms that become possible with printed speaker technology. It is obvious that we can create traditional flat planer speakers (Figure 4, top) that are common today and that have been explored before. Therefore, we do not explore this category of speaker in this paper.

At the next level of complexity speakers can take a variety of basic 3D geometrical shapes including traditional cone-shaped speakers, cylindrical, spherical and others (Figure 4, middle). All these shapes produce sound in all directions around the speaker, i.e., omnidirectional sound production. Note that designing 3D geometrical speakers using traditional speaker technologies is challenging. Using our 3D printed speaker approach, however, designing various geometrical speakers is a relatively trivial problem. We will discuss it later in the paper.

The most challenging and important aspect of 3D printed speakers is that they can be integrated into objects of arbitrary shapes, becoming an unobtrusive and invisible part of their design (Figure 4, bottom). 3D printed speaker technology provides an alternative to traditional techniques of integrating loudspeaker functionality into objects and devices.

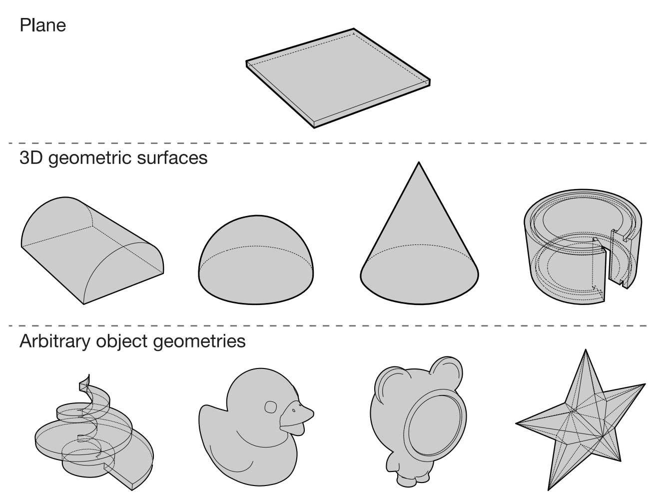

Figure 4. 3D printed speakers design space

Here speakers take arbitrary shapes making them an integral part of the object. In some cases only parts of an object may have speaker functionality and in other cases the entire body of the object generates sound.

Diaphragm Design for 3D Printed Speakers

The key factor influencing the sound quality of printed speakers is *the design of the diaphragm*. Figure 5 presents the results of the displacement measurements for two 3D printed diaphragms with the thicknesses of 1.0 mm and 0.5 mm and weighing 5.94 g and 3.65 g, respectively, driven by a 100 Hz sinusoid signal. The Keyence® LK-H057 laser displacement sensor is used to measure the movement of the diaphragm at a 20 kHz sampling rate with 0.025 µm accuracy. In addition to displacement, an Extech® 407730 Sound Level Meter (SLM) is used to measure sound pressure levels (SPL) 30 cm away from the speaker.

The experiments demonstrate that a) printed speakers work as designed, and b) lighter and thinner diaphragms produce significantly larger displacement and therefore louder sound. In fact, the displacement nearly doubles when we decrease the thickness of the diaphragm by half. The emitted speaker energy increases with the increase of the displacement, which is supported by the measurements that resulted in 54.8 dB_{SPL} and 53.2 dB_{SPL} for 0.5 mm and 1.0 mm diaphragms using 2 kHz input signal.

The latter observation, while seeming straightforward, is not obvious. As diaphragms become thinner, they also become much more flexible. Initially it was not clear to us that thinner, yet more flexible, diaphragms would outperform slightly thicker and stiffer ones. The experiments demonstrate that the stiffness of a diaphragm is not as important as its thickness and weight. This finding allows us to significantly expand the range of materials and processes that may be used to create effective diaphragms for 3D printed speakers.

Directionality and Geometry of 3D Printed Speakers

Printed speakers allow for transforming the surface of an object into a sound producing device. Among other things, this allows us to design speakers that have either highly directive or, adversely, omnidirectional sound. This is a unique and exciting property of ESR speaker technology.

Indeed, designing speakers that are either highly directive or omnidirectional is a challenging problem. It usually requires designing speaker arrays where each speaker has to be individually controlled and calibrated, both of which are expensive and labor intensive. In the case of 3D printed speakers, the entire surface of an object contributes to sound production. The sound direction is normal to the diaphragm geometry [25]. Therefore, the directionality of sound can be partially controlled by the object's surface geometry.

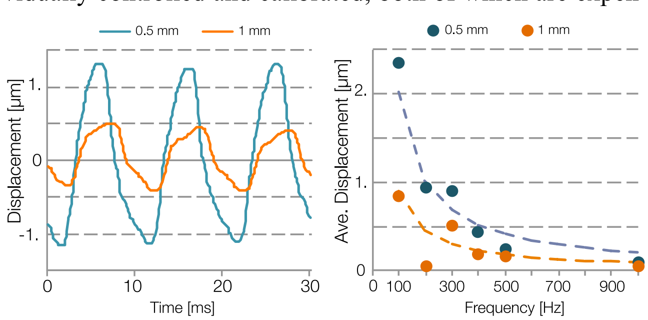

Figure 5. Displacements of 3D printed diaphragms.

To investigate this observation, four speaker shapes are designed, including a classic speaker *cone*, a *half cylinder*, a *full cylinder* and a *slit* speaker where the vibrating diaphragm is inside (Figure 6). The diaphragm area for all speakers is kept constant at 5625 mm^2. Common aluminum metallized polyester film is used for diaphragms. Metalized polyester offers an inexpensive and easy to use alternative to 3D printed diaphragms for simple geometrical shapes: it is light, durable, thin (~0.127 mm) and easily accessible.

We evaluated the directionality of each printed speaker using input signal frequencies at 2 kHz and 10 kHz. A printed speaker is placed on a laser-cut experimental base plate with engraved registration marks for sound level meter (SLM) locations. We move the SLM by hand between measurements. The duration of measurements are 5 sec for each SLM location. Because the sound pressure produced by small printed speakers is relatively low, the measurement volume is small (~1m^3). Therefore, we are able to isolate the experimental setup from the environment noise by carefully shielding the measurement apparatus with accessible soundproof materials.

Figure 6 shows the results of the SPL measurements at different angles for each of the 3D printed speakers. The graph is normalized in relation to the sound pressure levels at 0 degrees and plotted with a 22.5 degree interval. The results of the measurement demonstrate that sound directionality is indeed defined by the surface geometry of the printed speaker. Each point of the diaphragm emits sound in an approximately normal direction, as is expected. The directionality is stronger at higher frequencies, which is also expected. We are particularly impressed with 3D printed cylindrical speakers: the sound distribution is nearly perfectly uniform (Figure 6d), making a relatively high quality yet very inexpensive omnidirectional speaker.

The *slit speaker* allows for the production of directional sound and is presented on Figure 7. Note that we were not able to measure sound pressure levels in 90° – 270° diapason at 10 kHz because the sound pressure levels were below the SPL sensitivity thresholds. A 3D printed slit speaker provides a very useful configuration where the speaker has to be placed inside of the object, e.g., inside of a toy character with a mouth opening. This creates the impression of sound coming directly from the character's mouth – increasing both realism and engagement. Furthermore, the slit design protects the user from the electrical circuitry.

Electrode Arrays in Printed Speakers

3D printed speakers can be designed with any electrode configuration and number of electrodes. In the case of electrode arrays, each electrode acts as an *independent 3D printed speaker*, even though all of them share a single diaphragm.

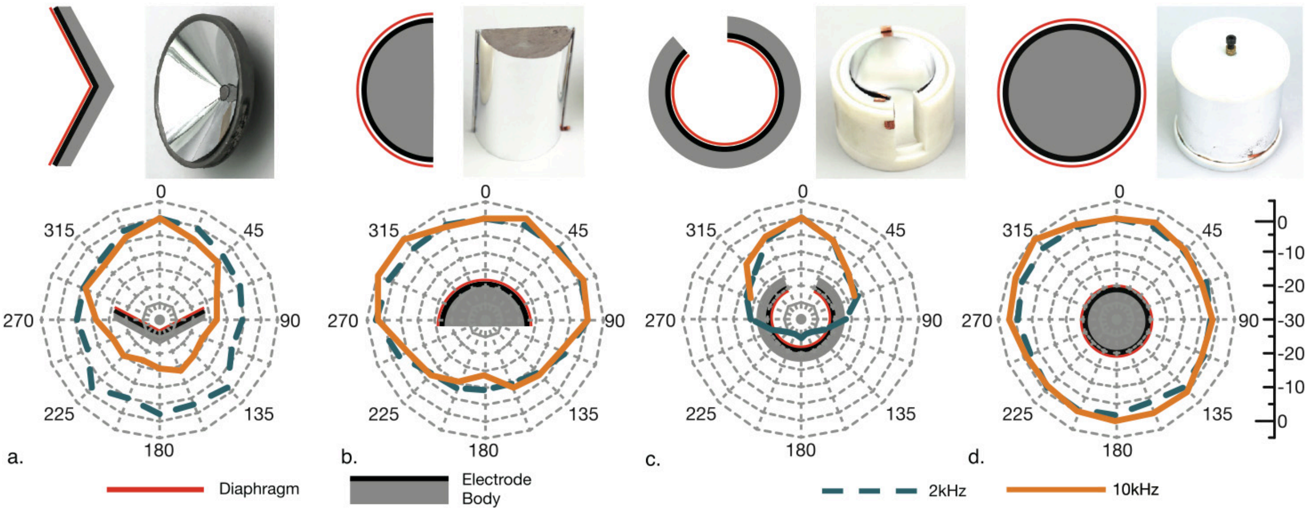

Figure 6. Directionality and geometry of 3D printed speakers.

To test 3D printed electrode arrays we measured sound pressure level distributions for a half cylindrical speaker with painted electrodes at 20^o – 90^o, 30^o – 330^o and 340^o – 270^o degrees (Figure 8). A single metalized polyester diaphragm is used as in previous experiments (Figure 6b). The same measurement setup is used in the directionality measurements reported above.

Figure 8 shows the measurement results using a 2 kHz input signal for each electrode. We can clearly observe that each painted electrode produces directive sound output in its respective direction. This demonstrates the versatility of printed speaker technology: A single object can have multiple electrodes sharing the same diaphragm and yet acting as individual speakers, with individual and directive sound output. Location-based audio displays, both on a small-object scale and on the scale of entire environments, can be easily created using 3D printed speakers.

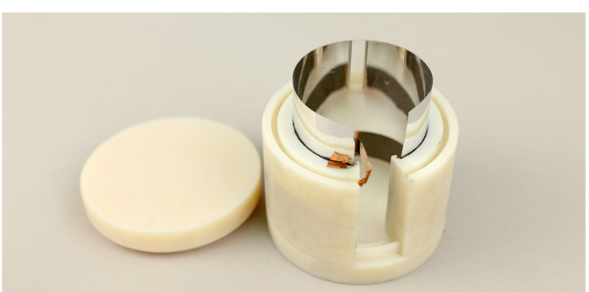

Figure 7. The design of a slit printed speaker

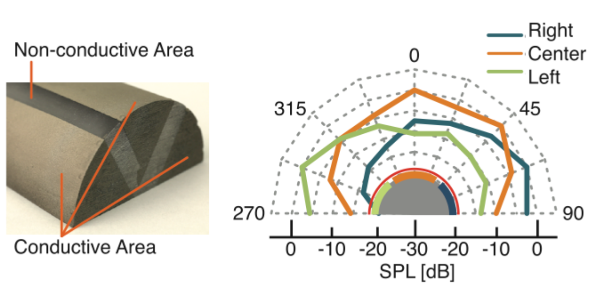

Figure 8. Multi-electrode 3D printed speakers

Integrating 3D Printed Speakers into Objects

The vision behind 3D printed speakers is the integration of loudspeaker functionality into objects at the design stage. Although our current prototypes presently require a certain amount of hand assembly, in the future we envision designers picking and dropping speakers into objects and devices as one of the elements of their CAD programs [28]. In this section we investigate possible means for integrating loudspeaker functionality into objects.

The most straightforward way to integrate speaker functionality into an object is to simply place one of the basic geometrical speakers (Figure 4) into the appropriate place in the object. As an example of this approach we created a toy bear with a speaker embedded within the head (Figure 1, 3). Such integration is trivial and any of the geometric speaker shapes can be used. The disadvantage of this approach is that the speaker is visible and, although the design process is simplified, from the user's perspective there is no difference between the printed speaker and a traditional speaker.

An alternative approach to embedding the speaker is to enhance the actual body of the object with loudspeaker functionality: the entire object's surface or any part of it would become the speaker, seamless and invisible to the user. In the simplest approach, only the *parts of the object surface* that can be augmented with 3D printed diaphragms would be, turning the object into the speaker. Figure 9 demonstrates a *Spiral Speaker*. The 3D printed diaphragm is shown on the left and an assembled speaker is shown on the right. The diaphragm is attached on the speaker body using a soft silicon compound. Similarly, any other object that has any number of flat faces can be easily turned into a speaker. Thus, we can imagine toys, decorations, household items and other objects augmented with loudspeaker functionality.

Another approach to augment objects with loudspeaker functionality is to turn the entire body of the object into a

Figure 9. 3D printed Spiral Speaker.

Figure 10. 3D printed Duck Speaker.

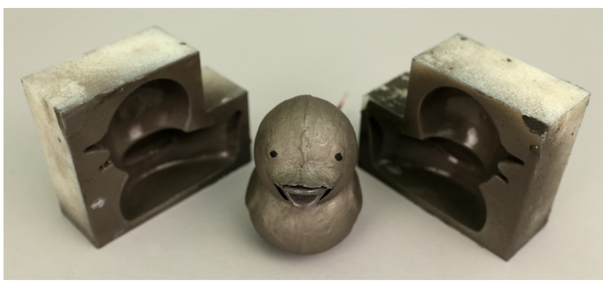

Figure 11. Thin film diaphragm fabrication.

speaker by covering the object with the diaphragm. Figure 10 demonstrates a *Duck Speaker* where the entire 3D printed duck toy is wrapped in a compliant diaphragm, creating one *single* sound-emitting surface.

The challenge in designing full body object speakers is creating a diaphragm that is thin, robust and covers the entire body of the object. The experimental evaluation reported earlier in the paper has demonstrated that a thinner and softer diaphragm produces louder sound pressure levels. However, the minimum thickness of a 3D printed diaphragm using our Objet printer is limited to ~0.3 mm, resulting in a relatively heavy diaphragm, reducing sound levels.

In order to create thin, reliable, full-body object compliant diaphragms we developed a new fabrication procedure that uses film coatings and molds to create diaphragms that are ~0.14 mm thin and weigh 1.1 g. Figure 12 demonstrates the process. First, negative molds are 3D printed using the same CAD model as for the object (Figure 11). Then both the mold and the object are sprayed with nickel-based conductive paint. The mold is then coated with polyethylene coating spray (3M Paint Defender™ Spray Film), forming a thin soft film bonded to the conductive paint (Figure 12c).

The polyethylene coating spray is a poor insulator inappropriate for high-voltage applications. Therefore, the object body is then coated with a silicone-based insulation spray over the nickel-based paint layer. We fast dry the molds in an oven and carefully remove the formed film from the mold (Figure 12d). The resulting diaphragm is strong, conductive, thin, and mirrors the object shape. It is used to cover the entire body of the object, turning it into a speaker.

INTERACTIVE USES OF 3D PRINTED SPEAKERS

The basic purpose of 3D printed speakers is to produce an effective sound display. In addition, however, 3D printed speakers also allow for additional interactive functionality that we discuss in this section.

Ultrasonic Tracking and Identification

Figure 13 demonstrates the frequency response of cone-shaped 3D printed speakers. It shows that they can effectively reproduce sound over 20 kHz, i.e., in ultrasonic frequencies. Thus, objects enhanced with 3D printed speakers can both output audible sound and produce signals at ultrasonic frequencies that can be used for lightweight *data transmission* and *object tracking*.

To make a compact audio driver we use a small high-voltage regulator with current-limited output. Therefore, there is an amplitude drop at ultrasonic frequencies (Figure 13). This is because, with the increase of signal frequency, the impedance drops and the regulator cannot support the subsequent current increase. A larger 3W high-voltage power supply allows for a nearly flat response. However, we have found that for short-range tracking and data transmission the ultrasound signal produced with printed speakers is efficient even with lower signal amplitude.

We explored two interactive applications of printed speakers that are enabled by their ultrasonic capabilities. These consist of lightweight *character identification* in a storytelling application and *distance tracking* between a computer and a 3D printed character. In both applications no additional equipment has to be provided: we use a standard microphone embedded in the laptop computer.

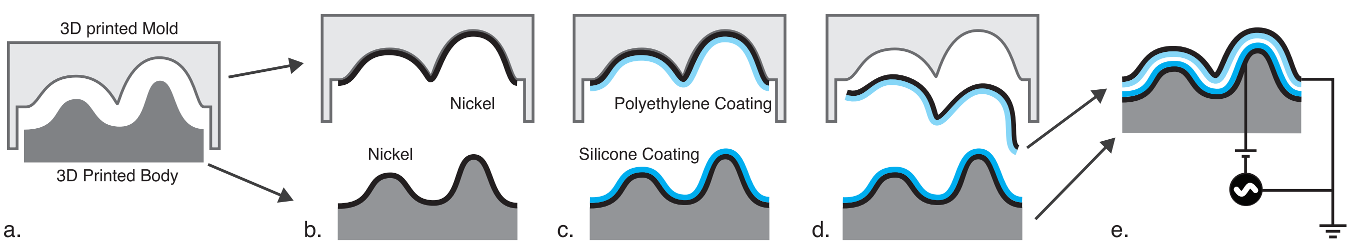

Figure 12. Fabrication process of thin-film diaphragms.

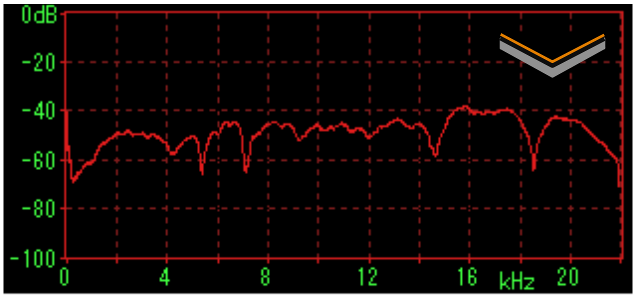

Figure 13. The frequency response of printed speakers.

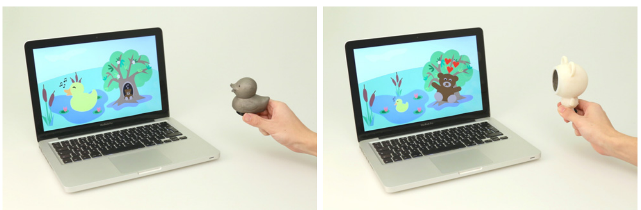

Figure 14. Character identification.

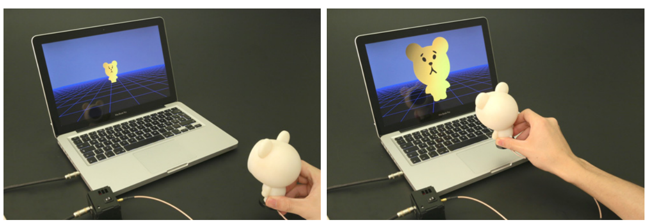

Figure 15. Distance tracking.

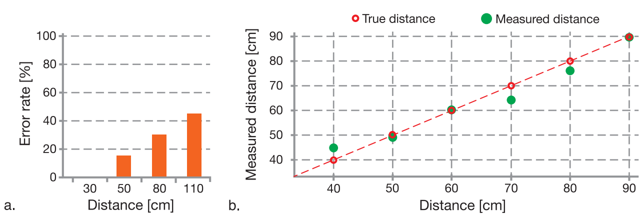

Figure 16. a) Identification error
b) Distance measurement error

Character identification

The ultrasound Frequency Shift Keying (FSK) modulation is used to create unique object IDs for two 3D printed characters: a duck and a bear. The FSK ID is an 8-bit long ASCII code and has no parity bits. When the user brings characters within ~1m of the computer microphone, the application software detects a modulated ultrasound signal, decodes the character ID and presents feedback by animating the appropriate cartoon character on the screen (Figure 14). Note that no physical connection between the computer and character is required, i.e., character identification can be completely ad hoc.

Figure 16a presents the results of identification error measurements for the bear-shaped speaker at 30, 50, 80 and 110 cm distance of the computer microphone. The character ID is sent 20 times with a 500ms interval for each test distance. The measured error rate is approximately 0, 15, 30, and 45 percent at each distance, respectively. It also means that we can achieve 100 percent accuracy when all 20 measurements are used for object identification. The experiments demonstrate that at close distances (~1m) the object identification is effective and can be significantly improved by introducing data redundancy and error correction codes. The error rate is also affected by the speaker orientation and can be minimized by using an omnidirectional design.

Distance tracking

The 3D printed bear toy is used to implement and evaluate ultrasonic distance tracking (Figure 15). The bear is connected to the computer, which outputs a 20KHz ultrasonic impulse on the embedded 3D printed speaker. The application software detects the impulse by using a built-in microphone and Discrete Fourier Transform (DFT), then measures the time difference between the initial and returned impulses and calculates the distance. The resulting distance can then be used for 3D interaction and gesture recognition, games and storytelling applications.

Figure 16b presents the results of preliminary distance error measurements for the bear-shaped speaker at various distances from the computer microphone. The tracking impulse signal is outputted 30 times at each position. The root mean square error of tracking is 3.83 cm and standard deviation is 4.04. The tracking accuracy is sufficient for most of the envisioned interactive applications. We believe that, with better data processing and low-level optimization of the internal audio processing, the tracking error can be reduced to a minimum. Furthermore, with the improved performance more detailed and rich gesture interaction can potentially be implemented, for example, by using the Doppler effect [7]. A stereo microphone or a microphone array would allow for the tracking of the 3D position of the character with the embedded 3D printed speaker. We are electing to leave this research for future work.

Touchable and Tactile Feedback

A 3D printed speaker can be touched and held by the users and still function effectively as a speaker. In ESR speakers the entire thin, elastic diaphragm participates in creating sound and, therefore, even when users touch and hold some part of the diaphragm, the rest of it still functions as a speaker (see Figure 17).

We measure the effect of touching and holding a 3D printed cone speaker on sound output levels at different frequencies. Figure 18 presents the measurement for no touch, pinching with three fingers and full hand contact conditions. The data show that the effect of a single digit touching the speaker is negligible, and, indeed, during the experiments we were unable to hear any discernable difference. When a whole hand is placed on the speaker the sound pressure level drops ~10dB on average, which is expected. Indeed, any sound source is muffled when covered with a human hand.

This property of ESR printed speakers is quite unique, as the same does not hold true for traditional electromagnetic loudspeakers. In electromagnetic speakers only the voice coil vibrates, other speaker parts are passive, solely transfer-

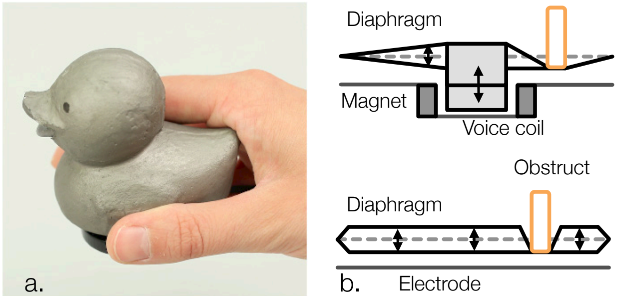

Figure 17. The diaphragm can vibrate when user holds an object creating effective tactile feedback.

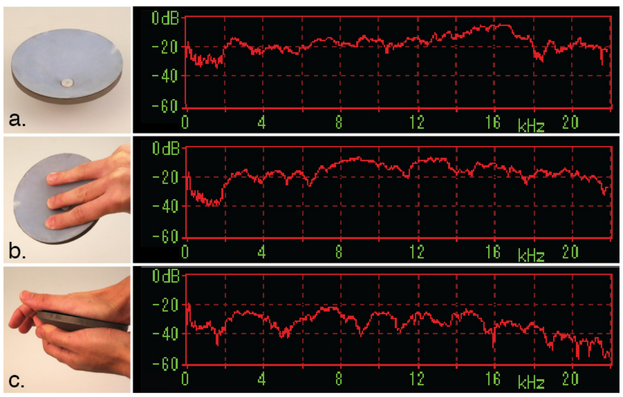

Figure 18. Printed speaker performance when touched by the user: a) no touch, b) three finger pinch and c) holding with both hands.

ring and amplifying these vibration forces. Therefore, touching the diaphragm of an electromagnetic speaker *anywhere* significantly impedes its operation (Figure 17).

The fact that printed speakers can be touched and held in the hand means that we can use them to communicate simple tactile feedback to the user. In our early tests we discovered that the user can clearly feel bursts of signals at the 20 ~ 120 Hz frequency range. We will investigate this exciting and unique property of printed speakers in future work.

DISCUSSION AND CONCLUSIONS

This paper reports on the design and investigation of 3D printed speaker technology based on electrostatic sound reproduction principles. Experimental evaluation of 3D printed speakers demonstrates that, among other things:

1. It is possible to produce audible sound with a broad range of speaker geometries at about 60 dB_{SPL};

2. We can effectively control the directivity of sound by changing the shape of the speakers and using various electrode arrays;

3. Multiple speaker shapes can be designed and embedded into objects and devices;

4. 3D printed speakers provide unique interaction properties, such as tracking and identification using ultrasonic frequencies;

5. Speakers can be touched and manipulated by the user's hand without a noticeable decrease in speaker sound quality, providing the possibility for simple tactile feedback; and

6. The resulting speakers are simple, inexpensive, low powered and can be run from a battery.

There are also a number of *limitations* of 3D printed speaker technology that warrant further research efforts:

First, the current implementation of 3D printed speakers requires manual assembly. 3D printers that are capable of printing with conductive materials are not accessible at this moment. However, the principles of the design and application of 3D printed speakers are general and scalable. They do not depend on the limitations of current technology. We believe that in the near future 3D printers capable of printing with conductive materials will become commonplace, and the vision of 3D printed speakers will become a reality.

Second, although a large variety of shapes can be used to make effective 3D printed speakers, there are also limitations. The most critical limitation is avoiding shapes that result in a charge concentration along sharp edges. Such a charge concentration would result in isolation breakdown and a short circuit between the body and diaphragm, with adverse effect on sound reproduction.

Third, the direction of sound strongly depends on object shape. Therefore, special care should be taken in using object shapes that allow for the sound directions that are appropriate for the applications where the object is used.

Fourth, the sound level produced by 3D printed speakers is appropriate for small hand-held objects and devices but may not be effective in large scale or outdoor applications unless the size of the diaphragm is significantly increased.

Fifth, the ESR technology and 3D printed speakers are less effective for low frequency sound playback than for medium and high frequency sounds. The human voice, birds, animals, nature sounds, stringed instruments and computer-generated blips are some of the examples of the content that can be effectively reproduced on 3D printed speakers.

In the future we plan on exploring the interactive applications of 3D printed speakers, especially focusing on ultrasonic tracking, tactile feedback and enhancing both of these applications with touch sensitivity. Additional planned research will focus on exploring printed speaker arrays and developing techniques for printing very large printed speakers.

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